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# PERFORMANCE ENHANCEMENT OF WIRELESS COMMUNICATION SYSTEMS THROUGH QOS OPTIMISATION

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Doctor of Philosophy

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## Abstract

Providing quality of service (QoS) in a communication network is essential but challenging, especially when the complexities of wireless and mobile networks are added. The issues of how to achieve the intended performances, such as reliability and efficiency, at the minimal resource cost for wireless communications and networking have not been fully addressed.

In this dissertation, we have investigated different data transmission schemes in different wireless communication systems such as wireless sensor network, device-to-device communications and vehicular networks. We have focused on cooperative communications through relaying and proposed a method to maximise the QoS performance by finding optimum transmission schemes. Furthermore, the performance trade-offs that we have identified show that both cooperative and non-cooperative transmission schemes could have advantages as well as disadvantages in offering QoS.

In the analytical approach, we have derived the closed-form expressions of the outage probability, throughput and energy efficiency for different transmission schemes in wireless and mobile networks, in addition to applying other QoS metrics such as packet delivery ratio, packet loss rate and average end-to-end delay. We have shown that multi-hop relaying through cooperative communications can outperform non-cooperative transmission schemes in many cases. Furthermore, we have also analysed the optimum required transmission power for different transmission ranges to obtain the maximum energy efficiency or maximum achievable data rate with the minimum outage probability and bit error rate in cellular network.

The proposed analytical and modelling approaches are used in wireless sensor networks, device-to-device communications and vehicular networks. The results generated have suggested an adaptive transmission strategy where the system can decide when and how each of transmission schemes should be adopted to achieve the best performance in varied conditions. In addition, the system can also choose proper transmitting power levels under the changing transmission distance to increase and maintain the network reliability and system efficiency accordingly. Consequently, these functions will lead to the optimized QoS in a given network.

Keywords— QoS, cooperative communications, wireless sensor network, device-to-device, vehicle-to-infrastructure.

*To*

*MY DAD's SOUL*

*"This research is for you dad, this is the moment you always dreamed of. You were and you will always be with me in every step in my life because you are one of the main reasons of who I am, I miss you so much"*

*MY LOVING PARENTS*

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# Contents

# Abbreviations

| | |
|---|---|
| WSN | Wireless Sensor Networks |
| V2I | Vehicle-to-Infrastructure |
| V2V | Vehicle-to-Vehicle |
| VRC | Vehicle-to-Roadside |
| D2D | Device-to-Device |
| CUE | Cellular user equipment |
| BS | Base station |
| V | Vehicle |
| S | Source |
| D | Destination |
| I | Infrastructure |
| AODV | Ad-hoc On-demand Distance Vector |
| DSDV | Destination sequenced Distance Vector |
| VANETs | vehicular Ad Hoc networks |
| QoS | Quality-of-service |
| ITS | Intelligent Transportation Systems |
| NS-2 | Network Simulator 2 |
| MIMO | Multiple-Input-Multiple-Output |
| LTE | Long Term Evolution |
| LTE-A | Long Term Evolution-Advanced |
| DTx | D2D transmitter |
| DRx | D2D receiver |
| ISM | Industrial, scientific and medical bands |
| LPWAN | Low-Power Wide-Area Network |
| GPS | Global Positioning System |
| DGPS | Differential Global Positioning System |
| AP | Access point |
| NLOS | Non-line-of-sight |
| LOS | Line-of-sight |
| AWGN | Additive white Gaussian noise |
| SNR | Signal-to-noise ratio |
| bps | bits/second |
| DF | Decode-and-forward |

| | |
|---|---|
| AF | Amplify-and-forward |
| SC | Selection combining |
| MRC | Maximal ratio combining |
| EGC | Equal gain combining |
| SDC | Switched diversity combining |
| MAC | Medium Access Control |
| RC-MAC | Receiver-centric MAC protocol |
| PM | Power management |
| URA-MAC | Upstream resource allocation MAC protocol |
| DCF | Distribution Coordination Function |
| TDMA | Time division multiple access |
| SPBM | Spectrum penetration based multi-channel MAC |
| EDCA | Enhanced Distributed Channel Access |
| WLAN | Wireless local area network |
| CFB | Contention Free Burst |
| IoV | Internet of vehicle |
| PHY | Physical layer |
| FTSHM | Fault-tolerance in structural health monitoring |
| PRR | Packet reception ratio |
| SCMA | Sparse code multiple access |
| RG | Resource group |
| BE | Bandwidth efficiency |
| SE | Spectral efficiency |
| MBAOW | Mobility-based Backoff Algorithm with Optimal Window |
| IEGRP | Infrastructure enhanced geographic routing protocol |
| RSU | Road-Side Unit |
| MISO | Multiple-input–single-output |
| DSM | Distributed Sorting Mechanism |
| SDF | Selective decode and forward |
| S-MAC | Sensor-MAC |
| SYNC | Synchronise packet |
| RTS | Request-to-send |
| RTH | Request-to-help |
| CTS | Clear-to-send |
| ACK | Acknowledgment |
| SIFS | Short inter-frame space |
| DIFS | Distributed inter-frame space |
| CM | Cellular mode |

| | |
|---|---|
| EE | Energy efficiency |
| DR | Achievable data rate |
| DM | Dedicated mode |
| CoopD2D | Cooperative D2D mode |
| *PDR* | Packet Delivery Ratio |
| *PLR* | Packet Loss Rate |
| *E2E* | Average End-to-End Delay |
| OTcl | Object-oriented Tool Command Language |
| TclCL | Tcl/C++ interface |
| AWK | Aho Weinberg Brian |
| IEEE | Institute of Electrical and Electronic Engineers |

# Symbols

| | |
|---|---|
| $C$ | Channel capacity |
| $G_t$ | Transmit antenna gain |
| $G_r$ | Receive antenna gain |
| $\lambda$ | Carrier wavelength |
| $d$ | Distance between transmitter and receiver |
| $L$ | System losses |
| $P_s$ | Transmit power |
| $P_r$ | received power |
| $h$ | Channel coefficient |
| $h_t$ | Transmitted antenna height |
| $h_r$ | Received antenna height |
| $p_{out}$ | Outage probability |
| $\beta$ | SNR threshold |
| $S_{thi}$ | Throughput |
| $E_{bi}$ | Energy per bit |
| $P_{SDir}$ | Direct Transmission Power |
| $d_{SD}$ | Distance between the source *S* and the destination *D* |
| $\gamma_{sd}$ | Pathless between the source *S* and the destination *D* |
| $\alpha$ | Path loss exponent |
| $h_{sd}$ | Channel coefficient of the *S*-*D* link |
| $G$ | Total gain of the transmit and receive antennas |
| $M_l$ | Link margin |
| $N_f$ | Noise figure |
| $U$ | System Reliability |
| $p_{outDir}$ | Outage probability for direct transmission |
| $SNR_{Dir}$ | Signal-to-noise ratio for direct transmission |
| $P_{Sopt}$ | Optimum required transmission power for direct transmission |
| $E_{bDir}$ | Energy consumption per bit for direct transmission |
| $B$ | Channel Bandwidth in Hertz |
| $N$ | The noise spectral efficiency |
| $P_{AM,Dir}$ | The power amplifier consumption for direct transmission |
| $\eta$ | Efficiency of the amplifier |
| $\xi$ | The average peak-to-peak ratio |
| $R_b$ | Bit rate in bits/s |

| | |
|---|---|
| $P_{TX}$ | Transmitting power consumed by the internal circuitry |
| $P_{RX}$ | Receiving power consumed by the internal circuitry |
| $\lambda_{Dir}$ | Lagrangian optimisation factor for the direct transmission scheme |
| $P_{totDir}$ | Total power consumption for direct transmission |
| $P_{Sopt}$ | Optimum required transmission power for the direct transmission |
| $P_{totDirmin}$ | Minimum required transmission power for the direct transmission |
| $P_{AM,,Dirmin}$ | Minimum amplification power for direct transmission |
| $E_{bDirmin}$ | Minimum energy consumption per bit for direct transmission |
| $S_{th}$ | System Throughput |
| $S_{thDir}$ | System Throughput for direct transmission |
| $L_p$ | The average packet payload length |
| $p_s$ | The probability that each node to successfully transmit a DATA packet |
| $p_o$ | The probability that the transmission queue of a node is empty |
| $p_{eDir}$ | Packet error probability for the direct transmission |
| $p_{bDir}$ | System Bit error rate for direct transmission |
| $SNR_{Dir}$ | Signal-to-noise ratio for the direct transmission scheme |
| $N_s$ | Number of transmitted sensor node |
| $T_{SDir}$ | The total time to successfully transmit a packet for the direct transmission scheme |
| $T_{SYNC}$ | The required time to send synchronise packet |
| $T_{rts}$ | The required time to send request-to-send packet |
| $T_{rth}$ | The required time to send request-to-help packet |
| $T_{cts}$ | The required time to send clear-to-send packet |
| $T_{Ack}$ | The required time to send acknowledgement |
| $T_{SIFS}$ | The required time for changing the node's transmit/receive mode |
| $T_{DIFS}$ | The required time before the node went to sleep mode |
| $\Lambda_{Dir}$ | Lagrangian optimisation factor for system throughput in direct transmission |
| Qs | Required QoS |
| $S_{thsopt}$ | Optimum throughput for direct transmission |
| $L_{popt}$ | Optimum average packet payload length |
| $n$ | Number of relays |
| $d_{ij}$ | Distance between node *i* and node *j* |
| $P_{\mathrm{Sij}}$ | Required transmission power node *i* and node *j* |
| $h_{ij}$ | Channel coefficient of the *i*-*j* link |
| $\gamma_{ij}$ | Pathloss between node *i* and node *j* |
| $SNR_{ij}$ | Signal-to-noise ratio between node *i* and node *j* |
| $p_{outMH}$ | Outage probability for multi-hop transmission scheme |
| $p_{outSR_1}$ | Outage probability of the link between the source and first relay |

| | |
|---|---|
| $p_{outR_1R_2}$ | Outage probability of the link between first and second relay |
| $p_{outR_nD}$ | Outage probability of the link between last relay and destination |
| $P_S$ | Source transmission power |
| $P_{R_1}$ | First relay node transmission power |
| $P_{R_n}$ | Last relay node transmission power |
| $\upsilon_{ij}$ | The power coefficient between node $i$ and node $j$ |
| $P_{SD}$ | The transmission power between source-destination |
| $P_{RD}$ | The transmission power between relay-destination |
| $P_{SMH}$ | Required power consumption for multi-hop transmission |
| $P_{AM,MH}$ | The power amplifier consumption for multi-hop transmission |
| $\lambda_{MH}$ | Lagrangian optimisation factor for multi-hop transmission |
| $P_{totMH}$ | Total power consumption for multi-hop transmission |
| $P_{MHopt}$ | The optimum required transmission power for multi-hop transmission scheme |
| $P_{totMHmin}$ | The minimum total required transmission power for multi-hop transmission |
| $P_{AM,MHmin}$ | The minimum amplification power for multi-hop transmission |
| $E_{bMHmin}$ | Minimum energy consumption per bit for multi-hop transmission |
| $S_{thMH}$ | Throughput for multi-hop transmission |
| $p_{eMH}$ | Packet error rate for multi-hop transmission |
| $p_{bSR_1MH}$ | Bit error rate of source-relay link in multi-hop relays |
| $p_{bR_{i-1}R_iMH}$ | Bit error rate of relay-relay link in multi-hop relays |
| $p_{bR_nDMH}$ | Bit error rate of relay-destination link in multi-hop relays |
| $T_{SMH}$ | Total time to successfully transmit a packet for multi-hop transmission scheme |
| $\Lambda_{MH}$ | Lagrangian optimisation factor for system throughput for multi-hop transmission |
| $S_{thMHopt}$ | Optimum throughput for multi-hop transmission |
| $L_{pMHopt}$ | Optimum average packet payload length for multi-hop transmission |
| $r_{SR}$ | The received symbol by relays |
| $r_{RD}$ | The received symbol by the destination from relays |
| $R_S$ | The spectral efficiency |
| $P_C$ | Relay transmission power |
| $h_{SR}$ | The channel coefficients of the source-relay |
| $h_{RD}$ | The channel coefficients of the relay-destination link |
| $K$ | Number of branches |
| $p_{outMB}$ | The outage probability for multiple branches transmission scheme |

| | |
|---|---|
| $P_{SMB}$ | Required power consumption for multiple branches transmission scheme |
| $P_{AM,MB}$ | The power amplifier consumption for multiple branches transmission scheme |
| $\lambda_{MB}$ | Lagrangian optimisation factor for multiple branches transmission scheme |
| $P_{totMB}$ | Total power consumption for multiple branches transmission scheme |
| $P_{MBopt}$ | The optimum required transmission power for multiple branches transmission |
| $P_{totMBmin}$ | Total minimum required transmission power for multiple branches transmission |
| $P_{AM,MBmin}$ | Minimum amplification power for multiple branches transmission |
| $E_{bMBmin}$ | Minimum energy consumption per bit for multiple branches transmission scheme |
| $S_{thMB}$ | Throughput for multiple branches transmission scheme |
| $p_{eMB}$ | Packet error rate for multiple branches transmission scheme |
| $p_{bSDMB}$ | Bit error rate of source-destination link in multiple branches transmission scheme |
| $p_{bSRMB}$ | Bit error rate of source-relay link in multiple branches transmission scheme |
| $p_{bRDMB}$ | Bit error rate of relay-destination link in multiple branches transmission scheme |
| $T_{SMB}$ | Total time to successfully transmit a packet for multiple branches transmission scheme |
| $\Lambda_{MB}$ | Lagrangian optimisation factor for system throughput for multiple branches transmission scheme |
| $S_{thMBopt}$ | Optimum throughput for multiple branches transmission scheme |
| $L_{pMBopt}$ | Optimum average packet payload length for multiple branches transmission scheme |
| $SNR_{MBopt}$ | Optimum Signal-to-noise ratio for multiple branches transmission scheme |
| $p_{outMHB}$ | The outage probability for multiple branches with multiple relays |
| $P_{SMHB}$ | Required power consumption for multiple branches with multiple relays |
| $P_{AM,MHB}$ | The power amplifier consumption for multiple branches with multiple relays |
| $\lambda_{MHB}$ | Lagrangian optimisation factor for multiple branches with multiple relays |
| $P_{totMHB}$ | Total power consumption for multiple branches with multiple relays |
| $P_{MHBopt}$ | The optimum required transmission power for multiple with multiple relays |
| $P_{totMHBmin}$ | The minimum required transmission power for multiple branches with multiple relays |
| $P_{AM,MHBmin}$ | Minimum amplification power for multiple branches with multiple relays |
| $E_{bMHBmin}$ | Minimum energy consumption per bit for multiple branches with multiple relays |

| | |
|---|---|
| $S_{thMHB}$ | Throughput for multiple branches with multiple relays |
| $p_{eMHB}$ | Packet error rate for multiple branches with multiple relays |
| $p_{bSDMHB}$ | Bit error rate of source-destination link in multiple branches with multiple relays |
| $p_{bSR_1MHB}$ | Bit error rate of source-relay link in multiple branches with multiple relays |
| $p_{bR_{i-1}R_iMHB}$ | Bit error rate of relay-relay link in multiple branches with multiple relays |
| $p_{bR_nDMHB}$ | Bit error rate of relay-destination link in multiple branches with multiple relays |
| $T_{SMHB}$ | Total time to successfully transmit a packet for multiple branches with multiple relays transmission scheme |
| $\Lambda_{MHB}$ | Lagrangian optimisation factor for system throughput for multiple branches with multiple relays transmission scheme |
| $S_{thMHBopt}$ | Optimum throughput for multiple branches with multiple relays transmission scheme |
| $L_{pMHBopt}$ | Optimum average packet payload length for multiple branches with multiple relays transmission scheme transmission |
| $\delta$ | The portion of the exclusive resources allocated to the cellular user |
| $EE_{CM}$ | Cellular mode Energy Efficiency |
| $DR_{DM}$ | Cellular mode Achievable data rate |
| $R_{CBCM}$ | Achievable Data Rate of the CUE-BS link in CM |
| $P_C$ | Transmission power of the CUE-BS link |
| $P_o$ | Internal circuitry power consumption of the CUE-BS link |
| $P_D$ | Transmission power of Dtx |
| $P_B$ | Transmission power of BS |
| $R_{DTxB}$ | Achievable data rate at the uplink of the D2D link |
| $R_{BDRx}$ | Achievable data rate at downlink of the D2D link |
| $SINR_{CBCM}$ | The signal-to-noise ratios of the CUE-BS link in CM |
| $SINR_{DTxB}$ | The signal-to-noise ratios of the BS-DRx link in CM |
| $SINR_{DBRx}$ | The signal-to-noise ratios of the BS-DRx links in CM |
| $p_{outCBCM}$ | Outage probability of CUE-BS link in CM |
| $p_{outD2DCM}$ | Outage probability of D2D link in CM |
| $P_{Creq}$ | Required transmission power between CUE-BS link in CM |
| $P_{Dreq}$ | Required transmission power between D2D link in CM |
| $\psi_{CCM}$ | Lagrangian factor for CUE-BS power constraint in CM |
| $\psi_{DCM}$ | Lagrangian factor for D2D power constraint in CM |
| $\Omega_{CCM}$ | Lagrangian factors for power constraint of CUE-BS link in CM |
| $\Omega_{DCM}$ | Lagrangian factors for power constraint D2D link in CM |

| | |
|---|---|
| $R_{DTxB}$ | Achievable data rate at the uplink of the D2D link |
| $R_{BDRx}$ | Achievable data rate at downlink of the D2D link |
| $SINR_{CBCM}$ | The signal-to-noise ratios of the CUE-BS link in CM |
| $SINR_{DTxB}$ | The signal-to-noise ratios of the BS-DRx link in CM |
| $SINR_{DBRx}$ | The signal-to-noise ratios of the BS-DRx links in CM |
| $\gamma_{oij}$ | The path loss constant |
| $p_{outCBCM}$ | Outage probability of CUE-BS link in CM |
| $p_{outD2DCM}$ | Outage probability of D2D link in CM |
| $P_{Creq}$ | Required transmission power between CUE-BS link in CM |
| $P_{Dreq}$ | Required transmission power between D2D link in CM |
| $EE_{DM}$ | Dedicated mode Energy Efficiency |
| $DR_{DM}$ | Dedicated mode Achievable data rate |
| $EE_{CBDM}$ | Energy efficiency the CUE-BS link in DM |
| $R_{CBDM}$ | Achievable rate of the CUE-BS in DM |
| $EE_{D2DDM}$ | Energy efficiency of the D2D link in DM |
| $R_{D2DDM}$ | Achievable data rate of the D2D link in DM |
| $SINR_{CBDM}$ | Signal-to-interference-and-noise ratios of the CUE-BS link |
| $SINR_{D2DDM}$ | Signal-to-interference-and-noise ratios of the D2D link |
| $p_{outCBDM}$ | The outage probability of CUE-BS link in DM |
| $p_{outD2DDM}$ | The outage probability of D2D link in DM |
| $P_{CDMreq}$ | Required transmission power of CUE-BS link in DM |
| $P_{DDMreq}$ | Required transmission power of CUE-BS link in DM |
| $\psi_{DCM}$ | Lagrangian factor for CUE-BS power constraint in DM |
| $\psi_{DDM}$ | Lagrangian factor for  D2D power constraint in DM |
| $\Omega_{CDM}$ | Lagrangian factors for power constraint of CUE-BS link in DM |
| $\Omega_{DDM}$ | Lagrangian factors for power constraint D2D link in DM |
| $EE_{CD}$ | CoopD2D mode Energy Efficiency |
| $DR_{CD}$ | Dedicated mode Achievable data rate |
| $EE_{CBCoopD2D}$ | Energy efficiency the CUE-BS link in CoopD2D |
| $R_{CBCoopD2D}$ | Achievable rate of the CUE-BS in CoopD2D |
| $EE_{CoopD2D}$ | Energy efficiency of the D2D link in CoopD2D |
| $R_{CoopD2D}$ | Achievable data rate of the D2D link in CoopD2D |
| $SINR_{CBCoopD2D}$ | Signal-to-interference-and-noise ratios of the CUE-BS link |
| $SINR_{CoopD2D}$ | Signal-to-interference-and-noise ratios of the D2D link |
| $p_{outCBCoopD2D}$ | The outage probability of CUE-BS link in CoopD2D |
| $p_{outCoopD2D}$ | The outage probability of D2D link in CoopD2D |

| | |
|---|---|
| $P_{CCoopreq}$ | Required transmission power of CUE-BS link in CoopD2D |
| $P_{DCoopreq}$ | Required transmission power of CUE-BS link in CoopD2D |
| $\psi_{CCD}$ | Lagrangian factor for CUE-BS power constraint in CoopD2D |
| $\psi_{DCD}$ | Lagrangian factor for D2D power constraint in CoopD2D |
| $\Omega_{CCD}$ | Lagrangian factors for power constraint of CUE-BS link in CoopD2D |
| $\Omega_{DCD}$ | Lagrangian factors for power constraint D2D link in CoopD2D |
| $P_{VD}$ | Vehicle transmission power in the direct transmission scheme |
| $r_{VI}$ | V2I received symbol |
| $R_{VI}$ | V2Ispectral efficiency |
| $d_{VI}$ | Distance between the vehicle $V$ and the infrastructure $I$ |
| $h_{VI}$ | Channel coefficient of the $V$-$I$ link |
| $SNR_{VI}$ | The Signal-to-Noise Ratio (SNR) in the V-I link |
| $p_{outVI}$ | Outage probability of the direct transmission between vehicles and infrastructure |
| $P_C$ | The internal circuit power |
| $P_{AM,VD}$ | The power amplification for direct V2I transmission |
| $p_{outVI}$ | Outage probability of multi-hop V2I transmission scheme |
| $\lambda_{VD}$ | Lagrangian optimisation factor for direct V2I transmission scheme |
| $P_{VD}$ | Total power consumption for direct V2I transmission |
| $P_{Vopt}$ | Optimum required transmission power for the direct V2I transmission |
| $P_{VDmin}$ | Minimum required transmission power for the direct transmission |
| $P_{totVDmin}$ | The minimum total required transmission power for direct V2I transmission |
| $P_{AM,,VDmin}$ | Minimum amplification power for direct transmission |
| $E_{bVDmin}$ | Minimum energy consumption per bit for direct transmission |
| $p_{outVR_1}$ | Outage probability between the vehicle source and first relay node |
| $p_{outR_nI}$ | Outage probability between the last relay node and infrastructure |
| $P_V$ | Vehicle Transmission power |
| $P_{Vij}$ | Required transmission power between two successive vehicles |
| $P_{AM,VMH}$ | The power amplification of V2I multi-hop transmission |
| $P_{VMH}$ | Required power consumption of V2I multi-hop transmission |
| $\lambda_{VMH}$ | Lagrangian optimisation factor of V2I multi-hop transmission |
| $P_{VMHopt}$ | Optimum required transmission power of V2I multi-hop transmission |
| $P_{totVMHmin}$ | The minimum total required transmission power for multi-hop V2I transmission |
| $P_{VMHmin}$ | Minimum required transmission power of V2I multi-hop transmission |
| $P_{AM,,VMHmin}$ | Minimum amplification power of V2I multi-hop transmission |
| $E_{bVMHmin}$ | Minimum energy consumption per bit of V2I multi-hop transmission |

| | |
|---|---|
| $r_{VR}$ | Received symbol by relay vehicles |
| $r_{RI}$ | Received symbol by the infrastructure from relays |
| $h_{VR}$ | Channel coefficients of vehicle-relay link |
| $h_{RI}$ | Channel coefficients relay-infrastructure link |
| $p_{outVI}$ | Outage probability between vehicle and infrastructure |
| $p_{outVR}$ | Outage probability between vehicle and relay branch |
| $p_{outRI}$ | Outage probability between the relay branch and infrastructure |
| $p_{outVMB}$ | Outage probability of cooperative multiple branches V2I transmission |
| $P_{VMB}$ | Required power consumption of V2I multiple branches transmission |
| $P_{AM,VMB}$ | The power amplification of V2I multiple branches transmission |
| $P_{VMB}$ | Required power consumption of V2I multiple branches transmission |
| $\lambda_{VMB}$ | Lagrangian optimisation factor of V2I multiple branches transmission |
| $P_{VMBopt}$ | Optimum required transmission power of V2I multiple branches transmission |
| $P_{totVMBmin}$ | The minimum total required transmission power of V2I multiple branches |
| $P_{VMBmin}$ | Minimum required transmission power of V2I multiple branches transmission |
| $P_{AM,,VMBmin}$ | Minimum amplification power of V2I multiple branches transmission |
| $E_{bVMBmin}$ | Minimum energy consumption per bit of V2I multiple branches transmission |
| $p_{outVMHB}$ | Outage probability of cooperative multiple branches and relays V2I transmission |
| $P_{VMHB}$ | Required power consumption of multiple branches and relays V2I transmission |
| $P_{AM,VMHB}$ | The power amplification of multiple branches and relays V2I transmission |
| $P_{VMHB}$ | Required power consumption of multiple branches and relays V2I transmission |
| $\lambda_{VMHB}$ | Lagrangian optimisation factor of multiple branches and relays V2I transmission |
| $P_{totVMHBmin}$ | The minimum total required transmission power of multiple branches and relays V2I transmission |
| $P_{VMHBopt}$ | Optimum required transmission power of multiple branches and relays V2I |
| $P_{VMHBmin}$ | Minimum required transmission power of multiple branches and relays V2I |
| $P_{AM,,VMHBmin}$ | Minimum amplification power of multiple branches and relays V2I transmission |
| $E_{bVMHBmin}$ | Minimum energy consumption per bit of multiple branches and relays V2I |

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# Chapter One

# Introduction

In the past decade, wireless communications networks have attracted much attention from the research community, as they have a significant impact on people's everyday life. Through them information can be sent through them easily, efficiently and with minimum infrastructure costs. People and businesses use wireless networks to send and share data quickly, whether they are in an office building or travelling across the world. Another important use of wireless networks is to form rapid and inexpensive connections to the internet in countries and regions where the major telecommunications infrastructures are poor or where a lack of resources exists. Consequently, wireless networks have continued to grow and found a wide range of applications, including web browsing, email and video streaming, which at the same time require improvement to their quality-of-service.

Many wireless communications systems are embedded in people's day to day activities through different applications such as wireless sensor networks (WSN), vehicular networks and cellular networks. WSNs have been deployed widely for both civilian and military applications, such as environmental monitoring, surveillance for safety and security, automated health care, intelligent building control, traffic control and object tracking [1]. It also influences the way we live as they can provide real-time and vital information needed on daily basis [2]. Being able to connect objects and collect data ubiquitously while facing new challenges is the core value of a WSN, more research is needed to address the problems in a large-scale sensor network with limited resources [3, 4] in order to maintain this value.

Vehicular networks normally have vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) communications modes. In vehicular networks mobile users are able to access internet services such as traffic condition broadcast, video streaming, digital map downloading and information of road hazard and accident alarm, via fixed roadside units. The most recent research in this area has been focused on the vehicular ad-hoc networks (VANET) [5, 6], including its connection to the Fourth-Generation or Long-Term Evolution (LTE and LTE-Advance) cellular networks and the provision of good solutions to V2I in order to ensure low latency and high reliability communications [7, 8, 9]. V2I and V2V are also important and relevant applications of the intelligent transportation system (ITS).

As mobile wireless devices and networks become increasingly important, device-to-device (D2D) communications underlaying a cellular network infrastructure have attracted great attention for enhancing the performance of cellular networks and improving the battery lifetime of user equipment (UE) [10, 11]. D2D has been investigated as a promising method for future cellular networks, due to the benefits that it offers over traditional cellular communications [12]; such as reducing signaling overhead or saving the limited resources of local cells and the network as a whole. Existing research in the area has been mainly focused on how D2D communications can run efficiently as an underlay to cellular networks to save energy consumption of UEs and the base station (BS) and improve network performance such as spectral efficiency [13, 14].

## 1.1 Research Motivation

With the increasing demand of quality-of-service (QoS) in wireless communication networks, many requirements are needed in order to satisfy the QoS for wireless communication systems. However, meeting these requirements faces challenges attributed to both physical and resource limitations. These limitations including high loss rates are caused by changes in terrain, multipath fading, Doppler spread, interference, and noise changes in transmission condition such as buildings, environmental factors and other physical structures. This will not only affect network performance but also waste the limited power of the devices involved. Therefore, to provide desirable QoS performance in a wireless communications technology is a big challenge.

QoS in the networking area refers to the capability of a network to provide service differentiation and resource assurance to different streams according to their requirements. The following are some QoS parameters reflecting the service differentiation:

- Throughput: The Desired Bit Rate (bps) or bandwidth.
- Energy Consumption: The energy needed in order to send and receive data.
- End-to-End (E2E) Delay: Delay encountered by a packet, the sum of transmission delay, processing delays (includes router look-up), queuing delay etc.
- Delay Jitter: Variations in E2E delay.
- Packet Loss Rate: The percentage of lost packets due to channel error or queue overflow.
- Packet Error Rate: This is the errors that are present in a packet due to corrupted bits. This should be as low as possible.
- Reliability: The availability of a connection.

Providing QoS guarantees to various applications is an important objective in designing any wireless communication network. Different applications can have very diverse QoS requirements in terms of data rates, delay and packet loss, among others. For example, applications such as power plant control demands reliable and timely delivery of control commands; hence, it is critical to guarantee that no packet is delayed or lost during the packet transmission. This type of QoS guarantees is usually called deterministic or hard guarantees. On the other hand, most multimedia applications including video telephony, multimedia streaming and Internet gaming, do not require such stringent QoS. This is because these applications can tolerate a certain small probability of QoS violation. This type of QoS guarantees is commonly referred to as statistical or soft guarantees. In order to guarantee the variation of QoS required from different applications, we propose an adaptive transmission scheme for three different transmission systems. For each system we study the limitations based on its required QoS, we propose an optimum solution for each system in order to guarantee their required QoS.

Wireless sensor networks have been studied to understand what are the limitations affecting QoS of such networks. WSNs are formed by many sensor nodes, which are capable of collecting, transmitting and receiving data. Building WSNs efficiently poses a considerable technical challenge because of the many constraints imposed by the environment, or by the WSN node capabilities themselves. One of the main challenges faced by the WSNs designers is the finite supply of energy. Since the wireless sensor nodes are battery operated, they need to be as efficient and reliable as possible so that the nodes and hence the network itself do not expire. For example, some environmental monitoring networks and health care sensor nodes must be built with network lifetime on the order of months to years. Excluding the battery replacement (recharging) as an option for networks with thousands of physical embedded nodes, energy efficiency, system throughput and reliability designs are the most important factors that determines the usability of such networks. Although, energy harvesting scheme with a rechargeable battery or with another storage system such as a thin film rechargeable battery or a supercapacitor can be implemented for wireless sensor networks to increase the network lifetime. The research goal in this area is to propose a QoS design for WSN, increasing reliability and throughput while decreasing costs by decreasing the energy wasted by sensor nodes.

Studying WSN was a gateway to studying vehicle-to-infrastructure and vehicle-to-vehicle communication, which are a part of the intelligent transportation system (ITS). The demand for Vehicle-to-Vehicle (V2V) and Vehicle-to-Roadside (VRC) or Vehicle-to-Infrastructure (V2I) communication will continue to grow, as mobile wireless devices and networks become increasingly important. The system must be capable of making automatic or semiautomatic decisions, providing warnings/information and potentially effecting actions, sending and receiving messages in the most efficient and reliable way. This would help in avoiding accidents, reducing traffic congestion, facilitating traffic monitoring and increasing traffic safety. The research goal in this area is to propose an efficient and reliable V2I system, increasing the overall network throughput, increasing packet delivery ratio and decreasing packet loss rate while decreasing the overall energy consumption of V2I.

Additionally, the work has been expanded to cellular networks which include device-to-device communication (D2D) underlaying cellular networks. D2D communications in well-planned cellular networks brings out new technical challenges, including problems of energy efficiency, radio resource management, interference management, enhancing spectral efficiency, coexistence with other techniques and technologies; all these issues should be addressed in order to guarantee the QoS of D2D communications in cellular infrastructure. In D2D overlaid networks, some issues need to be tackled: how to partition the channels with existing cellular users, what is the best cellular transmission mode for each user, the overall system energy efficiency and the overall achievable data rate or throughput. While in the underlay approach, the important challenges include finding new methods to deal with the extra source of interference, i.e., D2D transmissions, as more interference means more transmitting power to overcome the interference. The research goal in this area is to propose an energy-efficient D2D system, as well as determining the best transmission mode of operation, increasing the overall network throughput, increasing the system efficiency with minimum transmitting power, interference and minimum packet loss.

## 1.2 Objectives

This work is aimed to provide a framework which can be used to optimize QoS for wireless communications and networks. It is focused on how to establish appropriate transmission strategies among different commonly used transmission schemes, including both cooperative and non-cooperative schemes. In addition, it intends to reveal the trade-offs between cooperative and non-cooperative transmission schemes and shows how to utilize this property to achieve the optimized performance through adaptive cooperative communications. In order to properly describe how the adaptive systems work and perform, analytical system modes are proposed and formulated in this work as well, based on which appropriate transmission schemes can be decided to optimize system performance under diverse network conditions.

This work targets different wireless communications and networks for the proposed framework to demonstrate the capability of the proposed adaptive strategies and analytical models to optimize QoS in different wireless communications applications. The aimed objectives for each of these scenarios will be discussed in Chapters 3, 4, and 5, respectively.

## 1.3 Methodology

To meet the objectives of this research, investigations are carried out through analytical optimization methods and computer simulation tests. The optimisation methods and their simulations are based on cooperative and non-cooperative transmission schemes that perform in the context of a WSN, cellular and vehicular networks. We also investigate the strengths and limitations of cooperative transmission schemes in comparison with non-cooperative schemes, under different conditions.

In WSN, we intend to find how both cooperative and non-cooperative communications schemes perform in terms of energy efficiency and throughput under different conditions, such as transmission distance, relaying method and channel condition (path loss exponent). For investigating the performance of WSN, different transmission schemes are presented which are direct transmission, multi-hop, cooperative transmission using multiple branches each with one or more relays.

In D2D, we examine the energy efficiency and achievable data rate or throughput performances of three different mobile cellular transmission modes that involve both D2D and cellular user equipment to base station (CUE-BS) communications. Through this investigation we can identify proper transmission schemes for optimising the system performances of the network under varied conditions.

In V2I, we intend to find how both cooperative and non-cooperative communications schemes perform in terms of energy efficiency, throughput, packet delivery ratio and packet loss rate under different vehicular communications scenarios, such as transmission distance, relaying method and path loss. For investigating the performance of V2I, different transmission schemes are presented such as direct transmission, multi-hop, cooperative transmission involving multiple branches and single or multiple relays.

Analytical methods specify the mechanisms of system performance optimisation which are verified by simulations. The results obtained from experimental tests can help refine the theoretical and simulation models accordingly. Those refined models can then be used to build an intelligent adaptive transmission system which can decide the appropriate and efficient transmission schemes to be adopted in a dynamic manner.

## 1.4 Novelty and Contributions

In this research, we investigate new adaptive transmission schemes using optimisation methods in order to determine the best transmission scheme based on environmental conditions. Their goal is to enhance QoS for three different wireless communication systems namely WSN, cellular networks and V2I. In order to achieve QoS provisioning objectives in wireless communication networks, we have made the following contributions:

1. WSN requires hard constraints on energy consumption due to network lifetime. Firstly, we target the reduction of the energy consumption for each node or the increment of the overall system throughput. We propose adaptive intelligent transmission nodes, which are capable of choosing the efficient required transmission scheme through analytical modelling and simulation of outage probability, optimum required transmission power,

optimum energy consumption and optimum throughput for four different transmission schemes based on transmission distance between any source (S) and destination (D) and based on WSN constraints.

2. Then, we propose an adaptive transmission scheme in order to increase the energy efficiency and the throughput of cellular networks. Therefore, we apply analytical modelling of three different mobile cellular transmission modes that accommodate device-to-device (D2D) and cellular user equipment (CUE) to base station (BS), and perform simulation of outage probability, optimum required transmission power, optimum energy consumption and optimum achievable data rate for them.
3. Analytical modelling and simulation of outage probability, optimum required transmission power, optimum energy consumption for four different transmission schemes based on transmission distance between any vehicle (V) and infrastructure (I) in V2I networks are proposed. As V2I requires reliable and efficient system, we target the reduction of the energy consumption by each vehicle. Based on the proposed analytical model we implement the results in NS-2 in order to evaluate the overall system throughput, packet delivery ratio, packet losses and average end-to-end-delay.

In this research, we investigate the strengths and limitations of three wireless communication networks. These findings are used to identify proper transmission schemes that can optimise the system performance for the whole network under varied environmental conditions. In addition, we derive the closed form outage probability that contributes to the models for the energy efficiency and throughput. The proposed approach is unique in the sense that it provides an efficient way to find the best transmission scheme between any source-destination pairs.

## 1.5 Outline

We have investigated different analytical models for various transmission schemes applying to WSN, cellular networks and V2I. The system performance of WSN and cellular networks is evaluated using Matlab and the system performance of V2I is evaluated using Matlab and NS-2. With computer simulation, we have carried out their performance evaluation in terms of overall energy consumption, energy efficiency, overall system throughput, bit error rate, packet delivery ratio, packet loss and outage probability considering several scenarios under different conditions. In the rest of this dissertation, the following chapters are presented:

In Chapter 2, the classification and background of some wireless communication systems has been described briefly. In addition, the wireless channel characterisations have been studied including propagation models, path loss models, channel capacity and outage probability. Additionally, some of the most well-known wireless communications technologies such as diversity, multiple-input-multiple-output, cooperative communications and medium access control have been presented. Finally, the limitations of some wireless communication systems have been described.

Chapter 3 focuses on the performance evaluation of WSN. The investigation of the strengths and limitations of cooperative transmission schemes in comparison with non-cooperative schemes in the context of a multi-hop WSN has been presented in this chapter. The numerical approaches and performance analysis of adaptive transmission schemes have been presented as well. Also, the closed form of the outage probability, energy consumption and throughput are derived for both cooperative and non-cooperative communications under different conditions, such as transmission distance, relaying method and channel condition (path loss exponent). In addition, we proposed a possible adaptive transmission scheme, which enhances QoS. The performance analysis is then presented for the proposed optimum transmission schemes in terms of the minimum energy consumption or maximum system throughput for WSN. The results obtained from the analytical and simulation models show that either cooperative or non-cooperative transmission schemes can be used to achieve the highest energy efficiency depending on certain environmental conditions such as the channel quality or transmission range. Furthermore, the energy-throughput trade-off has been analysed and finally an adaptive transmission scheme has been presented and explained.

In Chapter 4, we examine of the energy efficiency and achievable data rate or throughput performances of three different mobile cellular transmission modes which involve both D2D and CUE-to-BS (or CUE-BS) communications. In addition, the numerical approaches and performance analysis have been presented for the proposed adaptive transmission schemes. Also, the closed form outage probability, energy consumption and throughput formulas are derived under different conditions, such as transmission distance, relaying method and channel conditions. The performance analysis of the proposed optimum transmission schemes is then presented in terms of the maximum energy efficiency and overall achievable data rate, minimum outage probability and bit error rate for three different cellular networks. The results of the analytical and simulation model indicate how the problem of interference between D2D communications and other existing communication links (CUE-BS) can be properly solved. Based on these results and findings energy-throughput trade-off has been analysed. Furthermore, proper transmission schemes that can optimise the QoS for the whole network in varied environmental conditions are proposed.

Chapter 5 focuses on the enhancement of QoS for vehicular networks. The numerical approaches and performance analysis have been presented for the proposed adaptive transmission schemes for V2I. Both cooperative and non-cooperative transmission schemes have been investigated. This chapter reveals how these schemes perform in the context of a vehicular network, in terms of energy consumption, throughput, packet delivery ratio, packet loss rate and average end-to-end-delay under different conditions such as transmission distance, relaying method and channel conditions. Also, the closed forms of outage probability, energy consumption are derived for both schemes under different environmental conditions, such as transmission distance, relaying method and channel conditions. Additionally, the proposed approach is unique in the sense that it provides an efficient way to find the best transmission method for the transmission between any V2I links. The proposed method facilitates V2I communications, which is assisted by vehicle-to-vehicle (V2V) communications when needed, and evaluates the performance of this approach based on the models we derive. The results show that both cooperative and non-cooperative transmission schemes can exhibit the best performance under certain environmental conditions. Based on the results obtained from the analytical and simulation models, adaptive transmission schemes can be formed. This adaptive transmission strategy is able to select an appropriate transmission scheme in a changing environment to maintain the best QoS performance in a dynamic way, in terms of achieving the highest throughput with a fixed energy budget or the lowest energy cost for a given throughput target.

The conclusions and the contributions of this work and recommendations for future research are given in Chapter 6.

# Chapter Two

# Background On Wireless Communication Networks

Recent years have seen an increasing interest in wireless communication networks, as wireless networks play a crucial role in communication systems nowadays. Providing QoS guarantees to various applications is an important objective in designing any wireless communication system. Different applications can have very diverse QoS requirements in terms of data rates, delay bounds and delay bound violation probabilities, among others.

To support QoS guarantees, two general approaches have been proposed. The first approach is network-centric. That is, the routers, switches and base stations in the network are required to provide QoS support to satisfy data rate, bounded delay and packet loss requirements requested by applications. The second approach is solely end-system-based that does not impose any requirements on the network. In particular, the end systems employ control techniques to maximise the application-layer quality without any QoS support from the transport network.

## 2.1 Classification of Wireless Communication Networks

Many types of wireless communication systems exist, but a distinguishing attribute of a wireless network is that communication takes place between sensor nodes, vehicles, computers and devices such as mobiles. There are many types of wireless communication systems that fall into several categories, which will be discussed in the following subsections.

### 2.1.1 Cellular Networks

A cellular network, as illustrated in Figure 2.1, is a radio network, which consists of a number of cells where each cell is served by fixed location transceiver known as base station (BS). These cells together provide radio coverage over a wider area than the area of one cell. Therefore, cellular user equipments (CUEs) are able to communicate during transmission while moving through different cells. Cellular networks give users advanced features over alternative solutions, including:

- Increased capacity.
- Small battery power usage.
- A larger geographical coverage area.

- Reduced interference from other signals.

Additionally, it has some special requirements such as:

- The required infrastructure or base station must include switches for call forwarding from one cell to another, location registers etc.
- The mobile station has to perform a handover when changing from one cell to another very frequently.
- To avoid interference, each cellular user has to use different set of frequencies.

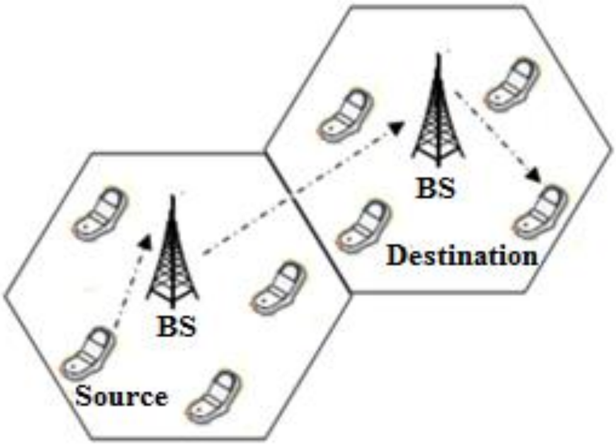



Figure 2.1: Wireless cellular networks

LTE (Long Term Evolution) also known as 4G refers to wireless broadband or mobile network technologies, which are designed to support roaming internet access via cell phones and handheld devices. It refers to a standard for smooth and efficient transition toward more advanced leading-edge technologies to increase the capacity and speed of wireless data networks [15]. LTE offers significant improvements over older cellular communication standards. The issues that make LTE distinct from other wireless cellular systems are the following:

- The cellular providers have the opportunity to offer data access to a wide variety of devices.
- Allows more users to utilise the same frequency, increasing the overall number of users who are able to access the technology.
- More flexible.
- More reliable.
- Higher bandwidth.
- Better overall end user experience than 3G network.

Additionally, there are some deficiencies in LTE such as:

- Involves the possibility of some interference.

- Capable of being attacked (jamming frequencies) and the invasion of the privacy increased.
- Needs complex hardware.
- Requires expensive infrastructure for operation.

LTE-Advanced (LTE-A) is a cellular network that offers a more advanced set of standards and technologies that will enable the delivery of higher and faster wireless data payloads. The most important thing to know is that LTE-A promises to deliver true 4G speeds, unlike current LTE networks, as the real-world speed of LTE-A can be two to three times faster than today's LTE. It should also be robust, with fewer dropped connections as you move around. Mobile users may use LTE-A to increase the network capacity. LTE-A networks use multiple-input, multiple-output (MIMO) technology [16] to meet the increasing demand of future wireless systems. MIMO requires multiple antennas to receive those signals, which can limit its use in compact mobile devices such as smartphones and tablets.

### 2.1.2 Device-to-Device Communications (D2D)

In the conventional cellular transmission mode, the cellular user equipment (CUE) first transmits its data to the BS using uplink resources; then the BS forwards the data to the corresponding receiver using downlink resources. However, if the transmitting CUE and the receiving CUE are in close proximity to each other, the BS can allow the users to directly communicate with each other; this is referred to as D2D communications, see Figure 2.2.

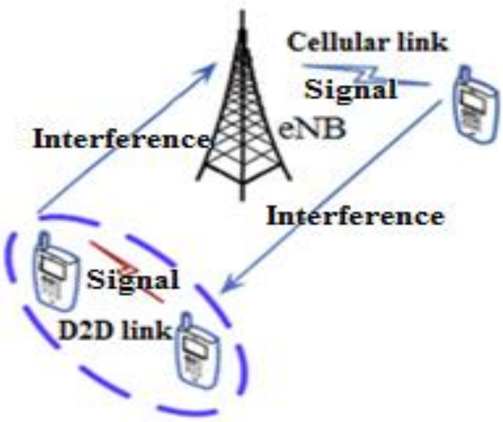



Figure 2.2: D2D communications

D2D communications normally take place through a direct and reliable link between D2D devices to satisfy the quality-of-service (QoS) requirement for both the D2D links and the cellular system simultaneously. In terms of spectrum resources, they are further divided into two categories, which are inband and outband D2D transmissions [17] as shown in Figure 2.3.

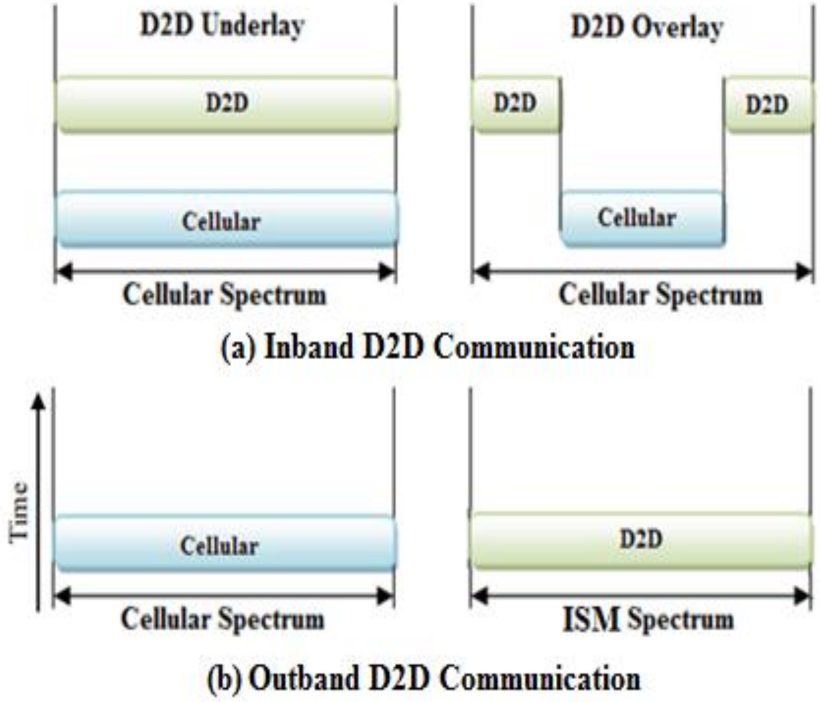



Figure 2.3: Inband and outband D2D communications

- In inband D2D communications, the communication occurs under licensed spectrum, where the cellular spectrum is used for D2D and cellular links as shown in Figure 2.3 (a). In addition, there is high control on the cellular spectrum. The inband D2D communications consists of two different categories, device-to-device underlay cellular networks and device-to-device overlay cellular networks.
    - Device-to-Device underlay cellular networks: In D2D underlay cellular networks, direct D2D and cellular user use the same network resources, which causes interference between receiver D2D (DRx) with transmitter cellular user equipment (CUE) and transmitter D2D (DTx) with the base station (BS). This interference can be reduced by introducing different high complexity resource allocation methods, which increase the computational overhead of the BS or D2D users.
    - Device-to-Device overlay cellular networks: In D2D overly cellular networks, D2D communications links are given dedicated cellular resources which are subtracted from cellular users in order to eliminate interference for the D2D communications on cellular transmissions.

The advantages of using inband D2D communications are:

- Any cellular device is capable of using inband D2D communications because it is licensed.

- QoS is more achievable because the cellular spectrum can be managed by the base station.
- Underlay D2D communications increases the spectral efficiency that is why it is more popular than the overlay D2D communications.
- The transmission range can reach 1km using multiple D2D links.

Additionally, in inband D2D communications there are some deficiencies, which are:

- The cellular resources wasted by the overlay D2D communications.
- The interference caused by the D2D and cellular links in underlay D2D communications.

- In outband D2D communications, the communication occurs under unlicensed spectrum, such as industrial, scientific and medical (ISM) bands as shown in Figure 2.3 (b). It aims to eliminate the interference issue between D2D and cellular links. In addition, it requires an extra interface usually using Wifi, Zigbee or Bluetooth. It is classified into two categories, controlled and autonomous.
    - Controlled outband D2D communications, in which the coordination between radio interfaces controlled by the base station.
    - Autonomous outband D2D communications, in which the base station has no control over D2D communications, the coordination between radio interfaces is by the cellular users themselves.

The advantages of using an outband D2D communications are:

- The elimination of the interference between D2D and cellular links, as D2D communications occurs under unlicensed spectrum.
- Users can have cellular and D2D transmissions simultaneously.

In addition, there are some special requirements such as:

- More power consumption due to the need of extra interfaces.
- Lower transmission range.
- Lower transmission data rate.

### 2.1.3 Wireless Sensor Networks (WSNs)

A wireless sensor network (WSN) is a wireless network consisting of number of distributed nodes or devices using sensors. These sensor nodes are connected to the base station through a gateway sensor node as shown in Figure 2.4 to monitor physical or environmental conditions like temperature, pressure, humidity, or location of objects, processing the data gathered and communicating over the network to the monitoring station. In addition, they have to cooperate to fulfill their tasks. Sensor nodes use wireless link nodes to communicate and collaborate with each other. WSN's are a category of wireless networks that are used to connect wireless sensor node without an infrastructure. The activity of sensing can be periodic or sporadic [18, 19].

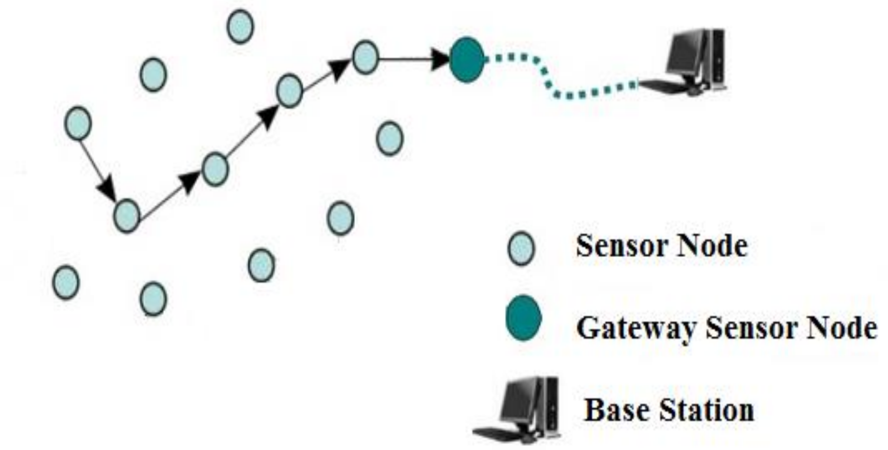



Figure 2.4: Wireless sensor networks architecture

The issues that make WSNs distinct from other wireless communication systems are as follows:

- Sensor networks consist of a large number of sensor nodes that have to scale several orders of magnitude more than ad-hoc networks and thus require different and more scalable solutions.
- Due to the nature of WSN, the data rate is expected to be very low.
- A sensor network is usually deployed by a single owner.
- The inquiries in a sensor network are directed to nodes that have data satisfying certain conditions and unique addressing is not possible as they do not have global identifiers, that is why sensor networks are data centric.
- Most of the sensor nodes are generally stationary and are usually deployed once in their lifetime.
- Sensor nodes are designed for self-configuration, but the difference in traffic and energy consumption requires varied solutions. One of the most important metrics to be considered is energy consumption. Sensor nodes have limited power supply and recharge of power is impractical considering the large number of nodes and the environment in which they are deployed.
- A customised solution for each application problem is needed, because sensor networks are application specific.

- LPWAN has been designed for WSN to allow a long range communications at a low bit rate.
- Since there is a restriction on energy consumption in WSN, the communications and the computational software must be more efficient than traditional software used for the same purpose.
- WSN simply can be integrated into internet of things.

The advantages of wireless sensor networks might be summarised in the following [20]:

- WSN doesn't need the existence of a fixed infrastructure.
- The reachability of previously non-reachable places such as over the sea, mountains, rural areas or deep forests.
- Flexibility in adding additional workstation as needed.
- Cheap implementation costs.
- Elimination of excessive wiring requirements.
- New devices might be accommodated at any time.
- The easy of expansion and reduction of the coverage area.

The deficiencies of wireless sensor networks can be summarised as follows [20]:

- Hackers can hack the access point and obtain all information making WSN less secure.
- Compared to wired network, WSNs have lower speeds and are more complicated to configure.
- It can be negatively affected by surroundings (walls, microwave, large distances due to signal attenuation, etc).

### 2.1.4 Vehicular Communication Networks

In vehicular communication networks, each vehicle sends, receives and routes to broadcast information to the vehicular network or transportation agency, which uses the information to ensure safe, free-flow of traffic. Vehicles must be equipped with some sort of radio interface (e.g., LTE, Wifi) or OnBoard Unit (OBU) in order to establish the communication between vehicles and infrastructure, which enables short-range wireless ad hoc networks to be formed. In addition, a Global Positioning System (GPS) or a Differential Global Positioning System (DGPS) receiver must also be fitted in vehicle for permitting detailed position information. To facilitate the communication between vehicle and infrastructure, infrastructure should be fixed, as it is connected to the backbone network. The communication protocol used is based on the number and distribution of infrastructure [21]. For example, some protocols require infrastructure to be distributed evenly throughout the whole road network, some require infrastructure only at intersections, while others require infrastructure only at region borders. Though it is safe to assume that infrastructure exists to some extent and vehicles have access to it intermittently, it is unrealistic to require that vehicles always have wireless access to infrastructure. The possible communication configuration in vehicular communication networks are vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) as shown in Figure 2.5.

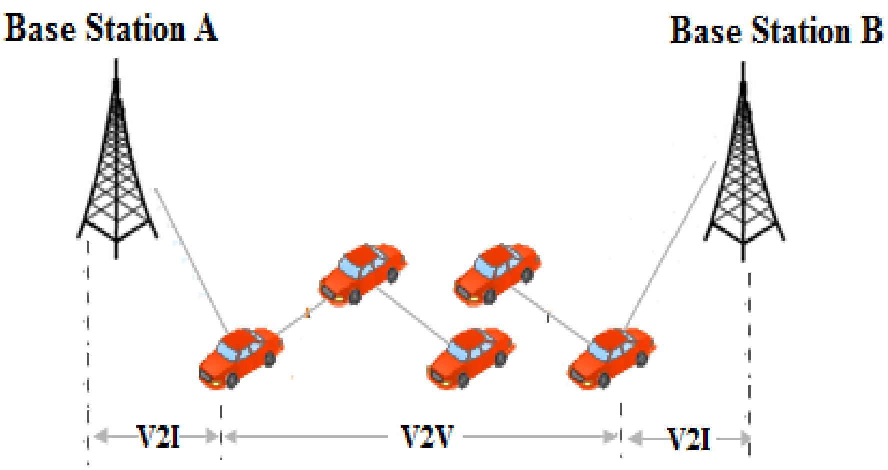



Figure 2.5: Vehicular communication networks

- Vehicle-to-Vehicle communication approach is most suited for short range vehicular networks, as it is considered to be a fast and reliable communication approach. It does not need any roadside or infrastructure. However, the connectivity between vehicles may not be available all the time since the vehicles are moving with different velocities which need quick network topology changes. In addition, it is the receiver's responsibility to decide which messages are considered as emergency and decide on appropriate actions. Without any roadside infrastructure, multihop forwarding must be enabled to propagate the messages or signals between V2V nodes [22].
- Vehicle-to-Infrastructure communication approach is most suited for long range vehicular networks. It makes use of the preexisting network infrastructure such as wireless access points (AP). The information from infrastructure (or base station) to vehicle as well as the information from vehicle to server connected to AP or base station are received through the V2I technique. In V2I communication, the continuity and reliability of transmit processing are still critical problems. Due to the high-speed mobility of vehicles and frequent hand-off, the connection between vehicle and the infrastructure is not always stable [23].

## 2.2 Wireless Channel Characterisations

The term channel refers to the medium between the transmitter and receiver. The major purpose of channel characterisation is in the design and planning of communication systems. Wireless communication channels are usually described by considering several separable phenomena, namely, channel propagation model, path loss model, wireless channel capacity formulation and outage probability. In the following, we briefly overview various efforts to characterise such aspects of wireless communication channels and describe why they are important.

### 2.2.1 Channel Propagation Models

A signal, as it travels through the wireless channel, undergoes many kinds of propagation effects such as reflection, diffraction and scattering, due to the presence of buildings, mountains and other such obstructions as shown in Figure 2.6. The propagation models are developed to predict the loss of signal strength or coverage in a particular location. The characteristic, which defines the wireless channel, is the channel strength variations over time and over frequency, such as propagation environment, interference and noise. These variations can be divided into two types as follows [24]:

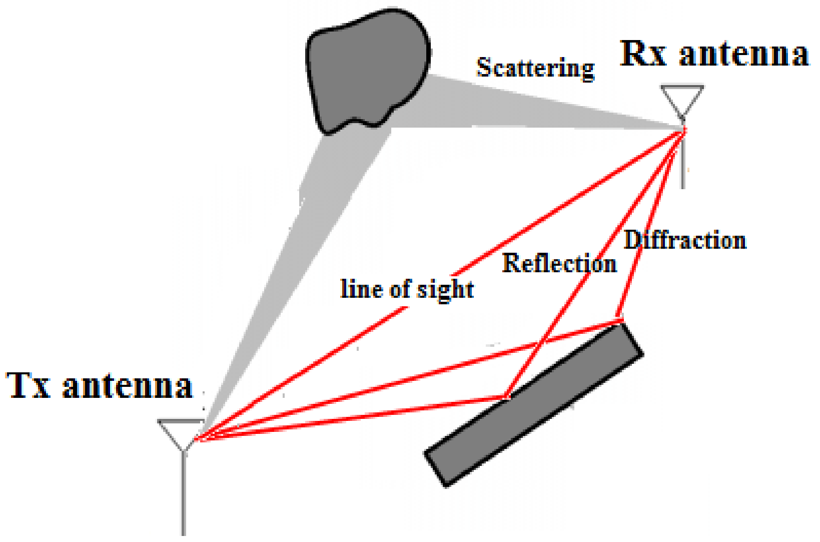



Figure 2.6: Wireless channel propagation

- Large-scale fading, usually is defined as the average signal power attenuation or path loss due to motion over large areas. This depends on shadowing which is the presence of obstacles in the signal path and on the path loss, which is the position of the device unit and its distance from the transmitter. Hence, the combined effect between shadowing and path loss refers to large-scale fading. The statistics of large-scale fading provide a way of computing an estimate of path loss as a function of distance.
- Small-scale fading refers to rapid or dramatic changes in signal amplitude and phase that can be experienced over short period of time or distance as a result of small changes in the spatial separation between a receiver and transmitter. It is caused by interference between two or more versions of the transmitted signal, which arrive at the receiver at different times. The two most important small-scale fading effects are the multi-path fading, which is the reception of multiple copies of the same signal as shown in Figure 2.7, which has been attenuated, and phase shifted, and the Doppler shift which is the shift in received signal

frequency due to motion. Small-scale fading can follow Rayleigh probability distribution or Rician probability distribution; this will depend on the strength of scattering components during transmission.

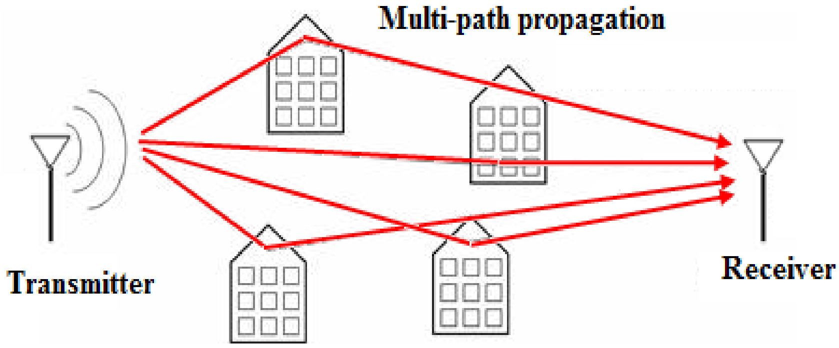



Figure 2.7: Multi-path propagation

- Rayleigh Fading Channel: The amplitude of a channel is modelled as zero-mean complex Gaussian random process having a Rayleigh distribution. Such channels occur when there is non-line-of-sight (NLOS) between transmitter and receiver. This type is also called flat fading channel.
- Rician Fading Channel: The amplitude of a channel is modelled as zero-mean complex Gaussian random process having a Rician distribution. Such channels occur when there is line-of-sight (LOS) between transmitter and receiver.

### 2.2.2 Path Loss Models

Path loss is one of the parameters that affect any wireless channel. Path loss is defined as the ratio between the transmitted power $P_s$ to the received power $P_r$ [25, 26, 27].

$$P_L = \frac{P_s}{P_r} \qquad (2.1)$$

It also represents the signal attenuation caused by the free space propagation, scattering, reflection and diffraction. An efficient design for any wireless system requires that the path loss exponent should be accurately estimated as it has a strong impact on the quality of the link and on the overall network performance [28].

We can also define the path loss of the channel as the difference in dB between the transmitted signal power and received signal power:

$$P_L[dB] = 10\log_{10}\left(\frac{P_s}{P_r}\right) \qquad (2.2)$$

In general path loss is a nonnegative number since the channel does not contain active elements, and thus can only attenuate the signal. The path gain in dB is defined as the negative of the path loss:

$$P_G = -P_L = 10\log_{10}\left(\frac{P_r}{P_s}\right) \tag{2.3}$$

Three of the most important path loss models that should be addressed as they have a strong impact on the wireless communication and networks are Friis free space path loss model, two ray path loss model and log-normal shadowing model.

In Friis free space model, a signal propagates along a straight line between transmitter and receiver without attenuation or reflection following the free space path propagation law [27]. The corresponding received signal is called the LOS signal or ray, because the channel model associated with this transmission is called a LOS channel. In this channel the path loss is based on the received signal power, which is inversely proportional to the square of the distance *d* between transmit and receive antennas.

$$P_r \,\alpha\, \frac{1}{d^2} \tag{2.4}$$

The received power is obtained by the following equation:

$$P_r = P_s \frac{G_t G_r \lambda^2}{(4\pi d)^2 L} \tag{2.5}$$

where $G_t$ and $G_r$ are the gains transmit and received antennas, $\lambda$ is the carrier wavelength in meters and $L$ represents other system losses such as transmission line attenuation. In this model $L$=1 because there is no such system loss. Then, the path loss and the gain of the free-space model can be written as:

$$P_L[dB] = 10\log_{10}\frac{P_s}{P_r} = 10\log_{10}\left(\frac{(4\pi d)^2}{G_t G_r \lambda^2}\right) \tag{2.6}$$

$$P_G = -P_L = 10\log_{10}\frac{P_r}{P_s} = 10\log_{10}\left(\frac{G_t G_r \lambda^2}{(4\pi d)^2}\right) \tag{2.7}$$

In the two-ray model, a signal propagates between transmitter and receiver considering both the direct path and the ground reflection path follow the two ray path propagation law [27]. The received signal consists of two components: the LOS component or ray, which is just the transmitted signal propagating through free space and a reflected component or ray, which is the transmitted signal reflected off the ground as shown in Figure 2.8.

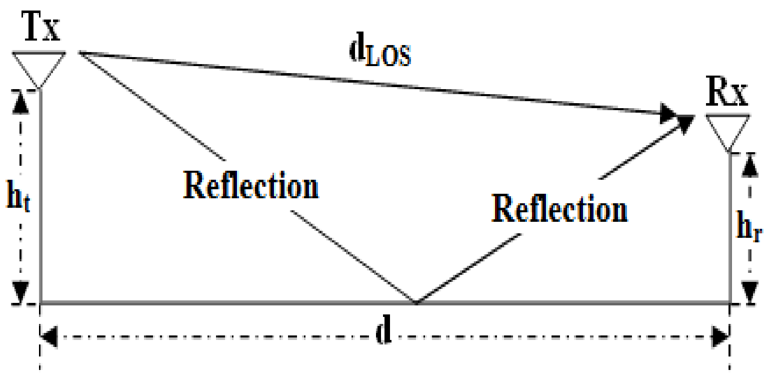



Figure 2.8: Two-ray path loss model

It is shown that this model gives more accurate prediction compared to the free space model for long distances [25]. Thus, the received power of the two-ray model at distance *d* is predicted by:

$$P_r = P_s \frac{G_t G_r h_t^2 h_r^2}{d^4 L} \tag{2.8}$$

where $h_t$ and $h_r$ are the height of transmit and received antennas. The above equation shows a faster power loss than Equation 2.5 as distance increases. However, due to the variation in the signal caused by the constructive and destructive combination of the two rays model, it does not give a good result for a short distance. Instead, the free space model is still used when *d* is small. Then, the path loss and the gain of the two-ray model can be written as:

$$P_L[dB] = 10\log_{10}\frac{P_s}{P_r} = 10\log_{10}\left(\frac{d^4}{G_t G_r h_t h_r \lambda^2}\right) \tag{2.9}$$

$$P_G = -P_L = 10\log_{10}\frac{P_r}{P_s} = 10\log_{10}\left(\frac{G_t G_r h_t h_r \lambda^2}{d^4}\right) \tag{2.10}$$

In the log-normal shadowing model, the Log distance path loss model is a generic model and an extension to the Friis free space model. As long as, the Friis free space model is restricted to an unobstructed or direct clear path between transmitter and receiver. The log normal shadowing model is used to predict the propagation loss for a wide range of environments. It is considered as a statistical model for variations on the received signal amplitude due to many factors contributing to the overall path loss such as diffraction, combinations of free space loss, reflection, transmission, etc. Each of these losses or variations can be modelled as a random variable, $X_\sigma$, which has a Gaussian distribution. When $X_\sigma$ is expressed in dB, it has zero mean and standard deviation $\sigma$ dB. Usually the shadowing effect cannot be neglected in order to model real environments. The path loss becomes a straight line if the shadowing effect is neglected. A zero-mean Gaussian random variable with standard deviation $\sigma$ must be added to the equation to show the shadowing effect. The actual path loss may still vary due to other factors, that is why the path loss exponent and the standard deviation of the random variable should be known precisely for better system design and modelling. The path loss of the log-normal path loss model can be expressed as [27]:

$$PL[dB] = PL(d_o) + 10\alpha \log_{10}\left(\frac{d}{d_o}\right) + X_\sigma \qquad 0 \le d_o \le d \tag{2.11}$$

where $PL(d_o)$ is considered as a path loss at a reference distance $d_o$ in dB, $d_o$ must be less than or equal to the distance between the transmitter and receiver and α is the path loss exponent. The path loss exponent is an important parameter which affects system performance drastically. Therefore, in designing and modelling any system, the estimation of the path loss exponent for the given environment must be taken into consideration. Path loss exponent estimation is done by equating the observed (empirical) values over several time instants to the established theoretical values.

### 2.2.3 Wireless Channel Capacity Formulation

After the explanation of the wireless channel propagation and the path loss models, it is important to measure the optimal performance achievable on a given wireless channel. The basic measure of the performance is the capacity of a channel. The capacity of the channel is defined as the maximum rate of communication for which an arbitrarily low probability of error can be achieved.

When considering an additive white Gaussian noise (AWGN) channel with input signal *s*, output signal *y* and additive white Gaussian noise random process *n* with zero-mean and variance *V*, $n \sim N(0, V)$. The output signal at the receiver can be written as:

$$y = \sqrt{P_s\, d^{-\alpha}}\, c\, s + n \tag{2.12}$$

where $P_S$ is the transmitting power and *d* is the distance between sender and receiver, $\alpha$ is the path loss exponent and *c* is a constant of proportionality.

Assume a channel bandwidth *B* and signal to the noise ratio (SNR) which is equal to the ratio between the input signal power and the noise power is given by:

$$SNR = \frac{P_s}{N_o\, B} \tag{2.13}$$

where $N_o$ is the power spectral density of the noise. Then the capacity of this channel is given by Shannon's well-known formula [29]:

$$C = B \log_2 [1 + SNR] \tag{2.14}$$

where the unit of the capacity is bits/second (bps). Shannon's coding theorem proves that a code exists that achieves data rates arbitrarily close to the capacity with an arbitrarily small probability of bit error. The converse theorem shows that any code with rate $R > C$ has a probability of error bounded away from zero.

When considering flat fading channels where all frequency components of the signal will experience the same magnitude of fading because the coherence bandwidth of the channel is larger than the bandwidth of the signal. Since the channel coefficient is a random parameter, the capacity of a fading channel is random as well. For a given channel realisation with channel coefficient $h$, the output signal at the receiver can be written as:

$$y = \sqrt{P_s d^{-\alpha}} h s + n \qquad (2.15)$$

where $P_S$ is the transmitting power and $d$ is the distance between sender and receiver, $\alpha$ is the path loss exponent and $n$ is an additive white Gaussian noise random process with zero-mean and variance $V$. Then the capacity of this channel is given [29]:

$$C = B \log_2 [1 + SNR |h|^2] \qquad (2.16)$$

### 2.3.4 Outage Probability

Outage probability is a key figure of merit in wireless communications. Fading channels always lead to an variable SNR at different locations, especially for mobile users which experience rapid variation in SNR, due to their mobility. The characteristics of the channel and the computation of the bit error rate (BER) can be obtained by using the average SNR. For many applications, BER is not the primary concern as long as it is below a certain threshold. A more realistic measure is the outage probability. Outage probability is commonly defined as the probability that the signal-to-noise ratio (SNR) of a received signal is below a given threshold.

Outage probability, $P_{out}$, is the percentage of time that an acceptable quality of communication is not available. $P_{out,}$ can be calculated by the minimum SNR for the system to work properly. From the minimum acceptable BER, the minimum SNR, $\varepsilon_{min}$, can be calculated; in this case the outage probability can be expressed as:

$$P_{out} = \Pr(\varepsilon \prec \varepsilon_{\min}) = \int_0^{\varepsilon_{\min}} P_\varepsilon(\varepsilon) d\varepsilon \qquad (2.17)$$

where $P_\varepsilon(\varepsilon)$ is the pdf of $\varepsilon$. For the frequency-flat Rayleigh fading channel the signal to noise ratio is expressed as:

$$\varepsilon = \frac{P_s |h|^2}{N_o\ B} \tag{2.18}$$

Then the outage probability can be written as [30]:

$$P_{out} = 1 - e^{-\left(\frac{\varepsilon_{\min} P_s |h|^2}{N_o\ B}\right)} \tag{2.19}$$

# 2.3 Wireless Communication Technologies

Wireless communication technologies are various technologies presented by different researchers which can be implemented to improve the performance of the wireless communication systems. Wireless communication technologies utilise channel properties to send data between any source and destination to enhance system performance for example multiple-input-multiple-output exploits the spatial properties of the channel to improve performance. Such technologies can be used to enhance the received signal by decreasing the error in the received signal, increase system reliability and improve the QoS of the whole networks. There are different type of wireless communication technologies that should be studied in order to enhance the system performance such as diversity techniques, multiple-input-multiple-output and cooperative transmission.

## 2.3.1 Diversity Technique

The basic concept of diversity is transmitting the signal through several independent branches to obtain multiple signal replicas. Diversity schemes provide two or more signals at the receiver such that the fading among these signal are uncorrelated as shown in Figure 2.9. For example, if one of the received signals undergoes deep fade at a particular point in time, another independent path may have a proper signal at the receiver. Then if the probability of a deep channel fade is $p$ and there is $R$ independent channels, so the probability will be $P^R$, which decreases the probability of link failure compared to using only one channel. It can be deduced that diversity techniques requires multiple branches and low correlation between branches for enhancing system performance.

Diversity technique can be implemented by different means as follows [31]:

- Frequency selective diversity: consists of $R$ independent channels with frequency separation exceeding the coherence bandwidth. It needs only one antenna and the transmitted power splits among carriers.
- Space diversity: consists of $R$ independent antennas which are used at the receiver to obtain uncorrelated fading channel at the receiver, the total transmitted power will be split among the transmitted antennas.

- Time diversity: consists of $R$ separated time slot or different period of time, each signal will be transmitted at a different time slot. In this type the interval between the transmission of the same symbol must be at least coherence time. It will cause reduction of efficiency, because the effective data rate will be less than the actual data rate.
- Polarisation diversity: receiving multiple copies of the signal with different field polarisation, but this type of diversity needs unequal transmitting power among branches and has less diversity gain.

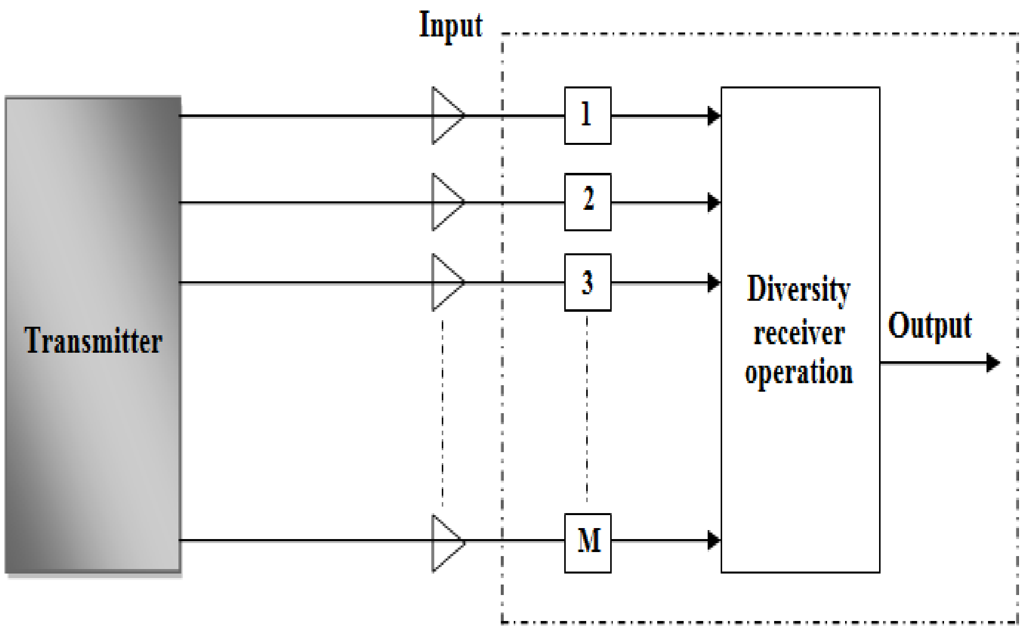



Figure 2.9: Diversity technique

In addition, there are four different diversity combining techniques that must be addressed which are [31]:

- Selection combining techniques (SC): the basic concept of this combining technique is selecting the branch which has the maximum SNR.
- Maximal ratio combining (MRC): the basic concept of this combining technique is coherent combining for all signal branches with different gains in order to maximise the output SNR.
- Equal gain combining (EGC): the basic concept of this combining technique is coherent combining for all signal branches with equal gains and then all the signal branches will be added. It is simplified version of MRC.
- Switched diversity combining (SDC): the basic concept of this combining technique is if the transmitted signal branch is with high quality, so there is no need to use other branches. The system will look at the other branches if and only if the signal of the transmitted branch is with poor quality.

### 2.3.2 Multiple-Input-Multiple-Output (MIMO)

Multiple-input-multiple-output, or MIMO, is a technique where multiple antennas are used at both the transmitter and the receiver to receive multiple copies of signals as shown in Figure 2.10 in order to increase the link reliability, the spectral efficiency, or both [32, 33]. This concept has been around for many years but recently it has been used in wireless standards. MIMO techniques are used today in technologies like Wi-Fi and to evaluate the performance of LTE [34] and new techniques are under study for future standards like LTE Advanced [16].

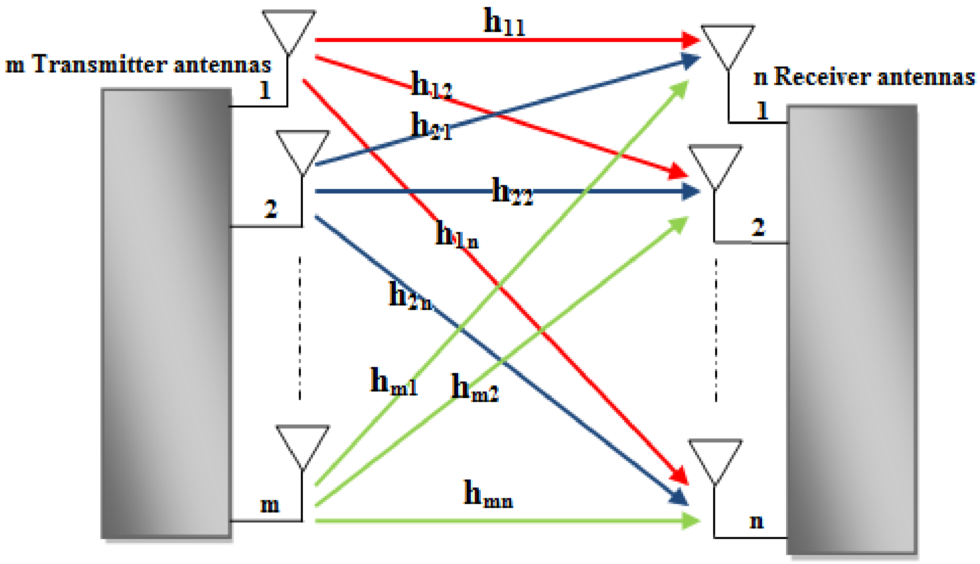


Figure 2.10: A multiple-input-multiple-output (MIMO) system

MIMO is found between a transmitter and a receiver, the signal is transmitted through many paths. Additionally, the paths used will change by moving the antennas even a small distance. The number of objects that appear to the direct path or even to the side path between the transmitter and receiver were considered as interference. But by using MIMO, these additional paths can be used as advantage, because they can be used to provide additional robustness to the radio link by improving the signal-to-noise ratio, or by increasing the link data capacity.

The two main formats for MIMO are given below:

- Spatial diversity: In this technique the signal is sent across an independent fading channel to overcome fading, due to the different path or channel used to send the signal the amount of the fade suffered by each transmitted signal will be different. Spatial diversity used in this narrower sense often refers to transmit and receive diversity. Also, it reduced the co-channel interference. Thus, it is used to provide improvements in the signal-to-noise ratio and they are characterised by improving the reliability of the system with respect to the various forms of fading [32].

- Spatial multiplexing: This form of MIMO is used to transmit independent information sequence, often known as layers, over multiple antennas in order to provide additional data capacity by utilising the different paths to carry additional traffic, such as enhancing the data throughput capability [32].

### 2.3.3 Cooperative Communications

Cooperative communication is simply defined as, a technique where one or more active nodes (helpers, partners, relays) are operating in a common wireless network as shown in Figure 2.11, share their resources to jointly transmit messages in order to achieve better performance.

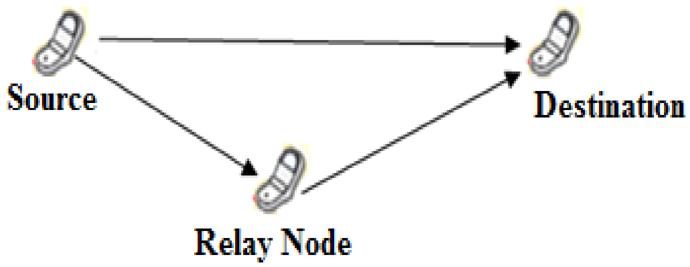



Figure 2.11: Cooperative communications

Cooperative communication is implemented among users with different relaying protocols and techniques. This could be employed depending on the relative user location, channel conditions and transceiver complexity. Also, these are methods which define how data is processed at the relays before sending the data from the source to the destination. There are different types of cooperative communication protocols which will be outlined. The two most well-known cooperative communications are Amplify and Forward (AF) and Decode and Forward (DF) protocols [35].

- Amplify and Forward: it is a simple cooperative signaling method proposed by [35], the main concept of this method is amplifying the received signal by each relay node and then forwarding it to the destination or the base station. Then, the destination or the base station receives two independent faded versions of the signal and can make better decisions on the detection of the information. The main deficiency in this method lies in the fact that noise contained in the transmitted signal is amplified and forward as well with the signal to the destination.
- Decode and Forward: this method follows that the relay nodes decode the received signal from the source, then re-encode and forwarding it to the destination or the base station. This method is more preferable because there is no noise amplification in the transmitted signal [36]. But the only concern in this method is the decoded process by each relay node which will take a lot of computing time leading to more transmission process time.

Cooperative communication has been introduced as an effective technique to combat the detrimental effects of channel fading by exploiting spatial diversity gain, resulting in improved throughput and network performance [37, 38]. Cooperative communication is considered an efficient solution for mobile nodes, where some difficulties in terms of physical size and energy consumption arise from implanting multiple antennas. However, involving more relays will consume more energy, although this can be mitigated to some degree through a proper power allocation scheme [39, 40]. This issue can potentially impede the delivery of quality of service (QoS) of the wireless communication systems.

### 2.3.4 Medium Access Control Protocol

A wireless medium is a shared medium where it is possible for several terminals or network nodes to communicate within a multiple access network. The medium access control protocol (MAC) plays an important role in sending given information efficiently. MAC protocols for wireless networks are considered very essential when evaluating the networks performance. The necessity of MAC protocols in determining how nodes in the network share limited bandwidth increases owing to the unique characteristics of the wireless networks.

In WSN, a MAC protocol has to be properly designed in order to enhance the system performance. [41] presented a survey on some popular MAC layer protocols, it also provides a brief analysis of these protocols which could be helpful for future work in this direction. Moreover, a proper MAC design in WSN has been proposed by [42] to ensure proper operation of the sensor nodes with energy harvesting. In addition, a novel receiver-centric MAC protocol called RC-MAC that seamlessly integrates duty cycling and receiver-centric scheduling, providing high throughput without sacrificing the energy efficiency was proposed by [43]. Also, [44] presented a wake-up variation reduction power management (PM) to solve the problem of energy limitation in WSN. On the other hand, a new MAC was presented by [45] to provide a good trade-off between energy consumption, complexity and performance in terms of throughput and delay.

Whereas, the design of the MAC protocol in D2D is quite challenging because there is no infrastructure and various QoS requirements are needed. [46] investigated a new strategy called upstream resource allocation MAC protocol (URA-MAC), the main advantages of this protocol are the increase of cell throughput and high spectral reuse level. A novel centralised full duplex MAC protocol for wireless networks while considering D2D communications using spatial channel reuse algorithm was proposed by [47], this proposed protocol can minimise the scheduling overhead while maximising the network throughput. In addition, [48] proposed a multichannel MAC protocol for data channel competition, this protocol resolves all channel collisions in only a few iterations. Moreover, the collision resolution time is dominated by the number of channels, rather than the number of D2D transmitters.

However, the design of MAC in a vehicular network is a challenging task due to the high speed and mobility of the nodes, the frequent changes in topology, the lack of an infrastructure and various QoS requirements. [49] Presented an efficient MAC protocol based on IEEE 802.11 DCF, which minimises the unfairness problem of two-way vehicle ad hoc networks. While, in order to improve the system throughput, [50] proposed a multi-round elimination contention-based multi-channel medium access control (VEC-MAC) scheme for vehicular ad hoc networks. In addition, [51] identified the reasons for using the collision-free MAC paradigm in VANETs and then present a novel topology-based classification and we provide an overview of TDMA-based MAC protocols that have been proposed for VANETs in order to improve the performance of V2V communications. On the other hand, [52] proposed spectrum penetration based multi-channel MAC (SPBM) protocol that makes full use of the seven channels and idle subcarriers specified in the IEEE 802.11p to ensure the timely safety message broadcast and improve the throughput of non-safety messages.

#### 2.3.4.1 Wireless Access

Various wireless access technologies are available in order to enhance the system performance of wireless communication systems such as IEEE 802.11, IEEE 802.11e, IEEE 802.11p and IEEE 802.15.4. [53] proposed a hybrid WSN which uses IEEE 802.11 (WLAN) for high rate data transmission combined with a proprietary wireless communication system operating on Sub-GHz short range devices for synchronisation. A consensus-based synchronisation algorithm is used to be independent from the number of WSN nodes and node failure. While, [54] analysed energy consumption and evaluated the performance of the 802.11e Enhanced Distributed Channel Access (EDCA) with and without mechanism Contention Free Burst (CFB), compared with IEEE 802.11 DCF in order to show that the use of EDCA CFB gives better performance and offers a very good relationship between energy consumption and traffic performance, which is recommended in WMSN.

On the other hand, [55] presented a new adaptive approach for QoS and energy management in IEEE 802.15.4 networks, entitled Skip Game. This approach targets a trade-off between increasing the network lifetime and maintaining the QoS of the network, aiming for a greater number of nodes to participate in the monitoring application. In addition, [56] proposed a solution to overcome WSN limitations and derived an efficient IEEE 802.15.4-based on a set of network parameters setting to improve the network performance in terms of latency, energy and bandwidth utilisation. Also, [57] evaluated an analytical method for throughput measurement of IEEE 802.15.4 WSN networks under the interference of an IEEE 802.11 WLAN network with help of mathematical calculation in order to increase the throughput of WSN.

However, IEEE 802.11p is considered the first standard specifically designed for vehicle communications; it showed obvious drawbacks such as low reliability, hidden node problem which occurs when a node is visible from a wireless AP, but not from other nodes communicating with that AP, unbounded delay and intermittent V2I connectivity [58]. IEEE 802.11p supports the unique requirements of vehicular communications such as achieving high and reliable performance in highly mobile, often densely populated and frequently non-line-of-sight environments [59, 60, 61]. In addition, IEEE 802.15.4 standard, which comprises a simple physical (PHY) layer, an energy efficient medium access control and also is designed to flexibly support both real-time and contention-based services, has been considered as a promising candidate for internet of vehicle (IoV) and vehicular sensor networks [62, 63].

## 2.4 Challenges in Wireless Communication Networks

The design of a new protocol or algorithm in wireless communication and networks faces some issues and challenges. Therefore, these issues and challenges need to be addressed in order to design a better and more efficient protocol or algorithm. In this section, some of these challenges are discussed.

### 2.4.1 Challenges in Wireless Sensor Networks

WSN is a promising system, as it offers a wide variety of applications which can be implemented in the real world. More efficient protocols and algorithms are needed in order to implement these applications. In the field of WSN, there are many of challenges and issues that face the improvement of WSN performance. Some of these challenges are summarised below [18, 19, 20].

**Energy Constraints**: The limited battery power is one of the most important constraints in a wireless sensor network. It is not possible to recharge and replace a sensor node, because some of them are left in unreachable environments. Thus, the effectiveness of the sensor network is measured by the sensor node's lifetime which dependents directly on battery power. Hence, the energy consumption is the main issue that must be taken into consideration when a protocol is designed.

Cooperative communications in WSNs is one of the most effective techniques to overcome the problem of energy constraints [64, 65] as wireless sensor nodes are often powered by batteries that are not possible to be recharged due to the nature of WSN. Work in [66] showed that the best position of sensor nodes can be found to minimise the total power of the network. Moreover, in [67] the transmission power is minimized based on the outage probability of each transmission scheme. Additionally, relay selection schemes can also contribute to the minimisation of the overall energy consumption of a WSN [68]. Furthermore, an optimised MAC was proposed in [69] in order to solve the energy in-efficiency taking into account the node latency based on the network traffic.

In addition, a novel receiver-centric MAC protocol in [43] that integrates the duty cycle and receiver-centric scheduling was presented in order to provide high throughput without affecting energy efficiency. While, in [70] a maximum and optimal power saving protocol that outperforms existing power saving protocols was proposed. However, an intelligent hybrid low power control was presented in [71] to achieve high energy efficiency under different traffic loads. Another study was proposed in [72] in order to save energy, increase reliability and decrease delay based on the effects of multiple receiver nodes, size of preamble and variable duty-cycle in number of retransmissions and how the retransmissions increase the energy efficiency and delay.

**Resource Constraints**: The network resources are another important constraint in wireless sensors. Wireless sensors may handle and process a limited amount of data through the wireless channel, which causes limited transmission capability and limited channel bandwidth, thus limiting the channel radio range.

Properly designed relay selection algorithms can improve throughput and coverage performance in WSNs through the creation of cooperative diversity [73]. For systems employing such diversity techniques in slow-fading channels, outage probability and outage capacity are important performance measures for power limited terminals and for determining throughput [74, 75]. While, the cooperative multiple-input–multiple-output (MIMO) and data aggregation techniques are jointly adopted to reduce the energy consumption per bit in wireless sensor networks by reducing the amount of data for transmission and better usage of network resources through cooperative communication are presented in [76]. Also, the end-to-end performance of un-coded incremental relaying cooperative diversity network was studied in [77] to show that the maximum possible diversity can be achieved compared with the regular cooperative-diversity with higher channel utilisation.

**Quality-of-Service (QoS) Constraint**: Qos is one of the most important issues that must be addressed. Wireless sensor nodes offered wide variety of applications, some applications like multi-media or time critical needs an efficient transmission system with better QoS [78]. A good quality of contents is required by multi-media applications such as video, audio and image. But in time critical applications, the data should be delivered within a certain period of time from the moment it accesses the channel; otherwise the data will be useless. New protocols which are designed for such applications should handle QoS. [79] exploited the geographic opportunistic routing (GOR) for QoS provisioning with both end-to-end reliability and delay constraints in WSNs. While, [80] proposed an energy-aware, multi-constrained and multipath QoS provisioning mechanism for WSNs based on optimisation approach.

**Fault Tolerance**: Fault tolerance is the ability to sustain sensor network functionalities without any interruption due to sensor node failures [81]. Due to lack of power, or physical damage or environmental interference, some sensor nodes may fail or be blocked. The failure of sensor nodes should not affect the overall task of the sensor network. This is the reliability or fault tolerance issue. The protocols and algorithms designed for WSN may be designed to address the level of fault tolerance required. [82] presented an approach, called FTSHM (fault-tolerance in SHM), to repair the WSN and guarantee a specified degree of fault tolerance. While, [83] developed and analysed of a low-complexity, distributed, real-time algorithm, which uses the binary observations of the sensors for identifying, localising and tracking multiple targets in a fault tolerant way.

**Scalability:** The number of WSN nodes deployed in any networks varies depending on each application. The variation in number of sensor nodes deployed in studying a phenomenon may be on the order of hundreds or thousands. New schemes must be able to work with this number of nodes. They must also be able to utilise the high density of the sensor networks. The density can range from few sensor nodes to few hundred sensor nodes in a region. [84] discussed the performance of the network for different BS positions. Ad-hoc On Demand Distance Vector Protocol (AODV) and Destination Sequenced Distance Vector Protocol (DSDV) are selected to demonstrate the performance. The number of nodes is varied and performance is evaluated on basis of Packet Reception ratio (PRR), average delay and average energy. Comparison of these protocols is discussed based on the above parameters. While, [85] presented an open architecture for the development of a simple WSN mote based on a runtime reconfigurable hardware platform (the TelosB node and a programmable System on Chip device). The IEEE 1451 family of standards is used in cooperation with the TinyOS operating system to improve the scalability and flexibility of the proposed WSN mote.

**Production Costs:** The production cost of a sensor node is a very challenging issue, since the cost of a single node is very important to justify the overall cost of the network. The sensor network is not cost-justified, if the cost of the network is more expensive than deploying traditional sensors. As a result, the cost of each sensor node has to be kept low. [86] developed a system which is able to perform distance measurements without adding any extra hardware or costs. It is based on phase measurements performed by the IEEE 802.15.4 transceiver chip that is normally solely used to realise communication. On the other hand, [87] proposed a new method of communication adapted to sensor networks for both one-to-many and many-to-one topologies. This type of networks is characterised by its price, size and energy consumption.

**Security:** Security is a quite challenging issue as WSN is not only being deployed in battlefield applications but in many different and critical systems such as airports and hospitals. The information traveling between the sensor nodes or between the sensors and the base station must be protected; otherwise the network will be eavesdropped. In sensor networks, the integrity of data should be maintained, so each sensor node and base station must have the ability to verify that the data received was really sent by a trusted sender and not by an adversary that sent a hacked or false data. A false data can change the way a network could be predicted. Cryptography techniques, a key management scheme, secure routing protocols, secure data aggregation and intrusion detection are categories that manage the security issue [88, 89].

**Hardware Constraints:** The sensor nodes consist of four basic components which are a sensing unit, a processing unit, a transceiver unit and a power unit. They may also have additional application-dependent components such as a location finding system, power generator and mobiliser. So WSN should has the goals of consuming extremely low power, operating in high volumetric densities, having low production cost, being dispensable and autonomous, operating unattended and being adaptive to the environment [90, 91].

**Deployment:** Deployment means implementing the wireless sensor network in a real world location. The WSN deployment usually depends on the geographical location of the application. Network deployment is a very laborious and cumbersome activity and depends on the demographic location of the application. Efficient sensor node deployment is extremely important in wireless sensor networks. It earns great practical meanings through using fewer sensor nodes as far as possible to satisfy different requirements such as energy consumption, overcome the sensor failure, sensor coverage and network connectivity [92, 93].

**Environment:** The environment where the sensor nodes are deployed is an important factor which affects network performance. Sensor networks are usually located either very close or directly inside the phenomenon to be observed. They work under high pressure in the bottom of an ocean, in harsh environments such as a debris or a battlefield, under extreme heat or cold such as in the nozzle of an aircraft engine or in arctic regions and in an extremely noisy environment such as under intentional jamming. This gives an idea about the conditions under which sensor nodes are expected to work and how they should be implemented in order to satisfy the WSN requirements.

### 2.4.1 Challenges in Device-to-Device Communications

D2D communications is a new promising communication method which has attracted the attention of many researchers in the last few years. However, to satisfy the D2D communications requirements, there are many of challenges and issues that face the improvement of D2D performance. These challenges are summarised as follows [94].

**Resource Allocation:** Resource allocation is an important issue that should be addressed, resource allocation in D2D communications is affected by the interference between DTx-BS and CUE-DRx links. Achieving high spectral efficiency is an important part of satisfying and increasing the demands of D2D users. Attractive ways to achieve more efficient utilisation of radio resources by D2D communications have been proposed recently. [95] developed efficient resource allocation algorithms for D2D underlaying cellular systems, which maximises the minimum weighted energy efficiency (EE) of D2D links while guaranteeing the QoS of cellular links. While, [96] studied the co-existence of a multiple-input single-output (MISO) primary link with a MIMO secondary link and tackling the problem of energy-efficient resource allocation. Recently, the cooperative D2D communications idea was exploited for enhancing social ties in human social networks to promote efficient cooperation among devices [97].

In addition, [98] proposed a contract-based cooperative spectrum sharing mechanism to exploit transmission opportunities for the D2D links and achieve the maximum profit of the cellular links. On the other hand, [99] proposed a distributed energy-efficient resource allocation algorithm in order to investigate the trade-off between energy efficiency and spectral efficiency in D2D communications underlaying cellular networks. In order to support massive D2D connectivity and expand the network capacity, sparse code multiple access (SCMA) has been recently proposed [100] for future wireless networks, as it allows nonorthogonal spectrum resource sharing and enables system overloading.

**Energy Efficiency:** Generally, maximising the energy efficiency of D2D communications is achieved by minimising the overall power consumption of D2D. Power-Saving algorithms should be developed for D2D communications in order to decrease the overall power consumption of the network, as more devices means more power consumption. Multi-user multiple-input multiple-output (MIMO) systems are also considered obtaining the maximal possible energy efficiency for cellular networks [101]. On the other hand, [102] studied the energy efficient power control for individual and total D2D communications underlying cellular networks. While [103] analysed the robust power control problem in D2D communications underlaying cellular networks, where two types of channel uncertainty sets are considered. In addition, [104] proposed two matching algorithms to achieve coordination between users demanding data and users willing to act as relays in order to maximise energy efficiency. Work in [105] investigates multihop D2D communications where user equipment (UE) may help a pair of UEs to exchange information in order to enhance energy efficiency.

**Interference:** Interference is also an important factor that affects network performance. Interference usually happens when CUE and D2D links share the same spectral efficiency or when several D2D pairs use overlapping resources, but have dedicated bandwidth with respect to the cellular communication. In different previous scenarios, interference management could be complex in terms of computational and communication load. Therefore, it is important to solve the problem of interference in order to enhance system performance. In order to avoid flooding interference, efficient resource sharing and interference management mechanisms have been proposed [106] in order to fully exploit the benefits of using D2D transmissions. On the other hand, when the overlaying mode is implemented, orthogonal resources are partially allocated to cellular users and D2D users, respectively [107].

**Security Mechanism:** One of the most important issues is to ensure that communication between any two pairs of D2D is secure, so it can be accepted by the receivers. Recently, the issue of security in D2D underlaying cellular networks has been considered [108]. For real-life D2D communications, D2D communications is overheard by randomly distributed eavesdroppers. It is necessary to make a complex and deep D2D security analysis for different D2D scenarios, in addition different topologies and protocols should be proposed in order to meet all the D2D requirements. [109] investigated two fundamental and interrelated aspects of D2D communications, security and privacy, which are essential for the adoption and deployment of D2D, also presented an extensive review of the state of-the-art solutions for enhancing security and privacy in D2D communications.

**Mode Selection:** Mode selection is considered a very challenging method, as switching between individual allocation modes depends on the current network. Since, wireless environment may change often due to different channel conditions, or user mobility. Mode selection is based on the identification of device distance and localization which is identified through the base station that manages the communication between the devices. Joint mode selection, resource group (RG) assignment and power allocation for D2D underlaid cellular communication systems are studied in order to formulate a resource allocation problem, which aims at maximising the system sum rate of all D2D and cellular links while guaranteeing the required minimum rates of cellular and D2D links [110]. On the Other hand, theoretical analyses on D2D mode selection with user mobility and uses of the stochastic geometry that can be deduced the D2D communications range can be well represented by biased circles with varying radii. Besides, a tractable analytical framework considering both absolute movement and relative movement for mode selection in moving D2D scenarios is presented [111].

**Mobility Management:** The D2D mobility refers to a D2D pair connected under the same coverage area and where one of the D2D users moves to another cell, thus handover to the new cell must be performed. As a result of the mobility, new algorithms must be proposed in order to overcome the transition from one cell to another. [112] investigated the relationship between energy efficiency and bandwidth efficiency in a mobile environment and propose an EE-BE-aware scheduling scheme with a dynamic relay selection strategy that is flexible enough for making the transmission decision, including relay selection, rate allocation and routing. On the other hand, Due to the limited storage capacity, each device can only cache a part of the popular content resulting in a distributed caching network. When the user needs to obtain all these file portions, the portions cached farther away naturally become the performance bottleneck. This is due to the fact that dominant interferers may be closer to the receiver than the serving device. Using a simple stochastic geometry model, we concretely demonstrate that this bottleneck can be loosened if the users are mobile. Gains obtained from mobility are quantified in terms of coverage probability [113].

**Quality-of-Service (QoS):** Enhancing the QoS of D2D communications is a promising technique of local service because D2D communications faces a lot of problems such as interference, mobility, spectral efficiency and energy efficiency. So to meet the QoS requirements and increasing system reliability of D2D communications networks, different protocols and algorithms should be presented. In order to improve the QoS at the BS [114] focused on the intra-cell interference and propose a D2D mode selection scheme to manage it inside a finite cellular network region. In addition, [115] investigates the overall transmission cost minimisation problem while guaranteeing users' QoS requirements in D2D based distributed storage systems.

### 2.4.3 Challenges in Vehicular Networks

Vehicular networks are new upcoming promising networks of the intelligent transportation systems. To enhance the system performance when deploying of a vehicular networking system, various challenges and issues should be resolved. Most of these V2I challenges are common with other wireless communication networks. Some related challenges and issues have been addressed [116, 117].

**Resource Allocation:** The required volume of V2I communication is expected to increase in the future. Therefore, it is important to increase the volume of V2I communication networks. The transmission power and rate control are two important parameters that have an effect on the enhancement of system capacity and the solution of the congestion problems. For systems employing cooperative diversity through exploiting the broadcast nature of wireless channels and using relays to improve link reliability, throughput in V2V through the creation of communication protocols exploiting polarisation diversity [118]. In addition, [119] proposed the use of graph theory to formulate the problem of cooperative communications scheduling in vehicular networks in order to improve the throughput and spectral efficiency (SE) of vehicular networks. Smart Antenna technology can also contribute to the increment of the service coverage and system throughput of V2I [120]. While in [121], the capacity of V2I communication has been maximised by an iterative resource-allocation method.

**Power Management:** Power Management in V2I is not concerned about energy efficiency, but rather about transmission power. This issue is important as the transmitted power can cause interference to other transmissions. Thus, the denser the network is, the lesser the Tx power should be. To improve power efficiency in vehicle-to-roadside infrastructure (V2I) communication networks, [122] proposed a joint power and sub-carrier assignment policy under delay aware quality of service (QoS) requirements. Due to the real-time nature of the V2I transmissions, the proposed policy should satisfy delay aware QoS requirements with minimum power consumption. In addition, the strong dependence on the environment due to multipath propagation is presented [123]. These results can aid in the identification of the optimal location of the transceivers which could be left active for latency critical application, to minimise power consumption and increase service performance.

**Mobility:** In vehicular networks, vehicles travel with high speed which tends to change the network topology when more and fast vehicles are being engaged in the transmission. For instance, two or more vehicles can communicate as far as they are in the same transmission range or cell. If one vehicle moves very fast to another cell, handover of the vehicle to the new cell must be performed. A new proposed algorithm called MBAOW (Mobility-based Backoff Algorithm with Optimal Window), which uses a constant optimal contention window in backoff stage to improve reliability, throughput and fairness [124]. The window can be adjusted with the vehicle speed and the network status. While, [125] tackled the performance evaluation of the virtual collision management proposed by IEEE in vehicular environment and overviewed the quality of service in presence of three ITS applications: Warning to a foggy zone, inter-distance measurement and road awareness. The objective of this study is to show the impact of virtual collision on vehicular network performance and dimension the roadside coverage area.

**Routing:** Mobility is essential in vehicular networks that is why the network always needs to quickly change the network topology and reconfigure the routing table for each vehicle to achieve the best system performance. In addition, frequent network partitioning in VANET requires a different approach. One of the problems that is commonly faced in transportation systems is the disruption of the emergency vehicle service, such as ambulances or fire fighting units, due to traffic congestion. [126] developed a simulation to provide the route guidance and navigation for emergency vehicles using V2I-based cooperative communication. While for urban vehicular environments, an Infrastructure Enhanced Geographic Routing Protocol (IEGRP) has been presented in [127]. IEGRP is a hybrid vehicular routing protocol that facilitates V2V or V2I unicast routing by dynamically changing its routing decisions in the presence of full or partial Road-Side Unit (RSU) infrastructure in order to maximise packet delivery rate.

**Quality-of-Service (QoS):** Enhancing the QoS of VANET is one of the most important challenges due to the high mobility of the vehicles and the huge scale node density. These issues need to be addressed carefully in order to achieve the QoS requirements of VANETs. A novel cooperative vehicle-to-vehicle (V2V) communication methods has been proposed by [128] to enhance the quality-of-service (QoS) and quality-of-experience (QoE) of V2V communication. [129] showed that the cooperative multiple-input–single-output (MISO) and multiple-input–multiple-output (MIMO) techniques are more energy-efficient than SISO and traditional multi-hop SISO techniques for medium and long range transmissions. A novel mechanism, called Distributed Sorting

Mechanism (DSM), was proposed in [130] in order to improve the efficiency of communication between V2I. Another study was proposed in [131] for high performance vehicle streams that integrates the transportation and new vehicle communication protocols.

**Scalability:** The number of vehicles in V2I networks changes periodically, so changes in the network size and density should be handled carefully to sustain network performance. In addition, system operability in high and low density scenarios is very important. The scalability problem is not comprehensively addressed by existing approaches, as they only focus on parts of the problem. [132] showed how a relevance-based, altruistic communication scheme helps realise scalability by optimising the application benefit and the bandwidth usage. In-vehicle and intervehicle message selection is based on a relevance function that makes use of the current context and the content of the messages. VANET in particular utilise broadcast as a primary communication mechanism in many applications. Such networks exhibit situations of very high node densities so it is important that the broadcast protocols used to support applications on these networks scale well to high densities. [133] evaluated existing broadcast protocols in terms of this scalability using both a high-level simulation assuming an ideal medium (WiBDAT) and a standard detailed wireless simulation (JiST/SWANS).

**Lack of Central Coordination:** VANET could be considered as an instantiation of MANET network; however their behavior is different. Thus, it is quite difficult for a centralised MAC protocol to access medium. Hence, to enhance the system performance of vehicular networks, a distributed MAC protocol is currently being proposed, even though it may require some additional applications to communicate with infrastructure or road side. Traffic safety applications using VANET can significantly improve road safety if safety packets can be delivered on time. Therefore, a MAC layer protocol for VANET that can guarantee timely delivery of data is critical, since the MAC layer protocol of IEEE 802.11 standard cannot guarantee an upper bounded delay for delivery of safety messages. To resolve this issue, [134] obtained the theoretical lower bound on the delay for delivery of safety messages. Then, a novel MAC layer protocol for intervehicular communication that guarantees the delivery of safety messages within a certain upper bound has been introduced. While recently, IEEE 802.11p has become the protocol that has been standardised as the medium access control (MAC) layer. Due to the highly dynamic topology and low delay constraints in vehicular ad hoc networks (VANETs). Some studies focused on the analysis of the 802.11p safety-critical broadcast on the control channel in a VANET environment and improved the existing work by taking several aspects into design consideration [135].

**Security and Privacy:** Security is an issue that needs to be addressed and evaluated in vehicular networks. The issues to be addressed include trust which is the ability of vehicles to trust the messages they received, resiliency for interference, maintenance and efficiency. [136] analysed and discussed Big Data solutions that can be leveraged to address some of the emerging challenges of VANETs, in order to enhance travel security and help address traffic control problems that modern society is facing today. In addition, [137] provided a summary of some major security attacks on security services such as availability, confidentiality, authentication, integrity and non-repudiation and the corresponding countermeasures to make VANET communications more secure.

Privacy is another issue that should be assessed. Non-trusted parties should not be tracked or identified by the vehicles during their transmission. The lack of taking the privacy concerns into account at the early design stage could result in multiple law suits after the network is deployed. A conditional privacy-preserving and authentication scheme for secure service provision in VANETs has been proposed [138] in order to not only satisfy the security requirements of VANETs, but also optimises the calculation process of signature generation and verification. In order to protect a user's privacy, an efficient and practical pseudonymous authentication protocol with conditional privacy preservation has been presented recently [139]. IEEE 802.11p introduced dynamically assigned MAC addresses, along with a mechanism for MAC address duplication discovery; in this way it is not possible to trace the vehicles or their drivers.

## 2.5 Summary and Conclusion

Wireless communication networks have a strong effect on our life. However, many types of wireless communication systems exist which fall into several categories. Some of these categories have been presented and studied.  In addition, the channel characteristics of wireless communications and networks have been classified and explained including path loss, fading, interference, etc. Hence, in order to solve these problems, limitation and difficulties, some wireless communication technologies were suggested in literature such as MIMO, diversity, cooperative communication, etc.

Moreover, the wireless MAC which is responsible for sending and receiving data efficiently among users has been presented and discussed, in addition to the various wireless access technologies proposed in the literature. These access technologies are available in order to enhance the system performance of wireless communication systems. Finally, the challenges, issues and their solutions for different wireless communication and networks have been presented.

This research aims to enhance the QoS of three wireless communication systems (WSN, D2D and V2I). The efficient design and the enhancement of the QoS in wireless communication systems is a challenging and an important area of research which faces a lot of challenges and needs to be further explored. So, different models for each wireless communication system are proposed in order to enhance their QoS based on different assumptions and conditions. In the next chapters these models will be presented, discussed and evaluated.

# Chapter Three

# Enhancing QoS in Wireless Sensor Networks

WSN is a wireless network that consists of numbers of sensor nodes. This type of networks are responsible for monitoring physical or environmental conditions like sound, pressure, temperature and co-operatively pass data through the network to a main location. In recent years, the design of an efficient wireless sensor network system has become a challenging and leading area of research. A sensor node, which is often powered by batteries, responds and detects some type of input from both the physical or environmental conditions, such as pressure, heat, light, etc. The output of the sensor is generally an electrical signal or set of data that is transmitted to a controller for further processing.

In this chapter, our focus will be the identification of the conditions for establishing appropriate transmission strategies among different commonly used transmission schemes including both cooperative and non-cooperative schemes in WSNs. This approach is based on the development of analytical models for four different transmission schemes and the appraisal of their performances in reliability, energy efficiency and throughput. Our work reveals the trade-offs between cooperative and non-cooperative transmission schemes and shows how to utilise this property to achieve the optimised QoS performance through adaptive cooperative communications.

## 3.1 System model

In this section, the analytical models of the required transmitting power, outage probability, energy efficiency and throughput in the context of a wireless sensor network are established for both cooperative and non-cooperative transmission schemes. Based on these models, an adaptive transmission strategy can be developed to optimise the energy performance.

Given a wireless sensor network with $N_s$ nodes, for any source-destination pair ($S$,$D$), the goal of optimising the transmission QoS is achieved by either maximising the end-to-end throughput or minimising the total energy consumed per bit with a throughput target set, i.e.,

$$Max \sum S_{thi} \qquad s.t.\{ Qs_{S\text{-}D} \}$$

or

$$Min \sum E_{bi} \qquad s.t.\{p_{outS\text{-}D}\} \tag{3.1}$$

where $S_{thi}$ and $E_{bi}$ are the throughput and energy consumed per bit, respectively, of the $i$-th path between $S$ and $D$, $Qs$ is the required quality of service and $p_{outS\text{-}D}$ is the fixed outage probability target set for transmission between $S$ and $D$.

Four commonly used transmission schemes in the context of wireless sensor networks are identified in Figure 3.1. In this work, we intend to examine and compare their performance in energy and throughput and to optimise the transmission scheme in different environmental conditions.

We consider a sensor network in which the transmission links are subject to narrowband Rayleigh fading with Additive White Gaussian Noise (AWGN) and propagation path-loss. The channel fades for different links are assumed to be statistically mutually independent. For medium access, the nodes are assumed to transmit over orthogonal channels, thus no mutual interference is considered in the signal model.

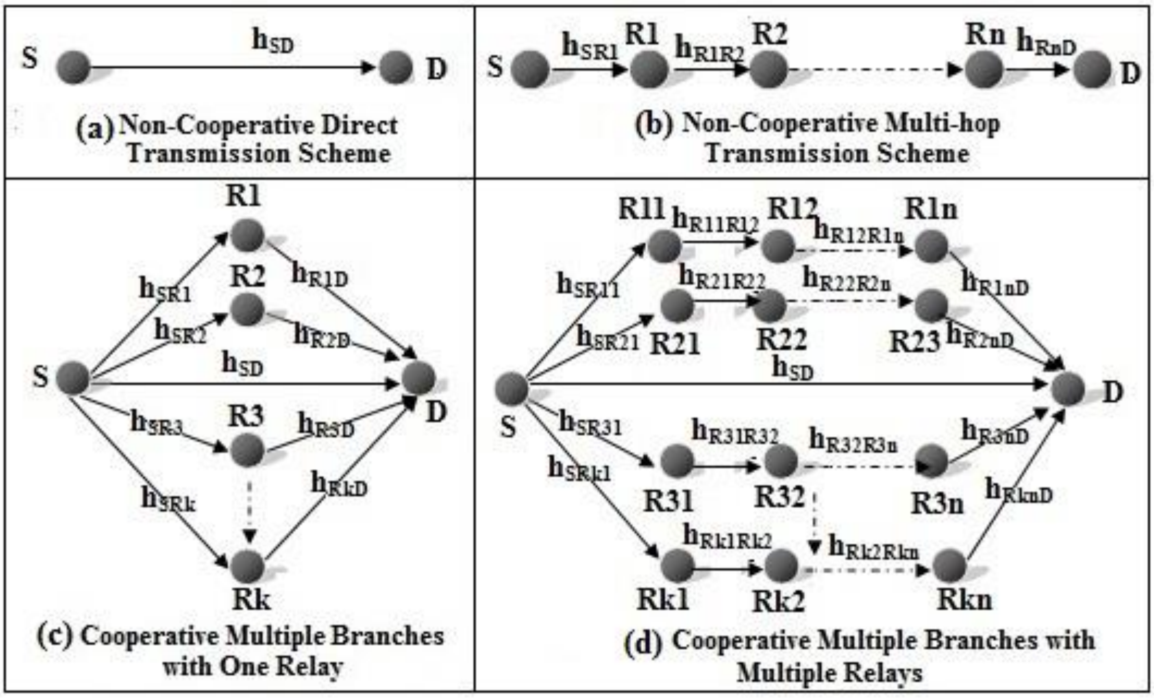



Figure 3.1: Different transmission schemes of WSN.

(a) Non-cooperative direct transmission scheme (b) Non-cooperative multi-hop transmission scheme (c) Cooperative multiple branches with one relay (d) Cooperative multiple branches with multiple relays

### 3.1.1 Non-Cooperative Transmission Schemes

In this subsection we formalise direct transmission and multi-hop transmission schemes. In the direct transmission, the source communicates directly with the destination, without any intermediate nodes. On the other hand, when multihop communication is established, a relay is responsible for forwarding the source information to the destination.

#### 3.1.1.1 Direct Transmission Scheme

In the direct transmission scheme, consider the transmission scheme for a direct link (*S*, *D*) as shown in Figure 3.1(a) where no additional relay paths are involved. We use $P_{SDir}$ to denote the source transmission power for this case. For the direct transmission between source *S* and destination *D*, the received symbol $r_{sd}$ and the spectral efficiency $R_S$ can be modelled as Equation (2.14) and [29]:

$$r_{SD} = \sqrt{P_{SDir}\, d_{SD}^{-\alpha}}\, h_{SD} s + N_o \tag{3.2}$$

$$R_S = \log_2\left(1 + SINR_{SD}\right) \tag{3.3}$$

where $d_{SD}$ is the distance between the source *S* and the destination *D*, $\alpha$ is the path loss exponent, $h_{SD}$ is the channel coefficient of the *S*-*D* link, $s$ is the transmitted symbol with unit power and $N_o$ is the additive Gaussian noise. The path gain between node $i$ and node $j$ is given by [27]:

$$\gamma_{ij} = \frac{G\lambda^2}{(4\pi)^2 d_{ij}{}^{\alpha} M_l N_f} \tag{3.4}$$

where $d_{ij}$ is the distance in meters between the two nodes, *G* is the total gain of the transmit and receive antennas, $\lambda$ is the wavelength, $M_l$ is the link margin and $N_f$ is the noise figure at the receiver. The Signal-to-Noise Ratio (*SNR*) in the S-D link is:

$$SNR_{Dir} = \frac{\gamma_{SD}\left|h_{SD}\right|^2 P_{SDir}}{N} \tag{3.5}$$

where $N$=$N_o B$, *N* is the noise power spectral density and *B* is the system bandwidth in Hertz.

As described previously, the outage probability for direct transmission occurs when the SNR at the receiver falls below a threshold $\beta$ which allows error free decoding. This threshold is defined as $\beta = 2^{2R_s} - 1$, where $R_s$ is the required system spectral efficiency. The outage probability of the single-hop transmission is given by [64]:

$$p_{outSD} = p\left(SINR_{Dir} \le \beta\right) = p\left(SINR_{Dir} \le 2^{2Rs} - 1\right) \tag{3.6}$$

$$p_{outSD} = 1 - e^{\left(\frac{-\left(2^{2R_s}-1\right)N}{P_{SDir}\left|h_{SD}\right|^2 \gamma_{SD}}\right)} \tag{3.7}$$

From the view of energy consumption, a WSN node has an energy source (i.e., batteries) and circuitry power. Each component has its power states and some preset state transitions. In order to evaluate the energy efficiency, we define the total energy consumption per bit of each transmission scheme. The total consumption takes into account the required power for transmission, which depends on the distance between each two sensor nodes, the power consumption of the circuitry and the bit rate. Thus, the total consumed energy per bit of the direct transmission is:

$$E_{bDir} = \frac{P_{AM,Dir} + P_{Tx} + P_{Rx}}{R_b} \tag{3.8}$$

$$P_{AM,Dir} = \frac{\xi}{\eta} P_{SDir} \tag{3.9}$$

where $P_{AM,Dir}$ is the power amplification for direct transmission which depends on the drain efficiency of the amplifier $\eta$, the average peak-to-peak ratio $\xi$ and the transmission power $P_{SDir}$, $R_b=R_sB$ is the bit rate in bits/s, $P_{TX}$ and $P_{RX}$ are the power consumed by the internal circuitry for transmitting and receiving, respectively.

Energy consumption is largely proportional to the successful transmission rate or the requirement of maintaining a certain level of transmission reliability. In order to maintain a required level of reliability, denoted by $U$, which is related to the reliability of a transmission link, the minimum outage probability is defined as:

$$p_{outDir} \leq 1\text{-}U \tag{3.10}$$

In order to find the optimum required transmission power with minimum energy consumption for direct transmission scheme. Lagrange optimisation technique has been used to solve the optimisation problem, this is an optimisation with one constraint variable and its Lagrangian is given by:

$$Min \sum E_{bDir} \qquad s.t. \{p_{outDir} \leq 1 - U\} \tag{3.11}$$

$$L(P_{SDir}, \lambda_{Dir}) = P_{totDir} + \lambda_{Dir}\left(p_{outDir} - 1 + U\right) \tag{3.12}$$

The main objective for the performance optimisation of a WSN is to minimise the total energy consumption under different environmental conditions. Thus, the optimum required transmission power $P_{Sopt}$ for the direct transmission scheme to satisfy the reliability requirement or be constrained by the outage probability must be:

$$P_{Sopt} \approx \left( \frac{-\left(2^{2R_s} - 1\right)N}{\ln U \left|h_{SD}\right|^2 \gamma_{SD}} \right) \tag{3.13}$$

The detailed derivation of this result is provided in Appendix (Appendix A-Ch3-1(a)).

We can obtain the minimum energy efficiency based on the optimum required transmission power by substituting Equation (3.13) in Equation (3.12) and then in Equation (3.8), hence then the minimum energy consumption $E_{bDirmin}$ can be formulated as:

$$E_{bDir\min} = \frac{P_{totDir\min}}{R_b} \tag{3.14}$$

where $$P_{totDir\min} = \left(P_{AM,Dir\min} + P_{Tx} + P_{Rx}\right) + \lambda_{Dir}\left(pout_{Dir} \text{ -}1 + U\right)$$

and $$P_{AM,Dir\min} = \frac{\xi}{\eta} P_{Sopt} \tag{3.15}$$

Network throughput can be defined as the amount of data successfully delivered within a unit time and typically measured in bits per second (bps). Based on the concept defined by Sensor-MAC (S-MAC) protocol defined in [140, 141] and according to the definition of the unified throughput, the throughput for the direct transmission $S_{th}$ can also be expressed as:

$$S_{thDir} = \frac{N_s\left(1 \quad p_o\right)p_s\left(1 \quad p_{eDir}\right)L_p}{T_{SDir}} \tag{3.16}$$

$$p_{eDir} = 1 - \left(1 - p_{bDir}\right)^{L_p} \tag{3.17}$$

$$p_{bDir} = Q\sqrt{2SNR_{Dir}} \tag{3.18}$$

where $L_p$ is the average packet payload length, $p_s$ is the probability that each node successfully transmits a DATA packet, $p_0$ is the probability that the transmission queue of a node is empty. We consider the effect of PHY packet error probability for the direct transmission, such as $p_{eDir}$ which depends on the bit error probability $p_{bDir}$ for the direct transmission and it varies from one transmission scheme to another. $SNR_{Dir}$ represents the signal-to-noise ratio for the direct transmission scheme. $N_s$ represents the total number of transmitting sensors. $T_{SDir}$ represents the total time needed to successfully transmit a packet. The value of $p_s$ and $p_o$ can be numerically calculated through simulation based on the concept presented in [141, 142]. $T_{SDir}$ can be expressed based on S-MAC protocol as [142, 143]:

$$T_{SDir} = T_{SYNC} + T_{rts} + T_{cts} + T_{L_p} + T_{Ack} + 3T_{SIFS} + T_{DIFS} \tag{3.19}$$

During the transmission process, sensor node will send synchronise packet (SYNC), Request-to-Send (RTS) and DATA ($L_p$) to the destination node and receive Clear-to-Send (CTS) and Acknowledgement (ACK) packets from the destination node as shown in Figure 3.2. *SIFS* and *DIFS* represent the required time for changing the node’s transmit/receive mode and the required time before the node go to sleep mode, respectively.

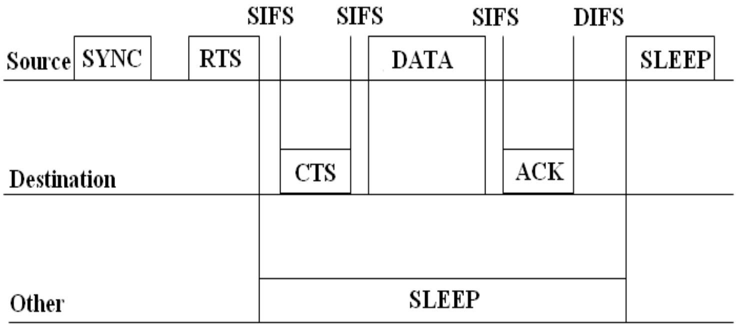



Figure 3.2: Frame diagram of the S-MAC

The optimum throughput of this transmission scheme $S_{thsopt}$ can be obtained by finding the optimum average packet payload length $L_{popt}$. Lagrange optimisation has been used as the optimisation technique. This is an optimisation problem with one constraint variable and its Lagrangian is given by:

$$Max \sum S_{thDir} \qquad s.t.\{N_s(1-p_o)p_s(1-p_{eDir}) \geq Qs\} \tag{3.20}$$

where Qs is the required QoS.

$$L(L_p, \Lambda_{Dir}) = S_{thDir} + \Lambda_{Dir}\left(N_s(1 \quad p_o)p_s(1 \quad p_{eDir}) \quad Qs\right) \tag{3.21}$$

$$L_{popt} = \frac{\ln\left(\dfrac{Qs}{N_s(1-p_o)p_s}\right)}{\ln(1-p_{bDir})} \tag{3.22}$$

The detailed derivation of this result is provided in Appendix (Appendix A-Ch3-1(b)).

The maximum throughput for the direct transmission scheme can be obtained by substituting Equation (3.21) and Equation (3.22) in Equation (3.16).

#### 3.1.1.2 Multi-Hop Transmission Scheme

In the multi-hop, non-cooperative transmission scheme with multi-hop relays *n*, as shown in Figure 3.1(b) the communications carried through multiple nodes called relays in our model. We assume that we have single or multi-hop relays $R \in \{1,n\}$, each relay is able to detect if the packet was received correctly and only in that case the relay will forward the information to the destination. Otherwise, the packet is considered lost. In this case the received signal $r_{ij}$ at each time slot can be expressed as:

$$r_{ij} = \sqrt{P_{Sij}\, d_{ij}^{-\alpha}}\, h_{ij} s + N_o \tag{3.23}$$

where $i \in \{S,R\}$, $j \in \{R,D\}$, $P_{Sij}$ is the transmission power required between $i - j$ link, this power must be lower than the direct transmission power as in this condition the distance between two consecutive nodes will be smaller than the total distance between source and destination. The Signal-to-Noise Ratio (*SNR*) in the $i - j$ link is:

$$SNR_{ij} = \frac{\gamma_{ij} \left| h_{ij} \right|^2 P_{Sij}}{N} \tag{3.24}$$

For any concatenation and based on the previous explanation of the outage probability, we can conclude that the total outage probability for the multi-hop transmission scheme is given by:

$$p_{outMH} = 1 - \left(1 - p_{outSR_1}\right)\left(1 - p_{outR_1R_2}\right) \cdots\cdots\cdots\cdots \left(1 - p_{outR_nD}\right) \tag{3.25}$$

where $p_{outSR_1} = 1 - e^{\left( \frac{-\left(2^{2R_s} - 1\right)N}{P_S \left| h_{SR_1} \right|^2 \gamma_{SR_1}} \right)}$, $p_{outR_1R_2} = 1 - e^{\left( \frac{-\left(2^{2R_s} - 1\right)N}{P_{R_1} \left| h_{R_1R_2} \right|^2 \gamma_{R_1R_2}} \right)}$ *and* $p_{outR_nD} = 1 - e^{\left( \frac{-\left(2^{2R_s} - 1\right)N}{P_{R_n} \left| h_{R_nD} \right|^2 \gamma_{R_nD}} \right)}$ (3.26)

$p_{outSR_1}$, $p_{outR_1R_2}$ and $p_{outR_nD}$ represent the outage probability between the source and first relay node, the outage probability between first and second relay nodes and the outage probability between the last relay node and destination, respectively. $P_S, P_{R_1}$, and $P_{R_n}$ are the transmission power of the source, first relay and last relay node, respectively. Then, the outage probability in this case can be expressed as:

$$p_{outMH} = 1 - e^{-\left(2^{2R_s} - 1\right)N \left( \frac{1}{P_S \left| h_{SR_1} \right|^2 \gamma_{SR_1}} + \sum_{i=2}^{n} \frac{1}{P_{Ri-1} \left| h_{Ri-1Ri} \right|^2 \gamma_{R_{i-1}R_i}} + \frac{1}{P_{Rn} \left| h_{RnD} \right|^2 \gamma_{R_nD}} \right)} \tag{3.27}$$

We set the transmission power to be proportional to the distance between two communicating nodes. For broadcast transmission, e.g., when the source transmits, the longest distance, i.e., the distance between the source and the destination $d_{SD}$, is considered. So, the power between two communicating nodes is given by:

$$P_{ij} = \upsilon_{ij}{}^{\alpha} P_{SD} = X P_{SD} \tag{3.28}$$

where $X = \upsilon_{ij}{}^{\alpha}$ and $\upsilon_{ij}$ denotes the power coefficient between node *i* and node *j*. In our model, we assume that the value of $\upsilon_{ij}$ depends on the distance of the source-destination, relay-relay or relay-destination links. For example, the transmission power for the relay-destination link is:

$$P_{RD} = \upsilon_{RD}{}^{\alpha} P_{SD} = \left( \frac{d_{RD}}{d_{SD}} \right)^{\alpha} P_{SD} \tag{3.29}$$

Based on Equation (3.28) and Equation (3.29), Equation (3.27) can be rewritten as:

$$p_{outMH} = 1 - e^{-\frac{\left(2^{2R_s}-1\right)N}{P_{SMH}}\left(\frac{1}{\left|h_{SR_1}\right|^2 \gamma_{SR_1}} + \sum_{i=2}^{n}\frac{1}{\upsilon_{R_{i-1}R_i}{}^{\alpha}\left|h_{R_{i-1}R_i}\right|^2 \gamma_{R_{i-1}R_i}} + \frac{1}{\upsilon_{R_nD}{}^{\alpha}\left|h_{R_nD}\right|^2 \gamma_{R_nD}}\right)} \tag{3.30}$$

Then the outage probability of the multi-hop transmission scheme can be approximated and expressed as follows:

$$p_{outMH} \approx \frac{\left(2^{2R_s}-1\right)N}{P_{SMH}}\left(\frac{1}{\left|h_{SR_1}\right|^2 \gamma_{SR_1}} + \sum_{i=2}^{n}\frac{1}{\upsilon_{R_{i-1}R_i}{}^{\alpha}\left|h_{R_{i-1}R_i}\right|^2 \gamma_{R_{i-1}R_i}} + \frac{1}{\upsilon_{R_nD}{}^{\alpha}\left|h_{R_nD}\right|^2 \gamma_{R_nD}}\right) \tag{3.31}$$

The total consumption takes into account the required power for the transmission, which depends on the distance between each two sensor nodes, the power consumption of the circuitry and the bit rate. Thus, the total consumed energy per bit of the multi-hop transmission scheme is:

$$E_{bMH} = pout_{SR_1}\frac{P_{AM,MH}+P_{Tx}+P_{Rx}}{R_b} + \left(1-pout_{SR_1}\right)\frac{\left(\sum_{i=2}^{n}\upsilon_{R_{i-1}R_i}{}^{\alpha}+\upsilon_{R_nD}{}^{\alpha}+1\right)P_{AM,MH}+(n+1)P_{Tx}+(n+1)P_{Rx}}{R_b} \tag{3.32}$$

The first term on the right-hand side corresponds to the consumed energy when the relay is not able to correctly decode the message from the source, which means that this link is in outage. In this case, only the source node consumes transmitting power and the destination node and *n* relays consume receiving power. The second term counts for the event that the source-relay link is not in outage, hence the relay transmitting and processing power and the extra receiving power at the destination are involved.

Substituting $\upsilon_{i-1i}{}^{\alpha} = X_{i-1i}$ and $\upsilon_{nD}{}^{\alpha} = X_{nD,}$ then Equation (3.32) can be written as:

$$E_{bMH} = pout_{SR_1}\frac{P_{AM,MH}+P_{Tx}+P_{Rx}}{R_b} + \left(1-pout_{SR_1}\right)\frac{\left(\sum_{i=2}^{n}X_{R_{i-1}R_i}+X_{R_nD}+1\right)P_{AM,MH}+(n+1)P_{Tx}+(n+1)P_{Rx}}{R_b} \tag{3.33}$$

$$P_{AM,MH} = \frac{\xi}{\eta}P_{SMH} \tag{3.34}$$

where $P_{AM,MH}$ is the power amplification for the multi-hop transmission scheme which depends on the drain efficiency of the amplifier $\eta$, the average peak-to-peak ratio $\xi$ as described previously.

Energy consumption required for the multi-hop transmission scheme in order to maintain a required level of reliability, denoted by *U*, which is related to the reliability of a transmission link, the minimum outage probability is defined as:

$$p_{outMH} \leq 1\text{-}U \tag{3.35}$$

In order to find the optimum required transmission power with minimum energy consumption for the multi-hop transmission scheme. Using Lagrange optimisation as mentioned previously. The optimisation problem with one constraint variable and its Lagrangian for this transmission scheme is given by:

$$Min \sum E_{bMH} \qquad s.t. \{p_{outMH} \leq 1 - U\} \tag{3.36}$$

$$L(P_{SMH}, \lambda_{MH}) = P_{totMH} + \lambda_{MH} \left(p_{outMH} - 1 + U\right) \tag{3.37}$$

Thus, the optimum required transmission power $P_{MHopt}$ for the multi-hop transmission scheme to satisfy the reliability requirement or be constrained by the outage probability for this transmission scheme must be:

$$P_{MHopt} \approx \frac{-\left(2^{2R_s} - 1\right)N}{\ln U} \left( \frac{1}{\left|h_{SR_1}\right|^2 \gamma_{SR_1}} + \sum_{i=2}^{n} \frac{1}{\upsilon_{R_{i-1}R_i}{}^{\alpha} \left|h_{R_{i-1}Ri}\right|^2 \gamma_{R_{i-1}R_i}} + \frac{1}{\upsilon_{R_n D}{}^{\alpha} \left|h_{R_n D}\right|^2 \gamma_{R_n D}} \right) \tag{3.38}$$

The detailed derivation of this result is provided in Appendix (Appendix A-Ch3-2(a)).

We can obtain the minimum energy efficiency based on the optimum required transmission power by substituting Equation (3.38) in Equation (3.37) and then in Equation (3.33), hence the minimum energy consumption $E_{bMHmin}$ can be formulated as:

$$E_{bMH\min} = \frac{P_{totMH\min}}{R_b} \tag{3.39}$$

where

$$P_{totMH\min} = pout_{SR_1} \left(P_{AM,MH\min} + P_{Tx} + P_{Rx}\right)$$
$$+ \left(1 - pout_{SR_1}\right) \left( \left( \sum_{i=2}^{n} X_{R_{i-1}R_i} + X_{R_n D} + 1 \right) P_{AM,MH\min} + (n+1)P_{Tx} + (n+1)P_{Rx} \right) + \lambda_{MH} \left(pout_{MH} - 1 + U\right)$$

and

$$P_{AM,MH\min} = \frac{\xi}{\eta} P_{MHopt} \tag{3.40}$$

Based on the definition of the throughput described in the previous subsections, the throughput for the multi-hop transmission scheme $S_{thMH}$ can be expressed as:

$$S_{thMH} = \frac{N_s \left(1 - p_o\right) p_s \left(1 - p_{eMH}\right) L_p}{T_{SMH}} \tag{3.41}$$

$$p_{eMH} = \left(1-(1-p_{bSR_1MH})^{L_p}\left(\prod_{i=2}^{n}(1-p_{bR_{i-1}R_iMH})^{L_p}\right)(1-p_{bR_nDMH})^{L_p}\right) \tag{3.42}$$

$$p_{bSR_1MH} = Q\sqrt{2SNR_{SR_1MH}},\ p_{bR_{i-1}R_iMH} = Q\sqrt{2SNR_{R_{i-1}R_iMH}},and\ p_{bR_nDMH} = Q\sqrt{2SNR_{R_nDMH}} \tag{3.43}$$

where $SNR_{SR_1MH} = \dfrac{\gamma_{SR_1}\left|h_{SR_1}\right|^2 P_{MH}}{N_oB}$, $SNR_{R_{i-1}R_iMH} = \dfrac{\gamma_{R_{i\text{-}1}R_i}\left|h_{R_{i\text{-}1}R_i}\right|^2 X_{R_{i\text{-}1}R_i}P_{MH}}{N_oB}$ $and\ SNR_{R_nDMH} = \dfrac{\gamma_{R_nD}\left|h_{R_nD}\right|^2 X_{R_nD}P_{MH}}{N_oB}$

where $p_{eMH}$ represents packet error probability for multi-hop transmission scheme which depends on $p_{bSR_1MH}$, $p_{bR_{i-1}R_iMH}$ and $p_{bR_nDMH}$. $p_{bSR_1MH}$, $p_{bR_{i-1}R_iMH}$ and $p_{bR_nDMH}$ represent the bit error rate of the source-relay link, relays-relays links and relay-destination link. $SNR_{SR_1MH}$, $SNR_{R_{i-1}R_iMH}$ and $SNR_{RnDMH}$ represent the bit error rate of the source-relay link, relays-relays links and relay-destination link. $T_{SMH}$ represents the total time to successfully transmit a packet. $T_{SMH}$ can be expressed as:

$$T_{SMH} = T_{SYNC} + T_{rts} + T_{rth} + T_{cts} + (n+1)T_{L_p} + T_{Ack} + (4+n)T_{SIFS} + T_{DIFS} \tag{3.44}$$

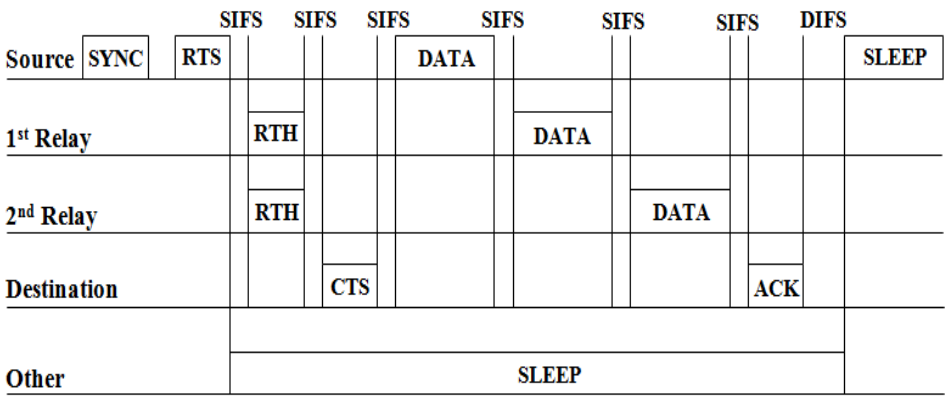



Figure 3.3: Frame diagram for multi-hop relay

In multi-hop transmission scheme when a sensor node transmits a packet, it will send a synchronise packet (SYNC), Request-to-Send (RTS) as shown in Figure 3.3. Any relay node is ready to help the source, the source will receive ready-to-help packet (RTH) from them beside Clear-to-Send (CTS) from the destination. Then DATA ($L_p$) will be sent to the first relay node, the first relay node will send DATA to the second node, the second relay node will send DATA to the destination and Acknowledgement (ACK) packets will be sent from the destination node to the source node.

The optimum throughput of this transmission scheme $S_{thMHopt}$ can be obtained by finding the optimum average packet payload length $L_{pMHopt}$. Lagrange optimisation has been used as an optimisation technique. This is an optimisation problem with one constraint variable and its Lagrangian is given by:

$$Max\sum S_{thMH} \qquad s.t. \ \{(N_s(1-p_o)p_s(1-p_{eMH}) \geq Qs)\} \tag{3.45}$$

$$L(L_p, \Lambda_{MH}) = S_{thMH} + \Lambda_{MH}(N_s(1-p_o)p_s(1-p_{eMH}) - Qs) \tag{3.46}$$

$$L_{pMHopt} = \frac{\ln\left(\frac{Qs}{N_s(1-p_o)p_s}\right)}{\left(\ln(1-p_{bSR_1}) + (n-1)\prod_{i=2}^{n}\ln(1-p_{bR_{i-1}R_i}) + \ln(1-p_{bR_nD})\right)} \tag{3.47}$$

The detailed derivation of this result is provided in Appendix (Appendix A-Ch3-2(b)).

The maximum throughput for multi-hop transmission scheme can be obtained by substituting Equation (3.47) in Equation (3.46).

## 3.1.2 Cooperative Transmission Schemes

In cooperative transmission, the sender *S* broadcasts its symbol to all potential receivers including the destination *D* and relays in the current time slot. Both the destination and relays receive noisy versions of the transmitted symbol. Then the relays transmit the received symbol after some processing to the destination. We present two types of cooperative transmission schemes: 1) using multiple cooperative relaying branches with one relay in each branch and 2) using multiple cooperative relaying branches with multiple relays in each branch. The selective decode and forward (SDF) relaying protocol is used in these two schemes and relays perform cooperation when the information from the source is correctly received by them. We assume that the selection combining technique is used at the destination on the received packets.

### 3.1.2.1 Cooperative Transmission using Multiple Branches with One Relay

In the cooperative transmission scheme with multiple branches *K* with one relay transmission scheme, the communications is carried through multiple relays nodes, each node located at a different branch as shown in Figure 3.1(c). Assuming that we have single or multiple relay branches $K \in \{1,k\}$, each relay is able to detect if the packet was received correctly and only in that case the relay will forward the information to the destination. Otherwise, the packet is considered lost. In this case, the received symbol by relays, $r_{SR}$, the received symbol by the destination from relays, $r_{RD}$ and the spectral efficiency $R_S$ can be expressed as:

$$r_{SR} = \sqrt{P_S d_{SR}^{-\alpha}} h_{SR} S + N_o \tag{3.48}$$

$$r_{RD} = \sqrt{P_C d_{RD}^{-\alpha}} h_{RD}\, s + N_o \tag{3.49}$$

$$R_S = \frac{1}{2}\log_2\left(1 + \frac{P_S|h_{SR}|^2}{N\,d_{SR}{}^{\alpha}} + \frac{P_C|h_{RD}|^2}{N\,d_{RD}{}^{\alpha}}\right) \tag{3.50}$$

where $P_S$ is the transmission power of the source and $P_C$ is the transmission power of relays, $h_{SR}$ and $h_{RD}$ are the channel coefficients of the source-relay link and the relay-destination link, respectively.

For any concatenation and based on the previous subsections, we can conclude that the outage probability for this transmission scheme is given by jointly considering the outages in *S-D*, *S-R* and *R-D* links, i.e.,

$$p_{outMB} = p_{outSD}\left(1-\left(1-p_{outSR}\right)\left(1-p_{outRD}\right)\right) \tag{3.51}$$

For multiple ($K$) branches, Equation (3.51) can be rewritten as:

$$p_{outMB} = p_{outSD}\left(1-\left(1-p_{outSR}\right)\left(1-p_{outRD}\right)\right)^K \tag{3.52}$$

where $p_{outSD} = 1 - e^{\left(\frac{-\left(2^{2R_S}-1\right)N}{P_S|h_{SD}|^2\gamma_{SD}}\right)}$, $p_{outSR} = 1 - e^{\left(\frac{-\left(2^{2R_S}-1\right)N}{P_S|h_{SR}|^2\gamma_{SR}}\right)}$ $and$ $p_{outRD} = 1 - e^{\left(\frac{-\left(2^{2R_S}-1\right)N}{P_R|h_{RD}|^2\gamma_{RD}}\right)}$

$p_{outSD}$, $p_{outSR}$ and $p_{outRD}$ represents the outage probability between the source and destination , the outage probability between source and relay branch and the outage probability between the relay branch and destination, respectively. $P_S$ and $P_R$ are the transmission power of the source and the relay power, respectively. Then, the outage probability of this transmission scheme can be expressed as:

$$p_{outMB} = \left(1 - e^{\left(\frac{-\left(2^{2R_S}-1\right)N}{P_S|h_{SD}|^2\gamma_{SD}}\right)}\right)\left(1 - e^{-\left(2^{2R_S}-1\right)N\left(\frac{1}{P_S|h_{SR}|^2\gamma_{SR}}+\frac{1}{P_R|h_{RD}|^2\gamma_{RD}}\right)}\right)^K \tag{3.53}$$

As described in the previous subsection, the power between two communicating nodes is given by:

$$P_R = \upsilon_{RD}{}^{\alpha} P_{SD} = \left(\frac{d_{RD}}{d_{SD}}\right)^{\alpha} P_{SD} = X P_{SD} \tag{3.54}$$

Based on Equation (3.54), so Equation (3.53) can be rewritten as:

$$p_{outMB} = \left(1 - e^{\left(\frac{-\left(2^{2R_S}-1\right)N}{P_{SMB}|h_{SD}|^2\gamma_{SD}}\right)}\right)\left(1 - e^{-\frac{\left(2^{2R_S}-1\right)N}{P_{SMB}}\left(\frac{1}{|h_{SR}|^2\gamma_{SR}}+\frac{1}{\upsilon_{RD}{}^{\alpha}|h_{RD}|^2\gamma_{RD}}\right)}\right)^K \tag{3.55}$$

Then the outage probability of the multiple branches transmission scheme can be approximated and expressed as follows:

$$p_{outMB} \approx \left( \frac{\left(2^{2R_s}-1\right)N}{P_{SMB}\left|h_{SD}\right|^2 \gamma_{SD}} \right) \left( \frac{\left(2^{2R_s}-1\right)N}{P_{SMB}} \left( \frac{1}{\left|h_{SR}\right|^2 \gamma_{SR}} + \frac{1}{\upsilon_{RD}{}^{\alpha} \left|h_{RD}\right|^2 \gamma_{RD}} \right) \right)^K$$

$$p_{outMB} \approx \frac{\left(2^{2R_s}-1\right)^{K+1} N^{K+1}}{P_{SMB}{}^{K+1}\left|h_{SD}\right|^2 \gamma_{SD}} \left( \left( \frac{1}{\left|h_{SR}\right|^2 \gamma_{SR}} + \frac{1}{\upsilon_{RD}{}^{\alpha} \left|h_{RD}\right|^2 \gamma_{RD}} \right) \right)^K \tag{3.56}$$

The total consumption takes into account the required power for the transmission, which depends on the distance between each two sensor nodes, the power consumption of the circuitry and the bit rate. Thus, the total consumed energy per bit of this transmission scheme is:

$$E_{bMB} = \left(pout_{SR}\right)^K \frac{P_{AM,MB} + P_{Tx} + K * P_{Rx}}{R_b} + \left(1 - \left(pout_{SR}\right)^K\right) \frac{\left(\sum_{l=1}^{K} \upsilon_{R_l D}{}^{\alpha} + 1\right) P_{AM,MB} + (K+1) P_{Tx} + (2K+1) P_{Rx}}{R_b} \tag{3.57}$$

The first term on the right-hand side corresponds to the consumed energy when the relay is not able to correctly decode the message from the source, which means that this link is in outage. In this case, only the source node consumes transmitting power and the destination node and *n* relays consume receiving power. The second term counts for the event that the source-relay link is not in outage, hence the relay transmitting and processing power and the extra receiving power at the destination are involved.

Replacing $\upsilon_{R_l D}{}^{\alpha}$ by $X_{R_l D}$, then Equation (3.57) can be written as:

$$E_{bMB} = \left(pout_{SR}\right)^K \frac{P_{AM,MB} + P_{Tx} + K * P_{Rx}}{R_b} + \left(1 - \left(pout_{SR}\right)^K\right) \frac{\left(\sum_{l=1}^{K} X_{R_l D} + 1\right) P_{AM,MB} + (K+1) P_{Tx} + (2K+1) P_{Rx}}{R_b} \tag{3.58}$$

$$P_{AM,MB} = \frac{\xi}{\eta} P_{SMB} \tag{3.59}$$

where $P_{AM,MB}$ is the power amplification for multiple branches transmission scheme which depends on the drain efficiency of the amplifier $\eta$, the average peak-to-peak ratio $\xi$ as described previously.

Energy consumption required for cooperative multiple branches transmission scheme in order to maintain a required level of reliability, denoted by *U*, which is related to the reliability of a transmission link, the minimum outage probability is defined as:

$$p_{outMB} \leq 1\text{-}U \tag{3.60}$$

In order to find the optimum required transmission power with minimum energy consumption for cooperative multiple branches transmission scheme, Lagrange optimisation is used. The optimisation problem with one constraint variable and its Lagrangian for this transmission scheme is given by:

$$Min\sum E_{bMB} \qquad s.t.\{p_{outMB} \leq 1-U\} \tag{3.61}$$

$$L(P_{SMB}, \lambda_{MB}) = P_{totMB} + \lambda_{MB}(p_{outMB} - 1 + U) \tag{3.62}$$

$$P_{SMB}{}^{K+1} = \frac{(2^{2R_s}-1)^{K+1} N^{K+1}}{(1-U)|h_{SD}|^2 \gamma_{SD}} \left( \left( \frac{1}{|h_{SR}|^2 \gamma_{SR}} + \frac{1}{\upsilon_{RD}{}^{\alpha} |h_{RD}|^2 \gamma_{RD}} \right) \right)^K \tag{3.63}$$

Thus, the optimum required transmission power $P_{MBopt}$ for the multiple branches transmission scheme to satisfy the reliability requirement or be constrained by the outage probability for this transmission scheme must be:

$$P_{MBopt} = (2^{2R_s}-1)N \left( \frac{1}{(1-U)|h_{SD}|^2 \gamma_{SD}} \left( \left( \frac{1}{|h_{SR}|^2 \gamma_{SR}} + \frac{1}{\upsilon_{RD}{}^{\alpha} |h_{RD}|^2 \gamma_{RD}} \right) \right)^K \right)^{\frac{1}{K+1}} \tag{3.64}$$

The detailed derivation of this result is provided in Appendix (Appendix A-Ch3-3(a)).

We can obtain the minimum energy efficiency based on the optimum required transmission power by substituting Equation (3.64) in Equation (3.62) and then in Equation (3.58), hence the minimum energy consumption $E_{bMBmin}$ can be formulated as:

$$E_{bMB\min} = \frac{P_{totMB\min}}{R_b} \tag{3.65}$$

where

$$P_{totMB\min} = (pout_{SR})^K (P_{AM,MB\min} + P_{Tx} + KP_{Rx})$$
$$+ \left(1 - (pout_{SR})^K\right)\left( \left( \sum_{l=1}^{K} X_{R_l D} + 1 \right) P_{AM,MB\min} + (K+1)P_{Tx} + (2K+1)P_{Rx} \right) + \lambda_{MB}(pout_{MB} - 1 + U)$$

and

$$P_{AM,MB\min} = \frac{\xi}{\eta} P_{MBopt} \tag{3.66}$$

Based on the definition of the throughput described in the previous subsections, the throughput for the cooperative using multiple branches with one relay transmission scheme $S_{thMB}$ can be expressed as:

$$S_{thMB} = \frac{N_s(1-p_o)p_s(1-p_{eMB})L_p}{T_{SMB}} \tag{3.67}$$

$$p_{eMB} = \left(1-(1-p_{bSRMB})^{L_p}(1-p_{bRDMB})^{L_p}\right)^K \left(1-(1-p_{bSDMB})^{L_p}\right) \tag{3.68}$$

Let $X_1 = (1-p_{bSDMB})^{L_p}$ and $X_2 = (1-p_{bSRMB})^{L_p}(1-p_{bRDMB})^{L_p}$

$$p_{bSDMB} = Q\sqrt{2SNR_{SDMB}},\ p_{bSRMB} = Q\sqrt{2SNR_{SRMB}},\ \text{and}\ p_{bRDMB} = Q\sqrt{2SNR_{RDMB}} \tag{3.69}$$

where $SNR_{SDMB} = \frac{\gamma_{SD}|h_{SD}|^2 P_{MB}}{N_o B}$, $SNR_{SRMB} = \frac{\gamma_{SR}|h_{SR}|^2 X_{SR} P_{MB}}{N_o B}$ and $SNR_{RDMB} = \frac{\gamma_{RD}|h_{RD}|^2 X_{RD} P_{MB}}{N_o B}$

where $p_{eMB}$ represents packet error probability for multiple branches with one relay transmission scheme which depends on $p_{bSDMB}$, $p_{bSRMB}$ and $p_{bRDMB}$. $p_{bSDMB}$, $p_{bSRMB}$ and $p_{bRDMB}$ represent the bit error rate of the source-destination link, source-relay link and relay-destination link. $SNR_{SDMB}$, $SNR_{SRMB}$ and $SNR_{RDMB}$ represent the bit error rate of the source-destination link, source-relay link and relay-destination link. $T_{SMB}$ represents the total time to successfully transmit a packet. $T_{SMB}$ can be expressed as:

$$T_{SMB} = T_{SYNC} + T_{rts} + T_{rth} + T_{cts} + (n+1)T_{L_p} + T_{Ack} + (4+n)T_{SIFS} + T_{DIFS} \tag{3.70}$$

In cooperative using multiple branches with one relay transmission scheme when sensor node transmits a packet, it will send synchronise packet (SYNC), Request-to-Send (RTS) as shown in Figure 3.4. If there are any relay nodes that are ready to help the source, the source will receive ready-to-help packet (RTH) from them beside Clear-to-Send (CTS) from the destination. Then DATA ($L_p$) will be sent at the same time to all available relay helper nodes and all relay nodes will send DATA to the destination and Acknowledgement (ACK) packets will be sent from the destination node to the source node.

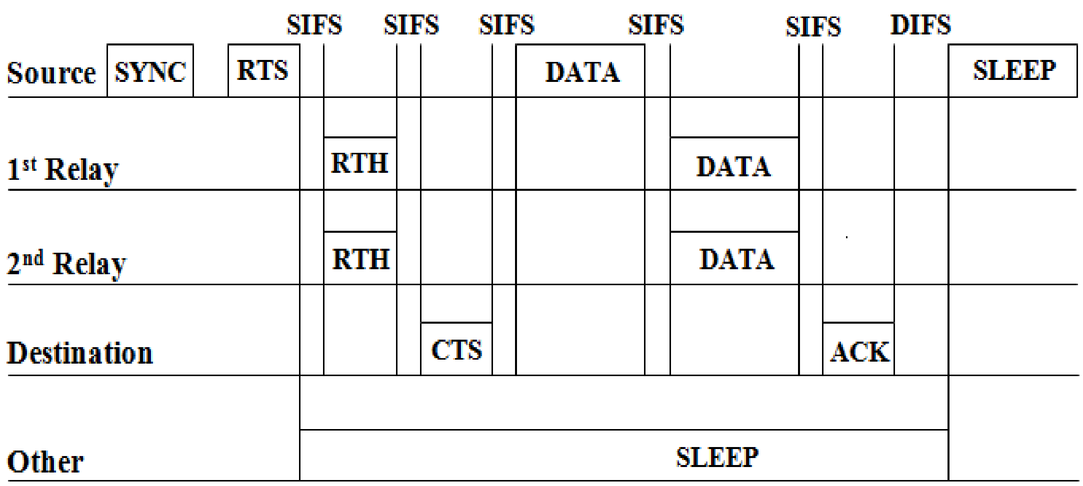



Figure 3.4: Frame diagram for cooperative using multiple branches with one relay

The optimum throughput of this transmission scheme $S_{thMBopt}$ can be obtained by finding the optimum average packet payload length $L_{pMBopt}$. As described in the previous subsections, this is an optimisation problem with one constraint variable and its Lagrangian is given by:

$$Max \sum S_{thMB} \qquad s.t. \{N_s (1 - p_o) p_s (1 - p_{eMB}) \geq Qs\} \tag{3.71}$$

$$L(L_p, \Lambda_{MB}) = S_{thMB} + \Lambda_{MB} \left(N_s (1 - p_o) p_s (1 - p_{eMB}) - Qs\right) \tag{3.72}$$

$$L_{pMBopt} = \left( \frac{Qs}{N_s (1 - p_o) p_s (-\ln(1 - p_{bSD}))(-(\ln(1 - p_{bSR}) + \ln(1 - p_{bRD})))^K} \right)^{\frac{1}{K+1}} \tag{3.73}$$

The detailed derivation of this result is provided in Appendix (Appendix A-Ch3-3(b)).

The maximum throughput for cooperative using multiple branches with one relay transmission scheme can be obtained by substituting Equation (3.73) in Equation (3.72) and then in Equation (3.67).

### 3.1.2.2 Cooperative Transmission using Multiple Branches with Multiple Relays

In this cooperative transmission scheme, assuming that we have single or multiple relay branches $K \epsilon \{1,k\}$, each branch has single or multiple relay nodes $R \epsilon \{1,n\}$, as shown in Figure 3.1(d). In this scheme, a relay will forward a packet to the destination only if it was received correctly. Otherwise, the packet is considered lost.

For this transmission scheme, we can conclude that the outage probability is given by jointly considering the outages in $S$-$D$, $S$-$R_1$, $R_1$-$R_2$ and $R_n$-$D$ links, i.e.,

$$p_{outMHB} = p_{outSD} \left(1 - \left((1 - p_{outSR_1})(1 - p_{outR_1R_2}) \cdots\cdots\cdots\cdots (1 - p_{outR_nD})\right)\right) \tag{3.74}$$

For multiple ($K$) branches, Equation (3.74) can be rewritten as:

$$p_{outMHB} = p_{outSD} \left(1 - \left((1 - p_{outSR_1})(1 - p_{outR_1R_2}) \cdots\cdots\cdots\cdots (1 - p_{outR_nD})\right)\right)^K \tag{3.75}$$

where $p_{outSD} = 1 - e^{\left(\frac{-(2^{2R_s} - 1)N}{P_S |h_{SD}|^2 \gamma_{SD}}\right)}$, $p_{outSR_1} = 1 - e^{\left(\frac{-(2^{2R_s} - 1)N}{P_S |h_{SR_1}|^2 \gamma_{SR_1}}\right)}$, $p_{outR_1R_2} = 1 - e^{\left(\frac{-(2^{2R_s} - 1)N}{P_{R_1} |h_{R_1R_2}|^2 \gamma_{R_1R_2}}\right)}$

and $p_{outR_nD} = 1 - e^{\left(\frac{-(2^{2R_s} - 1)N}{P_{R_n} |h_{R_nD}|^2 \gamma_{R_nD}}\right)}$

$p_{outSD}$, $p_{outSR_1}$, $p_{outR_1R_2}$ and $p_{outRD}$ represent the outage probability between the source and destination, the outage probability between the source and first relay node, the outage probability between first and second relay nodes and the outage probability between the last relay node and destination, respectively. $P_S, P_{R_1}$, and $P_{R_n}$ are the transmission power of the source, first relay node and last relay node, respectively. Then, the outage probability of this transmission scheme can be expressed as:

$$p_{outMHB} = \left(1 - e^{\left(\frac{-\left(2^{2R_s}-1\right)N}{P_S\left|h_{SD}\right|^2\gamma_{SD}}\right)}\right)\left(1 - e^{-\left(2^{2R_s}-1\right)N\left(\frac{1}{P_S\left|h_{SR_1}\right|^2\gamma_{SR_1}}+\sum_{i=2}^{n}\frac{1}{P_{Ri-1}\left|h_{Ri-1Ri}\right|^2\gamma_{R_{i-1}R_i}}+\frac{1}{P_{Rn}\left|h_{RnD}\right|^2\gamma_{R_nD}}\right)}\right)^K \quad (3.76)$$

The power between two communicating nodes is given by:

$$P_{R1} = \upsilon_{RD}{}^{\alpha} P_{SD} = \left(\frac{d_{RD}}{d_{SD}}\right)^{\alpha} P_{SD} = X P_{SD} \quad (3.77)$$

Based on Equation (3.77), so Equation (3.76) can be rewritten as:

$$p_{outMHB} = \left(1 - e^{\left(\frac{-\left(2^{2R_s}-1\right)N}{P_{SMHB}\left|h_{SD}\right|^2\gamma_{SD}}\right)}\right)\left(1 - e^{-\frac{\left(2^{2R_s}-1\right)N}{P_{SMHB}}\left(\frac{1}{\left|h_{SR_1}\right|^2\gamma_{SR_1}}+\sum_{i=2}^{n}\frac{1}{\upsilon_{R_{i-1}R_i}{}^{\alpha}\left|h_{R_{i-1}Ri}\right|^2\gamma_{R_{i-1}R_i}}+\frac{1}{\upsilon_{R_nD}{}^{\alpha}\left|h_{R_nD}\right|^2\gamma_{R_nD}}\right)}\right)^K$$

(3.78)

Then the outage probability of this transmission scheme can be approximated and expressed as follows:

$$p_{outMHB} \approx \left(\frac{\left(2^{2R_s}-1\right)N}{P_{SMHB}\left|h_{SD}\right|^2\gamma_{SD}}\right)\left(\frac{\left(2^{2R_s}-1\right)N}{P_{SMHB}}\left(\frac{1}{\left|h_{SR_1}\right|^2\gamma_{SR_1}}+\sum_{i=2}^{n}\frac{1}{\upsilon_{R_{i-1}R_i}{}^{\alpha}\left|h_{R_{i-1}Ri}\right|^2\gamma_{R_{i-1}R_i}}+\frac{1}{\upsilon_{R_nD}{}^{\alpha}\left|h_{R_nD}\right|^2\gamma_{R_nD}}\right)\right)^K$$

$$p_{outMHB} \approx \frac{\left(2^{2R_s}-1\right)^{K+1}N^{K+1}}{P_{SMHB}{}^{K+1}\left|h_{SD}\right|^2\gamma_{SD}}\left(\left(\frac{1}{\left|h_{SR_1}\right|^2\gamma_{SR_1}}+\sum_{i=2}^{n}\frac{1}{\upsilon_{R_{i-1}R_i}{}^{\alpha}\left|h_{R_{i-1}Ri}\right|^2\gamma_{R_{i-1}R_i}}+\frac{1}{\upsilon_{R_nD}{}^{\alpha}\left|h_{R_nD}\right|^2\gamma_{R_nD}}\right)\right)^K \quad (3.79)$$

The total consumption takes into account the required power for the transmission, which depends on the distance between each two sensor nodes, the power consumption of the circuitry and the bit rate. Thus, the total consumed energy per bit of this transmission scheme is:

$$\begin{aligned} E_{bMHB} &= \left(pout_{SR_1}\right)^K \frac{P_{AM,MHB} + P_{Tx} + K * P_{Rx}}{R_b} \\ &+ \left(1 - \left(pout_{SR_1}\right)^K\right)\frac{\left(\sum_{l=1}^{K}\left(\sum_{i=2}^{n}\upsilon_{(R_{i-1}R_i)_l}{}^{\alpha} + \upsilon_{(R_nD)_l}{}^{\alpha}\right)+1\right)P_{AM,MHB} + (K*n+1)P_{Tx} + (K*(n+1)+1)P_{Rx}}{R_b} \end{aligned} \quad (3.80)$$

The first term on the right-hand side corresponds to the consumed energy when the relay is not able to correctly decode the message from the source, which means that this link is in outage. In this case, only the source node consumes transmitting power and the destination node and *n* relays consume receiving power. The second term counts for the event that the source-relay link is not in outage, hence the relay transmitting and processing power and the extra receiving power at the destination are involved.

As explained in the previous subsections, Equation (3.80) can be written as:

$$E_{bMHB} = \left(pout_{SR_1}\right)^K \frac{P_{AM,MHB} + P_{Tx} + K * P_{Rx}}{R_b} + \left(1-\left(pout_{SR_1}\right)^K\right) \frac{\left(\sum_{l=1}^{K}\left(\sum_{i=2}^{n} X_{(R_{i-1}R_i)_l} + X_{(R_n D)_l}\right)+1\right)P_{AM,MHB} + \left(K*n+1\right)P_{Tx} + \left(K*\left(n+1\right)+1\right)P_{Rx}}{R_b} \quad (3.81)$$

$$P_{AM,MHB} = \frac{\xi}{\eta} P_{SMHB} \quad (3.82)$$

where $P_{AM,MHB}$ is the power amplification for multiple branches with multiple relays transmission scheme which depends on the drain efficiency of the amplifier $\eta$, the average peak-to-peak ratio $\xi$ as described previously.

Energy consumption required for cooperative using multiple branches and relays transmission scheme in order to maintain a required level of reliability, denoted by *U*, which is related to the reliability of a transmission link, the minimum outage probability is defined as:

$$p_{outMHB} \leq 1\text{-}U \quad (3.83)$$

In order to find the optimum required transmission power with minimum energy consumption for cooperative using multiple branches and relays transmission scheme Lagrange optimisation is used as mentioned previously. The optimisation problem with one constraint variable and its Lagrangian for this transmission scheme is given by:

$$Min \sum E_{bMHB} \qquad s.t.\left\{p_{outMHB} \leq 1 - U\right\} \quad (3.84)$$

$$L(P_{SMHB}, \lambda_{MHB}) = P_{totMHB} + \lambda_{MHB}\left(p_{outMHB} - 1 + U\right) \quad (3.85)$$

Thus, the optimum required transmission power $P_{MHBopt}$ for cooperative using multiple branches and relays scheme to satisfy the reliability requirement or be constrained by the outage probability for this transmission scheme must be:

$$P_{MHBopt} = \left(2^{2R_s} - 1\right) N \left( \frac{1}{(1-U)\left|h_{SD}\right|^2 \gamma_{SD}} \left( \left( \frac{1}{\left|h_{SR_1}\right|^2 \gamma_{SR_1}} + \sum_{i=2}^{n} \frac{1}{\upsilon_{R_{i-1}R_i}{}^{\alpha} \left|h_{R_{i-1}Ri}\right|^2 \gamma_{R_{i-1}R_i}} + \frac{1}{\upsilon_{R_nD}{}^{\alpha} \left|h_{R_nD}\right|^2 \gamma_{R_nD}} \right) \right)^{K} \right)^{\frac{1}{K+1}} \quad (3.86)$$

The detailed derivation of this result is provided in Appendix (Appendix A-Ch3-4(a)).

The minimum energy efficiency can be obtained by substituting Equation (3.86) in Equation (3.85) and then in Equation (3.81), hence the minimum energy consumption $E_{bMHBmin}$ can be formulated as:

$$E_{bMHB\min} = \frac{P_{totMHB\min}}{R_b} \quad (3.87)$$

where

$$P_{totMHB\min} = \left(pout_{SR_1}\right)^K \left(P_{AM,MHB\min} + P_{Tx} + K * P_{Rx}\right)$$
$$+ \left(1 - \left(pout_{SR_1}\right)^K\right) \left( \left( \sum_{l=1}^{K} \left( \sum_{i=2}^{n} X_{(R_{i-1}R_i)_l} + X_{(R_nD)_l} \right) + 1 \right) P_{AM,MHB\min} + (K*n+1) P_{Tx} + (K*(n+1)+1) P_{Rx} \right)$$
$$+ \lambda_{MHB}\left(pout_{MHB} - 1 + U\right)$$

and

$$P_{AM,MHB\min} = \frac{\xi}{\eta} P_{MHBopt} \quad (3.88)$$

Based on the definition of the throughput described in the previous subsections, the throughput for the cooperative using multiple branches with multiple relays transmission scheme $S_{thMHB}$ can be expressed as:

$$S_{thMHB} = \frac{N_s (1-p_o) p_s (1-p_{eMHB}) L_p}{T_{SMHB}} \quad (3.89)$$

$$p_{eMHB} = \left(1 - (1-p_{bSR_1MHB})^{L_p} \left( \prod_{i=2}^{n} (1-p_{bR_{i-1}R_iMHB}) \right)^{L_p} (1-p_{bR_nDMHB})^{L_p} \right)^K \left(1 - (1-p_{bSDMB})^{L_p}\right) \quad (3.90)$$

Let $X_1 = (1-p_{bSDMB})^{L_p}$

and $X_3 = (1-p_{bSR_1MHB})^{L_p} \left( \prod_{i=2}^{n} (1-p_{bR_{i-1}R_iMHB}) \right)^{L_p} (1-p_{bR_nDMHB})^{L_p}$

$$p_{bSDMHB} = Q\sqrt{2SNR_{SDMHB}},\ p_{bSR_1MHB} = Q\sqrt{2SNR_{SR_1MHB}},$$
$$p_{bR_{i-1}R_iMHB} = Q\sqrt{2SNR_{R_{i-1}R_iMHB}},\ and\ p_{bR_nDMHB} = Q\sqrt{2SNR_{R_nDMHB}} \quad (3.91)$$

$$SNR_{SDMHB} = \frac{\gamma_{SD}|h_{SD}|^2 P_{MHB}}{N_o B}, SNR_{SR_1MHB} = \frac{\gamma_{SR_1}|h_{SR_1}|^2 P_{MHB}}{N_o B},$$
$$SNR_{R_{i-1}R_iMHB} = \frac{\gamma_{R_{i-1}R_i}|h_{R_{i-1}R_i}|^2 X_{R_{i-1}R_i} P_{MHB}}{N_o B} \; and \; SNR_{R_nDMHB} = \frac{\gamma_{R_nD}|h_{R_nD}|^2 X_{R_nD} P_{MHB}}{N_o B} \tag{3.92}$$

where $p_{eMHB}$ represents packet error probability for multiple branches with multiple relays transmission scheme which depends on $p_{bSDMHB}$, $p_{bSRMHB}$ and $p_{bRDMHB}$. $p_{bSDMHB}$, $p_{bSRMHB}$ and $p_{bRDMHB}$ represent the bit error rate of the source destination link, the source-relay link, the relays-relays links and the relay-destination link. $SNR_{SDMHB}$, $SNR_{SR_1MHB}$, $SNR_{R_{i-1}R_iMHB}$ and $SNR_{R_nDMHB}$ represent the signal to the noise ratio of the source destination link, the source-relay link, relays-relays links and relay-destination link. $T_{SMHB}$ represents the total time to successfully transmit a packet for this transmission scheme. $T_{SMHB}$ can be expressed as:

$$T_{SMHB} = T_{SYNC} + T_{rts} + T_{rth} + T_{cts} + (n+1)T_{L_p} + T_{Ack} + (4+n)T_{SIFS} + T_{DIFS} \tag{3.93}$$

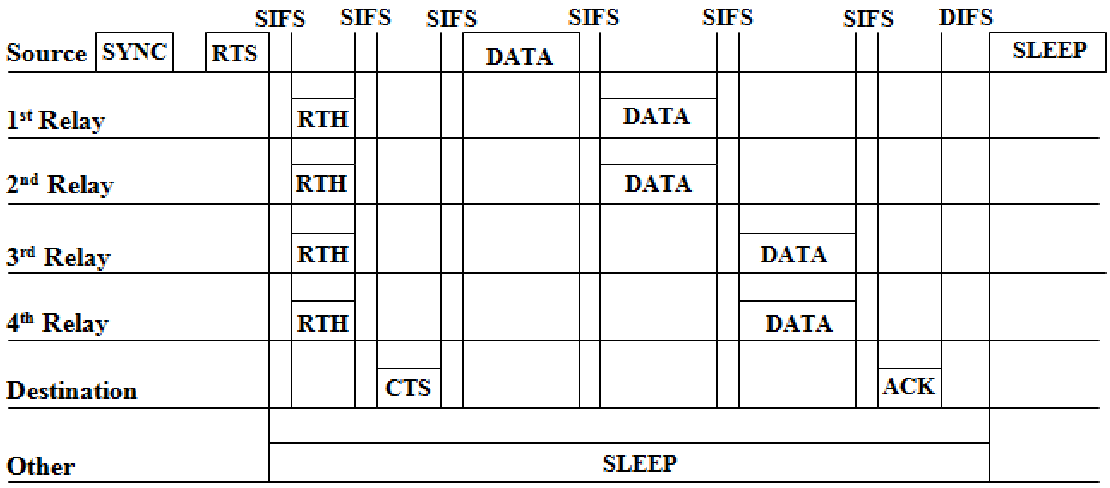



Figure 3.5: Frame diagram cooperative using multiple branches with multiple relays

In cooperative transmission scheme using multiple branches with multiple relays when a sensor node transmits a packet, it will send synchronise packet (SYNC) and Request-to-Send (RTS) as shown in Figure 3.5. If there are any relay nodes ready to help the source, the source will receive ready-to-help packet (RTH) from them beside Clear-to-Send (CTS) from the destination. Then DATA ($L_p$) will be sent at the same time to all available first parallel relay branches, then the DATA will be sent to the next relay in each parallel relay branch and then the second relay nodes in each branch will send DATA to the destination and the Acknowledgement (ACK) packets will be sent from the destination node to the source node.

The optimum throughput of this transmission scheme $S_{thMHBopt}$ can be obtained by finding the optimum average packet payload length $L_{pMHBopt}$. This is an optimisation problem with one constraint variable and its Lagrangian is given by:

$$Max \sum S_{thMHB} \qquad s.t. \{ N_s (1 - p_o) p_s (1 - p_{eMHB}) \geq Qs \} \tag{3.94}$$

$$L(L_p, \Lambda_{MHB}) = S_{thMHB} + \Lambda_{MHB} \left( N_s (1 - p_o) p_s (1 - p_{eMHB}) - Qs \right) \tag{3.95}$$

$$L_{pMHBopt} = \left( \frac{Qs}{N_s (1 - p_o) p_s (-\ln(1 - p_{bSD})) \left( -\left( \ln\left(1 - p_{bSR_1}\right) + (n-1) \prod_{i=2}^{n} \ln\left(1 - p_{bR_{i-1}R_i}\right) + \ln\left(1 - p_{bR_n D}\right) \right) \right)^{K}} \right)^{\frac{1}{K+1}} \tag{3.96}$$

The detailed derivation of this result is provided in Appendix (Appendix A-Ch3-4(b)).

The maximum throughput for cooperative using multiple branches with one relay transmission scheme by substituting Equation (3.96) in Equation (3.95) and then in Equation (3.89).

## 3.2 Performance Evaluation of the Proposed Models

The performance evaluation of the proposed transmission schemes, as described in the previous section, is presented in this section. The results focus on four performance metrics, which examine the energy efficiency and throughput for four transmission schemes under various channel and transmission conditions in a WSN as shown in Figure 3.1 using computer simulation (Matlab). We then show how a transmission scheme can be chosen in an adaptive way to optimise the energy and throughput performance.

The system performance is evaluated studying the QoS metrics and showing how the system performance is affected by configured parameters, e.g., path loss or transmission distance. For this evaluation a comparison between the four transmission schemes is presented. The performance differences between these transmission schemes as described in this chapter are analysed.

### 3.2.1 Network Topology

As mentioned before, a complete evaluation of the non-cooperative and cooperative transmission schemes are presented. The network settings used for simulation are listed in Table 3.1. For a given network topology, we choose different source-destination pair with different transmission distances under different channel conditions and environment, then we apply different transmission schemes for comparison purposes.

TABLE 3.1. WSN SIMULATION PARAMETERS

| Parameters | Value |
|---|---|
| $N_0$ | −174 dBm |
| $B$ | 10 kHz |
| $R_s$ | Between 1 and 2 bit/sec/Hz [68] |
| $P_{TX}$ | 97.9 mW [68] |
| $P_{RX}$ | 112.2 mW [68] |
| $\eta$ | 0.35 |
| ξ | 0.5 |
| $L_p$ | 50 bytes [144] |
| *SYNC* | 9 bytes [145] |
| *RTS* | 10 bytes [144, 145] |
| *CTS* | 10 bytes [144, 145] |
| *ACK* | 10 bytes [144, 145] |
| *SIFS* | 5 ms [144] |
| *DIFS* | 10 ms [144] |
| *fc* | 2.5 GHz [68] |
| *Ml* | 40 dB [68] |
| *Nf* | 10 dB [68] |
| *N* | 100 |
| *G* | 5 dBi [68] |
| *Qs* | 0.999 |

### 3.2.2 Energy Consumption Evaluation

The first evaluated metric is the energy consumption performance of the non-cooperative and cooperative transmission schemes. In Figure 3.6 energy performances of both cooperative and non-cooperative schemes are illustrated and compared through different required Qs. As we can see from Figure 3.6(a), when Qs is 0.99 the non-cooperative direct transmission has a much lower energy cost than all others for short-range ($d_{SD\backslash}$<7m); the non-cooperative transmission using multi-hop relays outperforms the direct transmission for short medium range. In particular, transmission using two intermediate relays ($n$=2) nodes has the lowest energy consumption for short mid-range (7m<$d_{SD}$<9m) and the cooperative transmission outperforms the direct and multi-hop transmission schemes for long-medium and long ranges. Specifically, transmission using one branch with two relays ($K$=1, $n$=2) has the lowest energy consumption for long mid-range (9m<$d_{SD}$<16m), but transmission using two branches with one relay ($K$=2, $n$=1) has the lowest energy consumption for mid-range ($d_{SD}$ <16m).

While, when Qs is 0.999 as shown in Figure 3.6(b), the non-cooperative direct transmission has a much lower energy cost than all others for short-range ($d_{SD}$<4.5m); the non-cooperative transmission using multi-hop relays outperforms the direct transmission for short medium range. In particular, transmission using two intermediate relays ($n$=2) nodes has the lowest energy consumption for short mid-range (4.5m<$d_{SD}$<5.3m) and the cooperative transmission outperforms the direct and multi-hop transmission schemes for long-medium and long ranges. Specifically, transmission using one branch with two relays ($K$=1, $n$=2) has the lowest energy consumption for long mid-range (5.3m<$d_{SD}$<9m), but transmission using two branches with one relay ($K$=2, $n$=1) has the lowest energy consumption for mid-range ($d_{SD}$<9m).

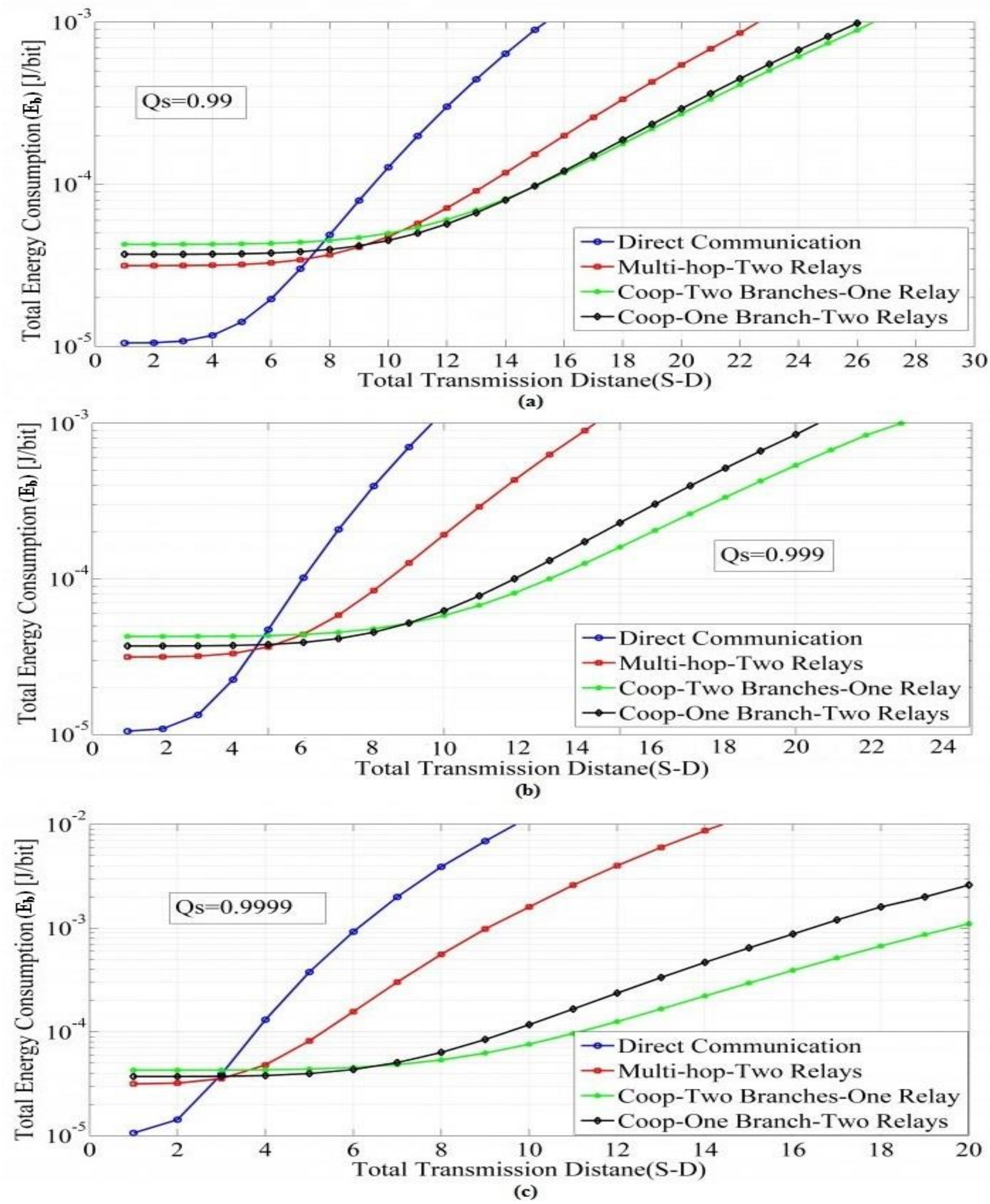


Figure 3.6: Total energy consumption vs total transmission distance

On the other hand, when the Qs is 0.9999 as depicted in Figure 3.6(c) the non-cooperative direct transmission has a much lower energy cost than all others for short-range ($d_{SD}$<2.8m); the non-cooperative transmission using multi-hop relays outperforms the direct transmission for short medium range. In particular, transmission using two intermediate relays ($n$=2) nodes has the lowest energy consumption for short mid-range (2.8m<$d_{SD}$<3.2m) and the cooperative transmission outperforms the direct and multi-hop transmission schemes for long-medium and long ranges.

### 3.2.3 System Throughput Evaluation

Based on the same scenarios described in the previous subsection, each transmission distance has its optimum transmission scheme in terms of minimum energy consumption, so in order to show that the system is efficient, the throughput for each transmission distance has to be evaluated. Assuming the transmission power is 0 dBm (1 mW), as shown in Figure 3.7, the non-cooperative direct transmission has a much higher throughput than all others for short-range ($d_{SD}$<6m); the cooperative transmission outperforms the direct transmission for medium and long range. In particular, the cooperative transmission ($K$=1, $n$=2) has higher throughput for short mid-range (6m<$d_{SD}$<10m), as for this range the probability of error will be very small which leads to the decrement of the retransmission time and the increment of the throughput. Although when the distance exceeds 10m, the cooperative transmission using multiple branches ($K$=2, $n$=1) becomes more efficient than the other transmission scheme. This is due to the diversity created by using multiple branches, as the diversity techniques increases the number of transmitted data through different branches and then increases the system throughput.

We also mentioned from Figure 3.7 that the non-cooperative using multi-hop relays is worse than the direct transmission and the cooperative transmission, due to the poor channel conditions assumed in our model (lower transmission power in a deep Rayleigh fading channel with high path loss exponent). This causes the overall link failure between source and destination nodes to be higher than the other transmission schemes; this increases the number retransmission and decreases the overall system throughput. In addition, using multi-nodes with the direct transmission increases the overhead and the total transmission time.

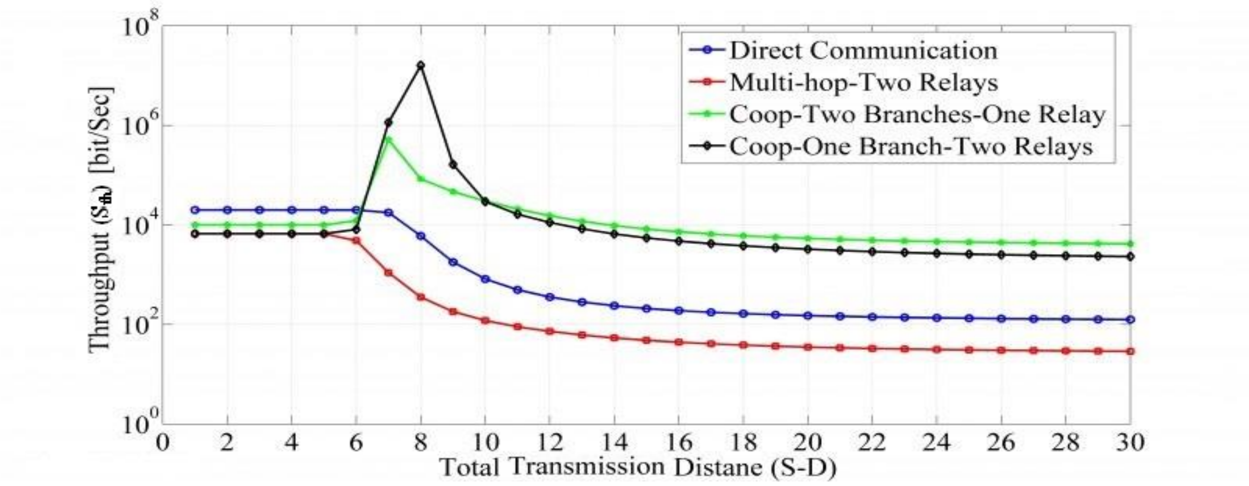



Figure 3.7: Throughput vs total transmission distance

Also, it can be noticed that between the transmission distance 6 and 10 m the cooperative transmission scheme specially using one branch with two relays outperforms non-cooperative transmission schemes due to the existence of an intermediate node which decreases the distance between S-D, which decreases the probability of failure and the retransmission time which increases the overall system throughput.

### 3.2.4 Quality of Service Contraints

In this subsection, we show simulation and analytical results for different transmission schemes with respect to the required QoS. Figure 3.8 demonstrates the energy performance for cooperative and non-cooperative transmission schemes with different required QoS (Qs) when the transmission distance is short, short -medium, long-medium and long. As shown in Figure 3.8(a) the distance between *S-D* is short ($d_{SD}$=5m), where the best transmission is the direct transmission as long as the QoS is less than 0.9984, while the multi-hop transmission scheme ($n$=2) has the lowest energy consumption among the other transmission schemes with the QoS exceeding 0.9984. In addition, Figure 3.8(b) represents the same performance when the distance becomes short medium ($d_{SD}$=10m), but the non-cooperative transmission is inefficient through this transmission range, although the cooperative transmission scheme using one branch with two relays ($K$=1, $n$=2) is more efficient than the other transmission scheme as long as the QoS is less than 0.998, but when the quality of service is greater than 0.998 the cooperative transmission scheme using two branches with one relays ($K$=2, $n$=1) outperforms the other transmission schemes.

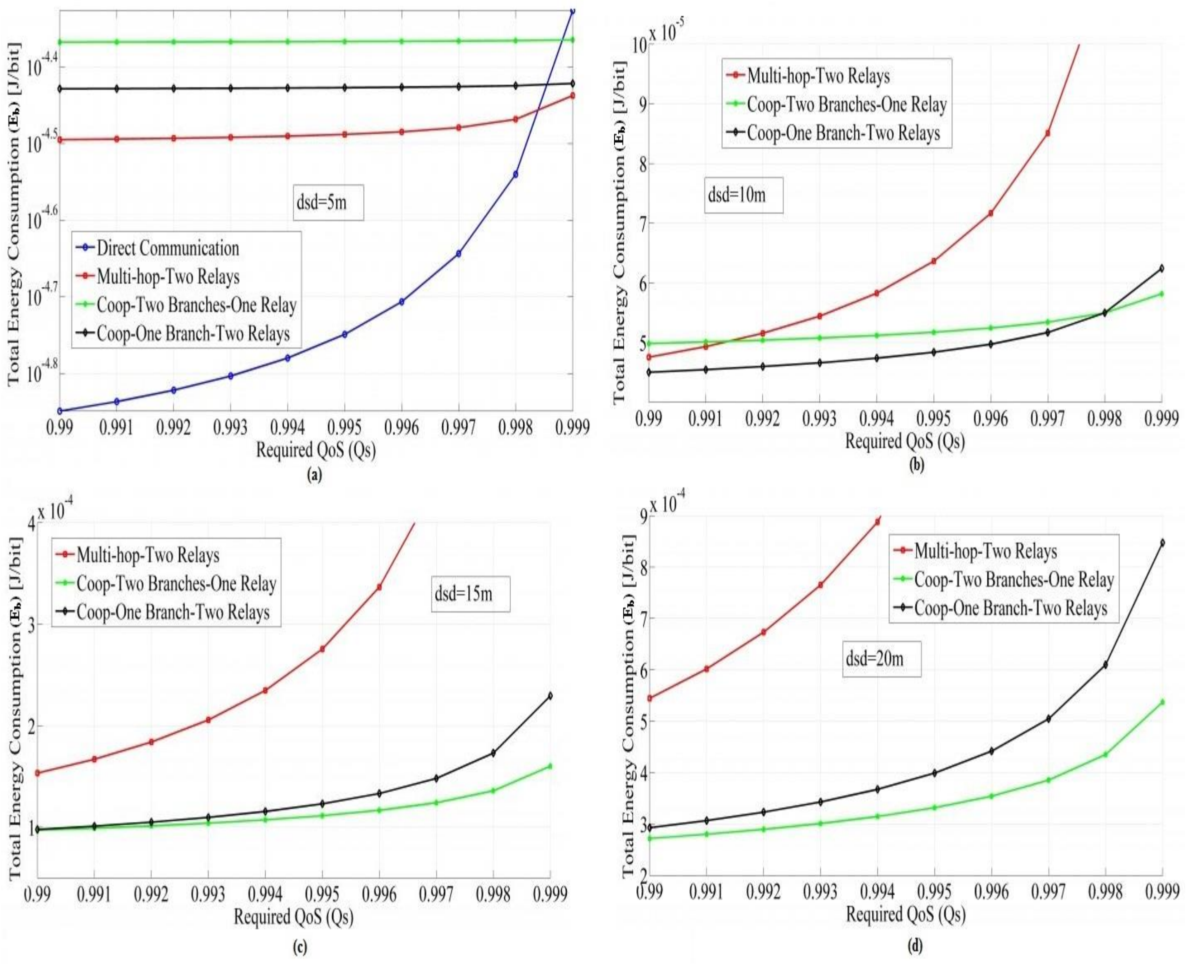



Figure 3.8: Total energy consumption vs required QoS.

Furthermore, when the distance becomes long-medium and long range ($d_{SD}$=15m and $d_{SD}$=20m) as shown in Figure 3.8(c) and Figure 3.8(d), the non-cooperative transmission scheme is not efficient for these ranges. While, for distance 15m the two presented cooperative transmission schemes have the same energy consumption performance as long as the quality of service is between 0.99 and 0991. But when the QoS exceeds 0.991 the cooperative communication using two branches with one relay ($K$=2, $n$=1) becomes more efficient. Moreover, for the transmission distance 20m only the cooperative transmission using two branches with one relay is the most efficient transmission scheme among others.

### 3.2.5 Effect of Spectral Efficiency on System Performance

In this subsection, the effect of using different spectral efficiency on the system performance is evaluated. Figure 3.9 depicts the energy performance for cooperative and non-cooperative transmission schemes with different spectral efficiency ($R_s$). As shown in Figure 3.9(a) the distance between $S$-$D$ is short ($d_{SD}$=5m), so the best transmission is the direct transmission as long as the spectral efficiency is less than 1.6.

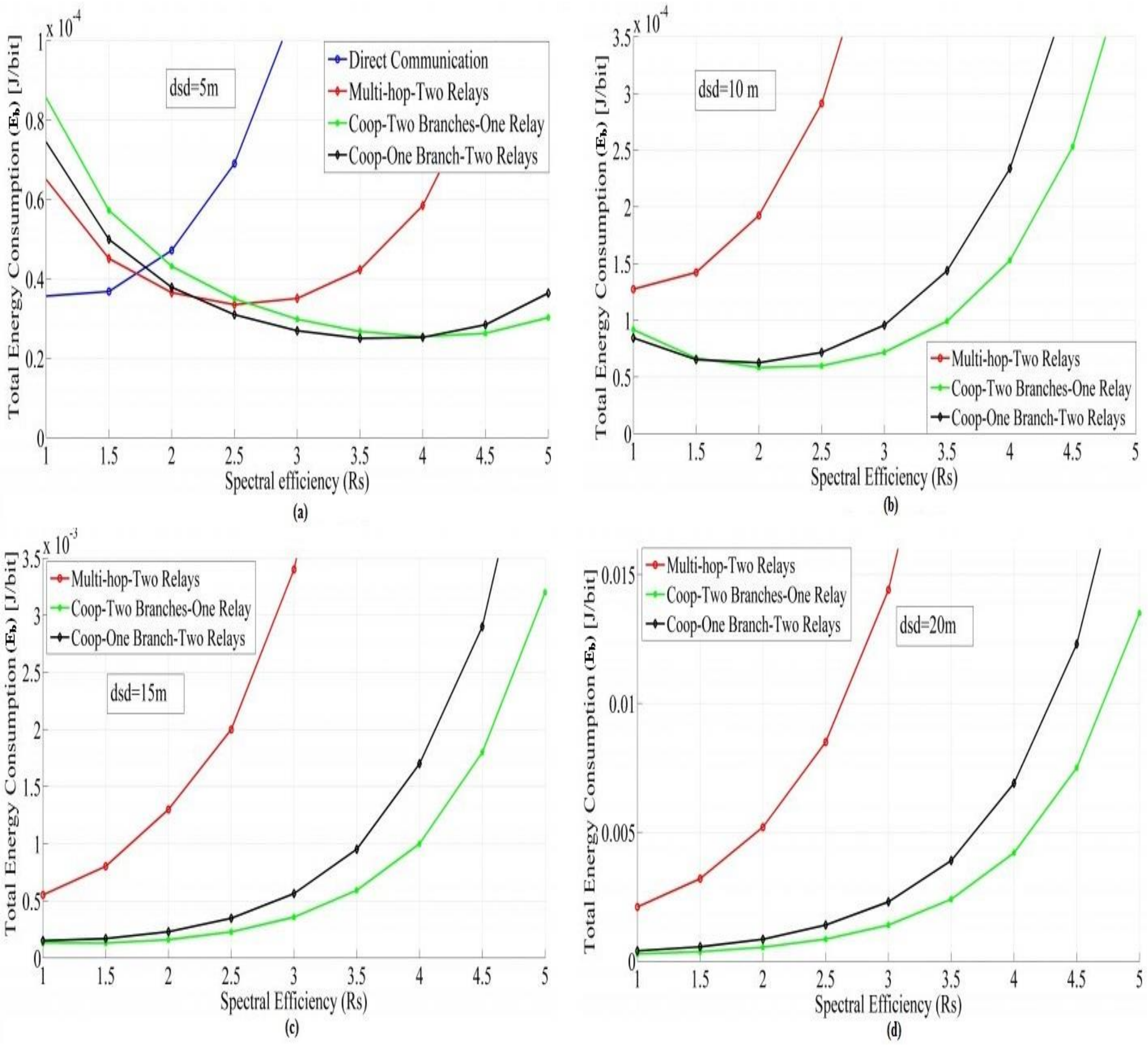



Figure 3.9: Total energy consumption vs spectral efficiency

While when the spectrum efficiency is between 1.6 and 2, the multi-hop transmission scheme outperforms the other transmission schemes. Although when the spectral efficiency exceeds 2, the cooperative transmission scheme outperforms the non-cooperative transmission scheme. In particular, the cooperative using one branch with multiple relays ($K$=1, $n$=2) has much lower energy consumption when the spectrum efficiency is between 2 and 4. But when the spectrum efficiency is beyond 4 the cooperative using multiple branches with one relay ($K$=2, $n$=1) has much lower energy consumption.

Furthermore, Figure 3.9(b) represents the same performance when the distance becomes short medium ($d_{SD}$=10m), with this transmission distance the non-cooperative transmission scheme is inefficient compared to cooperative transmission scheme. While, the cooperative using one branch with multiple relays ($K$=1, $n$=2) has much lower energy consumption when the spectrum efficiency is between 1 and 1.5. Then when the spectrum efficiency exceeds 1.5, the cooperative using multiple branches with one relay ($K$=2, $n$=1) has much lower energy consumption. Figure 3.9(c) and Figure 3.9(d) show the same performance, but when the distance becomes long-medium and long range ($d_{SD}$=15m and $d_{SD}$=20m), the non-cooperative is not efficient for these transmission ranges. Moreover, the cooperative communication using one branch with two relays ($K$=1, $n$=2) has the same performance as cooperative branches with one relay ($K$=2, $n$=1) as long as the spectral efficiency is between 1 and 1.5. But, when the spectral efficiency is greater than 1.5 the two branches with one relay ($K$=2, $n$=1) outperforms the other transmission schemes.

### 3.2.6 Effect of Path Loss Exponent on System Performance

Another important metric that should be evaluated and examined is the effect of the path loss exponent on the system performance. In Figure 3.10, the energy performances of both cooperative and non-cooperative schemes for different transmission ranges with different channel conditions in terms of the path loss exponent $\alpha$ have been evaluated. It can be observed from Figure 3.10(a) that, when the transmission distance is 5m the direct transmission is more energy efficient and significantly better than cooperative transmission which has relay nodes and additional transmission paths or branches as long as the path loss exponent is less than 2.71 ($\alpha$<2.71). This is because within a short distance direct transmission is good enough to meet the reliability requirement while having a less number of transmitters than the cooperative transmission scheme. For the same transmission range the performance gaps between them increase rapidly when the value of the path loss exponent exceeds 2.71, but transmission with multi-hop relays can also perform well during 2.71<$\alpha$<3.5. When path loss becomes higher $\alpha$>3.5, the cooperative transmission schemes perform better than others. For 3.5<$\alpha$<4.68, transmission with one branch and two relays is the best in terms of energy efficiency, with a trend that more relays are needed to maintain the highest possible efficiency when the channel condition gets worse. Although when the path loss exceeds 4.86 ($\alpha$>4.68) transmission with two branches and one relay in each branch performs well in short distance.

On the other hand, when $d_{SD}$=10m as shown in Figure 3.10(b), the energy consumption of direct transmission is much higher than non-cooperative transmission when $\alpha$>1.3. While, the cooperative using one branch with multiple relays ($K$=1, $n$=2) has much lower energy consumption when the path loss exponent is between 1.3 and 2.7. However, when the spectrum path loss is beyond 2.7 the cooperative using multiple branches with one relay ($K$=2, $n$=1) has much lower energy consumption.

In Figure 3.10(c), the energy performance of the same set of transmission schemes is displayed but $d_{SD}$ is 18m. It can be seen from these figures that non-cooperative transmission is less efficient than the other transmission schemes, although the cooperative using one branch with two relays has better energy consumption than others for $\alpha$<2.

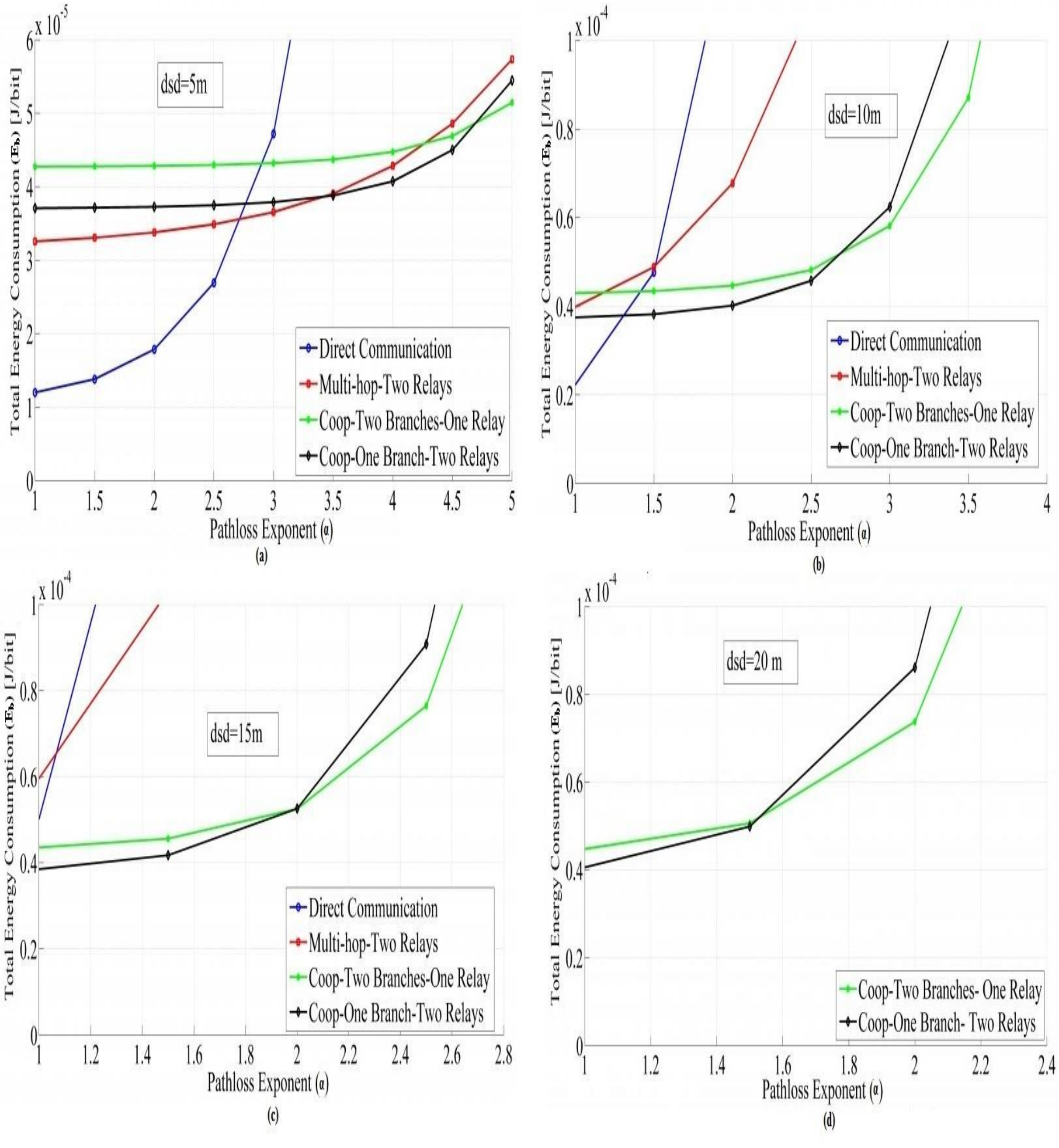



Figure 3.10 Total energy consumption vs path loss exponent (α)

However, transmission with two branches with one relay is more efficient than the others for $2<\alpha$. In Figure 3.10(d), the energy performance is obtained when $d_{SD}$ is 20m. It can be illustrated that non-cooperative is less efficient than the cooperative transmission schemes. For this transmission range it can be demonstrated that for $\alpha<1.5$transmission using one branch with two relays is more efficient than the others. But for $\alpha>1.5$ transmission with two branches and one relay in each branch can also perform better.

The performance obtained in Figure 3.10 is due to the fact of using more than one relay in each branch will lead to the decrease of the distance between the two adjacent nodes and the transmitting power of relays can be significantly reduced. In addition, shorter transmission distance will lead to the decrease of the link failure probability and consequently the total transmission time, which helps to reduce the total energy consumption as well. In addition, it can be indicated that even for long-range transmission the diversity has significant impact on the reduction of energy consumption than by simply adding more branches.

Next, we look at the system throughput, as shown in Figure 3.11(a) when $d_{SD}$=5m the direct transmission scheme has higher throughput for $\alpha<3.5$. While for $\alpha>3.5$ cooperative using one branch with two relays outperforms the other transmission schemes. However, in Figure 3.11(b) when $d_{SD}$=8m the direct transmission scheme has higher throughput for $\alpha<2$. While for $2.5<\alpha<3.8$ cooperative using one branch with two relays has the optimum throughput among other schemes and for $\alpha>3.8$ cooperative using two branches with one relay has the optimum throughput. Furthermore, as illustrated in Figure 3.11(c) when $d_{sd}$=12m the direct transmission scheme has higher throughput for $\alpha<1.5$. While for $1.5<\alpha<2.9$ cooperative using one branch with two relays has the optimum throughput among other schemes and for $\alpha>2.9$ cooperative using two branches with one relay has the optimum one.

In addition, Figure 3.11(d) and Figure 3.11(e), ($d_{SD}$=20m and $d_{SD}$=30m) show that the non-cooperative transmission has the lowest throughput due to the increase of retransmission time and link failure rate within this distance. Also, the effect of using diversity techniques is apparent as it increases the system throughput. While, in Figure 3.11(d) for $\alpha<2$ cooperative using one branch with two relays has the optimum throughput among other schemes and in Figure 3.11(e) it has the optimum throughput for $\alpha<1.5$. Although, cooperative using two branches with one relay has the optimum throughput for $\alpha>2$ and $\alpha>1.5$ as mentioned in Figure 3.11(d) and Figure 3.11(e). It can also be mentioned that the non-cooperative using multi-hop relays is worse than the direct transmission in Figure 3.11; this can be attributed to the increase of link failure between nodes which increases the number of retransmission.

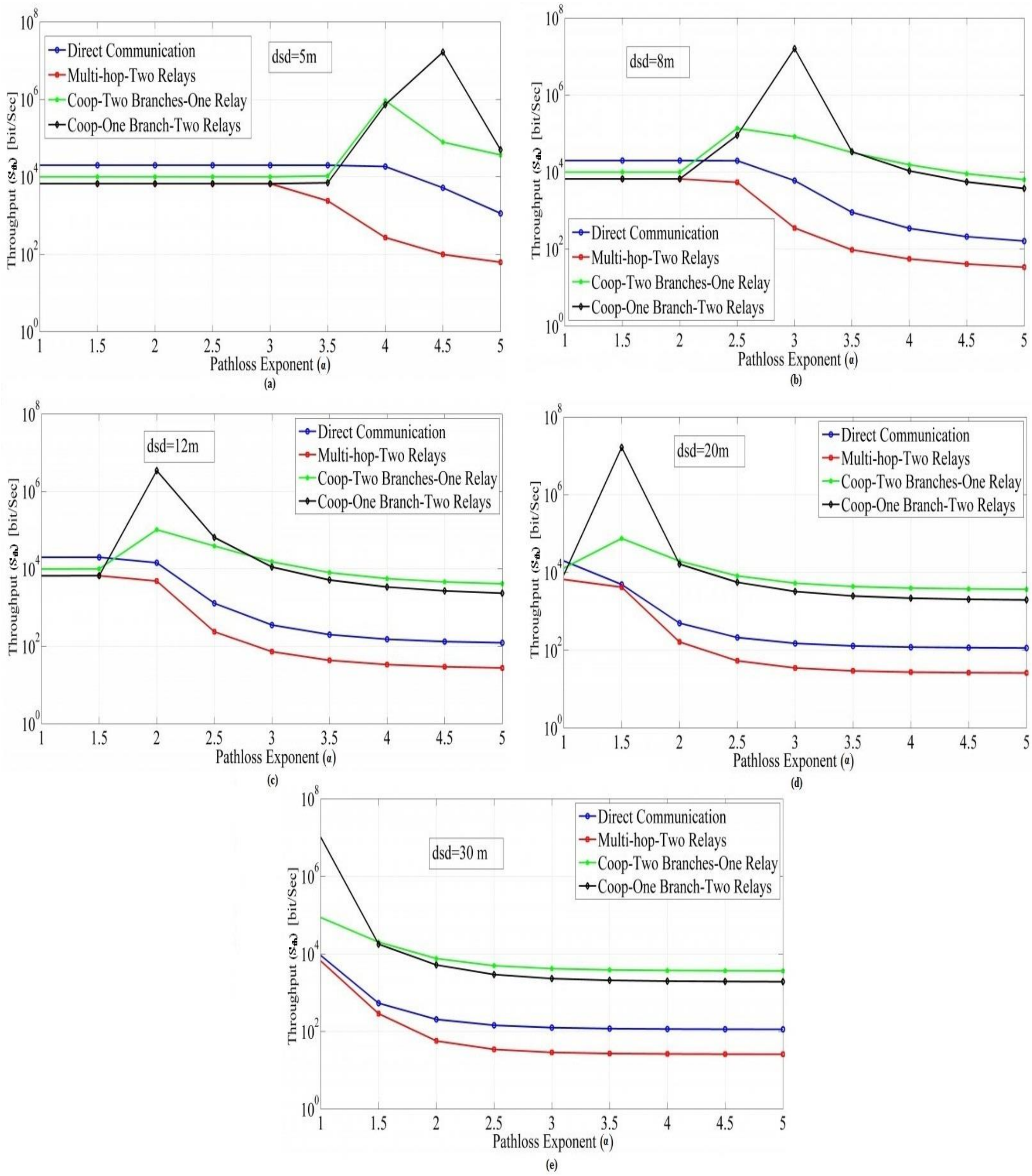



Figure 3.11: Throughput vs path loss exponent (α)

### 3.2.7 Effect of Using Multiple Branches and Relays

In this subsection, the effect of implementing different number of branches and relays is evaluated and discussed. Energy performance for multi-branch and multi-relays scenarios is examined again in Figure 3.12 but against the number of branches, $K$, involved in the cooperative schemes. For a given number of relays per branch, $n$=1, 2, … 5, the optimal number of branches can be found from Figure 3.12. As shown in Figure 3.12(a) for $d_{SD}$=5m and $\alpha$=3, when $n$=2, non-cooperative multi-hop can form the most efficient transmission scheme with two relays, which means that for the short range the non-cooperative outperforms the others. In case of long range as shown in Figure 3.12(b) ($d_{SD}$=8m.) when $n$=1 and $K$=1, this transmission scheme can form the most efficient transmission one.

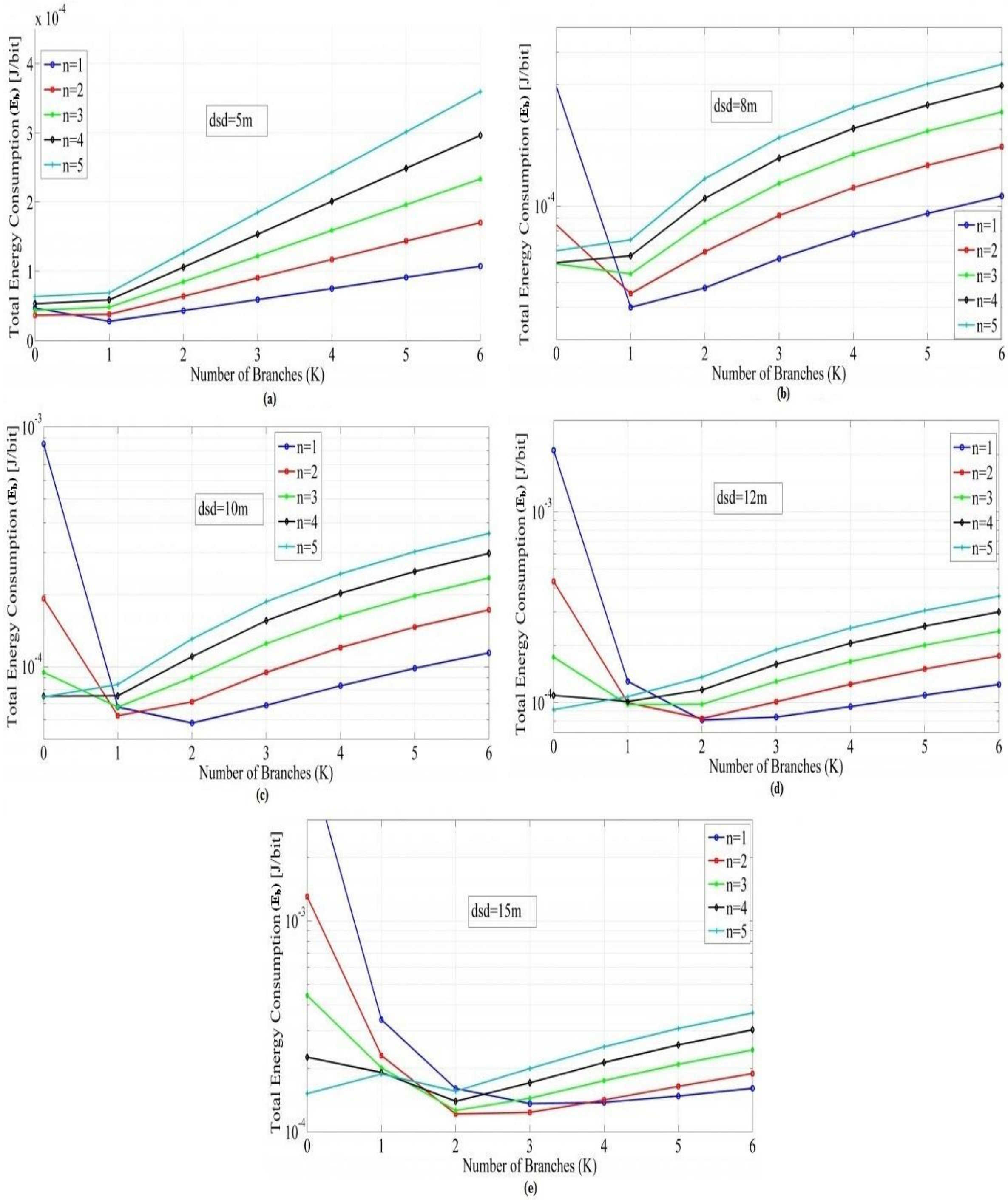



Figure 3.12: Total energy consumption vs number of branches [$K$]

Also, as shown in Figure 3.12(c), Figure 3.12(d) and Figure 3.12(e) ($d_{SD}$=10m, $d_{SD}$=12m and $d_{SD}$=15m) having $n$=1 and $K$=2, through these transmission distances and based on the channel conditions and environments, is the most efficient transmission scheme in terms of energy consumption. This performance shows and proves that increasing the number of branches and relays is not needed, i.e., $n$>2 and $K$>2, which increases the energy consumption as more relays nodes and branches means more circuitry power in the transmission system.

In Figure 3.13 the throughput for multi-branch and multi-relays scenarios has been evaluated. As illustrated in Figure 3.13(a) when $d_{SD}$=5m and for $\alpha$=3, multi-hop transmission scheme with one relay ($n$=1) has the optimum throughput compared to the other transmission schemes. In addition, when $d_{SD}$=8m the optimum required number of relays is two ($n$=2) as shown in Figure 3.13(b). Furthermore, when $d_{SD}$=12m the optimum required number of relays is five ($n$=5) as shown in Figure 3.13(c). It can also be mentioned from Figure 3.13(b) and Figure 3.13(c) that increasing the number of branches ($K$) increases the system throughput. From this figure, it can be illustrated that increasing the number of branches $K$ and relays $n$ respectively will increase the total system throughput.

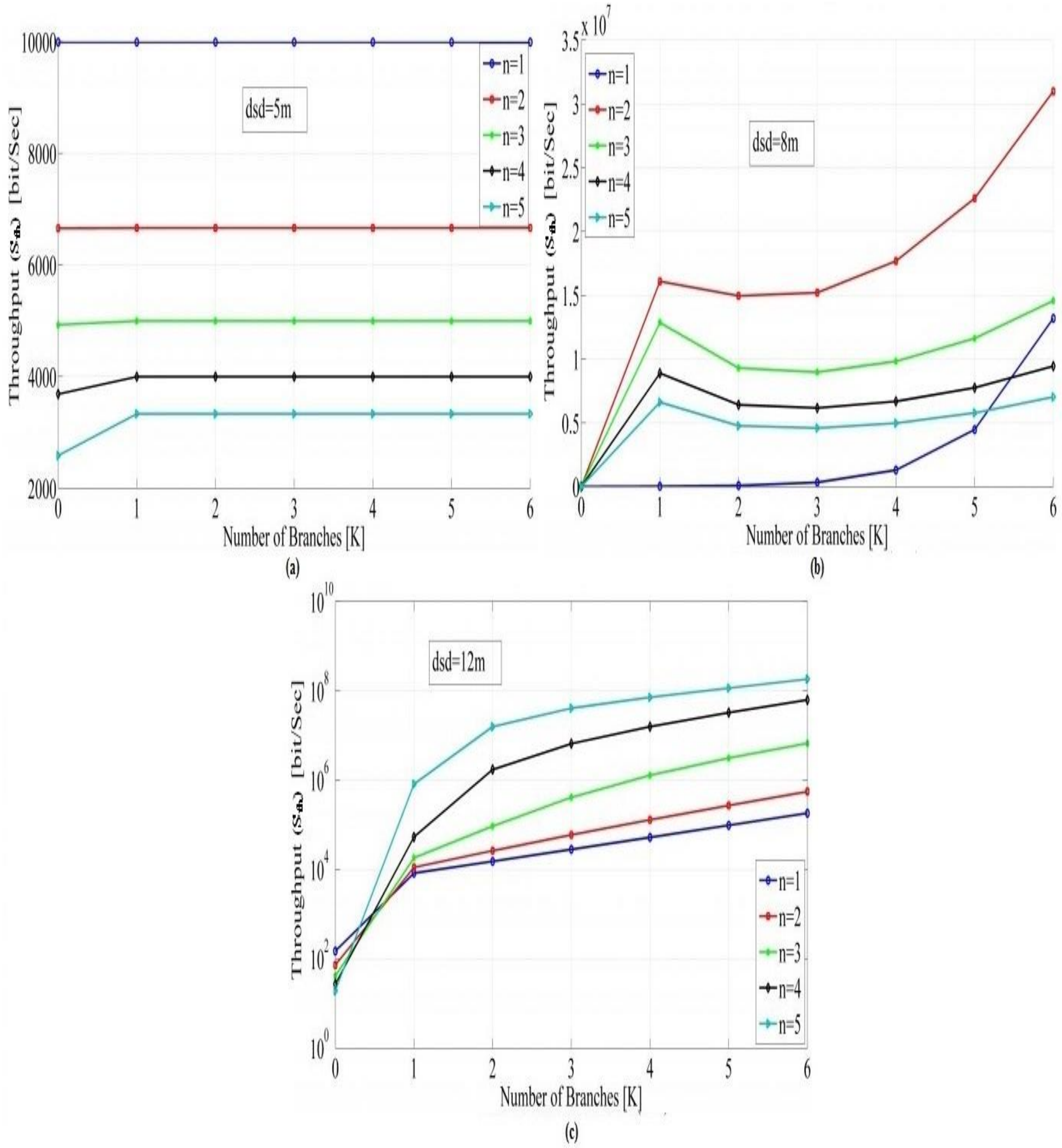



Figure 3.13: Throughput vs number of branches [$K$]

This is due to the use of diversity techniques in terms of using parallel branches $K$, in addition using the multi-hop relays $n$ decreases the probability of link failure between nodes and thus decreases the retransmission time. For the throughput performance, diversity and latency due to processing and retransmission delays are the main factors to be considered. In addition, a scheme with the highest throughput for a given S-D distance is not necessarily most efficient on energy consumption. Again, the trade-off between energy consumption and throughput must take place in this case and based on the system requirements a decision must be taken by adaptively choosing between the transmission scheme which decreases the energy consumption and the scheme which increases the throughput.

### 3.2.8 Energy-Throughput Trade-Off

Based on the performance obtained in the previous subsections, it was noted that at a certain distance the system has low energy consumption with high system throughput. While, at other distances it has low energy consumption with low system throughput. As mentioned previously in Figure 3.13(a), when $d_{sd}$=5m, the multi-hop transmission scheme with one relay ($n$=1) was the optimum transmission scheme in terms of throughput. But based on Figure 3.12(a), with same channel conditions, the optimum transmission scheme was multi-hop using two relays ($n$=2) in terms of energy consumption. Hence, a trade-off between energy consumption and throughput must be considered in this case and the transmission node must decide whether to use the transmission scheme which decreases the energy consumption or the scheme which increases the throughput.

### 3.2.9 Minimum Required Transmission Power

In this subsection, the minimum required transmission power in order to achieve the maximum throughput is analysed and discussed. In Figure 3.14 the throughput for the four transmission schemes with the total transmission power has been evaluated. As demonstrated in Figure 3.14(a) when $d_{SD}$=8m and for $\alpha$=3, the cooperative using one branch with two relays ($K$=1, $n$=2) has the optimum throughput with minimum total transmission power (from 0 dBm to 6 dBm) by comparing it with the other transmission schemes. But when the transmission power exceeds 6 dBm the direct transmission scheme has the highest throughput. While, when $d_{SD}$=12m as shown in Figure 3.14(b), the cooperative using two branches with one relay ($K$=2, $n$=1) with minimum total transmission power (0 dBm to 2 dBm) has the optimum throughput. However, the maximum throughput is obtained by the cooperative using one branch with two relays ($K$=2, $n$=1) but with higher total transmission power (2 dBm to 14 dBm). While when the transmission power exceeds 14 dBm, the direct transmission scheme has the highest throughput.

In addition, when $d_{SD}$=20m as shown in Figure 3.14(c), the cooperative using two branches with one relay ($K$=2, $n$=1) with minimum total transmission power (0 dBm to 14 dBm) has the optimum throughput compared to the other transmission schemes. But when the transmission power exceeds 14 dBm the cooperative using one branch with two relays ($K$=1, $n$=2) has the highest throughput. Furthermore, when $d_{SD}$=30m as shown in Figure 3.14(d), the cooperative using two branches with one relay ($K$=2, $n$=1) with minimum total transmission power has the optimum throughput compared to the other transmission schemes.

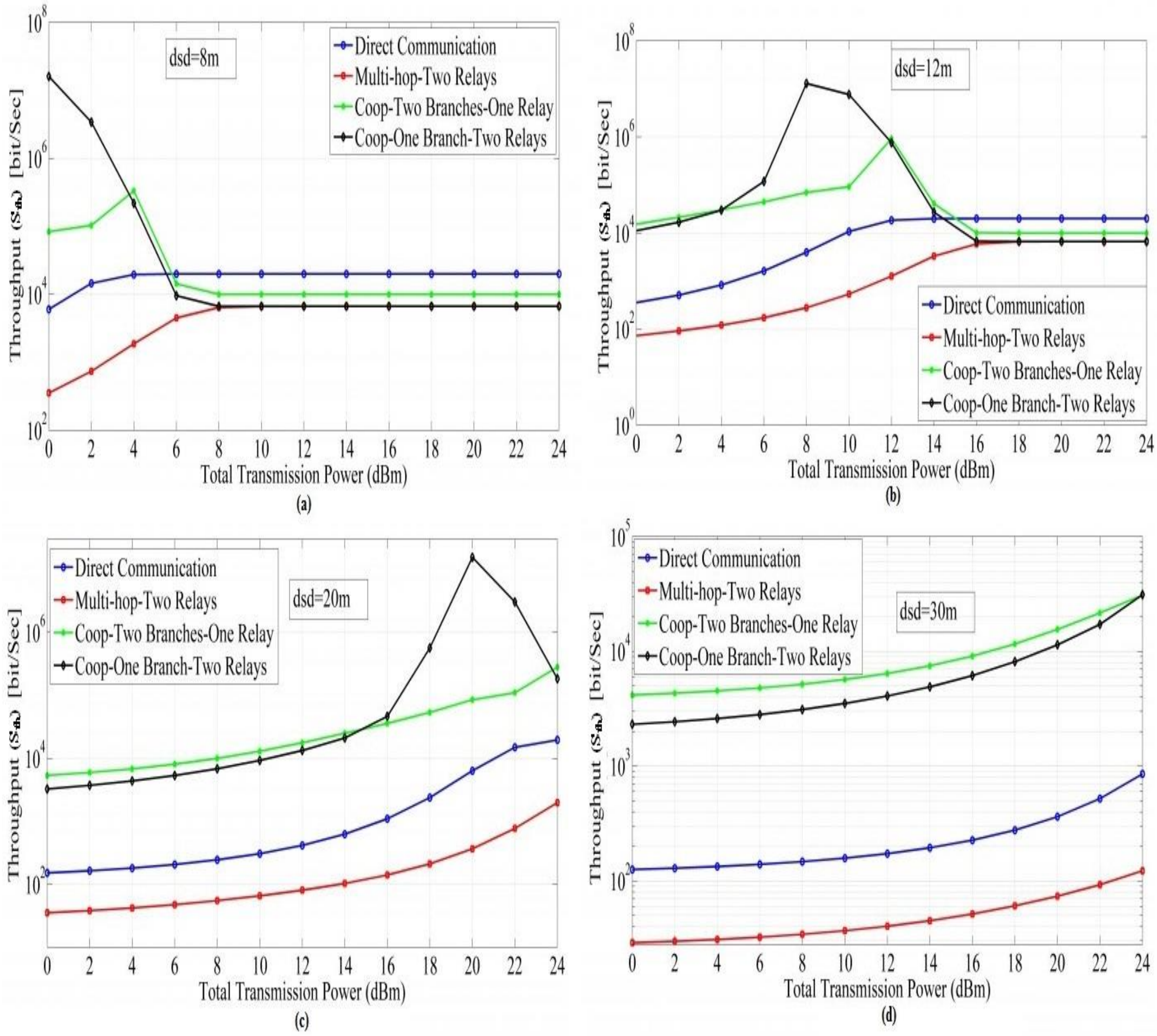


Figure 3.14: Throughput vs total transmission power (dBm)

### 3.2.10 Proposed Adaptive Transmission Scheme

In this subsection, an adaptive transmission is proposed that combines energy consumption, system throughput and system bit error rate. Since the QoS is our goal as we discussed previously and as shown from the simulation results in this section. The performance of these proposed transmission schemes depends on different parameters such as distance, spectral efficiency, path loss, noise power and channel link, i.e., the relay-to-destination link, relay-to-relay link and the source-to-relay link.

Hence, we propose an adaptive protocol as shown in Figure 3.15. Assuming Wireless sensor networks with multiple nodes, if source *S* wants to send DATA to *D* and the distance between any pair *S*-*D* is varying, the intermediate nodes are awake and ready to help *S* to send the message to *D*. Each node is going to adapt its transmission technique according to the distance between itself and the next node in order to achieve optimum QoS of the network. It is assumed that we have networks consisting of multiple wireless sensor nodes e.g., 100 nodes; each node has data to transmit. Different case studies were proposed in two different scenarios based on the explanation of the different transmission schemes in Section 3.3 and the simulation results of the previous subsections.

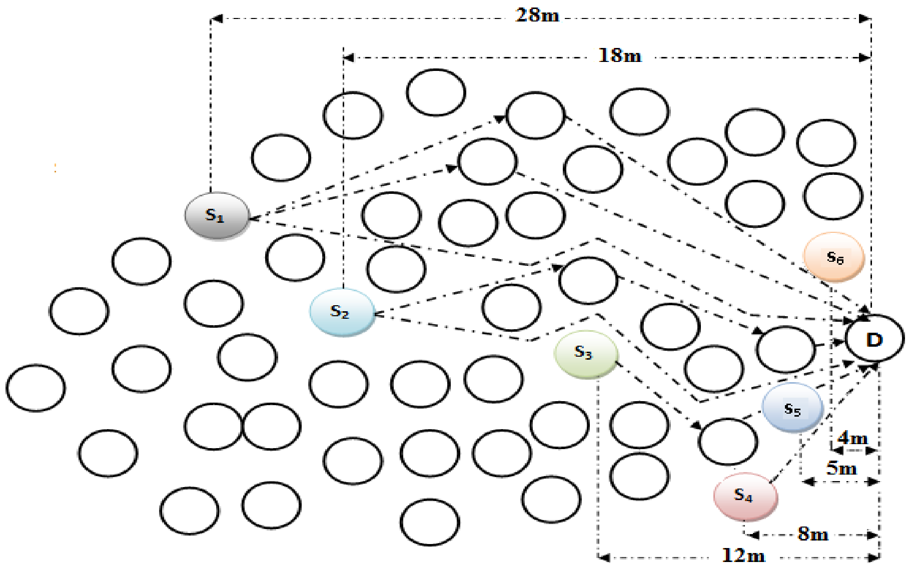



Figure 3.15: First adaptive transmission scheme

In the first adaptive scenario, it is assumed that there are always wireless sensor nodes that are ready to help the source to send the DATA to the destination under different channel and environmental conditions. As demonstrated in Table 3.2, when the distance between source and destination is 4m, the source node $S_6$ will decide to choose the direct transmission as the most efficient transmission scheme for this range compared to other schemes in terms of energy consumption. It also shows that if there is a fixed transmission power, it will be the optimum transmission scheme in terms of throughput and bit error rate. While, when the distance between source and destination is 5m, the source node $S_5$ will decide to choose multi-hop with two hop relays ($n$=2) as the most efficient transmission scheme for this range by comparison with other schemes in terms of energy consumption. But if a fixed total transmission power is used for transmission, the direct transmission scheme outperforms the other transmission schemes in terms of throughput. However, for node $S_4$ where the distance from the source to the destination is 8m the source will adapt to choose the cooperative using one branch with two relays ($K$=1, $n$=2) as it is the efficient transmission scheme in terms of energy consumption. In addition, it is the optimum transmission scheme in terms of throughput and bit error rate if a fixed power is used for transmission. Although, when the distance between $S$-$D$ is 12m the source $S_3$ decides to transmit the data through the cooperative using one branch with two relays ($K$=1, $n$=2) as it is the efficient transmission scheme in terms of energy consumption. But if a fixed transmission power is used for transmission the optimum transmission scheme that should be used for transmission is the cooperative using two branches with one relay ($K$=2, $n$=1). While, when the transmission distance is 18m and 28m where $S_2$ and $S_1$ locate, respectively, $S_2$ and $S_1$ will be adopted to use the cooperative using two branches with one relay ($K$=2, $n$=1) as the efficient transmission scheme in terms of energy consumption. It is also illustrated that if a fixed transmission power is used for transmission it will be the optimum transmission scheme during this transmission range.

TABLE 3.2. WSN ADAPTIVE TRANSMISSION SCHEMES I

| Transmission Node | Distance | Transmission Scheme | Energy Consumed [J/bit] With fixed required QoS | Throughput [bit/sec] With fixed Transmission Power [1 mWatt] | Bit Error Rate With fixed Transmission Power [1 mWatt] |
|---|---|---|---|---|---|
| $S_6 \rightarrow D$ | 4m | Direct Transmission | $2.2531*10^{-5}$ | $1.998*10^{4}$ | ≈ 0 |
| $S_6 \rightarrow D$ | 4 m | Direct Transmission with Two Multi-Hop Relays | $3.3161*10^{-5}$ | $6.66*10^{3}$ | ≈ 0 |
| $S_6 \rightarrow D$ | 4 m | Coop- Transmission Two Branches with one Relay | $4.2846*10^{-5}$ | $9.99*10^{3}$ | ≈ 0 |
| $S_6 \rightarrow D$ | 4 m | Coop-Transmission with one Branch with Two Relays | $3.7358*10^{-5}$ | $6.66*10^{3}$ | ≈ 0 |
| $S_5 \rightarrow D$ | 5m | Direct Transmission | $4.7204*10^{-5}$ | $1.998*10^{4}$ | ≈ 0 |
| $S_5 \rightarrow D$ | 5m | Direct Transmission with Two Multi-Hop Relays | $3.7358*10^{-5}$ | $6.6557*10^{3}$ | $5.2316*10^{-6}$ |
| $S_5 \rightarrow D$ | 5m | Coop- Transmission Two Branches with one Relay | $4.3207*10^{-5}$ | $9.99*10^{3}$ | ≈ 0 |
| $S_5 \rightarrow D$ | 5m | Coop-Transmission with one Branch with Two Relays | $3.7890*10^{-5}$ | $6.6557*10^{3}$ | ≈ 0 |
| $S_4 \rightarrow D$ | 8m | Direct Transmission | $3.9532*10^{-4}$ | $6.0180*10^{3}$ | 0.1960 |
| $S_4 \rightarrow D$ | 8m | Direct Transmission with Two Multi-Hop Relays | $8.4230*10^{-5}$ | 353.3359 | 0.5197 |
| $S_4 \rightarrow D$ | 8m | Coop- Transmission Two Branches with one Relay | $4.7789*10^{-5}$ | $8.3643*10^{4}$ | 0.0034 |
| $S_4 \rightarrow D$ | 8m | Coop-Transmission with one Branch with Two Relays | $4.5397*10^{-5}$ | $1.6085*10^{7}$ | 0.0078 |
| $S_3 \rightarrow D$ | 12m | Direct Transmission | 0.0029 | 356.7548 | 0.1960 |
| $S_3 \rightarrow D$ | 12m | Direct Transmission with Two Multi-Hop Relays | $4.3183*10^{-4}$ | 72.7902 | 0.5197 |
| $S_3 \rightarrow D$ | 12m | Coop- Transmission Two Branches with one Relay | $8.1182*10^{-4}$ | $1.5284*10^{4}$ | 0.0034 |
| $S_3 \rightarrow D$ | 12m | Coop-Transmission with one Branch with Two Relays | $1.0011*10^{-4}$ | $1.1203*10^{4}$ | 0.0078 |
| $S_2 \rightarrow D$ | 18m | Direct Transmission | 0.0222 | 165.4653 | 0.3780 |
| $S_2 \rightarrow D$ | 18m | Direct Transmission with Two Multi-Hop Relays | 0.0031 | 38.5637 | 0.7513 |
| $S_2 \rightarrow D$ | 18m | Coop- Transmission Two Branches with one Relay | $3.3476*10^{-4}$ | $6.0526 *10^{3}$ | 0.0886 |
| $S_2 \rightarrow D$ | 18m | Coop-Transmission with one Branch with Two Relays | $5.1561*10^{-4}$ | $3.8051*10^{3}$ | 0.1507 |
| $S_1 \rightarrow D$ | 28 m | Direct Transmission | 0.2021 | 128.1364 | 0.4590 |
| $S_1 \rightarrow D$ | 28 m | Direct Transmission with Two Multi-Hop Relays | 0.0277 | 29.5410 | 0.8378 |
| $S_1 \rightarrow D$ | 28 m | Coop- Transmission Two Branches with one Relay | 0.0027 | $4.2832*10^{3}$ | 0.2043 |
| $S_1 \rightarrow D$ | 28 m | Coop-Transmission with one Branch with Two Relays | 0.0044 | $2.4034*10^{3}$ | 0.3336 |

In the second adaptive scenario, as shown in Figure 3.16, it is assumed that we have multiple nodes that are ready to help the source to send data to the destination, but in this scenario the adaptive transmission is based on the minimum required transmission power for each transmission scheme in order to achieve the maximum throughput. The optimum transmission scheme required in the data sending process will be chosen based on the distance between the senders and the destination, channel and environmental conditions. As illustrated in Table 3.3, when the distance between source and destination is 5m, the source node $S_5$ will decide to choose the direct transmission as the most efficient transmission scheme for this range compared to other schemes in terms of minimum required transmission power with maximum throughput and minimum bit error rate. However, for node $S_4$ where the distance from the source to the destination is 8m, the source will adapt itself to choose the cooperative using one branch with two relays ($K$=1, $n$=2) as the most efficient transmission scheme in terms of minimum required transmission power with maximum throughput and minimum bit error rate. While, when the distance between $S$-$D$ is 15 the source $S_3$ will adapt itself whether to transmit the data through the minimum required power dedicated from the cooperative using one branch with two relays ($K$=1, $n$=2) with lower throughput than the other cooperative transmission schemes, or through the cooperative using two branches with one relay ($K$=2, $n$=1) but with an increment in the required transmission power in order to achieve maximum throughput. On the other hand, when the transmission distance is 25m where $S_2$ locates and all the transmission schemes will need the same minimum transmission power in order to achieve the maximum throughput. Hence, in this case $S_2$ will be adapted to use the cooperative using one branch with two relays ($K$=1, $n$=2) as the optimum transmission scheme in terms of throughput. Although, when the transmission distance is 35m where $S_1$ is located and also all the transmission schemes will need the same minimum transmission power in order to achieve the maximum throughput. So in this case $S_1$ will be adapted to use the cooperative using two branches with one relay ($K$=2, $n$=1) as the optimum transmission scheme in terms of throughput.

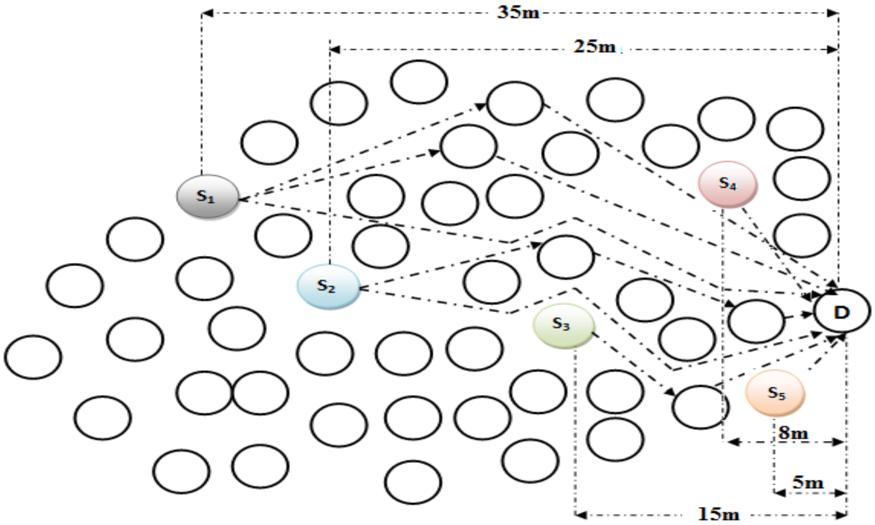



Figure 3.16: Second adaptive transmission scheme

TABLE 3.3. WSN ADAPTIVE TRANSMISSION SCHEMES II

| Transmission Node | Distance | Transmission Scheme | Minimum Required Transmission Power [Watt] | Maximum Throughput [bit/sec] | Bit Error Rate [BER] |
|---|---|---|---|---|---|
| $S_5 \rightarrow D$ | 5m | Direct Transmission | 0.001 | $1.998*10^{4}$ | $1.0909*10^{-14}$ |
| $S_5 \rightarrow D$ | 5m | Direct Transmission with Two Multi-Hop Relays | 0.001 | $6.6557*10^{3}$ | $5.2316*10^{-6}$ |
| $S_5 \rightarrow D$ | 5m | Coop- Transmission Two Branches with one Relay | 0.001 | $9.99*10^{3}$ | 0 |
| $S_5 \rightarrow D$ | 5m | Coop-Transmission with one Branch with Two Relays | 0.001 | $6.66*10^{3}$ | 0 |
| $S_4 \rightarrow D$ | 8m | Direct Transmission | 0.0063 | $1.998*10^{4}$ | $1.0909*10^{-14}$ |
| $S_4 \rightarrow D$ | 8m | Direct Transmission with Two Multi-Hop Relays | 0.0125 | $6.66*10^{3}$ | $5.2316*10^{-6}$ |
| $S_4 \rightarrow D$ | 8m | Coop- Transmission Two Branches with one Relay | 0.0025 | $3.3381*10^{5}$ | $3.5379*10^{-19}$ |
| $S_4 \rightarrow D$ | 8m | Coop-Transmission with one Branch with Two Relays | 0.001 | $1.6085*10^{7}$ | $2.5634*10^{-9}$ |
| $S_3 \rightarrow D$ | 15m | Direct Transmission | 0.1585 | $1.9980*10^{4}$ | $3.4228*10^{-10}$ |
| $S_3 \rightarrow D$ | 15m | Direct Transmission with Two Multi-Hop Relays | 0.2512 | $6.6570*10^{3}$ | $3.7055*10^{-6}$ |
| $S_3 \rightarrow D$ | 15m | Coop- Transmission Two Branches with one Relay | 0.0631 | $1.8318*10^{5}$ | $1.6840*10^{-16}$ |
| $S_3 \rightarrow D$ | 15m | Coop-Transmission with one Branch with Two Relays | 0.0251 | $1.4023*10^{5}$ | ≈ 0 |
| $S_2 \rightarrow D$ | 25m | Direct Transmission | 0.2512 | $4.1176*10^{3}$ | 0.0152 |
| $S_2 \rightarrow D$ | 25m | Direct Transmission with Two Multi-Hop Relays | 0.2512 | 283.1289 | 0.1668 |
| $S_2 \rightarrow D$ | 25m | Coop- Transmission Two Branches with one Relay | 0.2512 | $7.0704*10^{4}$ | $1.8199*10^{-8}$ |
| $S_2 \rightarrow D$ | 25m | Coop-Transmission with one Branch with Two Relays | 0.2512 | $1.4012*10^{7}$ | $3.2874*10^{-8}$ |
| $S_1 \rightarrow D$ | 35 m | Direct Transmission | 0.2512 | 403.1097 | 0.0514 |
| $S_1 \rightarrow D$ | 35 m | Direct Transmission with Two Multi-Hop Relays | 0.2512 | 78.9523 | 0.2819 |
| $S_1 \rightarrow D$ | 35 m | Coop- Transmission Two Branches with one Relay | 0.2512 | $1.7250*10^{4}$ | 0.0019 |
| $S_1 \rightarrow D$ | 35 m | Coop-Transmission with one Branch with Two Relays | 0.2512 | $1.2929*10^{4}$ | 0.0046 |

This subsection is an effective guidance for deciding when and how the cooperative or non-cooperative transmission schemes should be employed. It also shows that there are trade-offs between achieving the maximum throughput and minimum energy consumption. It also proves that our model can optimise energy efficiency or throughput and under some conditions they can be optimised at the same time.

## 3.3 Summary and Conclusion

In this chapter, we have investigated the strengths and limitations of cooperative transmission schemes in comparison with non-cooperative schemes in the context of a multi-hop WSN. We intended to find how both cooperative and non-cooperative communications schemes perform in terms of energy efficiency and throughput under different conditions, such as transmission distance, relaying method and channel conditions (path loss exponent). In addition, we derived the closed form outage probability that contributes to the models for the energy efficiency and throughput.

Based on our analysis and investigation we recognised, there is a number of factors affecting energy consumption and throughput in a WSN. Cooperative transmission uses additional paths and nodes (relays) compared to direct transmission, which costs more energy, but the diversity it creates can save energy by reducing the probability of link failure and consequently reducing the number of retransmissions. Diversity increases with the number of relay branches used but this increase could be marginal when the number of branches is large as it is difficult to ensure that all branches are uncorrelated. In addition, increasing the number of relays in each branch reduces the transmission distance for each relaying hop, which results in lower transmit power for relays as it is proportional to $d^{\alpha}$ where $d$ is either $d_{RD}$ or $d_{RR}$. But when the number of relays increases, the total circuitry power will accumulate as it depends on the number of transmitting nodes and is independent from the transmission distance. This implies that the total energy consumption will increase when more branches and relaying nodes are used to some extent.

Clearly, to achieve the best energy performance as discussed in this chapter, proper transmission schemes should be selected for the given transmission conditions, such as overall distance, $d_{SD}$ and channel quality in terms of $\alpha$. The findings of the work discussed in this chapter provide an effective guidance for deciding when and how the cooperative or non-cooperative transmission schemes should be employed. Based on our investigation, an energy-efficient transmission strategy can be formed in a WSN by adaptively choosing cooperative or non-cooperative transmission schemes under different network and transmission conditions. This involves determining the number of relaying branches and the number of relays if the cooperative scheme is to be used. By doing so, energy saving could be significant even with the direct transmission scheme under certain conditions, as shown from our results.

# Chapter Four

# Enhancing QoS in Device-to-Device Communications

Due to the popularity of video streaming, online gaming and other social media services, there has been an increasing demand on mobile broadband systems. Moreover, 4G wireless technologies are making a significant effort to keep up with this demand without decreasing the network performance. Besides the issue of large data volume in the upcoming decade, user experience is also an important challenge. Users want to be connected anytime, anywhere with the best possible quality-of-service. Current networks may offer good quality-of-service (QoS), but they cannot guarantee the extreme capacity demands on future wireless systems. On the other hand, increasing capacity and connectivity will translate into higher energy consumption and costs, which in turn are not economical or sustainable from operational perspective. One of the most promising techniques is Device-to-Device (D2D) communications which will change the nature of conventional network design.

Device-to-Device (D2D) communications in cellular networks allow devices to communicate directly without going through the base station (BS). It can bring many benefits, such as saving resources, improving spectrum usage and reducing latency. Moreover, in D2D communications mobile devices can relay the information of another out-of-range user to its destination which extending network coverage. Therefore, a greater degree of reliability and availability can be achieved in the network.

In this chapter, we will focus on the identifying of the conditions for establishing appropriate transmission strategies among different commonly used transmission schemes, in the context of a cellular network that accommodates D2D and CUE-BS links with cooperative relaying branches. This investigation is based on the development of analytical models for energy efficiency, achievable data rate and outage probability and demonstrates performances for these transmission schemes, including the trade-offs between cooperative and direct D2D transmission schemes.

## 4.1 System model

In this section, the analytical models for enhancing the QoS of a cellular and D2D communications links are established for both cooperative and non-cooperative transmission schemes. Based on these models, an adaptive transmission strategy can be developed for system performance optimisation.

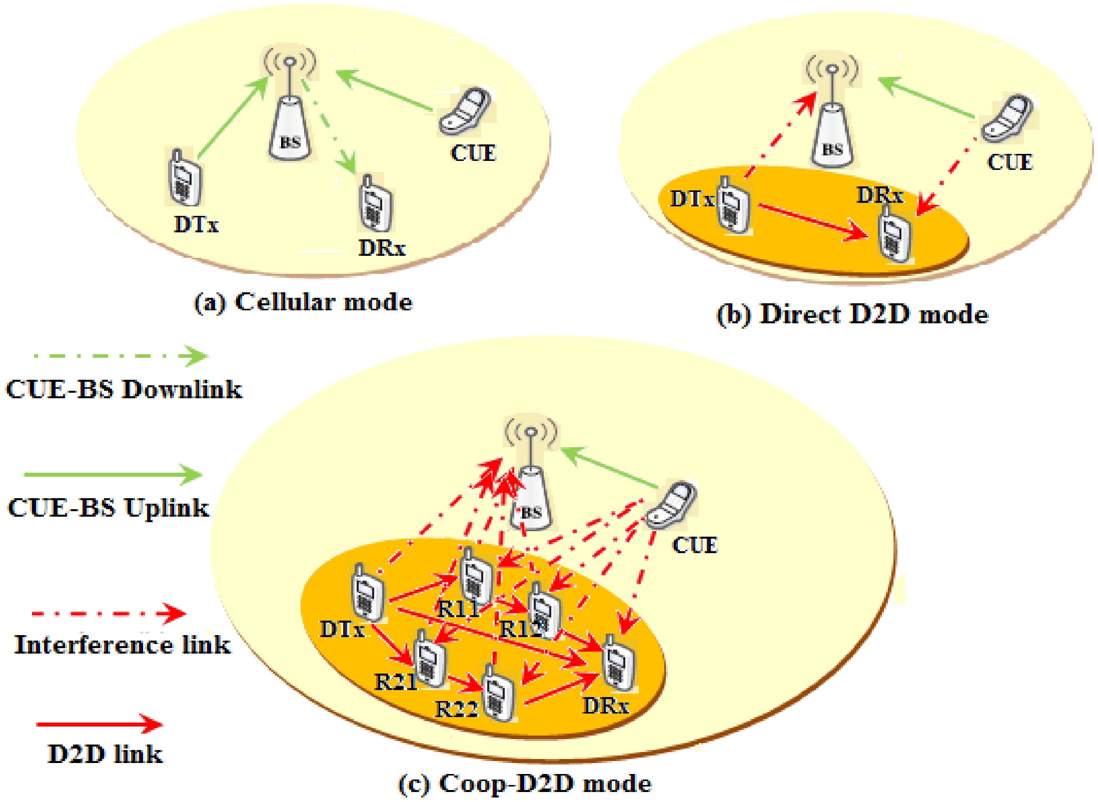



Figure 4.1: Transmission schemes in a cellular network

(a) Cellular mode (b) Direct D2D mode (c) CoopD2D mode

Given a cellular network with a BS, a number of D2D pairs and CUEs, there are three different transmission modes: as shown in Figure 4.1, (a) Cellular mode (CM) – traditional communications between CUEs and BS; (b) Direct D2D mode (DM) – direct D2D communications; and (c) Cooperative D2D mode (CoopD2D). The optimisation of system performance is achieved by maximising the overall energy efficiency and achievable data rate with minimum required transmission power set:

$$Max\, \Sigma\, EE_{bi} \qquad s.t. \{P_C, P_D\}$$

and

$$Max\, \Sigma\, DR_{bi} \qquad s.t. \{P_C, P_D\} \tag{4.1}$$

where $EE_{bi}$ and $DR_{bi}$ are the energy efficiency and achievable data rate, respectively, of the $i$-th transmission links either between CUE and BS or between D2D devices and $P_C$ and $P_D$ are the minimum required transmission power between CUE-BS and D2D links, respectively.

In the cooperative communications scenario Figure 4.1(c), relaying with a varied numbers of branches and relays in each branch are illustrated and will be considered in analytical modelling in connection with CUE-BS transmission in upcoming subsections.

We consider a cellular network in which the transmission links are subject to narrowband Rayleigh fading with Additive White Gaussian Noise (AWGN) and propagation path-loss. The channel fades for different links are assumed to be statistically mutually independent.

### 4.1.1 Cellular Mode (CM)

Consider the scenario shown in Figure 4.1(a) where D2D transmitter (DTx) and D2D receiver (DRx) will exchange information through BS that acts as a decode-and-forward relay node, in addition to the communication between CUE-BS links. The portion of the exclusive resources allocated to the cellular user is $\delta$ and the remaining (1-$\delta$) are allocated to D2D link. This mode is the same as a traditional cellular network.

The energy efficiency (EE) and achievable data rate (DR) in this mode are given by [146]:

$$EE_{CM} = \delta \frac{R_{CBCM}}{P_C + P_o} + \frac{1}{2}(1-\delta)\min\frac{\{R_{DTxB}, R_{BDRx}\}}{P_D + P_B + 2P_o} \tag{4.2}$$

$$DR_{CM} = \delta R_{CBCM} + \frac{1}{2}(1-\delta)\min\{R_{DTxB}, R_{BDRx}\} \tag{4.3}$$

where $R_{CBCM}$, $P_C$ and $P_o$ are the achievable rate, transmission power and internal circuitry power consumption of the CUE-BS link, respectively. $P_D$, $P_B$, $R_{DTxB}$ and $R_{BDRx}$ are transmission power of Dtx, transmission power of BS, achievable data rate at the uplink and downlink of the D2D link, respectively. Let $B$ be the system bandwidth. In order to avoid data loss at BS, we assume that $R_{DTxB}$=$R_{BDRx}$. The achievable rates $R_{CBCM}$, $R_{DTxB}$ and $R_{BDRx}$ in bits/s for CM are expressed as:

$$R_{CBCM} = B\log_2(1 + SINR_{CBCM}) \tag{4.4}$$

$$R_{DTxB} = B\log_2(1 + SINR_{DTxB}) \tag{4.5}$$

$$R_{BDRx} = B\log_2(1 + SINR_{DBRx}) \tag{4.6}$$

The signal-to-noise ratios of the CUE-BS link, $SINR_{CBCM}$ and the DTx-BS, BS-DRx links, $SINR_{DTxB}$, $SINR_{DBRx}$ are given by:

$$SINR_{CBCM} = \frac{P_C |h_{CB}|^2 \gamma_{CB}}{N} \tag{4.7}$$

$$SINR_{DTxB} = \frac{P_D |h_{DTxB}|^2 \gamma_{DTxB}}{N} \tag{4.8}$$

$$SINR_{BDRx} = \frac{P_B |h_{BDRx}|^2 \gamma_{BDRx}}{N} \tag{4.9}$$

where $N$ is the thermal noise power at any receiver, $|h_{ij}|$ is the channel fading coefficient between transmitter $i$ ($i$= {$C$ (CUE), $D$(DTx)}) and receiver $j$ ($j$ = {$B$(BS), $D$(DRx) }) where $h_{ij}$ follows a complex normal distribution $CN$(0, 1) and $\gamma_{ij}$ is path loss between transmitter $i$ and receiver $j$ with the same index sets used for $|h_{ij}|^2$, which is given by [147]:

$$\gamma_{ij} = \gamma_{oij}\, d_{ij}^{\,-\alpha} \tag{4.10}$$

where $d_{ij}$ is the distance between transmitter $i$ and receiver $j$ with the same index sets for $i$ and $j$ as described above, $\gamma_{oij}$ is the path loss constant, $\alpha$ is the path loss exponent.

An outage occurs when $SINR$ at the receiver falls below a threshold $\xi$ in the CUE-BS link ($pout_{CBCM}$) or $\eta$ in the D2D link ($pout_{D2DCM}$), which allows error free decoding. The outage probability of this mode is given by:

$$p_{outCBCM} = p\left(SINR_{CBCM} \le \xi\right)$$

$$p_{outCBCM} = 1 - \exp\left(\frac{-\xi N}{P_C |h_{CB}|^2 \gamma_{CB}}\right) \tag{4.11}$$

$$p_{outD2DCM} = p_{outDTxB} + p_{outBDRx} - p_{outDTxB} p_{outBDRx}$$

$$p_{outD2DCM} = 1 - \exp\left(\frac{-\eta N}{P_D |h_{DTxB}|^2 \gamma_{DTxB} + P_B |h_{BDRx}|^2 \gamma_{BDRx}}\right) \tag{4.12}$$

Transmit power in wireless cellular networks is a key degree of freedom in the management of interference, energy and connectivity. In our model we investigated the required transmission power in order to achieve the best possible system performance between CUE-BS and D2D links. Then, the required transmission power between CUE-BS ($P_{Creq}$) link and between the D2D ($P_{Dreq}$) link in CM can be given as:

$$P_{Creq} = \frac{\left(2^{\frac{R_{CBCM}}{\delta B}} - 1\right) N_o B}{|h_{CB}|^2 \gamma_{CB}}$$

$$P_{Dreq} = \frac{\left(2^{\frac{2R_{BDRx}}{(1-\delta)B}} - 1\right) N_o B}{\left|h_{DTxB}\right|^2 \gamma_{DTxB}} \quad (4.13)$$

The detailed derivation of this result is provided in Appendix (Appendix A-Ch4-1(a)).

Energy efficiency can be defined as the ratio between the system throughput and total transmission power. In the cellular mode the energy efficiency can be expressed as:

$$EE_{CM} = \delta \frac{B\log_2\left(1 + \frac{P_{Creq}\left|h_{CB}\right|^2 \gamma_{CB}}{N_o B}\right)}{P_{Creq} + P_o} + \frac{1}{2}(1-\delta)\frac{B\log_2\left(1 + \frac{P_{Dreq}\left|h_{DTxB}\right|^2 \gamma_{DTxB}}{N_o B}\right)}{P_B + P_{Dreq} + 2P_o} \quad (4.14)$$

The optimisation problem with two constraint variables and its Lagrangian for the cellular mode can be formulated as:

$$Max \Sigma EE_{CM} \qquad s.t.\{P_{Creq} \le P_{C\max}; P_{Dreq} \le P_{D\max}\} \quad (4.15)$$

$$L(P_{Creq}, P_{Dreq}, \psi_{CCM}, \psi_{DCM}) = EE_{CM} + \psi_{CCM}\left(P_{C\max} - P_{Creq}\right) + \psi_{DCM}\left(P_{D\max} - P_{Dreq}\right) \quad (4.16)$$

where $P_{Cmax}$ and $P_{Dmax}$ are CUE-BS and D2D maximum transmitted power, respectively. $\psi_{CCM}$ and $\psi_{DCM}$ denote Lagrangian factors for CUE-BS and D2D power constraint for CM, respectively.

$$P_{C\max} = P_{Creq} \quad (4.17)$$

$$P_{D\max} = P_{Dreq} \quad (4.18)$$

The detailed derivation of this result is provided in Appendix (Appendix A-Ch4-1(b)).

Achievable data rate (*DR*) can be defined as the maximum rate at which data can be transmitted over a given communication link or channel, it is measured in bps. The cellular mode achievable data rate can be expressed as:

$$DR_{CM} = \delta B\log_2\left(1 + \frac{P_{Creq}\left|h_{CB}\right|^2 \gamma_{CB}}{N_o B}\right) + \frac{1}{2}(1-\delta)B\log_2\left(1 + \frac{P_{Dreq}\left|h_{DTxB}\right|^2 \gamma_{DTxB}}{N_o B}\right) \quad (4.19)$$

The optimisation problem with two constraint variables and its Lagrangian for the cellular mode can be formulated as:

$$Max \Sigma DR_{CM} \qquad s.t.\{P_{Creq} \leq P_{C\max}; P_{Dreq} \leq P_{D\max}\} \tag{4.20}$$

$$L(P_{Creq}, P_{Dreq}, \psi_{CCM}, \psi_{DCM}) = DR_{CM} + \Omega_{CCM}\left(P_{C\max} - P_{Creq}\right) + \Omega_{DCM}\left(P_{D\max} - P_{Dreq}\right) \tag{4.21}$$

where $\Omega_{CCM}$ and $\Omega_{DCM}$ denote the Lagrangian factors for power constraint of CUE-BS and D2D links in CM, respectively.

$$P_{C\max} = P_{Creq} \tag{4.22}$$

$$P_{D\max} = P_{Dreq} \tag{4.23}$$

The detailed derivation of this result is provided in Appendix (Appendix A-Ch4-1(c)).

## 4.1.2 Dedicated Mode (DM)

Consider the scenario shown in Figure 4.1(b) where in addition to communication between cellular users through the base station, which forms CUE-BS links, cellular users can also communicate with each other directly in the D2D mode. When the D2D pair communicates by reusing the uplink (UL) resource of an active CUE that is transmitting data to the BS, the active CUE will interfere with the D2D receiver (DRx) and at the same time the D2D transmitter (DTx) causes interference to the BS.

The EE and DR in this mode can be expressed as:

$$EE_{DM} = EE_{CBDM} + EE_{D2DDM} = \frac{R_{CBDM}}{P_C + P_o} + \frac{R_{D2DDM}}{P_D + P_o} \tag{4.24}$$

$$DR_{DM} = DR_{CBDM} + DR_{D2DDM} = R_{CBDM} + R_{D2DDM} \tag{4.25}$$

where $EE_{CBDM}$, $R_{CBDM}$, $P_C$ and $P_o$ are the energy efficiency, achievable rate, transmission power and internal circuitry power consumption of the CUE-BS link, respectively. $EE_{D2DDM}$, $R_{D2DDM}$ and $P_D$ are the energy efficiency, data rate and power consumption of the D2D link, respectively. Let $B$ be the system bandwidth. The achievable rates $R_{CBDM}$ and $R_{D2DDM}$ in bits/s are expressed as:

$$R_{CBDM} = B\log_2\left(1 + SINR_{CBDM}\right) \tag{4.26}$$

$$R_{D2DDM} = B\log_2\left(1 + SINR_{D2DDM}\right) \tag{4.27}$$

and the signal-to-interference-and-noise ratios of the CUE-BS link, $SINR_{CBDM}$ and the D2D links, $SINR_{D2DDM}$ are given by:

$$SINR_{CBDM} = \frac{P_C |h_{CB}|^2 \gamma_{CB}}{P_D |h_{DB}|^2 \gamma_{DB} + N_o B} \tag{4.28}$$

$$SINR_{D2DDM} = \frac{P_D |h_{DD}|^2 \gamma_{DD}}{P_C |h_{CD}|^2 \gamma_{CD} + N_o B} \tag{4.29}$$

The outage probability of CUE-BS ($pout_{CBDM}$) link and D2D ($pout_{D2DDM}$) link in this transmission mode is given by [148]:

$$p_{outCBDM} = p\left(SINR_{CB} \le \xi\right)$$

$$p_{outCBDM} = 1 - \frac{P_C |h_{CB}|^2 \gamma_{CB}}{\xi P_D |h_{DB}|^2 \gamma_{DB} + P_C |h_{CB}|^2 \gamma_{CB}} \exp\left(-\frac{\xi N}{P_C |h_{CB}|^2 \gamma_{CB}}\right) \tag{4.30}$$

$$p_{outD2DDM} = p\left(SINR_{D2D} \le \eta\right)$$

$$p_{outD2DDM} = 1 - \frac{P_D |h_{DD}|^2 \gamma_{DD}}{\eta P_C |h_{CD}|^2 \gamma_{CD} + P_D |h_{DD}|^2 \gamma_{DD}} \exp\left(-\frac{\eta N}{P_D |h_{DD}|^2 \gamma_{DD}}\right) \tag{4.31}$$

Assume $\xi N << P_C |h_{CB}|^2 \gamma_{CB}$ and $\eta N << P_D |h_{DD}|^2 \gamma_{DD}$, so Equation (4.30) and Equation (4.31) can be rewritten as:

$$p_{outCBDM} = 1 - \frac{P_C |h_{CB}|^2 \gamma_{CB}}{\xi P_D |h_{DB}|^2 \gamma_{DB} + P_C |h_{CB}|^2 \gamma_{CB}} \tag{4.32}$$

$$p_{outD2DDM} = 1 - \frac{P_D |h_{DD}|^2 \gamma_{DD}}{\eta P_C |h_{CD}|^2 \gamma_{CD} + P_D |h_{DD}|^2 \gamma_{DD}} \tag{4.33}$$

The required transmission power between CUE-BS ($P_{CDMreq}$) and D2D ($P_{DDMrep}$) links in the dedicated mode can be expressed as:

$$P_{CDMreq} = \frac{\left(2^{\frac{R_{D2DDM}}{B}} - 1\right)\left(2^{\frac{R_{CBCM}}{B}} - 1\right)|h_{DB}|^2 \gamma_{DB} N_o B + \left(2^{\frac{R_{CBCM}}{B}} - 1\right) N_o B |h_{DD}|^2 \gamma_{DD}}{|h_{CB}|^2 \gamma_{CB} |h_{DD}|^2 \gamma_{DD} - \left(2^{\frac{R_{CBCM}}{B}} - 1\right)\left(2^{\frac{R_{D2DDM}}{B}} - 1\right)|h_{DB}|^2 \gamma_{DB} |h_{CD}|^2 \gamma_{CD}} \tag{4.34}$$

$$P_{DDMreq} = \frac{\left(2^{\frac{R_{D2DDM}}{B}} - 1\right) N_o B}{\left|h_{DD}\right|^2 \gamma_{DD}} + \frac{\left(2^{\frac{R_{D2DDM}}{B}} - 1\right) P_{CDMreq} \left|h_{CD}\right|^2 \gamma_{CD}}{\left|h_{DD}\right|^2 \gamma_{DD}} \tag{4.35}$$

The detailed derivation of this result is provided in Appendix (Appendix A-Ch4-2(a)).

In the Dedicated mode the energy efficiency can be expressed as:

$$EE_{DM} = \frac{B\log_2\left(1 + \frac{P_{CDMreq}\left|h_{CB}\right|^2 \gamma_{CB}}{P_{DDMreq}\left|h_{DB}\right|^2 \gamma_{DB} + N_o B}\right)}{P_{CDMreq} + P_o} + \frac{B\log_2\left(1 + \frac{P_{DDMreq}\left|h_{DD}\right|^2 \gamma_{DD}}{P_{CDMreq}\left|h_{CD}\right|^2 \gamma_{CD} + N_o B}\right)}{P_{DDMreq} + P_o} \tag{4.36}$$

The optimisation problem with two constraint variables and its Lagrangian for the dedicated mode can be formulated as:

$$Max \Sigma EE_{DM} \qquad s.t.\left\{P_{CDMreq} \le P_{C\max}; P_{DDMreq} \le P_{D\max}\right\} \tag{4.37}$$

$$L(P_{CDMreq}, P_{DDMreq}, \psi_{CDM}, \psi_{DDM}) = EE_{DM} + \psi_{CDM}\left(P_{C\max} - P_{CDMreq}\right) + \psi_{DDM}\left(P_{D\max} - P_{DDMreq}\right) \tag{4.38}$$

where $\psi_{CDM}$ and $\psi_{DDM}$ denote Lagrangian factors for CUE-BS and D2D power constraint for DM, respectively.

$$P_{C\max} = P_{CDMreq} \tag{4.39}$$

$$P_{D\max} = P_{DDMreq} \tag{4.40}$$

The detailed derivation of this result is provided in Appendix (Appendix A-Ch4-2(b)).

The achievable data rate for the dedicated mode can be given as:

$$DR_{DM} = B\log_2\left(1 + \frac{P_{CDMreq}\left|h_{CB}\right|^2 \gamma_{CB}}{P_{DDMreq}\left|h_{DB}\right|^2 \gamma_{DB} + N_o B}\right) + B\log_2\left(1 + \frac{P_{DDMreq}\left|h_{DD}\right|^2 \gamma_{DD}}{P_{CDMreq}\left|h_{CD}\right|^2 \gamma_{CD} + N_o B}\right) \tag{4.41}$$

The optimisation problem with two constraint variables and its Lagrangian for the dedicated mode can be formulated as:

$$Max \Sigma DR_{DM} \qquad s.t.\left\{P_{CDMreq} \le P_{C\max}; P_{DDMreq} \le P_{D\max}\right\} \tag{4.42}$$

$$L(P_{CDMreq}, P_{DDMreq}, \psi_{CDM}, \psi_{DDM}) = DR_{DM} + \Omega_{CDM}\left(P_{C\max} - P_{CDMreq}\right) + \Omega_{DDM}\left(P_{D\max} - P_{DDMreq}\right) \tag{4.43}$$

where $\Omega_{CDM}$ and $\Omega_{DDM}$ denote the Lagrangian factors for power constraint of CUE-BS and D2D links in DM, respectively.

$$P_{C\max} = P_{CDMreq} \tag{4.44}$$

$$P_{D\max} = P_{DDMreq} \tag{4.45}$$

The detailed derivation of this result is provided in Appendix (Appendix A-Ch4-2(c)).

### 4.1.3 Cooperative D2D Mode (CoopD2D)

In cooperative D2D transmission, D2D communications through relay devices, direct D2D communications and communications in CUE-BS links co-exist, as shown in Figure 4.1(c). Relays receive the noisy version of the transmitted symbol from the source and transmit the received symbol after some processing to the next relay or the DRx. In this case the D2D receiver (DRx) and the receiving relays will interfere with the CUE and at the same time the D2D transmitter (DTx) and the transmitting relays cause interference to the BS.

The EE and DR in this mode are expressed as:

$$EE_{CD} = EE_{CBCoopD2D} + EE_{CoopD2D} = \frac{R_{CBCoopD2D}}{P_C + P_o} + \frac{R_{CoopD2D}}{((K*n)+1)(P_D + P_o)} \tag{4.46}$$

$$DR_{CD} = DR_{CBCoopD2D} + DR_{CoopD2D} = R_{CBCoop} + R_{CoopD2D} \tag{4.47}$$

where, $EE_{CBCoopD2D}$, $R_{CBCoopD2D}$, $EE_{CoopD2D}$, $R_{CoopD2D}$, $K$ and $n$ are the energy efficiency, achievable rate, number of branches and number of relay nodes of the cooperative CUE-B and D2D link in CoopD2D mode, respectively. The achievable rate $R_{CBCoopD2}$, $R_{CoopD2D}$ in bits/s are expressed as:

$$R_{CBCoopD2D} = B\log_2\left(1 + \frac{P_C|h_{CB}|^2\gamma_{CB}}{\sum_{j=1}^{K}\sum_{l=1}^{n}P_D|h_{DjlB}|^2\gamma_{DjlB} + N_oB}\right) \tag{4.48}$$

$$R_{CoopD2D} = \frac{B}{K*n}\log_2\left(1 + SINR_{D2D} + \sum_{j=1}^{K}SINR_{rjDRx}\right) \tag{4.49}$$

where $K$ is the number of relaying branches, $n$ is the number of relays in each branch and the signal-to-interference-and-noise ratios of the $j$-th Relay-BS (R-BS) link, $SINR_{rjB}$ is given by:

$$SINR_{rjDRx} = \frac{P_{DD} \left| h_{rjDRx} \right|^2 \gamma_{rjDRx}}{P_C \left| h_{CDRx} \right|^2 \gamma_{CDRx} + N_o B} \tag{4.50}$$

where $P_{DD}$ is the transmitting power of cooperative relays, $h_{rjDRx}$ is the channel coefficient of the cooperative R-DRx link. In this research we present two types of cooperative transmission schemes: 1) using multiple ($K$) relaying branches with one relay in each branch and 2) using multiple relaying branches and with multiple ($n$) relays in each branch. The selective decode and forward (SDF) relaying protocol is used in these two schemes and relays perform cooperation when the information from the DTx is correctly received by them. We assume that the selection combining technique is used at the destination on the received packets.

The outage probability of CUE-BS ($pout_{CBCoop}$) link and D2D ($pout_{D2DCoop}$) link in this transmission mode is given by:

$$p_{outCBCoop} = 1 - \frac{P_C \left| h_{CB} \right|^2 \gamma_{CB}}{\xi \sum_{j=1}^{K} \sum_{l=1}^{n} P_D \left| h_{DjlB} \right|^2 \gamma_{DjlB} + P_C \left| h_{CB} \right|^2 \gamma_{CB}} \tag{4.51}$$

$$p_{outD2DCoop} = p_{outD2D} \left( 1 - \left( (1 - p_{outDTxr1}) \left( \prod_{l=2}^{n-1} (1 - p_{outrlrl+1}) \right) (1 - p_{outrnDRx}) \right) \right)^K \tag{4.52}$$

where $p_{outD2D}$ is the outage probability between Dtx and DRx, $p_{outDTxr1}$ is the outage probability between Dtx and the first relay, $p_{outrlrl+1}$ represents the outage probability between any two consecutive transmitting and receiving relay and $p_{outrnDRx}$ is the outage probability between the last relay node and DRx.

The required transmission power between CUE-BS ($P_{CCDreq}$) and D2D links in CoopD2D ($P_{DCDreq}$) mode can be expressed as:

$$P_{CCDreq} = \frac{\dfrac{N_o B}{\sum_{j=1}^{K} \sum_{l=1}^{n} P_D \left| h_{DjlB} \right|^2 \gamma_{DjlB}} \left[ \left( 2^{\frac{R_{CBCoopD2D}}{B}} - 1 \right) \sum_{j=1}^{K} \sum_{l=1}^{n} P_D \left| h_{DjlB} \right|^2 \gamma_{DjlB} \right] \left[ \dfrac{\left| h_{DD} \right|^2 \gamma_{DD}}{\left| h_{CD} \right|^2 \gamma_{CD} + N_o B} + \sum_{j=1}^{K} \dfrac{\left| h_{rjDRx} \right|^2 \gamma_{rjDRx}}{\left| h_{CDRx} \right|^2 \gamma_{CDRx} + N_o B} \right]}{\left[ \left[ \dfrac{\left| h_{DD} \right|^2 \gamma_{DD}}{\left| h_{CD} \right|^2 \gamma_{CD} + N_o B} + \sum_{j=1}^{K} \dfrac{\left| h_{rjDRx} \right|^2 \gamma_{rjDRx}}{\left| h_{CDRx} \right|^2 \gamma_{CDRx} + N_o B} \right] \left| h_{CB} \right|^2 \gamma_{CB} - \left[ \left( 2^{\frac{R_{CBCoopD2D}}{B}} - 1 \right) \sum_{j=1}^{K} \sum_{l=1}^{n} P_D \left| h_{DjlB} \right|^2 \gamma_{DjlB} \right] \left( 2^{\frac{((K*n)+1)*R_{CoopD2D}}{B}} - 1 \right) \right]} \tag{4.53}$$

$$P_{DCDreq} = \frac{\left(2^{\frac{((K*n)+1)*R_{CoopD2D}}{B}} - 1\right) P_{CCDreq}}{\left[\frac{|h_{DD}|^2 \gamma_{DD}}{|h_{CD}|^2 \gamma_{CD} + N_o B} + \sum_{j=1}^{K} \frac{|h_{rjDRx}|^2 \gamma_{rjDRx}}{|h_{CDRx}|^2 \gamma_{CDRx} + N_o B}\right]} \tag{4.54}$$

The detailed derivation of this result is provided in Appendix (Appendix A-Ch4-3(a)).

In the Cooperative D2D mode the energy efficiency can be expressed as:

$$EE_{CD} = \frac{B \log_2\left(1 + \frac{P_{CCDreq} |h_{CB}|^2 \gamma_{CB}}{\sum_{j=1}^{K}\sum_{l=1}^{n} P_{DCDreq} |h_{DjlB}|^2 \gamma_{DjlB} + N_o B}\right)}{P_{CCDreq} + P_o} + \frac{\frac{B}{((K*n)+1)} \log_2\left(1 + \frac{P_{DCDreq}|h_{DD}|^2 \gamma_{DD}}{P_{CCDreq}|h_{CD}|^2 \gamma_{CD} + N_o B} + \sum_{j=1}^{K} \frac{P_{DCDreq}|h_{rjDRx}|^2 \gamma_{rjDRx}}{P_{CCDreq}|h_{CDRx}|^2 \gamma_{CDRx} + N_o B}\right)}{((K*n)+1) P_{DCDreq} + P_o} \tag{4.55}$$

The optimisation problem with two constraint variables and its Lagrangian for the dedicated mode can be formulated as:

$$Max \Sigma EE_{CD} \qquad s.t. \{P_{CCDreq} \le P_{C\max}; P_{DCMreq} \le P_{D\max}\} \tag{4.56}$$

$$L(P_{CCDreq}, P_{DCDreq}, \psi_{CCD}, \psi_{DCD}) = EE_{CD} + \psi_{CCD}(P_{C\max} - P_{CCDreq}) + \psi_{DCD}(P_{D\max} - P_{DCDreq}) \tag{4.57}$$

where $\psi_{CCD}$ and $\psi_{DCD}$ denote Lagrangian factors for CUE-BS and D2D power constraint for CoopD2D, respectively.

$$P_{C\max} = P_{CCDreq} \tag{4.58}$$

$$P_{D\max} = P_{DCDreq} \tag{4.59}$$

The detailed derivation of this result is provided in Appendix (Appendix A-Ch4-3(b)).

Then, the achievable data rate for the CoopD2D mode can be given as:

$$DR_{CD} = B\log_2\left(1+\frac{P_{CCDreq}|h_{CB}|^2\gamma_{CB}}{\sum_{j=1}^{K}\sum_{l=1}^{n}P_{DCDreq}|h_{DjlB}|^2\gamma_{DjlB}+N_oB}\right)$$
$$+\frac{B}{((K*n)+1)}\log_2\left(1+\frac{P_{DCDreq}|h_{DD}|^2\gamma_{DD}}{P_{CCDreq}|h_{CD}|^2\gamma_{CD}+N_oB}+\sum_{j=1}^{K}\frac{P_{DCDreq}|h_{rjDRx}|^2\gamma_{rjDRx}}{P_{CCDreq}|h_{CDRx}|^2\gamma_{CDRx}+N_oB}\right) \quad (4.60)$$

The optimisation problem with two constraint variables and its Lagrangian for the dedicated mode can be formulated as:

$$Max\Sigma\, DR_{CD} \qquad s.t.\{P_{CCDreq} \le P_{C\max}; P_{DCDreq} \le P_{D\max}\} \quad (4.61)$$

$$L(P_{CCDreq}, P_{DCDreq}, \psi_{CCD}, \psi_{DCD}) = DR_{CD} + \Omega_{CCD}(P_{C\max} - P_{CCDreq}) + \Omega_{DCD}(P_{D\max} - P_{DCDreq}) \quad (4.62)$$

where $\Omega_{CDM}$ and $\Omega_{DDM}$ denote the Lagrangian factors for power constraint of CUE-BS and D2D links in DM, respectively.

$$P_{C\max} = P_{CDMreq} \quad (4.63)$$

$$P_{D\max} = P_{DDMreq} \quad (4.64)$$

The detailed derivation of this result is provided in Appendix (Appendix A-Ch4-3(c)).

## 4.2 Performance Evaluation of the Proposed Models

The results of the proposed transmission schemes as described in the previous section are presented in this section. These results focus on three performance metrics which examine the energy efficiency and achievable data rate for three transmission modes under various channel and transmission conditions in a cellular network as shown in Figure 4.1 using computer simulation (Matlab). We then show how a transmission scheme can be chosen in an adaptive way to optimise the energy performance.

The system performance is evaluated by studying the QoS metrics and showing how the system performance is affected by the configured parameters, e.g., path loss or transmission distance. For this evaluation a comparison between the three transmission modes is presented. The performance differences between these transmission modes are analysed.

### 4.2.1 Network Topology

As mentioned before, a complete evaluation of the three transmission modes is presented. The network settings used for simulation are listed in Table 4.1. For a given network topology, we randomly choose a CUE-BS, D2D pairs and apply different transmission schemes for comparison purposes. We assume that the minimum achievable rate $R$ in these scenarios is 10 Mbit/s and we consider that the density of mobile nodes ranging from 10 to 100, subjected to different transmission ranges

TABLE 4.1 CELLULAR NETWORKS SIMULATION PARAMETERS

| **Parameters** | **Value** |
|---|---|
| $N$ | −100dBm |
| $B$ | 10 MHz |
| $P_{Cmax}$ or $P_{Dmax}$ | 250Mw |
| $P_o$ | 100mW |
| Path loss for Cellular Link | 128.1 + 37.6 $\log_{10}$[d(km)] dB [146] |
| Path loss for D2D Link | 148 + 40 $\log_{10}$[d(km)] dB [146] |
| $fc$ | 2 GHz |
| Noise Figure | 7 dB |
| Number of mobile nodes | From 10 to 100 mobile nodes |
| $\delta$ | 0.5 |

### 4.2.2 Energy-Efficiency Evaluation

The first evaluated metric is the energy efficiency performance of the three transmission modes. Figure 4.2 shows the energy efficiency performance of the three transmission modes. In Figure 4.2(a) we assume that D2D distance changes from 2 to 100 m and the distance of CUE to the BS is fixed at 300 m. As we can observe, that direct and cooperative D2D are both superior to the traditional through BS regarding energy efficiency, whereas cooperative transmission outperforms the non-cooperative transmission when the transmission range is beyond 55 meters for the D2D link. In the case that the distance between DTx and DRx is >55m, cooperative transmission using $K$=1 branches with $n$=2 relays per branch outperforms the direct D2D link.

In Figure 4.2(b), we assume that CUE-BS distance changes from 10 to 500 m and the distance of D2D is fixed at 80 m. We can see that direct D2D and Coop-D2D are better than the traditional cellular network and Coop-D2D is further preferable. When the distance of the D2D link is short, the transmission power of DTx is proportionally low to the DTx transmit power in long transmission range and the interferences from DTx and the transmitting relay to BS are low as well. This reduces the overall required transmit power from CUE and thus increases energy efficiency, as shown in Figure 4.2(b).

In addition, Figure 4.3 depicts energy efficiency against the numbers of CUEs and D2D pairs which are uniformly distributed in a cellular cell in order to evaluate the overall network performance. Substantial performance gaps in energy efficiency can be observed from Figure 4.3(a) between the direct transmission scheme in D2D links and the optimal transmission scheme based on transmission distance as explained previously in Figure 4.2. Figure 4.3(a) shows that the overall energy efficiency is improved, when each mobile node adapts itself to transmit the data through the optimum transmission mode based on transmission distance and channel conditions, which can form an adaptive transmission system. Additionally, Figure 4.3(b) shows the enhancement of the energy efficiency of D2D links based on choosing the optimum transmission mode enhances the energy efficiency of CUE-BS links in return. As choosing the optimum transmission mode for each transmission distance leads to the decrease of the required transmission power for D2D links and CUE-BS links, decreasing the interference between CUE-DRX and DRx-BS links and the enhancement of the QoS.

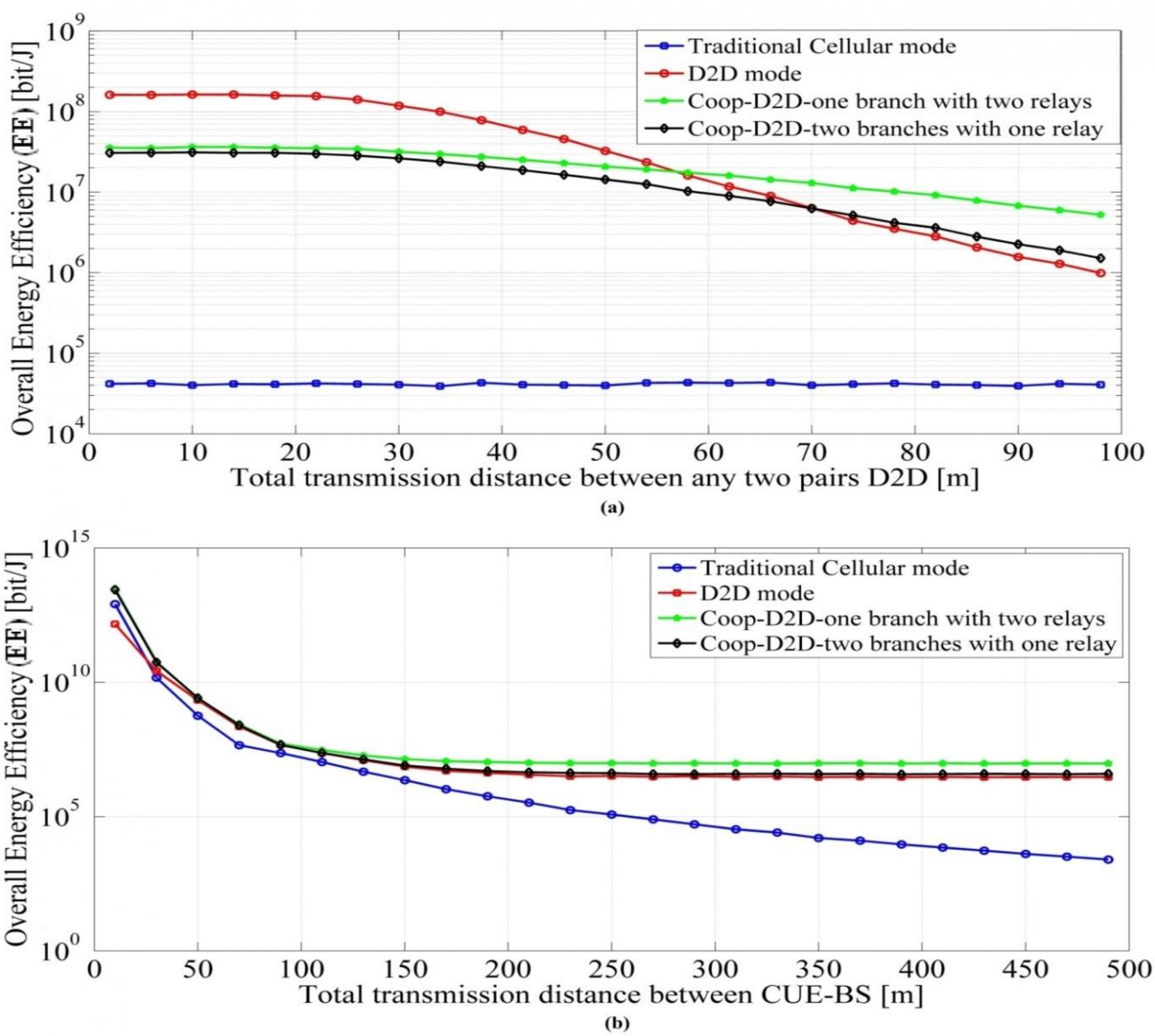



Figure 4.2: Overall energy efficiency vs

(a) Total transmission distance between D2D links (b) Total transmission distance between CUE-BS links

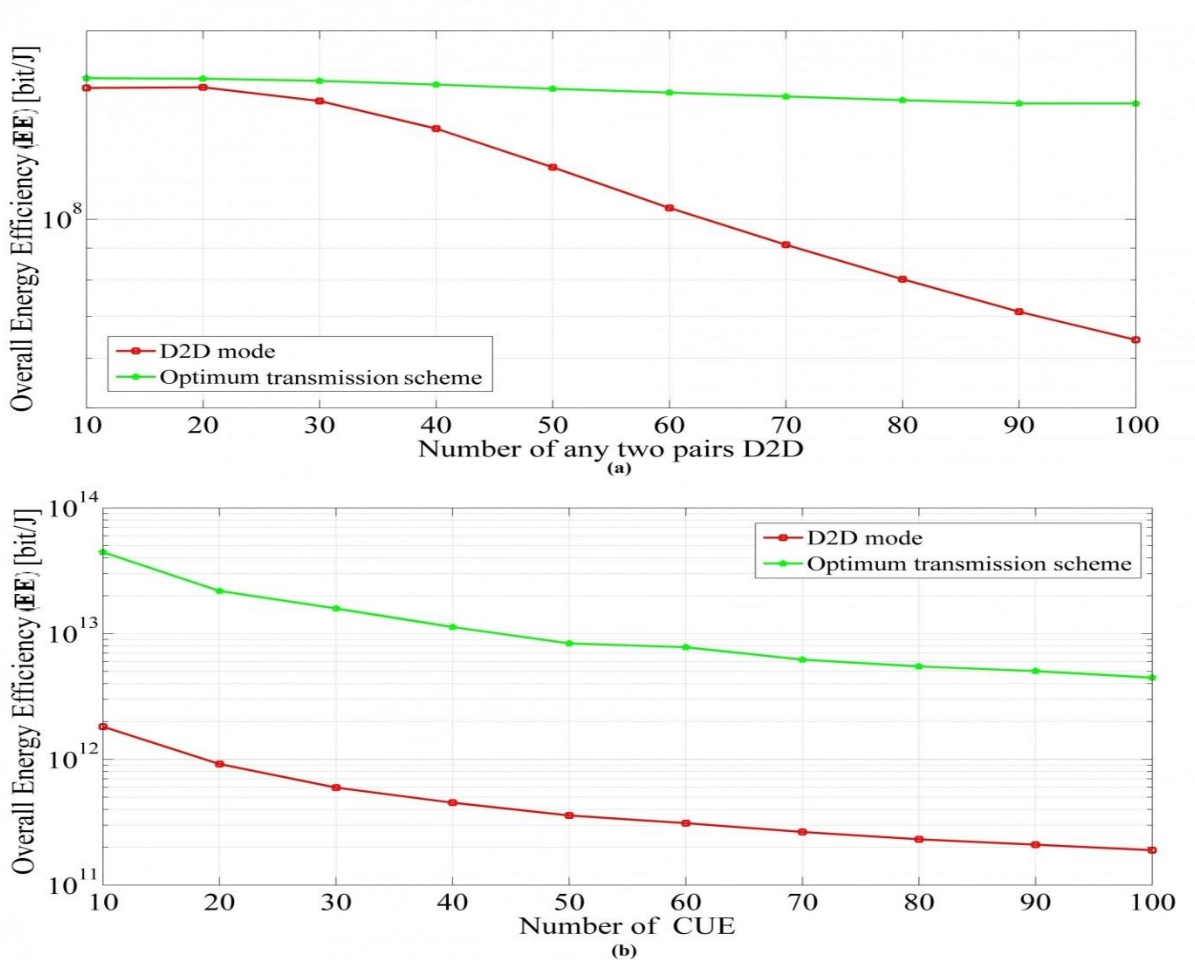



Figure 4.3: Overall Energy efficiency vs

(a) Numbers of D2D links (b) Numbers of CUEs

### 4.2.3 Achievable Data Rate Evaluation

Based on the scenarios described in the previous subsection, the achievable data rate performance in Figure 4.4 is observed to be substantially similar to performance in Figure 4.2 in terms of comparisons among traditional cellular CUE-BS, D2D and Coop-D2D modes. As shown in Figure 4.4(a) the achievable data rate of Coop-D2D is better than that of the direct D2D or cellular mode when D2D distance is less than 35 m. On the other hand, as the distance between direct D2D devices is not short enough (<35), the spectral efficiency of the direct D2D mode is also lower than that of the Coop-D2D mode. When deciding which mode to use, energy efficiency and achievable data rate can be jointly evaluated to achieve a desirable trade-off between the two performance metrics. Now, since CUE is far away from the BS, the achievable data rate of traditional cellular mode becomes lower than that of direct D2D and Coop-D2D transmissions as shown in Figure 4.4(b). In addition, the Coop-D2D helps increase the achievable data rate of CUE-BS link as it decreases the interference at the BS as it needs lower transmitting power than direct D2D communications.

Also, the overall achievable data rate against the numbers of CUEs and D2D pairs has been evaluated and analysed. Substantial performance gaps in overall achievable data rate can be observed from Figure 4.5(a) between the direct transmission scheme in D2D links and the optimal transmission schemes based on transmission distance as explained in the previous subsection. Figure 4.5(a) shows how the enhancement in overall achievable data rate is obtained when each mobile node decides the best transmission mode based on its transmission distance. As mentioned before this can form an adaptive transmission system where each mobile node will adapt itself based on the channel conditions and its transmission distance to use the suitable transmission mode to process the information between the sender and receiver. Additionally, Figure 4.5(b) shows that the enhancement of the overall achievable data rate of D2D links based on choosing the optimum transmission mode enhances the overall achievable data rate of CUE-BS links in return. As choosing the optimum transmission mode for each transmission distance leads to the decrease of the required transmission power for D2D and CUE-BS links, decreasing the interference between CUE-DRX and DRx-BS and the enhancement the QoS.

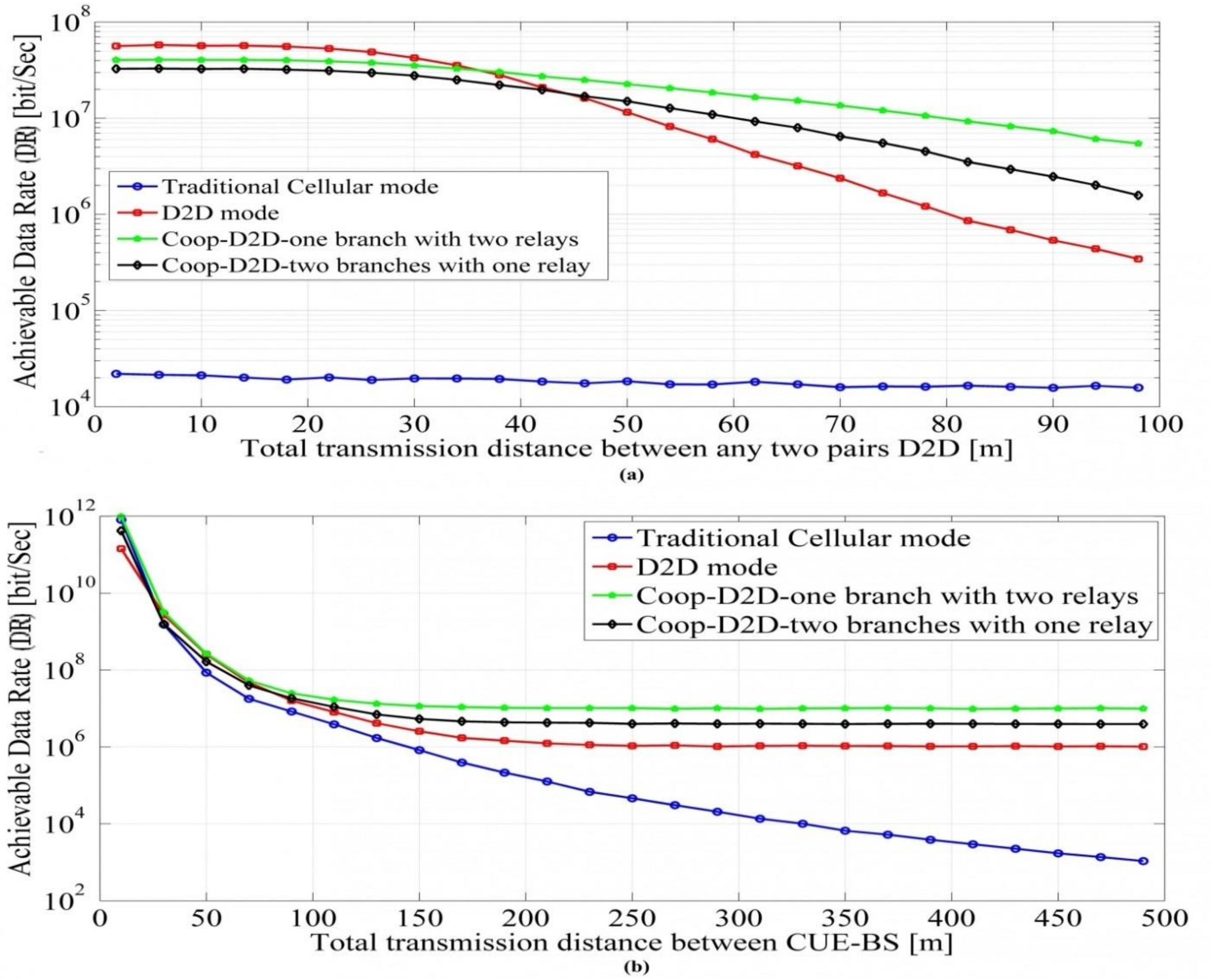



Figure 4.4: Overall achievable data rate vs

(a) Total transmission distance between D2D links (b) Total transmission distance between CUE-BS links

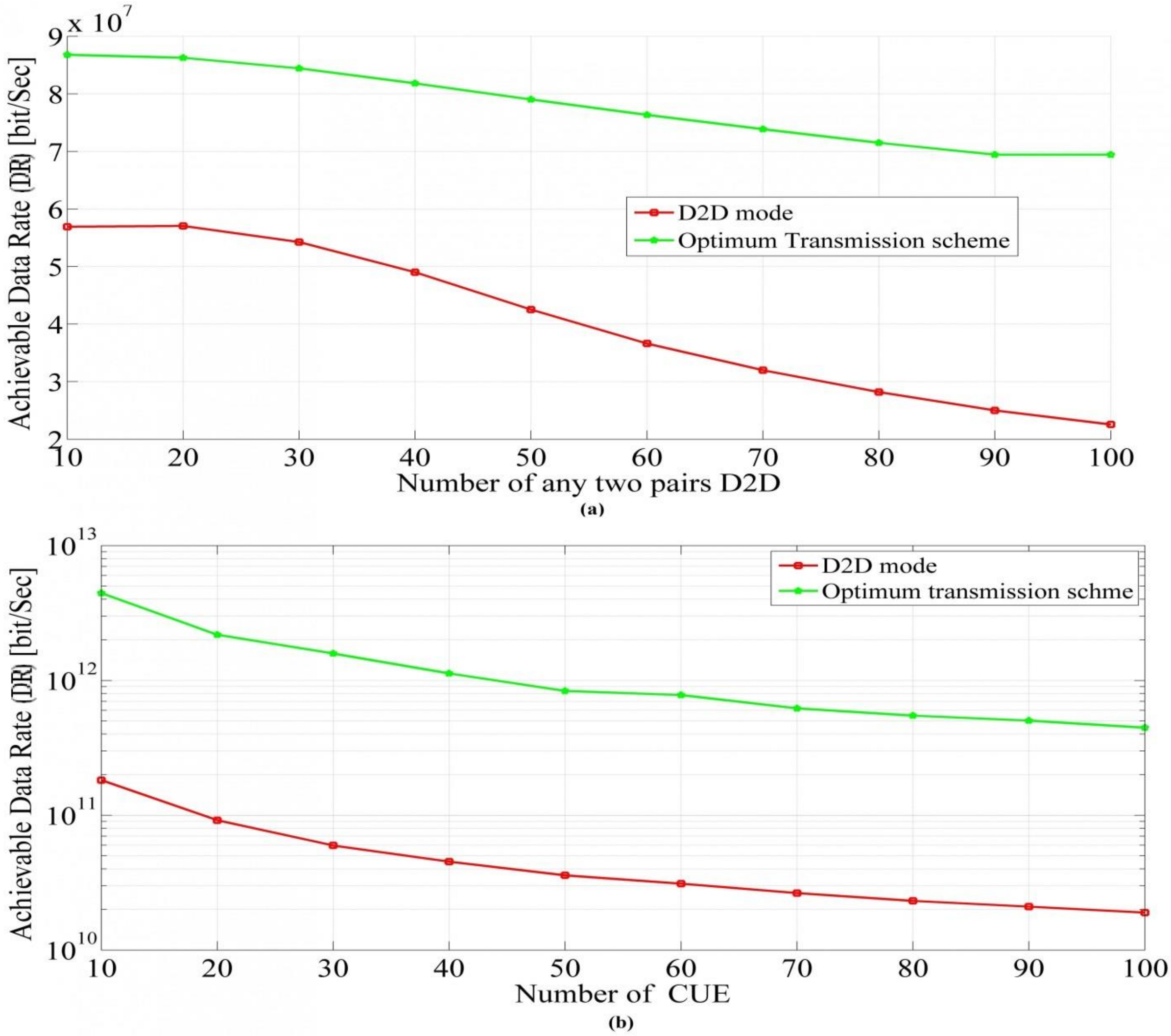



Figure 4.5: Overall achievable data rate vs

(a) Number of D2D links (b) Number of CUEs

### 4.2.4 Energy-Efficieny and Achievable Data Rate Trade-Off

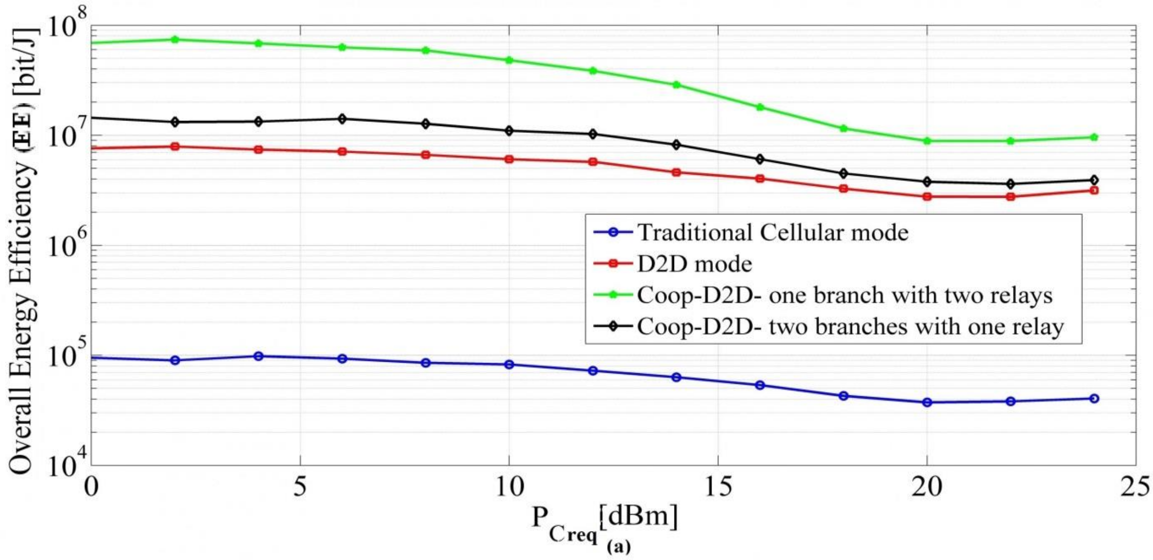
Based on the performance obtained in the previous subsections, it was noted that at certain distances the system has high energy efficiency with low achievable data rate. While, at other distances it has low energy efficiency with high achievable data rate, for example at a distance of 40 m D2D mode has higher energy efficiency than any other transmission mode and lower achievable data rate than coop-D2D. On the other hand, Coop-D2D one branch with two relays at a distance of 50 m has lower energy efficiency and higher achievable data rate. In these instances, the system will have to assess the trade-off between the two models and decide which is more suitable according to channel conditions.

### 4.2.5 Required Transmission Power

In this subsection, we show simulation and analytical results of the three transmission modes with respect to CUE transmission power $P_{Creq}$ using similar conditions. In this scenario we assume that

$P_{Creq}$ will vary and based on this power the D2D transmitted power $P_{Dreq}$ will be calculated in order to overcome the interference caused by DTx. The distance between two CUE-BS is 300 m and the distance between D2D links is 80 m. For energy efficiency and achievable data rate as shown in Figure 4.6(a) and Figure 4.6(b) the cooperative transmission is the optimal transmission scheme to maximise EE and DR as expected.

The same performance is obtained in Figure 4.7. In this scenario we assumed that $P_{Dreq}$ will vary and $P_{Creq}$ will be calculated in order to overcome the interference caused by the CUE transmitters. As shown in Figure 4.7(a) and Figure 4.7(b) cooperative transmission scheme outperforms the other transmission modes in terms of energy efficiency and achievable data rate. We can deduce from Figure 4.6 and Figure 4.7 that cooperative transmission is more efficient in term of power as less power is needed for transmission. This decreases the interference at the BS and DRx, increasing the overall energy efficiency and achievable data rate.



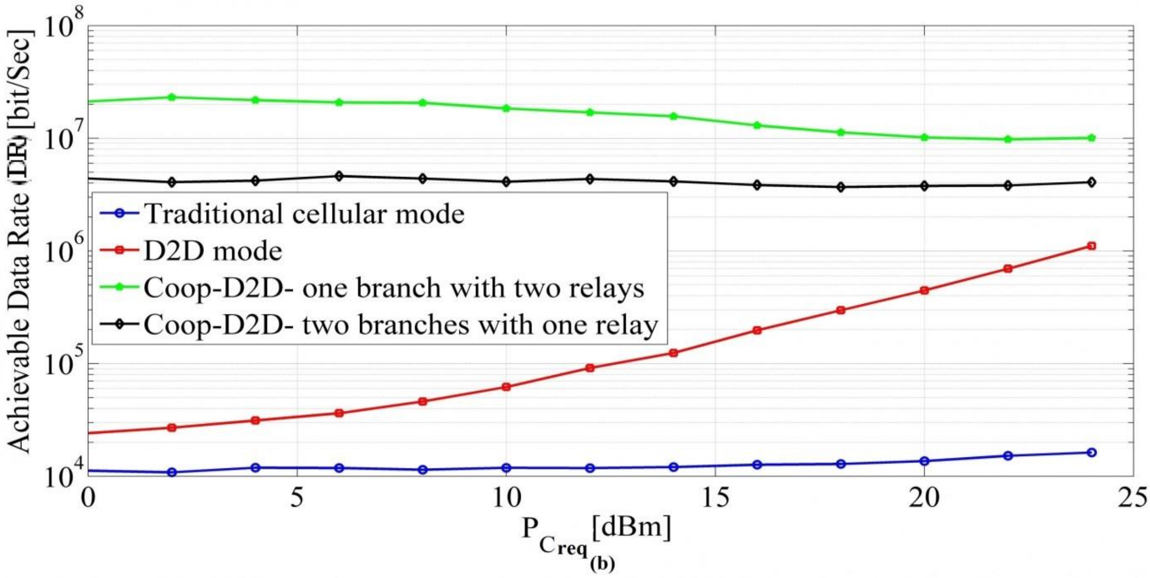




Figure 4.6: Required CUE transmission power $P_{Creq}$ vs

(a) Overall energy efficiency (b) Overall achievable data rate

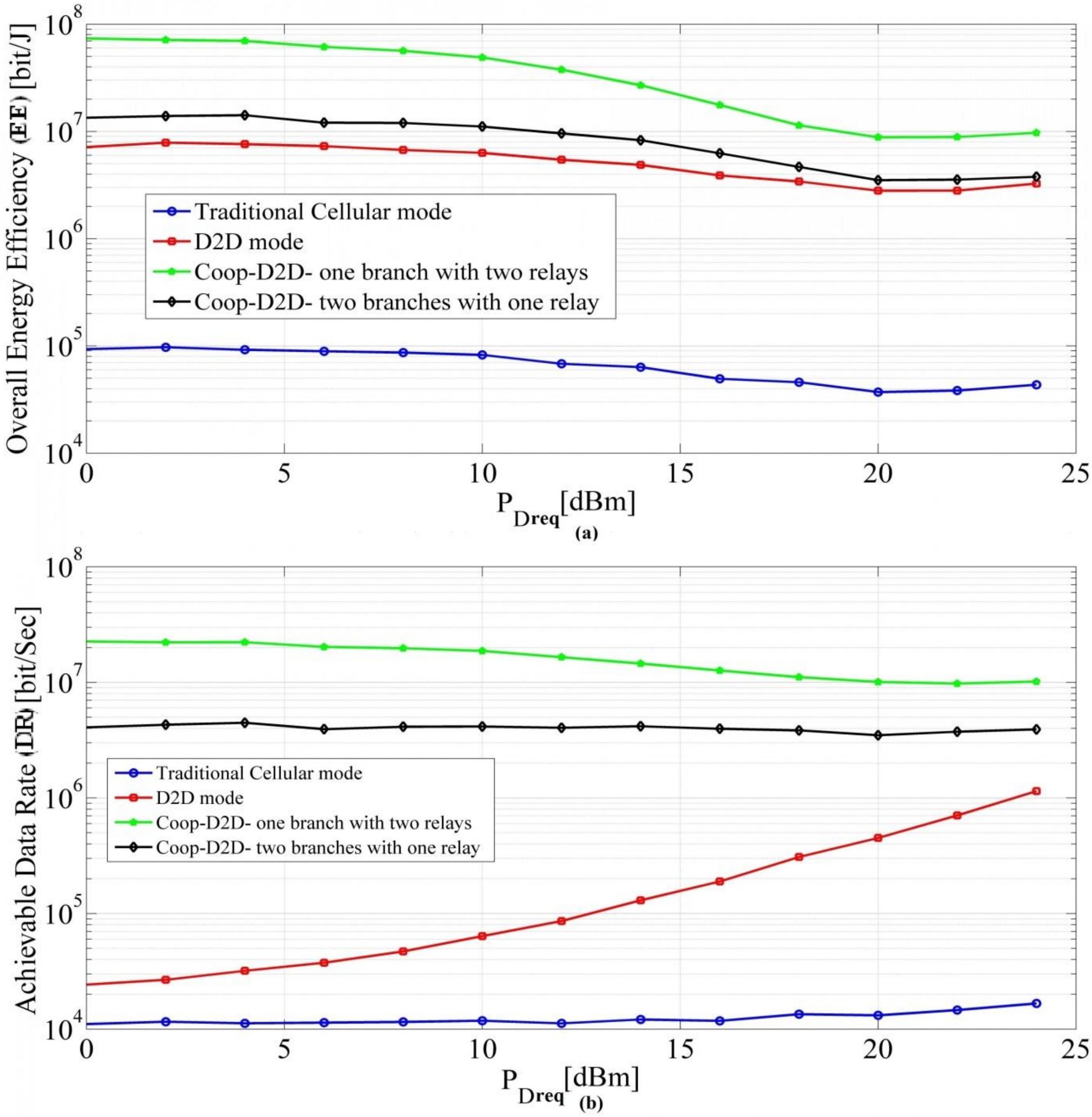



Figure 4.7: Required D2D transmission power $P_{Dreq}$ vs

(a) Overall Energy efficiency (b) Overall achievable data rate

### 4.2.6 Outage Probability Performance

Based on similar assumptions and conditions, the system outage probability has been evaluated for the three transmission modes. Figure 4.8 shows the Outage probability for each transmission modes. Assuming that D2D distance changes from 2 to 100 m and the distance of CUE-BS is fixed at 300 m. As we can observe from Figure 4.8(a), that direct D2D and cooperative D2D are superior to the traditional through BS regarding outage probability, whereas cooperative transmission outperforms the non-cooperative transmission. In addition, we notice that cooperative transmission using $K$=2 branches with $n$=1 relay per branch outperforms the cooperative transmission using $K$=1 branch with $n$=2 relays. Where, the effect of using the diversity technique appears, as multiple branches means less link failure. In Figure 4.8(b), we assume that CUE-BS distance changes from 10 to 500 m and the distance of D2D is fixed at 80 m. We can see that direct D2D and Coop-D2D are better than the traditional cellular network, and Coop-D2D is further preferable for enhancing the performance of CUE-BS links in return, because it leads to the decrease of the required transmission power for D2D links and CUE-BS links, decreasing the interference between CUE-DRX and DRx-BS links. When deciding which mode to use, the previous three performances can be jointly evaluated to achieve a desirable trade-off between them in order to enhance the QoS.

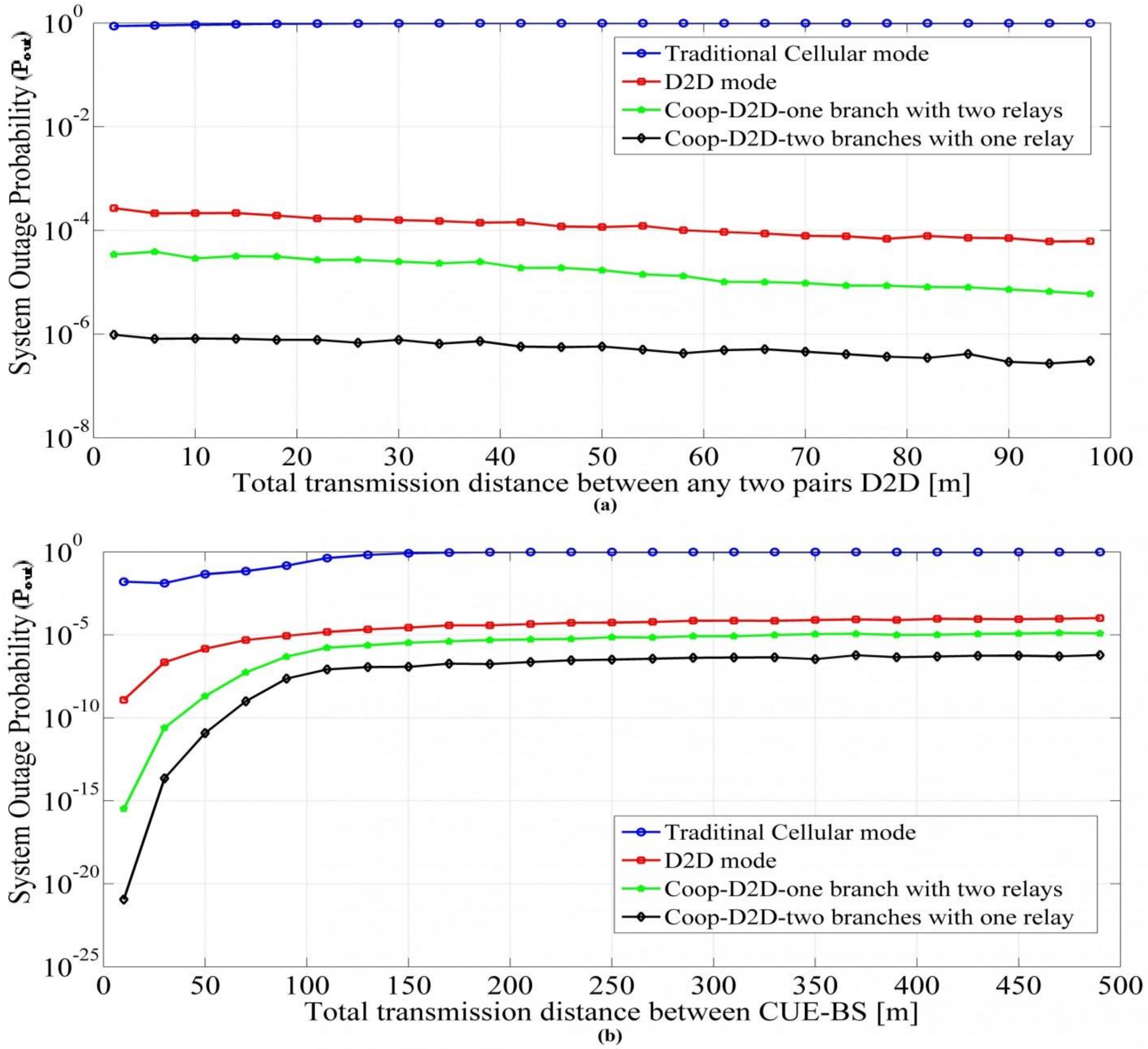



Figure 4.8: System outage probability vs

(a) Total transmission distance between D2D links (b) Total transmission distance between CUE-BS links

### 4.2.7 Bit Error Rate

Another metric is evaluated which is the bit error rate as we can observe from Figure 4.9, that direct D2D and cooperative D2D are both superior to the traditional through BS regarding BER, whereas cooperative transmission outperforms the non-cooperative transmission. In addition, we can see that cooperative transmission using $K$=1 branch with $n$=2 relays per branch outperforms the cooperative transmission using $K$=2 branches with $n$=1 relay. The obtained performance is due to the existence of intermediate nodes which decreases the overall distance between DTx and DRx and then decreases the overall system bit error rate. As we mentioned, this performance leads to enhancing the QoS and increases the system reliability, which is one of the requirements of cellular networks traffic.

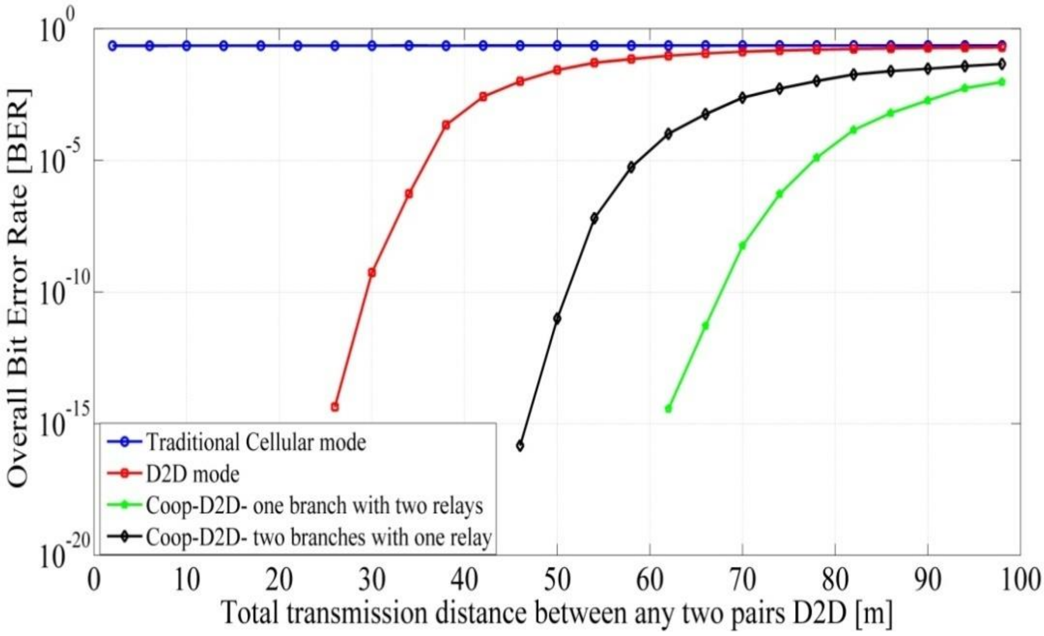



Figure 4.9: Overall bit error rate [BER] vs total transmission distance

### 4.2.8 Effect of Using Multiple Branches and Relays

Taking into consideration the number of branches and relays which needs to be implemented through cooperative communication networks, results in Figure 4.10 and Figure 4.11 show the energy performance and the achievable data rate for multi-branch and multi-relays scenarios. Assuming the distance between CUE-BS is 300 m and 80 m between D2D devices. In Figure 4.10 the energy performance is examined again but against the number of branches $K$. For a given number of relays per branch $n$=1, 2, … 4, the optimal number of branches can be found from this figure. When $n$=2, one branch can form the most energy efficient transmission scheme with two relays, but it is still outperformed by the schemes with more than one relay per branch for this source-destination distance. Although, the optimum achievable data rate can be obtained when one branch with four relays is implemented as shown in Figure 4.11, again when deciding the numbers of branches $K$ and relays $n$, energy efficiency and achievable data rate can be jointly evaluated to achieve an aimed trade-off between the two performance metrics.

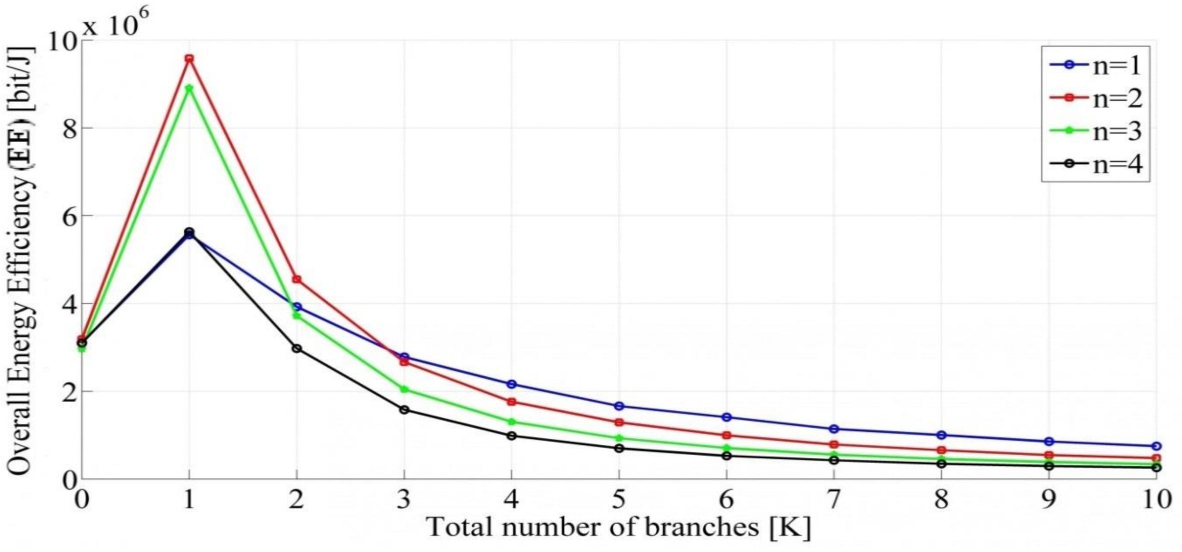



Figure 4.10: Overall energy efficiency vs total number of branches [*K*]

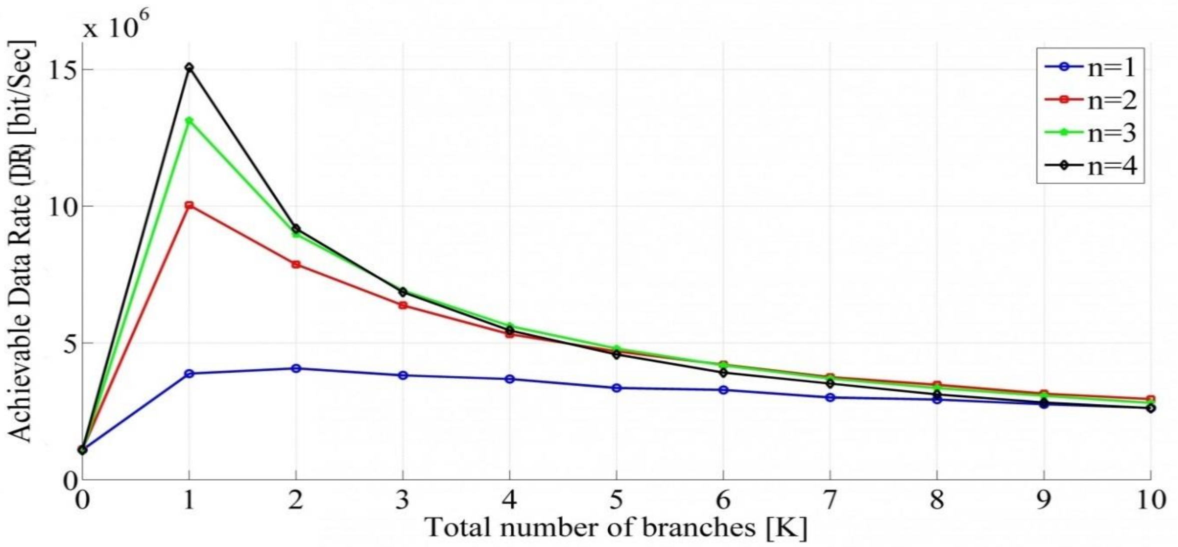



Figure 4.11: Overall achievable data rate vs total number of branches [*K*]

### 4.2.9 Proposed Adaptive Transmission Mode

In this subsection, an adaptive transmission is proposed that combines the energy consumption, achievable data rate or throughput and bit error rate. Since the QoS is our goal as discussed in previous section, the performance of these proposed transmission modes will depend on different parameters such as distance, path loss, noise power and channel link, i.e., the relay-to-destination link, relay-to-relay link and the source-to-relay link. Hence, we propose the adaptive protocol shown in Table 4.2. Assuming cellular networks with multiple mobile devices, beside CUE-BS transmission there is D2D communications links with variable distance and the distance of CUE-BS is fixed at 300 m. Each DTx decides at each transmission distance the best required transmission mode which enhances the D2D and CUE-BS links in order to improve the QoS for the whole network.

Assuming that, we have intermediate relay devices that are ready to help DTx in sending information to DRx. Each DTx adapts its transmission mode according to the distance between itself and the next node in order to achieve optimum QoS for the network. Different case studies were proposed based on the outcomes of the previous subsections.

In this scenario, it is assumed that there are always relay devices ready to help DTx to send information to DRx. As demonstrated in Table 4.2, when the distance between D2D is 20 m, DTx will choose the direct transmission as the most efficient transmission scheme for this range by comparison with other modes in terms of energy consumption, achievable data rate and bit error rate. However, when the distance between D2D is 40 m, DTx will adapt itself whether to choose the direct transmission or CoopD2D with one branch with two relays, as the direct transmission has the highest energy efficiency, while CoopD2D has the highest achievable data rate where the trade-off between energy efficiency and achievable data rate takes place.

On the other hand, when the distance between D2D links becomes 60 m or 80 m DTx chooses CoopD2D using one branch with two relays, as it is the most efficient transmission mode for this range in terms of energy efficiency, achievable data rate and bit error rate compared to other transmission modes. While, when the distance between D2D links becomes 100 m DTx chooses Coop-D2D using one branch with three relays as the optimum and efficient transmission mode in terms of energy efficiency, achievable data rate and bit error rate compared to other transmission modes.

TABLE 4.2. D2D ADAPTIVE TRANSMISSION SCHEMES

| **Distance between DTx and DRx** | **Transmission Scheme** | **Optimum Number of Branches [*K*] and Relays [*n*]** | **Energy Efficiency [bit/J]** | **Achievable Data rate [bit/sec]** | **Bit Error Rate [BER]** |
|---|---|---|---|---|---|
| 20 m | Cellular Mode | - | $4.2013*10^4$ | $1.9904*10^4$ | 0.4786 |
| 20 m | D2D Mode | - | $1.5661*10^8$ | $5.5*10^7$ | ≈ 0 |
| 20 m | Coop-D2D Mode One Branch with multiple Relays | *n*=1 | $6.1740*10^7$ | $4.3339*10^7$ | ≈ 0 |
| 20 m | Coop-D2D Mode Multiple Branches with One Relay | *K*=1 | $6.1740*10^7$ | $4.3339*10^7$ | ≈ 0 |
| 20 m | Coop-D2D Mode Multiple Branches with Multiple Relays | *n*=1, *K*=1 | $6.1740*10^7$ | $4.3339*10^7$ | ≈ 0 |
| 40 m | Cellular Mode | - | $4.0902*10^4$ | $1.8436*10^4$ | 0.4810 |
| 40 m | D2D Mode | - | $6.8634*10^7$ | $2.4104*10^7$ | 0.0017 |
| 40 m | Coop-D2D Mode One | *n*=2 | $2.5680*10^7$ | $2.8991*10^7$ | ≈ 0 |

| | | | | | |
|---|---|---|---|---|---|
| | Branch with Multiple Relays | | | | |
| 40 m | Coop-D2D Mode Multiple Branches with One Relay | $K$=1 | $3.8673*10^{7}$ | $2.7137*10^{7}$ | ≈ 0 |
| 40 m | Coop-D2D Mode Multiple Branches with Multiple Relays | $n$=1, $K$=1 | $3.8673*10^{7}$ | $2.7137*10^{7}$ | ≈ 0 |
| 60 m | Cellular Mode | - | $4.2267*10^{4}$ | $1.7680*10^{4}$ | 0.4841 |
| 60 m | D2D Mode | - | $1.4675*10^{7}$ | $5.1539*10^{6}$ | 0.1778 |
| 60 m | Coop-D2D Mode One Branch with Multiple Relays | $n$=2 | $1.6806*10^{7}$ | $1.7763*10^{7}$ | ≈ 0 |
| 60 m | Coop-D2D Mode Multiple Branches with One Relay | $K$=1 | $1.6099*10^{7}$ | $1.1279*10^{7}$ | 0.0016 |
| 60 m | Coop-D2D Mode Multiple Branches with Multiple Relays | $n$=1, $K$=1 | $1.6099*10^{7}$ | $1.1279*10^{7}$ | 0.0016 |
| 80 m | Cellular Mode | - | $4.0269*10^{4}$ | $1.6253*10^{4}$ | 0.4863 |
| 80 m | D2D Mode | - | $3.0821*10^{6}$ | $1.0824*10^{6}$ | 0.3486 |
| 80 m | Coop-D2D Mode One Branch with Multiple Relays | $n$=2 | $9.4892*10^{6}$ | $9.9409*10^{6}$ | $5.3483*10^{-5}$ |
| 80 m | Coop-D2D Mode Multiple Branches with One Relay | $K$=2 | $3.7457*10^{6}$ | $4.0281*10^{6}$ | 0.0142 |
| 80m | Coop-D2D Mode Multiple Branches with Multiple Relay | $K$=1, $n$=2 | $9.4892*10^{6}$ | $9.9409*10^{6}$ | $5.3483*10^{-5}$ |
| 100 m | Cellular Mode | - | $4.1898*10^{4}$ | $1.6317*10^{4}$ | 0.4881 |
| 100 m | D2D Mode | - | $8.9134*10^{5}$ | $3.1303*10^{5}$ | 0.4210 |
| 100 m | Coop-D2D Mode One Branch with Multiple Relays | $n$=3 | $6.2530*10^{6}$ | $8.6965*10^{6}$ | $1.3669*10^{-6}$ |
| 100 m | Coop-D2D Mode Multiple Branches with One Relay | $K$=4 | $9.4260*10^{5}$ | $1.5441*10^{6}$ | 0.0077 |
| 100 m | Coop-D2D mode Multiple Branches with Multiple Relay | $K$=1, $n$=3 | $6.2530*10^{6}$ | $8.6965*10^{6}$ | $1.3669*10^{-6}$ |

## 4.3 Summary and Conclusion

In this chapter, we have established D2D cooperative relaying scenarios. We analysed the optimum required transmission power for different transmission ranges to obtain maximum energy efficiency (EE) and maximum achievable data rate (DR) with minimum outage probability ($p_{out}$) and bit error rate (BER). This was investigated for D2D communications underlaying cellular networks in three transmission modes, namely, cellular mode (CM), direct D2D mode (DM) and cooperative D2D mode (CoopD2D) where cellular user equipment (CUE) devices help each other to exchange information.

Based on our analysis and investigation we recognised, that there are a number of factors that can affect energy efficiency, achievable data rate, outage probability and bit error rate in cellular networks. Cooperative transmission involves additional paths and devices (relays) compared to direct transmission, which costs more energy. But the diversity it creates can save energy by reducing the number of retransmissions due to the reduced packet loss rate. In addition, increasing the number of relays in each branch reduces the distance of each transmission hop, resulting in lower transmit power needed for relays. But when the number of relays increases, the total circuitry power will accumulate as it depends on the number of transmitting devices and is independent from the transmission distance. As a result, the total energy consumption will increase if too many branches and relays are used.

Therefore, to achieve the best energy performance and achievable data rate for both CUE-BS and D2D links, the optimum transmission schemes should be selected for given transmission conditions, such as distances between D2D devices and CUE-BS links and channel quality. The results of this work provide an effective guidance for deciding when and how the cooperative or direct transmission scheme should be employed. Based on our investigation, an energy-efficient transmission method can be found in cellular networks by adaptively choosing cooperative or non-cooperative transmission schemes for varied network and transmission conditions.

Based on the energy efficiency and achievable data rate optimisation models derived, we have shown that direct D2D and cooperative D2D modes are more preferable than the cellular mode in terms of EE and DR. We have also shown that direct D2D and Cooperative D2D transmission schemes can be used collectively to achieve the highest possible energy efficiency depending on environmental conditions such as the channel quality, transmission range between CUE-BS and transmission range between D2D pairs. Adaptive transmission strategies based on the results presented in this chapter can therefore be derived to optimise the energy performance and enhance the QoS in such networks.

# Chapter Five

# Enhancing QoS in Vehicle-to-Infrastructure Communications

Vehicular networking is considered as one of the most important enabling technologies required to implement several applications related to vehicles, vehicle traffic, drivers, passengers and pedestrians. These applications are not just ideas and innovations, Intelligent Transportation Systems (ITS) that aim to organise and improve the operation of vehicles, manage vehicle traffic, assist drivers with safety and other information, along with provisioning of convenience applications for passengers are no longer confined to laboratories and test facilities of companies. Vehicle-to-everything (V2X) is the current technology in vehicular networks like vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I). Providing quality of service (QoS) in vehicle networks hasn't received much attention from researchers. However, challenges stand and the problems of how to achieve the intended performances at minimal resource cost have not been well addressed.

Vehicle-to-infrastructure (V2I) technology uses and expands on current technologies being used for vehicle-to-vehicle (V2V) technology. V2I technology, when supported by V2V, will greatly improve safety, mobility and environmental benefits that will be of significant appeal to governmental, regional and local transportation entities.

In this chapter, our focus will be the identification of the conditions for establishing appropriate transmission strategies among different commonly used transmission schemes including both cooperative and non-cooperative schemes in V2I. This approach is based on the development of analytical models for these transmission schemes and the appraisal of their performances in reliability, energy consumption, packet delivery ratio, throughput and average end-to-end delay. Our work reveals the trade-offs between cooperative and non-cooperative transmission schemes and shows how to utilise this property to achieve the optimised performance through adaptive cooperative communications.

## 5.1 System model

In this section, the analytical models of the required transmitting power, outage probability, energy efficiency, throughput, packet losses, packet delivery ratio and average end-to-end delay in the context of a V2I are established for both cooperative and non-cooperative transmission schemes. Based on these models, an adaptive transmission strategy is developed to optimise the system performance.

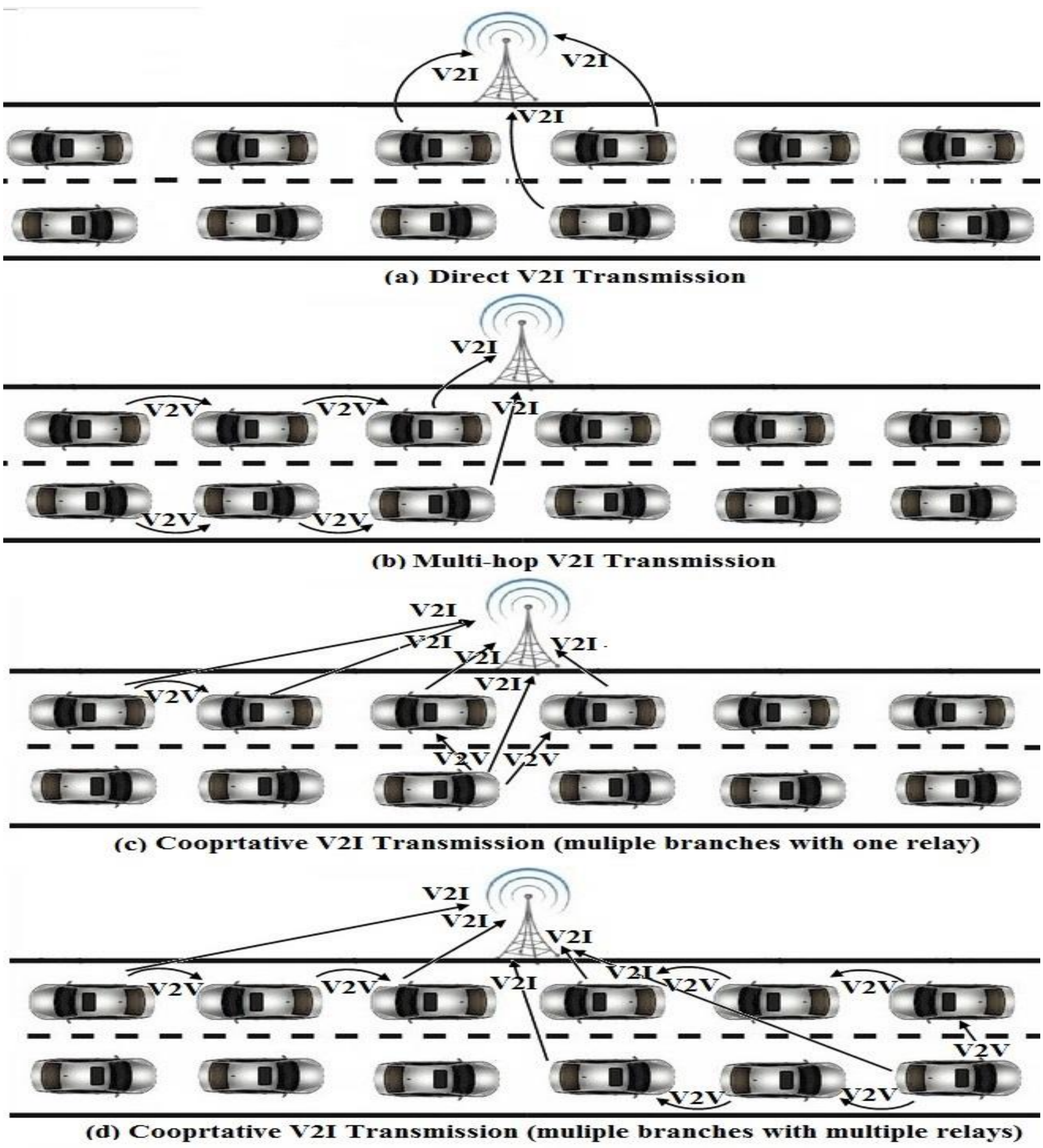



Figure 5.1: Transmission schemes in a Vehicular network

(a) Non-cooperative direct transmission scheme (b) Non-cooperative multi-hop transmission scheme (c) Cooperative multiple branches with one relay (d) Cooperative multiple branches with multiple relays

Given a V2I network with $N$ vehicles, for any vehicle-to-infrastructure pair ($V$, $I$), where $V \epsilon \{1, . . . , N\}$, the goal of optimising the transmission QoS is achieved by minimising the total energy consumed per bit (or energy efficiency) with outage probability target set. In addition, maximising the end-to-end throughput, packet delivery ratio and minimising packet losses based on the transmission distance between V2I, i.e.,

$$Min \sum E_{bi} \qquad s.t.\{p_{outVI}\}$$

and

$$Max \sum S_{thi} \qquad\qquad s.t.\{d_{VI}\}$$

(5.1)

where $E_{bi}$ and $S_{thi}$ are the energy consumed per bit and throughput, respectively, of the $i$-th path between ($V$) and Infrastructure ($I$), $p_{outVI}$ and $d_{VI}$ are the fixed outage probability target set and the total distance for transmission between $V$-$I$.

Four commonly used transmission schemes in the context of vehicle-to-infrastructure are identified in Figure 5.1. In this work, we intend to examine and compare their performance in energy efficiency, throughput, packet delivery ratio, packet loss, average end-to-end delay and to optimise the transmission scheme in different environmental conditions.

We consider a V2I network in which the transmission links are subject to narrowband Rayleigh fading with additive white Gaussian noise (AWGN) and propagation path-loss. The channel fades for different links are assumed to be statistically mutually independent. For medium access, vehicle nodes are assumed to transmit over orthogonal channels using the service channels specified in IEEE801.11p [6], thus no mutual interference is considered in this system model. These channels can be reused by other vehicle away from a certain distance.

## 5.1.1 Non-Cooperative Transmission Schemes

In this subsection we formalise direct transmission and multi-hop transmission schemes. In the direct transmission, the vehicle communicates directly with the infrastructure, without any intermediate helper nodes (vehicles). On the other hand, when multi-hop communication is established, a vehicle is responsible for forwarding another vehicle's information to the infrastructure.

### 5.1.1.1 Direct Transmission Scheme

Consider the transmission scheme for a direct link ($V$, $I$) as shown in Figure 5.1(a) where no additional relay paths are involved. We use $P_{VD}$ to denote the vehicle transmission power for this case. For the direct transmission between vehicle $V$ and infrastructure $I$, the received symbol $r_{VI}$ and the spectral efficiency $R_{VI}$ can be modelled as:

$$r_{VI} = \sqrt{P_{VD}\, d_{VI}^{\,-\alpha}}\, h_{VI}\, s + N_o \tag{5.2}$$

$$R_{VI} = \log_2\left(1 + SINR_{VI}\right) \tag{5.3}$$

where $d_{VI}$ is the distance between the vehicle $V$ and the infrastructure $I$, $\alpha$ is the path loss exponent, $h_{VI}$ is the channel coefficient of the $V$-$I$ link, s is the transmitted symbol with unit power and $N_o$ is the Gaussian noise.

The log-normal environment shadowing path loss model at a distance $d$ from node $i$ and node $j$ is given by [27]:

$$\gamma_{ij}[dB] = PL(d_o) + 10\alpha \log_{10}\left(\frac{d_{ij}}{d_o}\right) + X_\sigma \tag{5.4}$$

where $d_{ij}$ is the distance in meters between the two nodes and $X_\sigma$ is a zero-mean Gaussian distributed random variable with standard deviation σ and with time correlation. This variable is used only when there is a shadowing effect. If there is no shadowing effect, then this variable is zero. The $PL(d_o)$ is the path loss at a reference distance $d_o$ in dB. The Signal-to-Noise Ratio (SNR) in the $V - I$ link is:

$$SINR_{VI} = \frac{P_{VD}|h_{VI}|^2 \gamma_{VI}}{N} \tag{5.5}$$

where $N = No\ B$ is the noise power spectral density and $B$ is the system bandwidth in Hertz.

As described previously, an outage occurs when the SNR at the receiver falls below a threshold $\beta$. The outage probability ($p_{outVI}$) of the direct transmission between vehicles and infrastructure is given by [64]:

$$p_{outVI} = p(SINR_{VI} \leq \beta) = 1 - e^{\left(-\frac{(2^{2R_s} - 1)N}{P_{VD}|h_{VI}|^2 \gamma_{VI}}\right)} \tag{5.6}$$

The total power consumption of a typical V2I system consists of two components: the transmission power of the power amplifier and the circuit power $P_C$ of all RF circuit blocks and the bit rate. Thus, the total consumed energy per bit of the direct transmission between V2I based on [119, 130] can be expressed as:

$$E_{bVD} = \frac{P_{AM,VD} + P_c}{R_b} \tag{5.7}$$

$$P_{AM,VD} = \frac{\xi}{\eta} P_{VD} \tag{5.8}$$

$$P_C = P_{Tx} + P_{Rx} \tag{5.9}$$

where $P_{AM,VD}$ is the power amplification for direct transmission which depends on the drain efficiency of the amplifier $\eta$, the average peak-to-peak ratio $\xi$ and the transmission power $P_{VD}$, $R_b= R_sB$ is the bit rate in bits/s, $P_{TX}$ and $P_{RX}$ are the power consumed by the internal circuitry for transmitting and receiving, respectively.

As described previously, Energy consumption is largely proportional to the successful transmission rate or the requirement of maintaining a certain level of transmission reliability. In order to maintain a required level of reliability, denoted by $U$, which is related to the reliability of a transmission link, the minimum outage probability is defined as:

$$p_{outVD} \leq 1\text{-}U \tag{5.10}$$

In order to find the optimum required transmission power with minimum energy consumption for the direct transmission scheme. Lagrange optimisation has been used as optimisation technique. This is an optimisation problem with one constraint variable and its Lagrangian is given by:

$$Min\sum E_{bVD} \qquad s.t.\{p_{outVD} \leq 1-U\} \tag{5.11}$$

$$L(P_{VD},\lambda_{VD}) = P_{totVD} + \lambda_{VD}\left(p_{outVD} - 1 + U\right) \tag{5.12}$$

The main objective for the performance optimisation of a V2I is to minimise the total energy consumption under different environmental conditions. Thus, the optimum required transmission power $P_{Vopt}$ for the direct transmission scheme to satisfy the reliability requirement or be constrained by the outage probability must be:

$$P_{Vopt} \approx \left(\frac{-\left(2^{2R_s}-1\right)N}{\ln U |h_{VI}|^2 \gamma_{VI}}\right) \tag{5.13}$$

The detailed derivation of this result is provided in Appendix (Appendix A-Ch5-1).

The minimum energy efficiency can be obtained based on the optimum required transmission power by substituting Equation (5.13) in Equation (5.12) and then in Equation (5.7), hence the minimum energy consumption $E_{bVDmin}$ can be formulated as:

$$E_{bVD\min} = \frac{P_{totVD\min}}{R_b} \tag{5.14}$$

where $$P_{totVD\min} = \left(P_{AM,VD\min} + P_C\right) + \lambda_{VD}\left(pout_{VD} - 1 + U\right)$$

and $$P_{AM,VD\min} = \frac{\xi}{\eta} P_{Vopt} \tag{5.15}$$

### 5.1.1.2 Multi-Hop Transmission Scheme

The multi-hop transmission scheme is another type of non-cooperative transmission scheme. In multi-hop transmission the communications is carried through multiple vehicles called relays nodes ($n$) as shown in Figure 5.1(b). We assume that we have single or multi-hop relays $R \in \{1,n\}$, each relay is able to detect if the packet was received correctly and only in that case the relay will forward the information to the destination. Otherwise, the packet is considered lost. In this case the received signal at each time slot can be expressed as:

$$r_{ij} = \sqrt{P_{Vij}\, d_{ij}^{-\alpha}}\, h_{ij} s + N_o \tag{5.16}$$

where $i \in \{V,R\}$, $j \in \{R,I\}$, $P_{Vij}$ is the required transmission power between two successive vehicles, this power must be lower than the direct transmission power as in this condition the distance between two consecutive nodes will be smaller than the total distance between source and destination.

For any concatenation and based on the previous explanation of the outage probability, we can conclude that the total outage probability for the multi-hop transmission scheme is given by:

$$p_{outVMH} = 1-\left(1-p_{outVR_1}\right)\left(1-p_{outR_1R_2}\right)\cdots\cdots\cdots\left(1-p_{outR_nI}\right) \tag{5.17}$$

where $p_{outVR_1} = 1-e^{\left(\frac{-\left(2^{2R_s}-1\right)N}{P_V\left|h_{VR_1}\right|^2\gamma_{VR_1}}\right)}$, $p_{outR_1R_2} = 1-e^{\left(\frac{-\left(2^{2R_s}-1\right)N}{P_{R_1}\left|h_{R_1R_2}\right|^2\gamma_{R_1R_2}}\right)}$ $and$ $p_{outR_nI} = 1-e^{\left(\frac{-\left(2^{2R_s}-1\right)N}{P_{R_n}\left|h_{R_nI}\right|^2\gamma_{R_nI}}\right)}$ (5.18)

where $p_{outVR_1}$, $p_{outR_1R_2}$ and $p_{outR_nI}$ represent the outage probability between the vehicle source and first relay node, the outage probability between first and second relay nodes and the outage probability between the last relay node and infrastructure, respectively. $P_V, P_{R_1}$, and $P_{R_n}$ are the transmission power of the vehicle source, first relay and last relay node, respectively. Then, the outage probability in this case can be expressed as:

$$p_{outVMH} = 1-e^{-\left(2^{2R_s}-1\right)N\left(\frac{1}{P_V\left|h_{VR_1}\right|^2\gamma_{VR_1}}+\sum_{i=2}^{n}\frac{1}{P_{Ri-1}\left|h_{Ri-1Ri}\right|^2\gamma_{R_{i-1}R_i}}+\frac{1}{P_{Rn}\left|h_{RnI}\right|^2\gamma_{R_nI}}\right)} \tag{5.19}$$

We set the transmission power to be proportional to the distance between two communicating nodes. For broadcast transmission, e.g., when the source transmits, the longest distance, i.e., the distance between the vehicle and infrastructure $d_{VI}$, is considered. So, the power between two communicating nodes is given by:

$$P_{ij} = \lambda_{ij}{}^{\alpha} P_{VI} = X\, P_{VI} \tag{5.20}$$

where $X = \upsilon_{ij}{}^{\alpha}$ and $\upsilon_{ij}$ denotes the power coefficient between node $i$ and node $j$. In our model, we assume that the value of $\upsilon_{ij}$ depends on the distance of the vehicle-infrastructure, relay-relay or relay-infrastructure links. For example, the transmission power for the relay-destination link is:

$$P_{RI} = \upsilon_{RI}{}^{\alpha} P_{VI} = \left(\frac{d_{RI}}{d_{VI}}\right)^{\alpha} P_{VI} \tag{5.21}$$

Based on Equation (5.21) and Equation (5.20), so Equation (5.19) can be rewritten as:

$$p_{outVMH} = 1 - e^{-\frac{\left(2^{2R_s}-1\right)N}{P_{VMH}}\left(\frac{1}{\left|h_{VR_1}\right|^2 \gamma_{VR_1}} + \sum_{i=2}^{n}\frac{1}{\upsilon_{R_{i-1}R_i}{}^{\alpha}\left|h_{R_{i-1}R_i}\right|^2 \gamma_{R_{i-1}R_i}} + \frac{1}{\upsilon_{R_nI}{}^{\alpha}\left|h_{R_nI}\right|^2 \gamma_{R_nI}}\right)} \tag{5.22}$$

Then the outage probability of the multi-hop transmission scheme can be approximated and expressed as follows:

$$p_{outVMH} \approx \frac{\left(2^{2R_s}-1\right)N}{P_{VMH}}\left(\frac{1}{\left|h_{VR_1}\right|^2 \gamma_{VR_1}} + \sum_{i=2}^{n}\frac{1}{\upsilon_{R_{i-1}R_i}{}^{\alpha}\left|h_{R_{i-1}R_i}\right|^2 \gamma_{R_{i-1}R_i}} + \frac{1}{\upsilon_{R_nI}{}^{\alpha}\left|h_{R_nI}\right|^2 \gamma_{R_nI}}\right) \tag{5.23}$$

The total consumption takes into account the required power for the transmission, which is dependent on the distance between each two vehicles, the power consumption of the circuitry and the bit rate. Thus, the total consumed energy per bit of the multi-hop transmission scheme is:

$$E_{bVMH} = pout_{VR_1}\frac{P_{AM,VMH} + P_C}{R_b} + \left(1 - pout_{VR_1}\right)\frac{\left(\sum_{i=2}^{n}\upsilon_{R_{i-1}R_i}{}^{\alpha} + \upsilon_{R_nI}{}^{\alpha} + 1\right)P_{AM,VMH} + (n+1)P_C}{R_b} \tag{5.24}$$

The first term on the right-hand side corresponds to the consumed energy when the relay is not able to correctly decode the message from the vehicle, which means that this link is in outage. In this case, only the vehicle source consumes transmitting power and the infrastructure and $n$ relays consume receiving power. The second term counts for the event that the vehicle-relay link is not in outage, hence the relay transmitting and processing power and the extra receiving power at the infrastructure are involved.

where $\upsilon_{i-1i}{}^{\alpha}=X_{i-1i}$ and $\upsilon_{nD}{}^{\alpha}=X_{nD}$, Then Equation (5.24) can be written as:

$$E_{bVMH} = pout_{VR_1}\frac{P_{AM,VMH} + P_C}{R_b} + \left(1 - pout_{VR_1}\right)\frac{\left(\sum_{i=2}^{n}X_{R_{i-1}R_i} + X_{R_nI} + 1\right)P_{AM,VMH} + (n+1)P_C}{R_b} \tag{5.25}$$

$$P_{AM,VMH} = \frac{\xi}{\eta} P_{VMH} \tag{5.26}$$

where $P_{AM,VMH}$ is the power amplification for the multi-hop transmission scheme which depends on the drain efficiency of the amplifier $\eta$, the average peak-to-peak ratio $\xi$ as described previously.

Energy consumption required for the multi-hop transmission scheme in order to maintain a required level of reliability, denoted by $U$, which is related to the reliability of a transmission link, the minimum outage probability is defined as:

$$p_{outVMH} \leq 1\text{-}U \tag{5.27}$$

In order to find the optimum required transmission power with minimum energy consumption for the multi-hop transmission scheme, we use Lagrange optimisation as mentioned previously. The optimisation problem with one constraint variable and its Lagrangian for this transmission scheme is given by:

$$Min \sum E_{bVMH} \qquad s.t. \{p_{outVMH} \leq 1 - U\} \tag{5.28}$$

$$L(P_{VMH}, \lambda_{VMH}) = P_{totVMH} + \lambda_{VMH}\left(p_{outVMH} - 1 + U\right) \tag{5.29}$$

Thus, the optimum required transmit power $P_{VMHopt}$ for the multi-hop transmission scheme to satisfy the reliability requirement or be constrained by the outage probability for the multi-hop transmission must be:

$$P_{VMHopt} \approx \frac{-\left(2^{2R_s} - 1\right)N}{\ln U} \left( \frac{1}{\left|h_{VR_1}\right|^2 \gamma_{VR_1}} + \sum_{i=2}^{n} \frac{1}{\upsilon_{R_{i-1}R_i}{}^{\alpha} \left|h_{R_{i-1}Ri}\right|^2 \gamma_{R_{i-1}R_i}} + \frac{1}{\upsilon_{R_n I}{}^{\alpha} \left|h_{R_n I}\right|^2 \gamma_{R_n I}} \right) \tag{5.30}$$

The detailed derivation of this result is provided in Appendix (Appendix A-Ch5-2).

We can obtain the minimum energy efficiency based on the optimum required transmission power by substituting Equation (5.30) in Equation (5.29) and then in Equation (5.25), hence the minimum energy consumption $E_{bVMHmin}$ can be formulated as:

$$E_{bVMH\min} = \frac{P_{totVMH\min}}{R_b} \tag{5.31}$$

where

$$P_{totVMH\min} = pout_{VR_1}\left(P_{AM,VMH\min} + P_C\right) + \left(1 - pout_{VR_1}\right)\left(\left(\sum_{i=2}^{n} X_{R_{i-1}R_i} + X_{R_n I} + 1\right)P_{AM,VMH\min} + (n+1)P_C\right)$$
$$+ \lambda_{VMH}\left(pout_{VMH} - 1 + U\right)$$

and

$$P_{AM,MVH\min} = \frac{\xi}{\eta} P_{VMHopt} \tag{5.32}$$

## 5.1.2 Cooperative Transmission Schemes

In cooperative transmission, the sender *V* broadcasts its symbol to all potential receivers including the infrastructure *I* and relays in the current time slot. Both the infrastructure and relays receive noisy versions of the transmitted symbol. Then the relays transmit the received symbol after some processing to the destination. We present two types of cooperative transmission schemes: 1) using multiple cooperative relaying branches with one relay in each branch and 2) using multiple cooperative relaying branches and with multiple relays in each branch. We assume that the selection combining technique is used at the destination on the received packets.

### 5.1.2.1 Cooperative Transmission using Multiple Branches with One Relay

In the cooperative transmission scheme with multiple branches (*K)* with one relay in each branch, the communications are carried through multiple relays nodes, each node located at a different branch as shown in Figure 5.1(c). Assuming that we have single or multiple relay branches $K \epsilon \{1,k\}$, each relay is able to detect if the packet was received correctly and in that case will forward the information to the destination. Otherwise, the packet is considered lost. In this case, the received symbol by relay vehicles, $r_{VR}$, the received symbol by the infrastructure from relays, $r_{RI}$ and the spectral efficiency $R_S$ can be expressed as:

$$r_{VR} = \sqrt{P_V d_{VR}^{-\alpha}}\, h_{VR} S + N_o \tag{5.33}$$

$$r_{RI} = \sqrt{P_C d_{RI}^{-\alpha}}\, h_{RI} S + N_o \tag{5.34}$$

$$R_S = \frac{1}{2}\log_2\left(1 + \frac{P_V |h_{VR}|^2}{N\, d_{VR}^{\alpha}} + \frac{P_C |h_{RI}|^2}{N\, d_{RI}^{\alpha}}\right) \tag{5.35}$$

where $P_V$ is the transmission power of the source and $P_C$ is the transmission power of relays, $h_{VR}$ and $h_{RI}$ are the channel coefficients of vehicle-relay link and relay-infrastructure link, respectively.

We can conclude that the outage probability for the cooperative multiple branches (*K*) transmission scheme is given by jointly considering the outages in *V-I*, *V-R* and *R-I* links, i.e.,

$$p_{outVMB} = p_{outVI}\left(1-\left(1-p_{outVR}\right)\left(1-p_{outRI}\right)\right)^{K} \tag{5.36}$$

where $p_{outVI} = 1-e^{\left(\frac{-\left(2^{2R_s}-1\right)N}{P_V|h_{VI}|^2\gamma_{VI}}\right)}$, $p_{outVR} = 1-e^{\left(\frac{-\left(2^{2R_s}-1\right)N}{P_V|h_{VR}|^2\gamma_{VR}}\right)}$ *and* $p_{outRI} = 1-e^{\left(\frac{-\left(2^{2R_s}-1\right)N}{P_R|h_{RI}|^2\gamma_{RI}}\right)}$

$p_{outVI}$, $p_{outVR}$ and $p_{outRI}$ represents the outage probability between vehicle and infrastructure, the outage probability between vehicle and relay branch and the outage probability between the relay branch and infrastructure, respectively. $P_V$ and $P_R$ are the transmission power of the vehicle and the relay power, respectively. Then, the outage probability of this transmission scheme can be expressed as:

$$p_{outVMB} = \left(1-e^{\left(\frac{-\left(2^{2R_s}-1\right)N}{P_V|h_{VI}|^2\gamma_{VI}}\right)}\right)\left(1-e^{-\left(2^{2R_s}-1\right)N\left(\frac{1}{P_V|h_{VR}|^2\gamma_{VR}}+\frac{1}{P_R|h_{RI}|^2\gamma_{RI}}\right)}\right)^{K} \tag{5.37}$$

As described in the previous subsection, the power between two communicating nodes is given by:

$$P_R = \upsilon_{RI}{}^{\alpha}P_{VI} = \left(\frac{d_{RI}}{d_{VI}}\right)^{\alpha}P_{VI} = XP_{VI} \tag{5.38}$$

Based on Equation (5.37), so Equation (5.36) can be rewritten as:

$$p_{outVMB} = \left(1-e^{\left(\frac{-\left(2^{2R_s}-1\right)N}{P_{VMB}|h_{VI}|^2\gamma_{VI}}\right)}\right)\left(1-e^{-\frac{\left(2^{2R_s}-1\right)N}{P_{VMB}}\left(\frac{1}{|h_{VR}|^2\gamma_{VR}}+\frac{1}{\upsilon_{RI}{}^{\alpha}|h_{RI}|^2\gamma_{RI}}\right)}\right)^{K} \tag{5.39}$$

Then the outage probability of the multiple branches transmission scheme can be approximated and expressed as follows:

$$p_{outVMB} \approx \frac{\left(2^{2R_s}-1\right)^{K+1}N^{K+1}}{P_{VMB}{}^{K+1}|h_{VI}|^2\gamma_{VI}}\left(\left(\frac{1}{|h_{VR}|^2\gamma_{VR}}+\frac{1}{\upsilon_{RI}{}^{\alpha}|h_{RI}|^2\gamma_{RI}}\right)\right)^{K} \tag{5.40}$$

The total consumption takes into account the required power for the transmission, which depends on the distance between each two vehicles, the power consumption of the circuitry and the bit rate. Thus, the total consumed energy per bit of this transmission scheme is:

$$E_{bVMB} = \left(pout_{VR}\right)^K \frac{P_{AM,VMB} + P_{C1}}{R_b} + \left(1 - \left(pout_{VR}\right)^K\right) \frac{\left(\sum_{l=1}^{K} \upsilon_{R_l I}{}^{\alpha} + 1\right) P_{AM,VMB} + P_{C2}}{R_b} \tag{5.41}$$

where $P_{C1} = P_{Tx} + K * P_{Rx}$ and $P_{C2} = (K+1)P_{Tx} + (2K+1)P_{Rx}$

The first term on the right-hand side corresponds to the consumed energy when the relay is not able to correctly decode the message from the vehicle source, which means that this link is in outage. In this case, only the vehicle source consumes transmitting power and infrastructure and *n* relays consume receiving power. The second term counts for the event that the vehicle-relay link is not in outage, hence the relay transmitting and processing power and the extra receiving power at the infrastructure are involved.

where $\upsilon_{R_l I}{}^{\alpha} = X_{R_l I}$, Then Equation (5.41) can be written as:

$$E_{bVMB} = \left(pout_{VR}\right)^K \frac{P_{AM,VMB} + P_{C1}}{R_b} + \left(1 - \left(pout_{VR}\right)^K\right) \frac{\left(\sum_{l=1}^{K} X_{R_l I} + 1\right) P_{AM,VMB} + P_{C2}}{R_b} \tag{5.42}$$

$$P_{AM,VMB} = \frac{\xi}{\eta} P_{VMB} \tag{5.43}$$

where $P_{AM,VMB}$ is the power amplification for multiple branches transmission scheme which depends on the drain efficiency of the amplifier $\eta$, the average peak-to-peak ratio $\xi$ as described previously.

Energy consumption required for cooperative multiple branches transmission scheme in order to maintain a required level of reliability, denoted by *U*, which is related to the reliability of a transmission link, the minimum outage probability is defined as:

$$p_{outVMB} \leq 1\text{-}U \tag{5.44}$$

In order to find the optimum required transmission power with minimum energy consumption for cooperative multiple branches scheme. The optimisation problem as mentioned previously with one constraint variable and its Lagrangian for this transmission scheme is given by:

$$Min \sum E_{bVMB} \qquad s.t. \{p_{outVMB} \leq 1 - U\} \tag{5.45}$$

$$L(P_{VMB}, \lambda_{VMB}) = P_{totVMB} + \lambda_{VMB}\left(p_{outVMB} - 1 + U\right) \tag{5.46}$$

Thus, the optimum required transmission power $P_{VMBopt}$ for the multiple branches transmission scheme to satisfy the reliability requirement or be constrained by the outage probability for this transmission scheme must be:

$$P_{VMBopt} = \left(2^{2R_s} - 1\right)N\left(\frac{1}{(1-U)|h_{VI}|^2\gamma_{VI}}\left(\left(\frac{1}{|h_{VR}|^2\gamma_{VR}} + \frac{1}{\upsilon_{RI}{}^{\alpha}|h_{RI}|^2\gamma_{RI}}\right)\right)^K\right)^{\frac{1}{K+1}} \tag{5.47}$$

The detailed derivation of this result is provided in Appendix (Appendix A-Ch5-3).

We can obtain the minimum energy efficiency based on the optimum required transmission power by substituting Equation (5.47) in Equation (5.46) and then in Equation (5.42), hence the minimum energy consumption $E_{bVMBmin}$ can be formulated as:

$$E_{bVMB\min} = \frac{P_{totVMB\min}}{R_b} \tag{5.48}$$

where

$$P_{totVMB\min} = \left(pout_{VR}\right)^K\left(P_{AM,VMB\min} + P_{C1}\right) + \left(1-\left(pout_{VR}\right)^K\right)\left(\left(\sum_{l=1}^{K} X_{R_lI} + 1\right)P_{AM,VMB\min} + P_{C2}\right) + \lambda_{VMB}\left(pout_{VMB} - 1 + U\right)$$

and

$$P_{AM,VMB\min} = \frac{\xi}{\eta}P_{VMBopt} \tag{5.49}$$

#### 5.1.2.2 Cooperative Transmission using Multiple Branches with Multiple Relays

In this cooperative transmission scheme, assuming that we have single or multiple relay branches $K \in \{1,k\}$, each branch has single or multiple relay nodes $R \in \{1,n\}$, as shown in Figure 5.1(d). In this scheme, a relay will forward a packet to the destination only if it was received correctly. Otherwise, the packet is considered lost.

We can conclude that the outage probability for the multiple branches with multiple relays scheme is given by jointly considering the outages in $V$-$I$, $V$-$R_1$, $R_1$-$R_2$ and $R_n$-$I$ links, i.e.,

$$p_{outVMHB} = p_{outVI}\left(1-\left(\left(1-p_{outVR_1}\right)\left(1-p_{outR_1R_2}\right)\cdots\cdots\cdots\cdots\left(1-p_{outR_nI}\right)\right)\right)^K \tag{5.50}$$

where

$$p_{outVI} = 1 - e^{\left(\frac{-\left(2^{2R_S}-1\right)N}{P_V|h_{VI}|^2\gamma_{VI}}\right)},\ p_{outVR_1} = 1 - e^{\left(\frac{-\left(2^{2R_S}-1\right)N}{P_V|h_{VR_1}|^2\gamma_{VR_1}}\right)},\ p_{outR_1R_2} = 1 - e^{\left(\frac{-\left(2^{2R_S}-1\right)N}{P_{R_1}|h_{R_1R_2}|^2\gamma_{R_1R_2}}\right)}$$

and $p_{outR_nI} = 1 - e^{\left(\frac{-\left(2^{2R_S}-1\right)N}{P_{R_n}|h_{R_nI}|^2\gamma_{R_nI}}\right)}$

where $p_{outVI}$, $p_{outVR_1}$, $p_{outR_1R_2}$ and $p_{outR_nI}$ represent the outage probability between vehicle and infrastructure, the outage probability between the vehicle and first relay node, the outage probability between first and second relay nodes and the outage probability between the last relay node and infrastructure, respectively. $P_V, P_{R_1}$, and $P_{R_n}$ are the transmission power of the vehicle, first relay node and last relay node, respectively. Then, the outage probability of this transmission scheme can be expressed as:

$$p_{outVMHB} = \left(1 - e^{\left(\frac{-\left(2^{2R_s}-1\right)N}{P_V |h_{VI}|^2 \gamma_{VI}}\right)}\right)\left(1 - e^{-\left(2^{2R_s}-1\right)N\left(\frac{1}{P_V |h_{VR_1}|^2 \gamma_{VR_1}} + \sum_{i=2}^{n} \frac{1}{P_{Ri-1}|h_{Ri-1Ri}|^2 \gamma_{R_{i-1}R_i}} + \frac{1}{P_{Rn}|h_{RnI}|^2 \gamma_{R_nI}}\right)}\right)^K \tag{5.51}$$

The power between two communicating nodes is given by:

$$P_{RI} = \upsilon_{RI}{}^{\alpha} P_{VI} = \left(\frac{d_{RI}}{d_{VI}}\right)^{\alpha} P_{VI} = X P_{VI} \tag{5.52}$$

Based on Equation (5.52), so Equation (5.51) can be rewritten as:

$$p_{outVMHB} = \left(1 - e^{\left(\frac{-\left(2^{2R_s}-1\right)N}{P_{VMHB} |h_{VI}|^2 \gamma_{VI}}\right)}\right)\left(1 - e^{-\frac{\left(2^{2R_s}-1\right)N}{P_{VMHB}}\left(\frac{1}{|h_{VR_1}|^2 \gamma_{VR_1}} + \sum_{i=2}^{n} \frac{1}{\upsilon_{R_{i-1}R_i}{}^{\alpha}|h_{R_{i-1}Ri}|^2 \gamma_{R_{i-1}R_i}} + \frac{1}{\upsilon_{R_nI}{}^{\alpha}|h_{R_nI}|^2 \gamma_{R_nI}}\right)}\right)^K \tag{5.53}$$

Then the outage probability of this transmission scheme can be approximated and expressed as follows:

$$p_{outVMHB} \approx \left(\frac{\left(2^{2R_s}-1\right)N}{P_{VMHB}|h_{VI}|^2 \gamma_{VI}}\right)\left(\frac{\left(2^{2R_s}-1\right)N}{P_{VMHB}}\left(\frac{1}{|h_{VR_1}|^2 \gamma_{VR_1}} + \sum_{i=2}^{n} \frac{1}{\upsilon_{R_{i-1}R_i}{}^{\alpha}|h_{R_{i-1}Ri}|^2 \gamma_{R_{i-1}R_i}} + \frac{1}{\upsilon_{R_nI}{}^{\alpha}|h_{R_nI}|^2 \gamma_{R_nI}}\right)\right)^K$$

$$p_{outVMHB} \approx \frac{\left(2^{2R_s}-1\right)^{K+1} N^{K+1}}{P_{VMHB}{}^{K+1}|h_{VI}|^2 \gamma_{VI}}\left(\left(\frac{1}{|h_{VR_1}|^2 \gamma_{VR_1}} + \sum_{i=2}^{n} \frac{1}{\upsilon_{R_{i-1}R_i}{}^{\alpha}|h_{R_{i-1}Ri}|^2 \gamma_{R_{i-1}R_i}} + \frac{1}{\upsilon_{R_nI}{}^{\alpha}|h_{R_nI}|^2 \gamma_{R_nI}}\right)\right)^K \tag{5.54}$$

The total consumption takes into account the required power for the transmission, which depends on the distance between each two vehicles, the power consumption of the circuitry and the bit rate. Thus, the total consumed energy per bit of this transmission scheme is:

$$E_{bVMHB}=\left(pout_{VR_1}\right)^K \frac{P_{AM,VMHB}+P_{C3}}{R_b}+\left(1-\left(pout_{VR_1}\right)^K\right)\frac{\left(\sum_{l=1}^{K}\left(\sum_{i=2}^{n}\upsilon_{(R_{i-1}R_i)_l}{}^{\alpha}+\upsilon_{(R_nI)_l}{}^{\alpha}\right)+1\right)P_{AM,VMHB}+P_{C4}}{R_b} \tag{5.55}$$

where $P_{C3}=P_{Tx}+K*P_{Rx}$ and $P_{C4}=(K*n+1)P_{Tx}+(K*(n+1)+1)P_{Rx}$

The first term on the right-hand side corresponds to the consumed energy when the relay is not able to correctly decode the message from the vehicle, which means that this link is in outage. In this case, only the vehicle node consumes transmitting power and the infrastructure and *n* relays consume receiving power. The second term counts for the event that the vehicle-relay link is not in outage, hence the relay transmitting and processing power and the extra receiving power at the infrastructure are involved.

As explained in the previous subsections, Equation (5.55) can be written as:

$$E_{bVMHB}=\left(pout_{VR_1}\right)^K \frac{P_{AM,VMHB}+P_{C3}}{R_b}+\left(1-\left(pout_{VR_1}\right)^K\right)\frac{\left(\sum_{l=1}^{K}\left(\sum_{i=2}^{n}X_{(R_{i-1}R_i)_l}+X_{(R_nI)_l}\right)+1\right)P_{AM,VMHB}+P_{C4}}{R_b} \tag{5.56}$$

$$P_{AM,VMHB}=\frac{\xi}{\eta}P_{VMHB} \tag{5.57}$$

where $P_{AM,VMHB}$ is the power amplification for multiple branches with multiple relays transmission scheme which depends on the drain efficiency of the amplifier $\eta$, the average peak-to-peak ratio $\xi$ as described previously.

Energy consumption required for the cooperative using multiple branches and relays transmission scheme in order to maintain a required level of reliability, denoted by *U*, which is related to the reliability of a transmission link, the minimum outage probability is defined as:

$$p_{outMHB} \leq 1\text{-}U \tag{5.58}$$

In order to find the optimum required transmission power with minimum energy consumption for cooperative transmission scheme using multiple branches and relays, we use Lagrange optimisation as mentioned previously. The optimisation problem with one constraint variable and its Lagrangian for this transmission scheme is given by:

$$Min \sum E_{bVMHB} \qquad s.t.\{p_{outVMHB} \leq 1-U\} \tag{5.59}$$

$$L(P_{VMHB},\lambda_{VMHB}) = P_{totVMHB} + \lambda_{VMHB}\left(p_{outVMHB} - 1 + U\right) \tag{5.60}$$

Thus, the optimum required transmission power $P_{VMHBopt}$ for cooperative transmission scheme using multiple branches and relays scheme to satisfy the reliability requirement or be constrained by the outage probability for this transmission scheme must be:

$$P_{VMHBopt} = \left(2^{2R_s} - 1\right)N\left(\frac{1}{(1-U)\left|h_{VI}\right|^2 \gamma_{VI}}\left(\left(\frac{1}{\left|h_{VR_1}\right|^2 \gamma_{VR_1}} + \sum_{i=2}^{n}\frac{1}{\upsilon_{R_{i-1}R_i}{}^{\alpha}\left|h_{R_{i-1}Ri}\right|^2 \gamma_{R_{i-1}R_i}} + \frac{1}{\upsilon_{R_n D}{}^{\alpha}\left|h_{R_n I}\right|^2 \gamma_{R_n I}}\right)\right)^K\right)^{\frac{1}{K+1}} \tag{5.61}$$

The detailed derivation of this result is provided in Appendix (Appendix A-Ch5-4).

We can obtain the minimum energy efficiency based on the optimum required transmission power by substituting Equation (5.61) in Equation (5.60) and then in Equation (5.56), hence the minimum energy consumption $E_{bVMHBmin}$ can be formulated as:

$$E_{bVMHB\min} = \frac{P_{totVMHB\min}}{R_b} \tag{5.62}$$

where

$$P_{totVMHB\min} = \left(pout_{VR_1}\right)^K \left(P_{AM,VMHB\min} + P_{C3}\right)$$
$$+ \left(1 - \left(pout_{VR_1}\right)^K\right)\left(\left(\sum_{l=1}^{K}\left(\sum_{i=2}^{n} X_{(R_{i-1}R_i)_l} + X_{(R_n I)_l}\right) + 1\right)P_{AM,VMHB\min} + P_{C4}\right) + \lambda_{VMHB}\left(pout_{VMHB} - 1 + U\right)$$

and

$$P_{AM,VMHB\min} = \frac{\xi}{\eta} P_{VMHBopt} \tag{5.63}$$

## 5.2 QoS Metrics

To evaluate the QoS of each transmission scheme, the network simulator NS-2 was utilised, in order to evaluate their performance, some information required to be extracted from the simulations. Hence, an AWK script was implemented to extract this metrics from the trace files generated during the simulation using NS-2. Our AWK script has been designed to extract the following metrics:

### 5.2.1 Throughput Analysis

The throughput is the rate of successful packets delivery through a network connection per unit time or the rate at which information is sent through the network. The simulation time is 1000 seconds so it is divided into 5 different times of 200 seconds. Hence, the data throughput for each transmission scheme is calculated as a function of time considering the intervals of 200 seconds. The data throughput for each transmission scheme is defined by the Equation below.

$$\text{Throughput}[t] = \frac{\#\ \text{received\_bits}\ [t]}{\text{time}} \tag{5.64}$$

### 5.2.2 Packet Delivery Ratio

The reliability of the network connection is evaluated by the packet delivery ratio. It can be defined as the ratio or the percentage of data packets received by the destinations to those generated by the sources. Hence, for every increase in packet sent by the source node, there should be a relative increase in packet received by the destination node. Thus, the packet delivery ratio for each transmission scheme is defined by:

$$PDR = \frac{\#\ \text{received\_packets}}{\#\ \text{sent\_packets}} \tag{5.65}$$

### 5.2.3 Packet Loss Rate

Packet loss is the failure of one or more transmitted packets to reach their destination. It is typically caused by network congestion. It is defined as a percentage of packets lost with respect to packets sent. The packets lost are measured as the difference between the number of sent packets and the number of received packets. Thus, the packet loss rate for each transmission scheme is defined by:

$$PLR = \frac{\#\ \text{sent\_packets} - \#\ \text{received\_packets}}{\#\ \text{sent\_packets}} \tag{5.66}$$

### 5.2.4 Average End-to-End Delay

The average end-to-end delay is the average time it takes a data packet to reach the destination. This includes all possible delays caused by buffering, queuing, propagation. This metric can be calculated by subtracting the time at which the data packet arrives at the destination by the time at which the data packet was transmitted by the source. Thus, the average end-to-end delay for each transmission scheme is defined as the sum of the time spent to deliver packets at the destination over the total number of received packets by the destination:

$$E2E = \frac{\sum_{\text{received packets}} \text{time spent to deliver packets}}{\#\ \text{received\_packets}} \tag{5.67}$$

## 5.3 Performance Evaluation of the Proposed Models

The results of the proposed transmission schemes as described in the previous section are presented in this section. We examine the performance using Matlab and NS-2 simulations of different transmission schemes in terms of energy efficiency (energy consumption per bit), throughput, packet delivery ratio, packet losses and average end-to-end delay under various channel and transmission conditions in a V2I as shown in Figure 5.1. We then reveal the conditions for selecting the optimal transmission scheme through comparisons between them. To generate mobility, mobility-files are created in NS-2 simulation. In addition, we assume that all the vehicles are running at the same speed and keeping the same distance with each other.

### 5.3.1 Network Topology

As mentioned before, a complete evaluation of the non-cooperative and cooperative transmission schemes are presented. The network settings used for simulation are listed in Table 5.1. For a given network topology, we choose different V2I pair with different transmission distances under different channel conditions and environment, then we apply different transmission schemes for comparison purposes.

TABLE 5.1. V2I SIMULATION PARAMETERS

| Parameters | Value |
|---|---|
| $N_0$ | −174 dBm |
| $B$ | 10 kHz |
| $R_s$ | 2 bit/sec/Hz [130] |
| $P_{TX}$ | 97.9 mW [130] |
| $P_{RX}$ | 112.2 mW [130] |
| $\eta$ | 0.35 |
| $\xi$ | 0.5 |
| Packet Size | 512 bytes |
| $fc$ | 5.9 GHz |
| $\alpha$ | 3 |
| Simulation time | 1000 Sec |
| Nodes | 10/20/30/40/50 |
| Velocity | 5 km/h, 20 km/h, 60 km/h |
| Traffic Agent | TCP |
| Mac Protocol | IEEE 802.11p |
| Queue | PriQueue with size of 50 Packets |
| Propagation model | Log-normal shadowing Model (LOS) |
| Antenna | Omni-directional with height of 1m |
| Routing Protocol | AODV |
| Number of Seed | 3 |

### 5.3.2 Network Simulator

The network simulator, widely known as NS-2, is a discrete-event simulator developed by the University of California at Berkely and the simulator can be downloaded from the internet. Simulation of wired as well as wireless network functions and protocols (e.g., routing algorithms, TCP, UDP) can be done using NS-2. In general, NS-2 provides users with a way of specifying such network protocols and simulating their corresponding behaviors [149].

The NS-2 consists of two key language C++ and Object-oriented Tool Command Language (OTcl). While C++ defines the internal mechanism (i.e., a backend) of the simulation, OTcl sets up simulation by assembling and configuring objects as well as scheduling discrete events. C++ and OTcl are linked together using Tcl/C++ interface (TclCL).

NS-2 provides a large number of built-in C++ classes. It is advisable to use these C++ classes to set up a simulation via a Tcl simulation script. However, advanced users may find these classes insufficient. They may need to develop their own C++ classes and use an OTcl configuration interface to put together objects instantiated from these classes.

After simulation, NS-2 outputs either text-based or animation-based simulation results. To interpret these results graphically and interactively, tools such as NAM (Network AniMator) and XGraph are used. To analyze a particular behavior of the network, users can extract a relevant subset of text-based data and transform it to a more conceivable presentation.

Furthermore, AWK is a simple language that was presented by Alfred Aho, Peter Weinberger and Brian Kernighan. AWK is a language for processing of text files; it is used for processing the data from the log (trace) files which are obtained from NS-2. A file is treated as a sequence of records and by default each line is a record. Each line is broken up into a sequence of fields, so we can think of the first word in a line as the first field, the second word as the second field and so on.

### 5.3.3 Energy Consumption Evaluation

The first evaluated metric is the energy consumption performance of the non-cooperative and cooperative transmission schemes. In Figure 5.2 and Table 5.2 energy performances of both cooperative and non-cooperative schemes are illustrated and compared. As we can see, the non-cooperative direct transmission has the lowest energy cost of all transmission schemes for short-range ($d_{VI}$< 33m); the non-cooperative transmission using multi-hop relays outperforms the direct transmission for short medium range. In particular, transmission using two intermediate relays ($n$=2) nodes has the lowest energy consumption for short mid-range (33m<$d_{VI}$< 43m) and the cooperative transmission outperforms the direct and multi-hop transmission schemes for long-medium and long ranges. Specifically, transmission using one branch with two relays ($K$=1, $n$=2) has the lowest energy consumption for long mid-range (43m<$d_{VI}$< 58m), but transmission using two branches with one relay (*K*=2, *n*=1) has the lowest energy consumption for mid-range (58<$d_{VI}$< 80m), on the other hand transmission using two branches with two relays (*K*=2, *n*=2) has the lowest energy consumption for long-range ($d_{VI}$>80m).

TABLE 5.2. RECOMMENDED TRANSMISSION SCHEMES VS. TRANSMISSION DISTANCES

| **Schemes** | **Distance** |
|---|---|
| Direct Transmission | <33m |
| Multi-hop Transmission scheme (*n*=2) | Between 33m and 43m |
| Cooperative one branch with two relay nodes(*K*=1, *n*=2) | Between 43m and 58m |
| Cooperative two branches with one relay node (*K*=2, *n*=1) | Between 58m and 80m |
| Cooperative two branches with two relay nodes (*K*=2, *n*=2) | >80m |

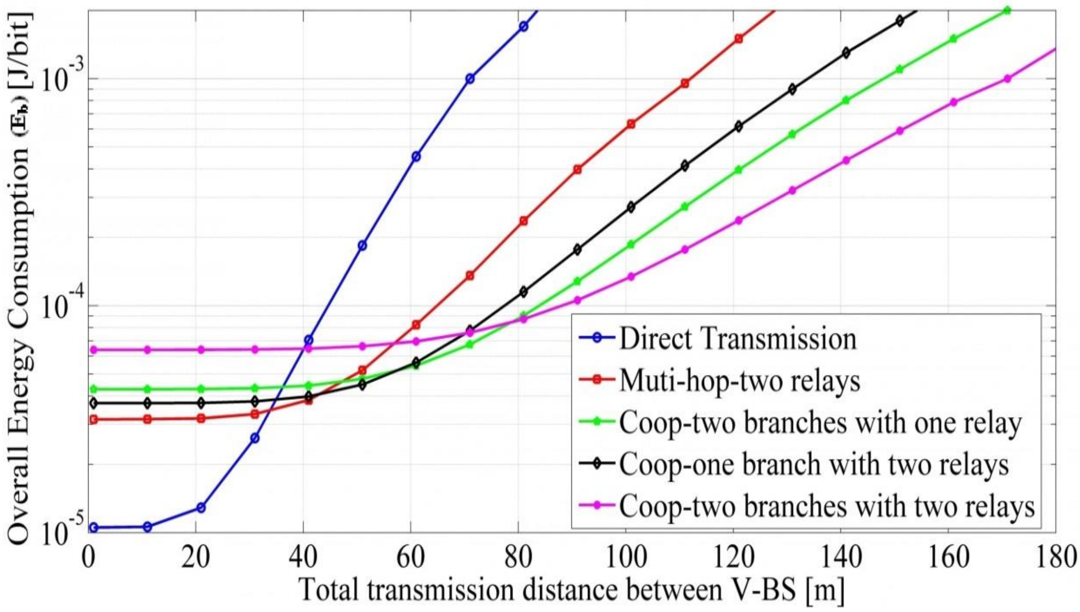



Figure 5.2: Total energy consumption vs total transmission distance

Based on the performance obtained in Figure 5.2 and Table 5.2, the performance has been evaluated based on two scenarios with different numbers of transmitted vehicles. In the first scenario; all the vehicles transmit using the direct link. While in the second, each vehicle transmits using the optimum transmission scheme based on its transmitted distance as mentioned in Table 5.2. As shown in Figure 5.3, the non-cooperative direct transmission has much higher energy consumption than the optimum transmission scheme, which will be chosen based on the transmission distance between vehicles and infrastructure.

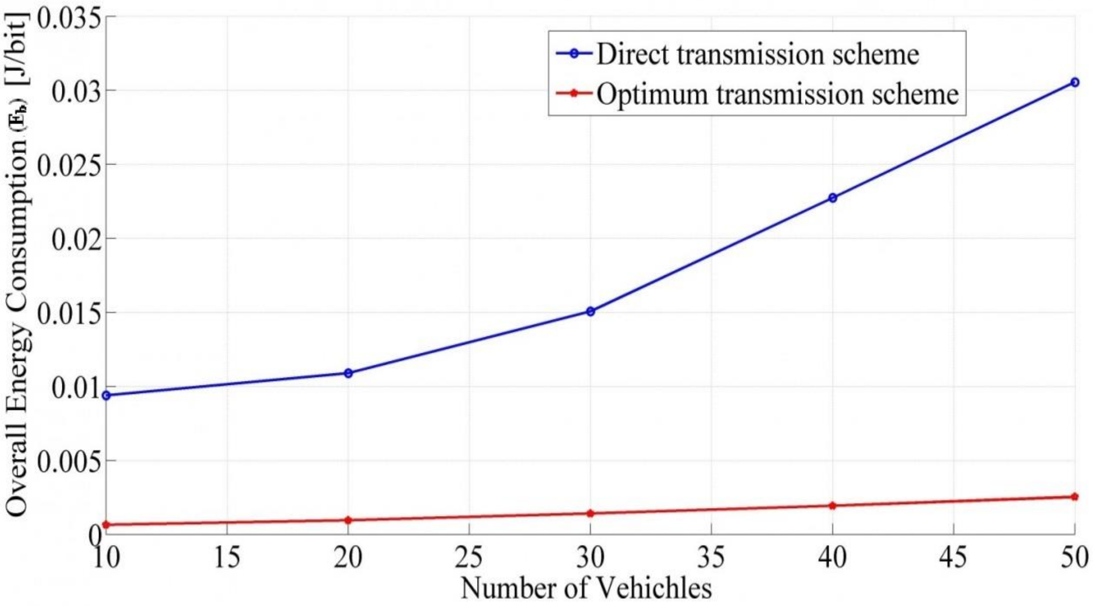



Figure 5.3: Overall energy consumption vs number of vehicles

### 5.3.4 System Throughput Evaluation

Based on the same scenarios described in the previous subsection, each transmission distance has its optimum transmission scheme in terms of minimum energy consumption. Thus, in order to show that the system is efficient, we evaluated the system throughput based on three different velocities 5 km/h, 20 km/h and 60 km/h, while varying the number of vehicles. As described previously, we have two scenarios, in the first scenario; all the vehicles transmit using the direct link. The second, each vehicle transmits using the optimum transmission scheme based on its transmitted distance.

As shown in Figure 5.4, for the three different velocities presented in Figure 5.4(a), Figure 5.4(b) and Figure 5.4(c), the optimum transmission scheme outperforms the direct transmission for every transmission distance. This is due to the impact of diversity techniques used by the cooperative transmission scheme, as more branches mean more diversities thus better throughput. It is also noticed that in the optimum transmission scheme when the number of transmitting vehicles increases the throughput decreases. This is due to the increased network overhead caused by the cooperative communication where the transmitting vehicles can be a source and a relay node at the same time.

As well, Figure 5.5 demonstrates the advancement of information throughput. In this figure, we assume that the vehicles have a constant speed of 60 km/h. We studied the cases with different number of transmitted vehicles for different simulation time as shown in Figure 5.5(a), Figure 5.5(b), Figure 5.5(c) and Figure 5.5(d). This figure shows that the optimum transmission scheme outperforms the direct transmission scheme even for different simulation time.

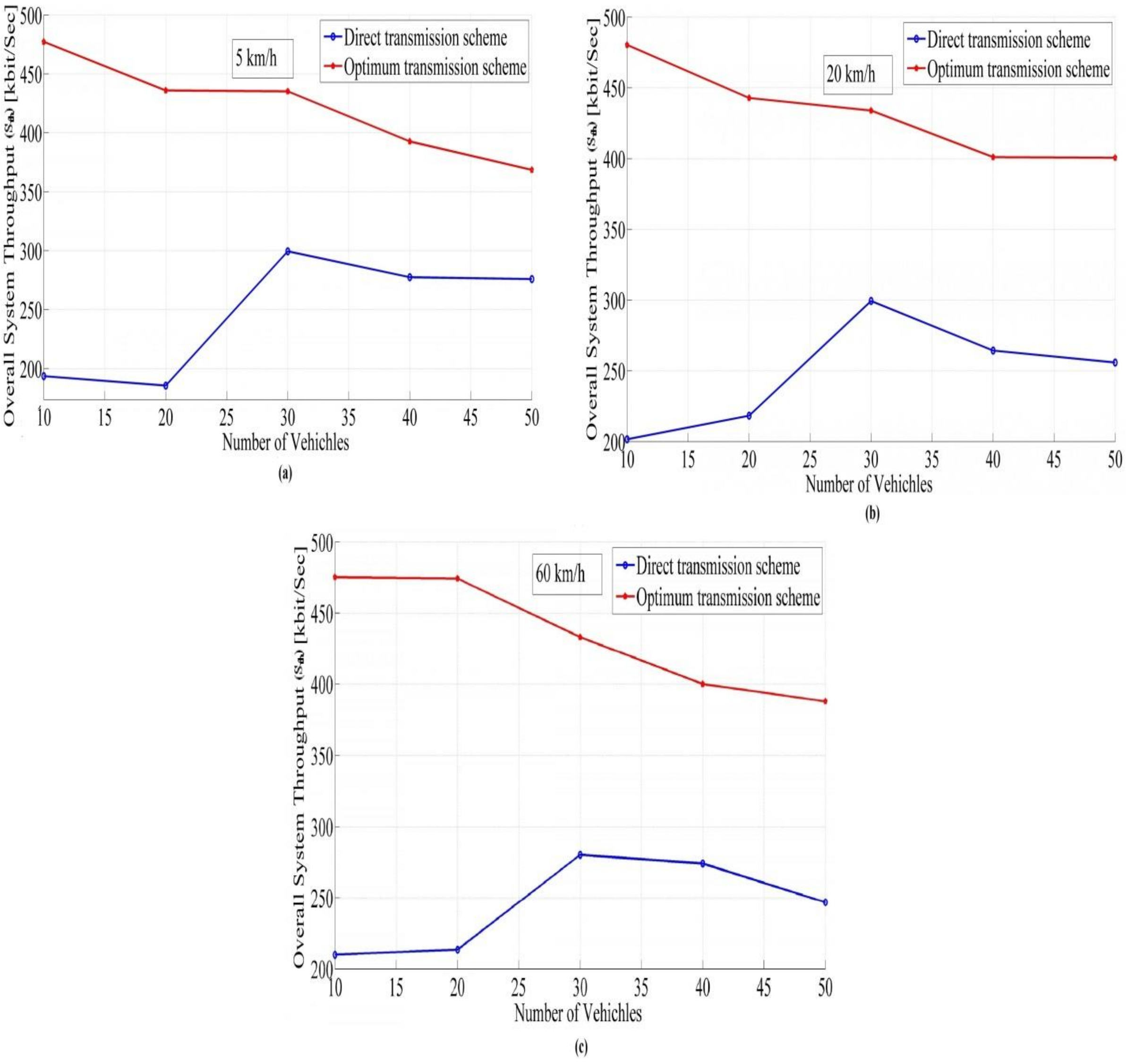
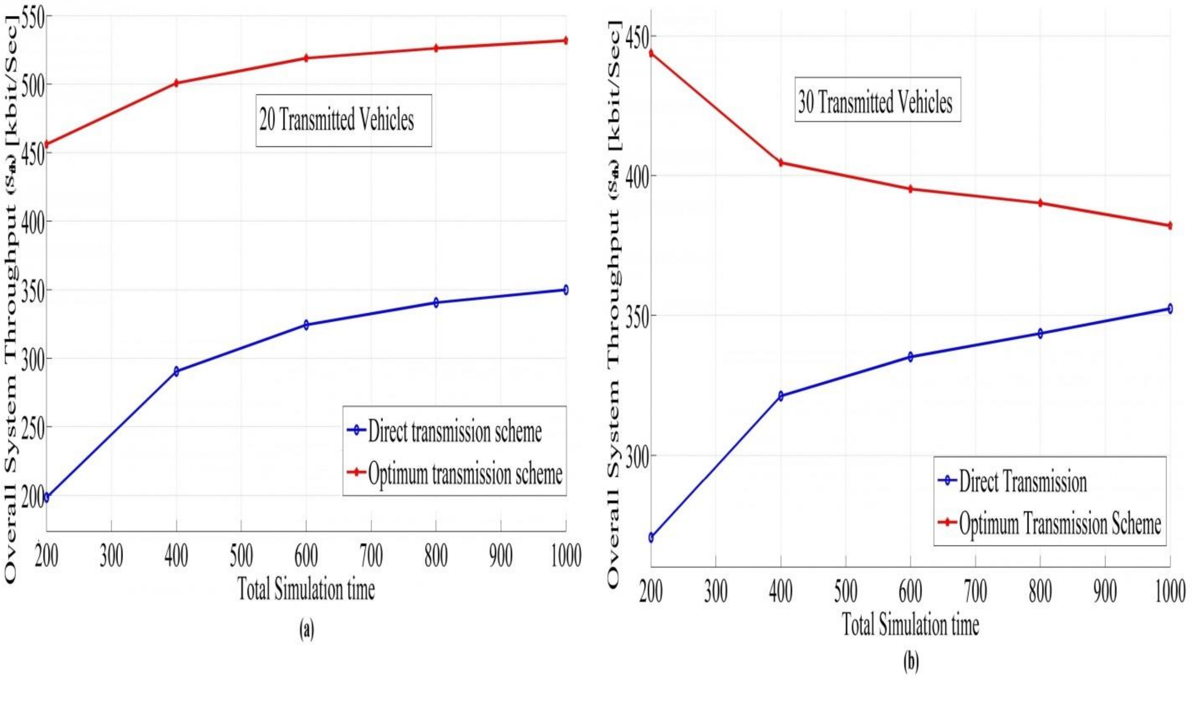



Figure 5.4: Overall system throughput vs number of vehicles



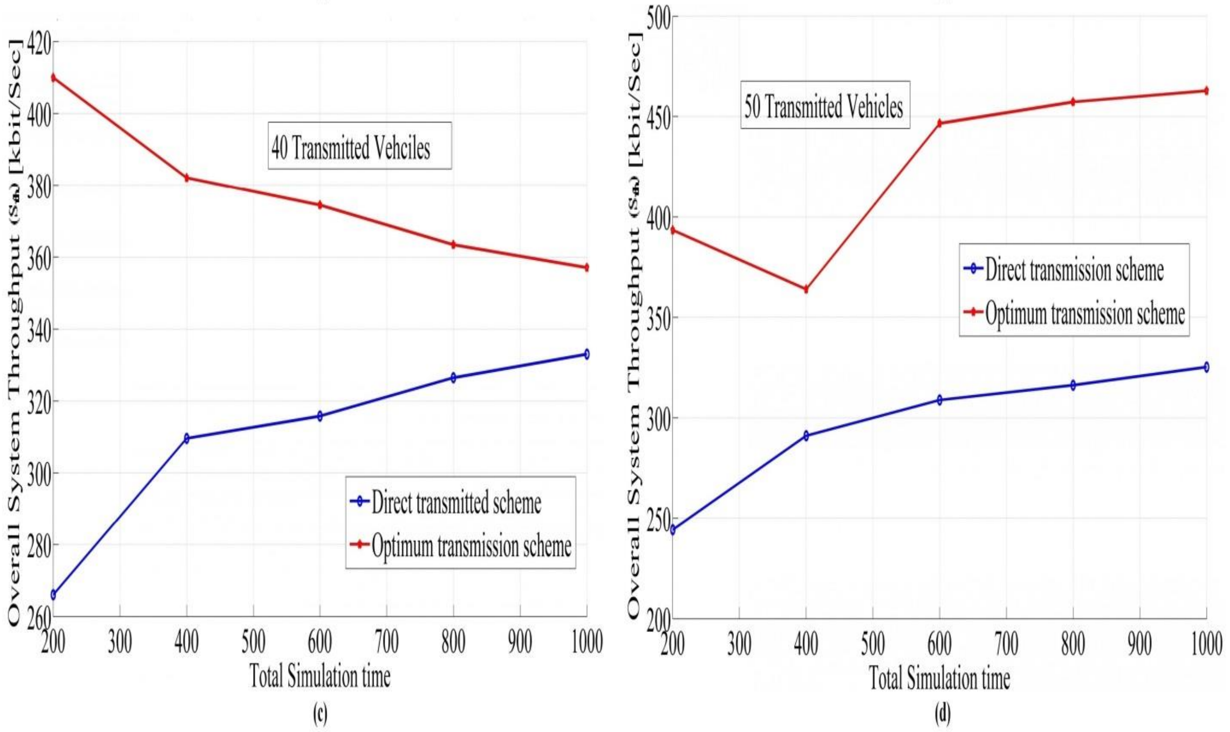



Figure 5.5: Overall system throughput vs total simulation time

### 5.3.5 Packet Delivery Ratio

In this subsection, the packet delivery ratio (PDR) of the direct transmission scheme and the optimum transmission scheme for each transmission is evaluated. Figure 5.6(a), Figure 5.6(b) and Figure 5.6(c) depict that the data packet efficiency of the optimum transmission scheme has an increasing tendency when comparing it with the direct transmission scheme regardless of the selected speed. It is also mentioned, that PDR has shown significant effect with change in vehicular density. Especially when the transmitted vehicles use the direct transmission schemes, PDR decreases gradually when the density of the vehicles increases. As the vehicular density increases, the congestion in the network increases due to increment of the numbers of transmitted nodes (vehicles). Also, it increases the network overhead, which causes a decrease in the PDR.

When using the cooperative transmission scheme, the distance between vehicles gradually decreases and there are more connectivity options for vehicles. An intermediate node and its position between source and destination plays a key role in routing packets, adding intermediate nodes promote easy and effective route selection and transmission of vehicles to the destination. This is the main reason for increment PDR for cooperative transmission scheme compared with direct transmission scheme. Re-transmitted packets will decrease PDR in turn increasing overhead. This is justified by the results obtained in Figure 5.4, that the higher the information throughput, the higher the packet delivery ratio.

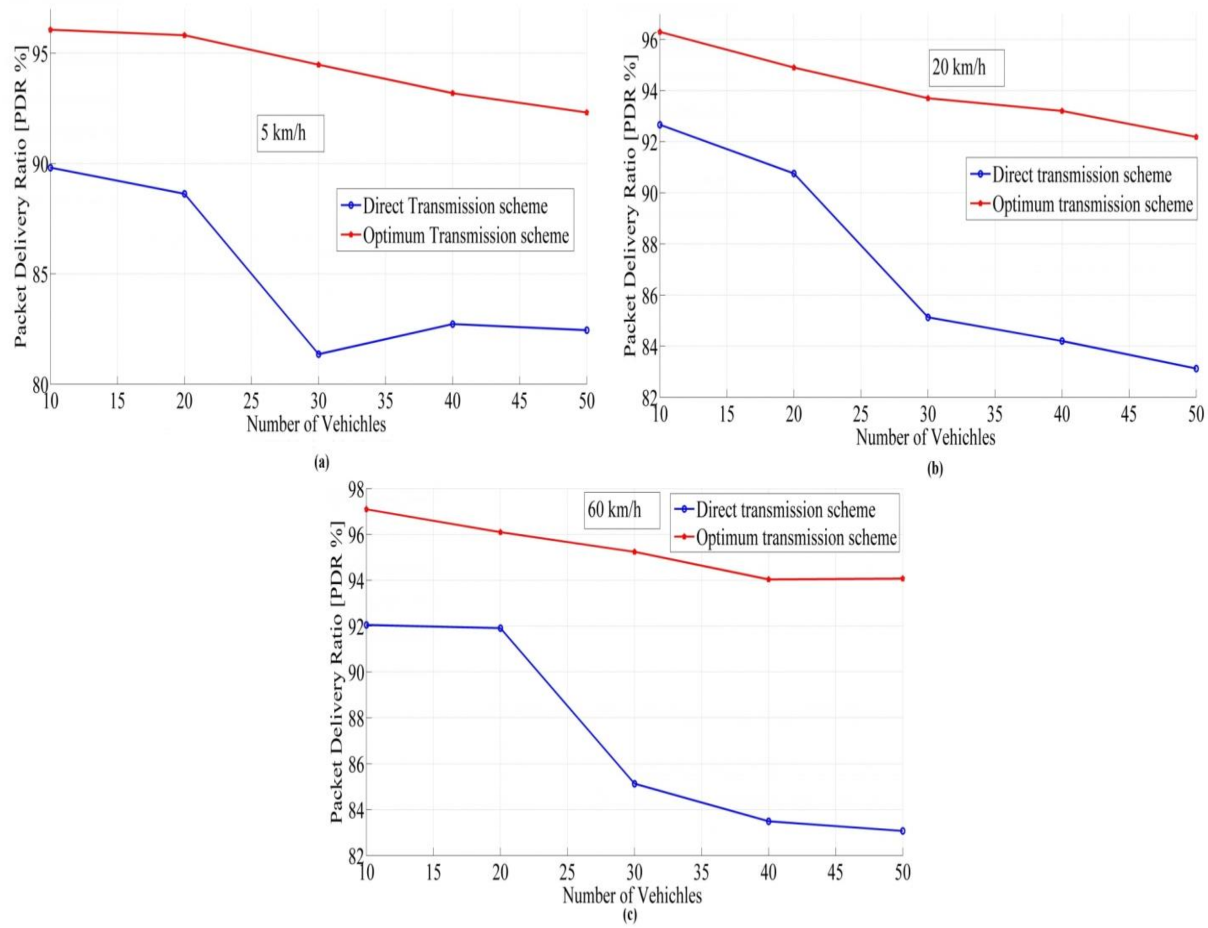



Figure 5.6: Packet delivery ratio vs number of vehicles

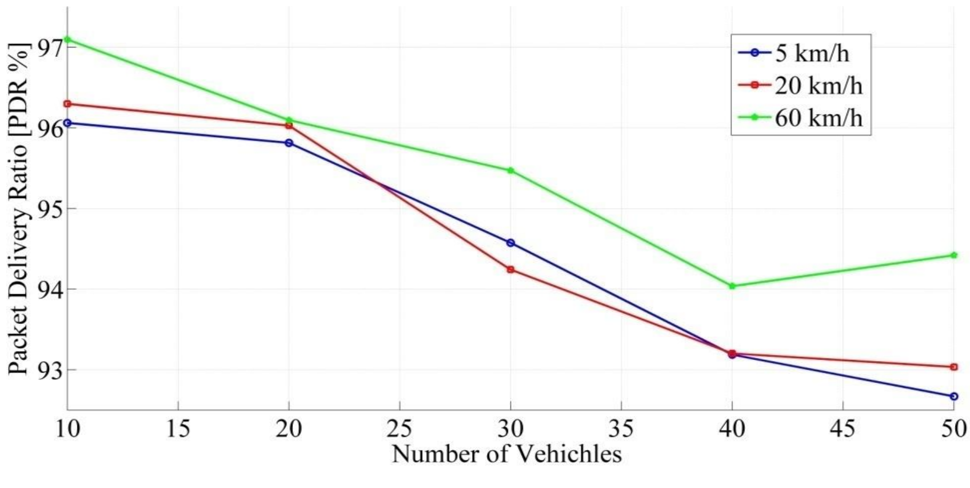



Figure 5.7: Packet delivery ratio vs number of vehicles

Additionally, Figure 5.7 shows the packet delivery ratio for three different velocities when each vehicle choses the optimum transmission scheme based on its transmission distance. It can be mentioned that when the velocity increases the packet delivery ratio increases. Based on our assumptions and scenarios, we have two-way road, so when velocity increases the vehicles could be able to approach each other faster, then they will have better communication which leads to more efficient transmission. In addition, the packet delivery ratio decreases when the number of transmitting vehicles increases, as this will lead to network congestion. It can be advised, that when the velocity is 20 km/h the packet delivery ratio of the 30 transmitting vehicles becomes lower than the two other velocities, this is due to the position and the distance of the vehicles during the transmission. It can also be deduced from this figure that each transmitting number of vehicles has an optimum required velocity.

### 5.3.6 Packet Loss Rate

Another important metric that should be evaluated and examined is the packet loss (PL) rate. Figure 5.8 depicts the overall system packet loss for direct transmission and optimum transmission schemes with different number of transmitted vehicles. As shown in Figure 5.8 packet loss increases when the number of transmitted vehicles increases for all transmission schemes, this is due to network congestion. It is also mentioned that this performance is obtained regardless of the selected speed, as shown in Figure 5.8(a), Figure 5.8(b) and Figure 5.8(c). In addition, it can be mentioned that the optimum transmission schemes has a much lower packet loss than the direct communication. This performance is due to the use of multiple relays in each branch, which leads to a decrease in the distance between adjacent nodes thus causing a significant reduction in packet loss. In addition, a shorter transmission distance leads to the decrease in packet loss between source and destination.

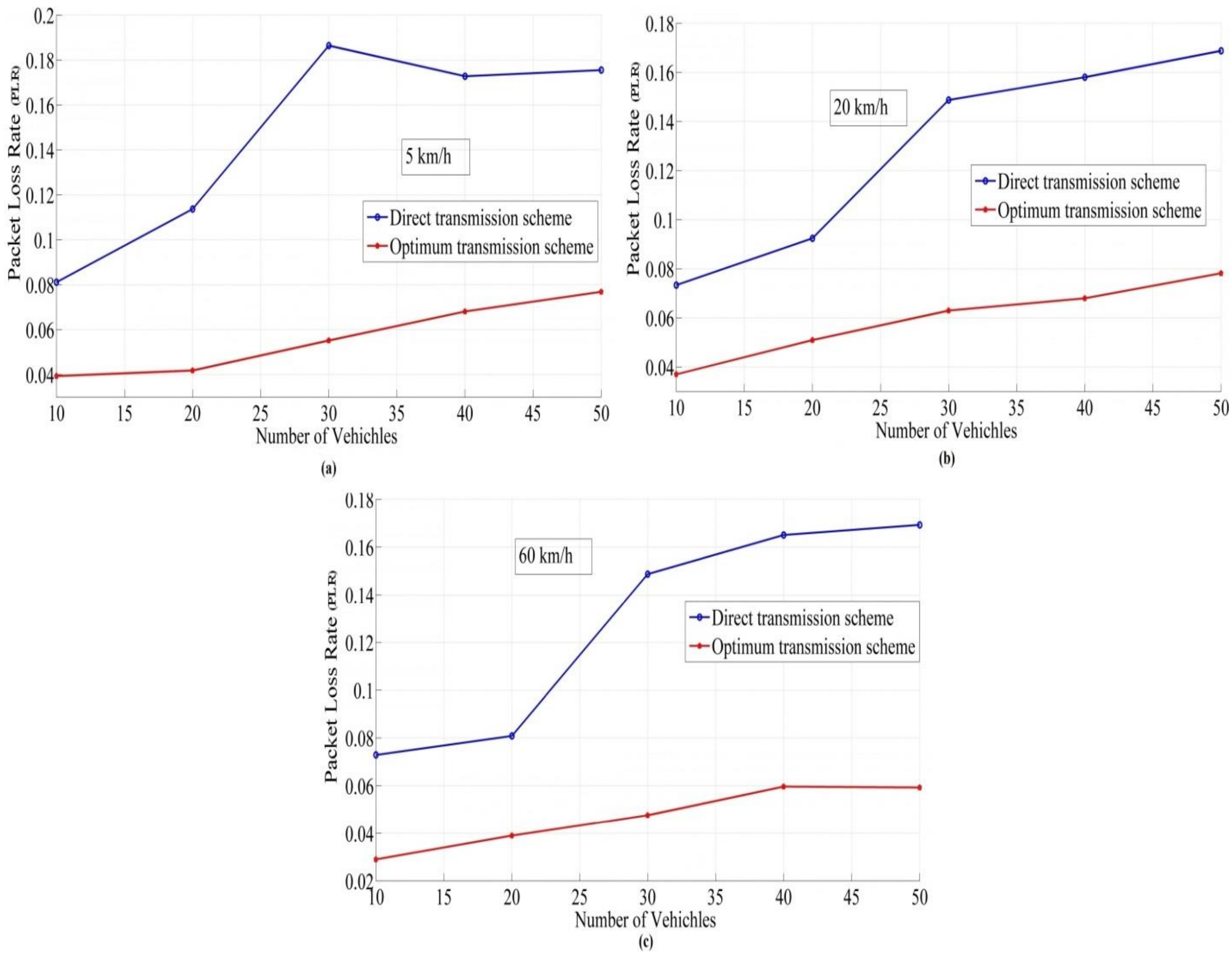



Figure 5.8: Packet loss rate vs number of vehicles

Additionally, Figure 5.9 shows the packet loss rate for three different velocities. It can be mentioned that when the velocity increases the packet loss rate decreases, as velocity increases the vehicles could be able to approach each other faster which decreases the transmission distance gradually by moving faster, which leads to better communication and more efficient transmission. Furthermore, the packet loss rate increases when the number of transmitting vehicles increases, as this will lead to network congestion. It can be advised, that when the velocity is 20 km/h the packet loss rate of the 30 transmitting vehicles becomes higher than the two other velocities, this is due to the position and the distance of the vehicles during the transmission. It can also be deduced from this figure that each transmitting number of vehicles has an optimum required velocity.

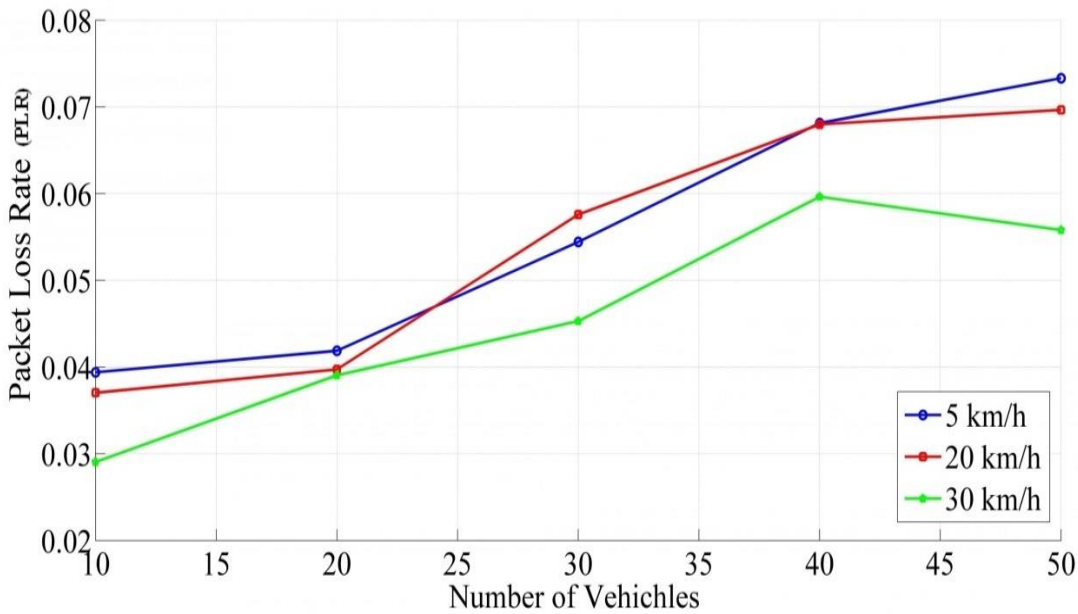



Figure 5.9: Packet loss rate vs number of vehicles

### 5.3.7 Average End-to-End Delay

In this subsection, we evaluate the average end-to-end delay of the direct transmission scheme and the optimum transmission scheme based on each transmission distance with transmitting velocity 60 km/h. As illustrated in Figure 5.10 the direct transmission scheme has much lower end-to-end delay than the optimum transmission scheme, this is due to the processing and retransmission time taken by the additional relay branches and multi-hop relays. Thus, a trade-off arises between enhancing the energy consumption, system throughput, packet delivery ratio and packet loss and decreasing the average end-to-end delay. If the user needs an efficient transmission, he has to use the optimum transmission scheme based on the transmission distance, if he needs to save time but with a less efficient system, he has to use the direct transmission scheme.

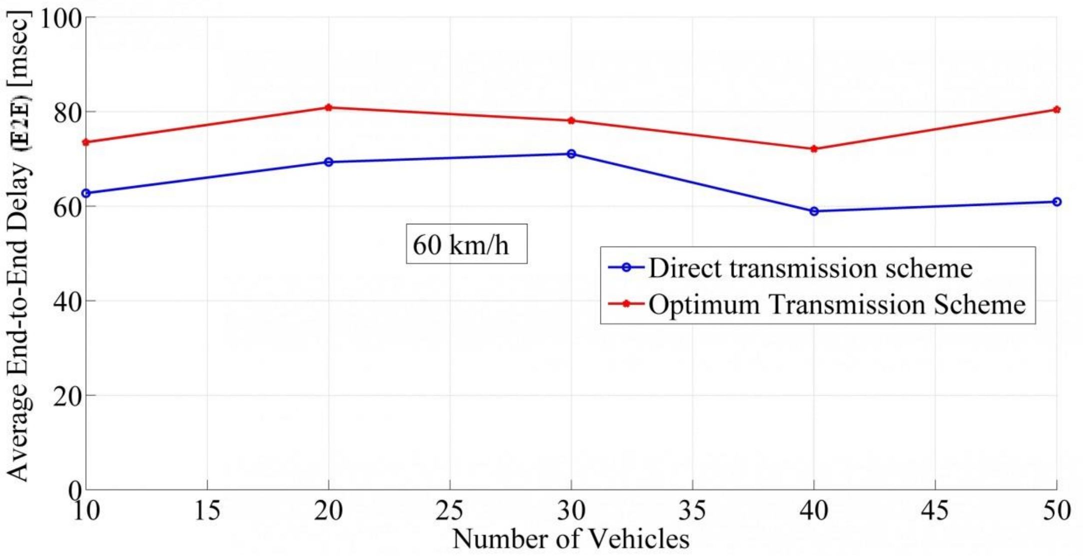



Figure 5.10: Average end-to-end delay vs number of vehicles

## 5.4 Summary and Conclusion

In this chapter, we have investigated different transmission schemes for their energy and throughput performances in a V2I, including the strengths and limitations of the cooperative transmission schemes in comparison with non-cooperative schemes. Based on the outage probability, energy efficiency, throughput, packet delivery ratio, packet losses and average end-to-end delay models, we have shown that both cooperative and non-cooperative transmission schemes can exhibit the best performance under a certain environmental condition. The optimal transmission scheme can be identified given the condition which, in our case, is the distance between the source node and the destination node in a V2I.

Moreover, based on our analysis and investigation we recognised that there are a number of factors affecting energy consumption, throughput, packet delivery ratio and packet loss rate in V2I. Cooperative transmission uses additional paths and nodes (relays) compared with direct transmission, which costs more energy, but the diversity it creates can save energy by reducing the probability of link failure and consequently reducing the number of retransmissions. Diversity increases with the number of relay branches used but this increase could be marginal when the number of branches is large as it is difficult to ensure to all branches are uncorrelated. In addition, increasing the number of relays in each branch reduces the transmission distance for each relaying hop, which results in lower transmit power for relays as it is proportional to $d^{\alpha}$ where $d$ is either $d_{RI}$ or $d_{RR}$. But when the number of relays increases, the total circuitry power will accumulate as it depends on the number of transmitting nodes and is independent from the transmission distance.

Clearly, to achieve the best energy performance as discussed in this chapter, proper transmission schemes should be selected for the given transmission conditions, such as overall distance, $d_{VI}$, vehicle position, vehicle velocity and channel quality in terms of $\alpha$. The findings of this work provide an effective guidance for deciding when and how the cooperative or non-cooperative transmission schemes should be employed. Based on our investigation, an energy-efficient transmission strategy can be formed in a V2I by adaptively choosing cooperative or non-cooperative transmission schemes under different network and transmission conditions. This involves determining the number of relaying branches and the number of relays if the cooperative scheme is to be used. By doing so, energy saving could be significant even with the direct transmission scheme in certain conditions, as shown from our results. However, still determining the distance between vehicles is a key and open problem.

# Chapter Six

# Conclusions, Contributions and Future Work

Creating adaptive transmission schemes for wireless communications and networks will be the major technological innovation for enhancing QoS in wireless networks. Cooperative and non-cooperative transmission schemes have been exploited to achieve dramatic improvements in systems performance. This work is focused on the establishment of appropriate transmission strategies to deal with different commonly used transmission schemes, including both cooperative and non-cooperative schemes, in an efficient and adaptive way. It also reveals the trade-offs between cooperative and non-cooperative transmission schemes and demonstrates how to achieve the optimised performance by properly handling these trade-offs, which has been implemented and evaluated through our analytical modelling and simulation. To meet the objectives of this research, we have investigated various wireless communications technologies and applied the methods described above in the context of WSN, cellular and vehicular networks. We have also examined the strengths and limitations of cooperative transmission schemes in comparison with non-cooperative schemes, under different environmental conditions.

## 6.1 Conclusions

To carry out the investigations addressed above, some related theories and models are discussed in Chapter 2. The classification and background of some wireless communication systems has been described briefly. Also, the wireless channel characterisations have been studied including propagation models, path loss models, channel capacity and outage probability. In addition, some of the most well-known wireless communications technologies such as diversity, multiple-input-multiple-output, cooperative communications and medium access control have been presented. Finally, the limitations of some wireless communication systems have been described.

Chapter 3 discussed the performance evaluation of WSN. We investigated different transmission schemes for their energy and throughput performances in a WSN, including the strengths and limitations of the cooperative transmission schemes in comparison with non-cooperative schemes. Based on the outage probability, energy efficiency and throughput models, we have shown that both cooperative and non-cooperative transmission schemes can exhibit the best performance under a certain environmental condition. The optimal transmission scheme can be identified given the conditions which, in our case, are the distance between the source node and the destination node, path loss and spectral efficiency in a WSN. If the distance between the source and destination is short, the direct transmission scheme was the appropriate transmission scheme, but when the distance increases the optimum transmission scheme as discussed varies among the other schemes based on the transmission distance and channel conditions. The results presented in this research is used to form an adaptive transmission strategy that is able to select an appropriate transmission scheme to achieve the best QoS performance for transmission between any source-destination pair, as discussed the highest throughput with lowest the energy consumption can be achieved, or the lowest energy cost for given throughput target.

In Chapter 4**,** we investigated the energy efficiency, achievable data rate and outage probability of three transmission and resource sharing modes involving D2D and cooperative D2D communications underlaying cellular networks. Based on the energy efficiency and achievable data rate optimisation models derived, we have shown that direct D2D (DM) and cooperative D2D (CoopD2D) modes are more preferable than the cellular mode (CM) in terms of EE and DR. We have also shown that DM and CoopD2D transmission schemes can be used collectively to achieve the highest possible energy efficiency depending on environmental conditions such as the channel quality, transmission range between CUE-BS and transmission range between D2D pairs. Adaptive transmission strategies based on the results presented was therefore derived to optimise the energy performance and enhance the QoS in such networks.

Chapter 5 focused on several transmission schemes which were investigated for their energy consumption, packet delivery ratio, packet losses and average end-to-end delay performances in a V2I. The strengths and limitations of the cooperative transmission schemes in comparison with non-cooperative schemes were also included. After the evaluation of the system performance based on the outage probability, energy efficiency, throughput, packet delivery ratio, packet losses and average end-to-end delay models, it was shown that under certain environmental conditions both cooperative and non-cooperative transmission schemes can exhibit the best performance. Noting that using the distance between the source node and the destination node in a V2I and vehicle position, as conditions, the optimal transmission scheme can be identified. We used the results presented to form an adaptive transmission strategy which has the ability to select an appropriate transmission scheme to achieve the best QoS performance for transmission between any source-destination pair, therefore we proposed a model where each vehicle is allowed to decide the optimum required transmission scheme for each transmission distance that optimises the overall QoS with the minimal resource cost.

## 6.2 Contributions

The following contributions have been achieved during this research, along with the conclusions summarised in Section 6.1:

- Adaptive transmission schemes based on cooperative and non-cooperative transmission schemes have been developed for WSN under different environment and channel conditions. Analytical modelling and simulation of outage probability, optimum required transmission power, optimum energy consumption and optimum throughput for four different transmission schemes based on the transmission distance between any source (S) and destination (D) and based on WSN constraints have been demonstrated.
- Adaptive transmission schemes in order to increase the energy efficiency and the throughput of cellular networks have been developed. Analytical and simulation modelling of outage probability, optimum required transmission power, optimum energy efficiency for three different mobile cellular transmission modes that accommodates device-to-device (D2D) and cellular user equipment (CUE) to base station (BS) have been deduced.
- As V2I requires a reliable and efficient system, we targeted the reduction of the energy consumption by each vehicle and based on the proposed analytical model as decreases energy consumption decreases fuel consumption which economically and financially beneficent. Then, we implemented the results in NS-2 in order to evaluate the overall system throughput, packet delivery ratio and packet losses. Analytical modelling and simulation of outage probability, optimum required transmission power, optimum energy consumption for four different transmission schemes based on transmission distance between any vehicle (V) and infrastructure (I) in V2I networks have been deduced.

## 6.3 Future work

During the development of this research there was a surge of ideas that would help to better understand and improve the obtained results. Several of these ideas were used and as we covered many issues some of the excess simulation results were not incorporated. For the benefits of continued research in these areas, the extensions to the current results achieved from this research are suggested as follows:

- Higher number of nodes can be simulated and analysed.
- The mobility must be studied further and other types of mobility simulators could be used as a tool to generate realistic mobility files.
- It would be interesting to see what will happen in the network if other channel conditions are assumed.
- It would be important to work on solving other network challenges such as scalability, production cost through improvement in lifetime or deployment and also the security and privacy of the network which could be a key area of investigation in regard to the transmission range, Quality of service and Quality of Experience.

- It was noted that the work done, the proposed schemes and the optimisation methods used offer a good gateway for the future study of the Internet of Things (IoT).
- It would be important to consider time-varying channel conditions.
- Investigation of LTE-V and 5G platform for vehicular communications must be considered.
- It is important to do more work in vehicular networks to fully justify or improve what we have done in the proposed model.
- WSN and D2D scenarios could not be simulated using NS2 or NS3 because the current versions of NS-2 and NS-3 do not support PHY implementation. Other new protocols to solve the deficiencies of the proposed transmission, if any, should be investigated.

## 6.4 Publications

1. R. A. Osman, X.-H. Peng and Z. Tang, "Energy efficient adaptive cooperative communications in wireless sensor networks," The 15th International Conference on Ubiquitous Computing and Communications (IUCC), Livelpool, UK, 2015.
2. R. A. Osman, X.-H. Peng and Z. Tang, "Energy efficient communications with device-to-device links in cellular networks," International Conference on Wireless and Mobile Communications (ICWNC), Barcelona, Spain, 2016.
3. R. A. Osman, X.-H. Peng and Z. Tang, "Energy efficiency and achievable data rate of device-to-device communications in cellular networks," in proceedings, The 10th IEEE International Conference on Cyber, Physical and Social Computing (CPSCom-2017), June 2017.
4. R. A. Osman, X.-H. Peng and M. A. Omar, "Enhancing QoS in vehicle-to-infrastructure approaches through adaptive cooperative communications," accepted, The Sixth International Conference on Advances in Vehicular Systems, Technologies and Applications (VEHICULAR 2017), July 2017.

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# APPENDIX

# Appendix A

## Appendix A-Ch3-1(a)

### This is the derivation of formula (3.13)

$$Min \sum E_{bDir} \qquad s.t.\{p_{outDir} \leq 1-U\} \tag{A3 1.1}$$

$$L(P_{SDir}, \lambda_{Dir}) = P_{totDir} + \lambda_{Dir}\left(p_{outDir} - 1 + U\right) \tag{A3 1.2}$$

where $\qquad P_{totDir} = P_{AM,Dir} + P_{Tx} + P_{Rx}$

$$\frac{\partial P_{totDir}}{\partial P_{SDir}} + \lambda_{Dir}\frac{\partial\left(p_{outDir} - 1 + U\right)}{\partial P_{SDir}} = 0 \tag{A3 1.3}$$

$$\frac{\partial P_{totDir}}{\partial \lambda_{Dir}} + \lambda_{Dir}\frac{\partial\left(p_{outDir} - 1 + U\right)}{\partial \lambda_{Dir}} = 0 \tag{A3 1.4}$$

The derivatives of the total power consumption $P_{totDir}$ and the outage probability $p_{outDir}$ with respect to the transmit power $P_{SDir}$ are given by:

$$\frac{\xi}{\eta} - \lambda_{Dir} \; e^{\left(\frac{-\left(2^{2R_s}-1\right)N}{P_{SDir}|h_{SD}|^2\gamma_{SD}}\right)} \; \frac{\left(2^{2R_s}-1\right)N}{P_{SDir}{}^2|h_{SD}|^2\gamma_{SD}} = 0 \tag{A3 1.5}$$

$$\lambda_{Dir} = \frac{\xi P_{SDir}{}^2|h_{SD}|^2\gamma_{SD}}{\eta\left(2^{2R_s}-1\right)Ne^{\left(\frac{-\left(2^{2R_s}-1\right)N}{P_{SDir}|h_{SD}|^2\gamma_{SD}}\right)}} \tag{A3 1.6}$$

Next, the derivatives of the total power consumption $P_{totDir}$ and the outage probability $p_{outDir}$ with respect to $\lambda_{Dir}$ are given by:

$$1 - e^{\left(\frac{-\left(2^{2R_s}-1\right)N}{P_{SDir}|h_{SD}|^2\gamma_{SD}}\right)} - 1 + U = 0 \tag{A3 1.7}$$

$$U = e^{\left(\frac{-\left(2^{2R_s}-1\right)N}{P_{SDir}|h_{SD}|^2\gamma_{SD}}\right)} \tag{A3 1.8}$$

By taking ln for both sides Equation (A 1.8) can be rewritten as:

$$\ln(U) = \frac{-\left(2^{2R_s}-1\right)N}{P_{SDir}|h_{SD}|^2\gamma_{SD}} \tag{A3 1.9}$$

$$P_{Sopt} \approx \left(\frac{-\left(2^{2R_s}-1\right)N}{\ln U|h_{SD}|^2\gamma_{SD}}\right) \tag{A3 1.10}$$

## Appendix A-Ch3-1(b)

### This is the derivation of formula (3.22)

$$Max \sum S_{thDir} \qquad s.t.\{N_s(1-p_o)p_s(1-p_{eDir}) \geq Qs\} \tag{A3 1.11}$$

$$L(L_p, \Lambda_{Dir}) = S_{thDir} + \Lambda_{Dir}\left(N_s(1-p_o)p_s(1-p_{eDir}) - Qs\right) \tag{A3 1.12}$$

$$\frac{\partial S_{thDir}}{\partial L_p} + \Lambda_{Dir}\frac{\partial\left(N_s(1-p_o)p_s(1-p_{eDir}) - Qs\right)}{\partial L_p} = 0 \tag{A3 1.13}$$

$$\frac{N_s(1-p_o)p_s\left((1-p_{bDir})^{L_p} + L_p\ln(1-p_{bDir})(1-p_{bDir})^{L_p}\right)*\left(T_1+\frac{L_p}{R_b}\right) - \frac{N_s(1-p_o)p_s(1-p_{bDir})^{L_p}}{R_b}}{\left(T_1+\frac{L_p}{R_b}\right)^2}$$

$$-\Lambda_{Dir} \quad N_s(1-p_o)p_s(1-p_{bDir})^{L_p}\ln(1-p_{bDir}) = 0$$

where $T_1 = T_{SYNC} + T_{rts} + T_{cts} + T_{Ack} + 3*T_{SIFS} + T_{DIFS}$

$$\Lambda_{Dir} = -\frac{T_1 + \ln(1-p_{bDir})L_p\left(T_1+\frac{L_p}{R_b}\right)}{\ln(1-p_{bDir})\left(T_1+\frac{L_p}{R_b}\right)^2} \tag{A3 1.14}$$

$$\frac{\partial S_{thDir}}{\partial \Lambda_{Dir}} + \Lambda_{Dir}\frac{\partial\left(N_s(1-p_o)p_s(1-p_{eDir}) - Qs\right)}{\partial \Lambda_{Dir}} = 0 \tag{A3 1.15}$$

$$N_s(1-p_o)p_s(1-p_{eDir}) - Qs = 0$$

$$(1-p_{bDir})^{L_p} = \frac{Qs}{N_s(1-p_o)p_s}$$

By taking ln for both side

$$L_{popt} = \frac{\ln\left(\frac{Qs}{N_s(1-p_o)p_s}\right)}{\ln(1-p_{bDir})} \tag{A3 1.16}$$

## Appendix A-Ch3-2(a)

**This is the derivation of formula (3.38)**

$$Min\sum E_{bMH} \qquad s.t.\{p_{outMH} \leq 1-U\} \tag{A3 2.1}$$

$$L(P_{SMH},\lambda_{MH}) = P_{totMH} + \lambda_{MH}\left(p_{outMH} - 1 + U\right) \tag{A3 2.2}$$

$$\frac{\partial P_{totMH}}{\partial P_{SMH}} + \lambda_{MH}\frac{\partial\left(p_{outMH} - 1 + U\right)}{\partial P_{SMH}} = 0 \tag{A3 2.3}$$

where

$$P_{totMH} = pout_{SR_1}\left(P_{AM,MH} + P_{Tx} + P_{Rx}\right) + \left(1 - pout_{SR_1}\right)\left(\left(\sum_{i=2}^{n} X_{R_{i-1}R_i} + X_{R_nD} + 1\right)P_{AM,MH} + (n+1)P_{Tx} + (n+1)P_{Rx}\right)$$

$$\frac{\partial P_{totMH}}{\partial \lambda_{MH}} + \lambda_{MH}\frac{\partial\left(p_{outMH} - 1 + U\right)}{\partial \lambda_{MH}} = 0 \tag{A3 2.4}$$

The derivatives of the total power consumption $P_{totMH}$ and the outage probability $p_{outMH}$ with respect to the transmit power $P_{SMH}$ are given by:

$$\frac{\partial P_{totMH}}{\partial P_{SMH}} = \left(1 - e^{\frac{-1}{P_{SMH}}\left(b_{SR_1}\right)}\right)\frac{\xi}{\eta} + \left(\frac{\xi}{\eta}P_{SMH} + P_{Tx} + P_{Rx}\right)\left(-e^{\frac{-1}{P_{SMH}}\left(b_{SR_1}\right)}\right)\frac{1}{P_{SMH}^{\;2}}\left(b_{SR_1}\right)$$
$$+\left(\left(\sum_{i=2}^{n} X_{R_{i-1}R_i} + X_{R_nD} + 1\right)\frac{\xi}{\eta}\right)\left(e^{\frac{-1}{P_{SMH}}\left(b_{SR_1}\right)}\right)$$
$$+\left(\left(\sum_{i=2}^{n} X_{R_{i-1}R_i} + X_{R_nD} + 1\right)\frac{\xi}{\eta}P_{SMH} + (n+1)P_{Tx} + (n+1)P_{Rx}\right)\left(e^{\frac{-1}{P_{SMH}}\left(b_{SR_1}\right)}\frac{1}{P_{SMH}^{\;2}}\left(b_{SR_1}\right)\right)$$

where $b_{SR_1} = \dfrac{\left(2^{2R_s} - 1\right)N}{\left|h_{SR_1}\right|^2 \gamma_{SR_1}}$

Let $W = \sum_{i=2}^{n} X_{R_{i-1}R_i} + X_{R_nD}$

$$\frac{\partial P_{totMH}}{\partial P_{SMH}} = \left(1 - e^{\frac{-b_{SR_1}}{P_{SMH}}}\right)\frac{\xi}{\eta} + \left(\frac{\xi}{\eta}P_{SMH} + P_{Tx} + P_{Rx}\right)\left(-e^{\frac{-b_{SR_1}}{P_{SMH}}}\right)\frac{b_{SR_1}}{P_{SMH}^{2}}$$

$$+\left((W+1)\frac{\xi}{\eta}\right)\left(e^{\frac{-b_{SR_1}}{P_{SMH}}}\right) + \left((W+1)\frac{\xi}{\eta}P_{SMH} + (n+1)P_{Tx} + (n+1)P_{Rx}\right)\left(e^{\frac{-b_{SR_1}}{P_{SMH}}} * \frac{b_{SR_1}}{P_{SMH}^{2}}\right)$$

$$\frac{\partial P_{totMH}}{\partial P_{SMH}} = \frac{\xi}{\eta} + W\frac{\xi}{\eta}e^{\frac{-b_{SR_1}}{P_{SMH}}} + W\frac{\xi}{\eta}\frac{b_{SR_1}e^{\frac{-b_{SR_1}}{P_{SMH}}}}{P_{SMH}} + n(P_{Tx} + P_{Rx})\frac{b_{SR_1}e^{\frac{-b_{SR_1}}{P_{SMH}}}}{P_{SMH}^{2}}$$

$$\frac{\partial(p_{outMH} - 1 + U)}{\partial P_{SMH}} = -e^{\frac{-C}{P_{SMH}}} * \frac{C}{P_{SMH}^{2}}$$

where $C = b_{SR1} + b_{R_{i-1}R_i} + b_{R_nD}$, $b_{R_{i-1}R_i} = \frac{(2^{2R_s} - 1)N}{\upsilon_{R_{i-1}R_i}^{\alpha}\left|h_{R_{i-1}R_i}\right|^2 \gamma_{R_{i-1}R_i}}$ and $b_{R_nD} = \frac{(2^{2R_s} - 1)N}{\upsilon_{R_nD}^{\alpha}\left|h_{R_nD}\right|^2 \gamma_{R_nD}}$

then $$\frac{\xi}{\eta} + W\frac{\xi}{\eta}e^{\frac{-b_{SR_1}}{P_{SMH}}} + W\frac{\xi}{\eta}\frac{b_{SR_1}e^{\frac{-b_{SR_1}}{P_{SMH}}}}{P_{SMH}} + n(P_{Tx} + P_{Rx})\frac{b_{SR_1}e^{\frac{-b_{SR_1}}{P_{SMH}}}}{P_{SMH}^{2}} - \lambda_{MH}\ e^{\frac{-C}{P_{SMH}}} * \frac{C}{P_{SMH}^{2}} = 0 \quad \text{(A3 2.5)}$$

$$\lambda_{MH} = \frac{\frac{\xi}{\eta}P_{SMH}^{2} + W\frac{\xi}{\eta}P_{SMH}^{2}e^{\frac{-b_{SR_1}}{P_{SMH}}} + W\frac{\xi}{\eta}P_{SMH}b_{SR_1}e^{\frac{-b_{SR_1}}{P_{SMH}}} + n(P_{Tx} + P_{Rx})b_{SR_1}e^{\frac{-b_{SR_1}}{P_{SMH}}}}{e^{\frac{-C}{P_{SMH}}}C} \quad \text{(A3 2.6)}$$

Next, the derivatives of the total power consumption $P_{totMH}$ and the outage probability $p_{outMH}$ with respect to $\lambda_{MH}$ are given by:

$$1 - e^{-\frac{(2^{2R_s}-1)N}{P_{SMH}}\left(\frac{1}{\left|h_{SR_1}\right|^2\gamma_{SR_1}} + \sum_{i=2}^{n}\frac{1}{\upsilon_{R_{i-1}R_i}^{\alpha}\left|h_{R_{i-1}Ri}\right|^2\gamma_{R_{i-1}R_i}} + \frac{1}{\upsilon_{R_nD}^{\alpha}\left|h_{R_nD}\right|^2\gamma_{R_nD}}\right)} - 1 + U = 0 \quad \text{(A3 2.7)}$$

$$U = e^{-\frac{(2^{2R_s}-1)N}{P_{SMH}}\left(\frac{1}{\left|h_{SR_1}\right|^2\gamma_{SR_1}} + \sum_{i=2}^{n}\frac{1}{\upsilon_{R_{i-1}R_i}^{\alpha}\left|h_{R_{i-1}Ri}\right|^2\gamma_{R_{i-1}R_i}} + \frac{1}{\upsilon_{R_nD}^{\alpha}\left|h_{R_nD}\right|^2\gamma_{R_nD}}\right)} \quad \text{(A3 2.8)}$$

By taking ln for both sides Equation (A3 2.8) can be rewritten as:

$$\ln(U) = -\frac{(2^{2R_s}-1)N}{P_{SMH}}\left(\frac{1}{\left|h_{SR_1}\right|^2\gamma_{SR_1}} + \sum_{i=2}^{n}\frac{1}{\upsilon_{R_{i-1}R_i}^{\alpha}\left|h_{R_{i-1}Ri}\right|^2\gamma_{R_{i-1}R_i}} + \frac{1}{\upsilon_{R_nD}^{\alpha}\left|h_{R_nD}\right|^2\gamma_{R_nD}}\right) \quad \text{(A3 2.9)}$$

$$P_{MHopt} \approx \frac{-(2^{2R_s}-1)N}{\ln U}\left(\frac{1}{\left|h_{SR_1}\right|^2\gamma_{SR_1}} + \sum_{i=2}^{n}\frac{1}{\upsilon_{R_{i-1}R_i}^{\alpha}\left|h_{R_{i-1}Ri}\right|^2\gamma_{R_{i-1}R_i}} + \frac{1}{\upsilon_{R_nD}^{\alpha}\left|h_{R_nD}\right|^2\gamma_{R_nD}}\right)$$
(A3 2.10)

## Appendix A-Ch3-2(b)

**This is the derivation of formula (3.47)**

$$Max \sum S_{thMH} \qquad s.t. \; \{(N_s(1-p_o)p_s(1-p_{eMH}) \geq Qs)\} \qquad \text{(A3 2.11)}$$

$$L(L_p, \Lambda_{MH}) = S_{thMH} + \Lambda_{MH}(N_s(1-p_o)p_s(1-p_{eMH}) - Qs) \qquad \text{(A3 2.12)}$$

$$\frac{\partial S_{thMH}}{\partial L_p} + \Lambda_{MH} \frac{\partial(N_s(1-p_o)p_s(1-p_{eMH}) - Qs)}{\partial L_p} = 0 \qquad \text{(A3 2.13)}$$

$$\frac{N_s(1-p_o)p_s\left(\left((1-p_{eMH}) + L_p(1-p_{eMH})\left(\ln(1-p_{bSR_1}) + (n-1)\prod_{i=2}^{n}\ln(1-p_{bR_{i-1}R_i}) + \ln(1-p_{bR_nD})\right)\right)*\left(T_2 + (n+1)\frac{L_p}{R_b}\right) - \frac{(n+1)L_p(1-p_{eMH})}{R_b}\right)}{\left(T_2 + (n+1)\frac{L_p}{R_b}\right)^2}$$

$$-\Lambda_{MH} \; N_s(1-p_o)p_s(1-p_{eMH})\left(\ln(1-p_{bSR_1}) + (n-1)\prod_{i=2}^{n}\ln(1-p_{bR_{i-1}R_i}) + \ln(1-p_{bR_nD})\right) = 0$$

where $T_2 = T_{SYNC} + T_{rts} + T_{rth} + T_{cts} + T_{Ack} + (4+n)*T_{SIFS} + T_{DIFS}$

$$\Lambda_{MH} = -\frac{T_2 + \left(\ln(1-p_{bSR_1}) + (n-1)\prod_{i=2}^{n}\ln(1-p_{bR_{i-1}R_i}) + \ln(1-p_{bR_nD})\right)L_p\left(T_2 + (n+1)\frac{L_p}{R_b}\right)}{\left(\ln(1-p_{bSR_1}) + (n-1)\prod_{i=2}^{n}\ln(1-p_{bR_{i-1}R_i}) + \ln(1-p_{bR_nD})\right)\left(T_2 + (n+1)\frac{L_p}{R_b}\right)^2} \qquad \text{(A3 2.14)}$$

$$\frac{\partial S_{thMH}}{\partial \Lambda_{MH}} + \Lambda_{MH} \frac{\partial(N_s(1-p_o)p_s(1-p_{eMH}) - Qs)}{\partial \Lambda_{MH}} = 0 \qquad \text{(A3 2.15)}$$

$$N_s(1-p_o)p_s(1-p_{eMH}) - Qs = 0$$

$$(1-p_{bSR_1MH})^{L_p}\left(\prod_{i=2}^{n}(1-p_{bR_{i-1}R_iMH})^{L_p}\right)(1-p_{bR_nDMH})^{L_p} = \frac{Qs}{N(1-p_o)p_s}$$

$$e^{L_p\left(\ln(1-p_{bSR_1}) + (n-1)\prod_{i=2}^{n}\ln(1-p_{bR_{i-1}R_i}) + \ln(1-p_{bR_nD})\right)} = \frac{Qs}{N(1-p_o)p_s}$$

By taking ln for both side

$$L_{pMHopt} = \frac{\ln\left(\frac{Qs}{N_s(1-p_o)p_s}\right)}{\left(\ln(1-p_{bSR_1}) + (n-1)\prod_{i=2}^{n}\ln(1-p_{bR_{i-1}R_i}) + \ln(1-p_{bR_nD})\right)} \qquad \text{(A3 2.16)}$$

## Appendix A-Ch3-3(a)

**This is the derivation of formula (3.64)**

$$Min\sum E_{bMB} \qquad s.t.\{p_{outMB} \le 1-U\} \tag{A3 3.1}$$

$$L(P_{SMB},\lambda_{MB}) = P_{totMB} + \lambda_{MB}\left(p_{outMB} - 1 + U\right) \tag{A3 3.2}$$

$$\frac{\partial P_{totMB}}{\partial P_{SMB}} + \lambda_{MB}\frac{\partial\left(p_{outMB} - 1 + U\right)}{\partial P_{SMB}} = 0 \tag{A3 3.3}$$

where

$$P_{totMB} = \left(pout_{SR}\right)^{K}\left(P_{AM,MB} + P_{Tx} + K*P_{Rx}\right) + \left(1-\left(pout_{SR}\right)^{K}\right)\left(\left(\sum_{l=1}^{K} X_{R_lD} + 1\right)P_{AM,MB} + (K+1)P_{Tx} + (2K+1)P_{Rx}\right)$$

$$\frac{\partial P_{totMB}}{\partial \lambda_{MB}} + \lambda_{MB}\frac{\partial\left(p_{outMB} - 1 + U\right)}{\partial \lambda_{MB}} = 0 \tag{A3 3.4}$$

The derivatives of the total power consumption $P_{totMB}$ and the outage probability $p_{outMB}$ with respect to the transmit power $P_{SMB}$ are given by:

$$\frac{\partial P_{totMB}}{\partial P_{SMB}} = \left(1-e^{\frac{-1}{P_{SMB}}(b_{SR})}\right)^{K}\frac{\xi}{\eta} + \left(\frac{\xi}{\eta}P_{SMB} + P_{Tx} + KP_{Rx}\right)K\left(1-e^{\frac{-1}{P_{SMB}}(b_{SR})}\right)^{K-1}\left(\frac{-e^{\frac{-1}{P_{SMB}}(b_{SR})}}{P_{SMB}{}^{2}}\left(b_{SR}\right)\right)$$

$$+\left(\left(\sum_{l=1}^{K} X_{lD} + 1\right)\frac{\xi}{\eta}\right)\left(1-\left(1-e^{\frac{-1}{P_{SMB}}(b_{SR})}\right)^{K}\right)$$

$$+\left(\left(\sum_{l=1}^{K} X_{lD} + 1\right)\frac{\xi}{\eta}P_{SMB} + (K+1)P_{Tx} + (2K+1)P_{Rx}\right)K\left(1-e^{\frac{-1}{P_{SMB}}(b_{SR})}\right)^{K-1}\left(\frac{e^{\frac{-1}{P_{SMB}}(b_{SR})}}{P_{SMB}{}^{2}}\left(b_{SR}\right)\right)$$

where $b_{SR} = \dfrac{\left(2^{2R_s} - 1\right)N}{\left|h_{SR}\right|^{2}\gamma_{SR}}$

Let $Z = \sum_{l=1}^{K} X_{lD}$ and $P_{outSR} = 1 - e^{\frac{-1}{P_{SMB}}(b_{SR})}$

$$\frac{\partial P_{totMB}}{\partial P_{SMB}} = \left(P_{outSR}\right)^K \frac{\xi}{\eta} + \left(\frac{\xi}{\eta} P_{SMB} + P_{Tx} + KP_{Rx}\right) K\left(P_{outSR}\right)^{K-1}\left(\frac{-e^{\frac{-1}{P_{SMB}}(b_{SR})}}{P_{SMB}^{\;2}}\left(b_{SR}\right)\right)$$
$$+\left(\left(Z+1\right)\frac{\xi}{\eta}\right)\left(1-\left(P_{outSR}\right)^K\right)$$
$$+\left(\left(Z+1\right)\frac{\xi}{\eta} P_{SMB} + \left(K+1\right)P_{Tx} + \left(2K+1\right)P_{Rx}\right) K\left(P_{outSR}\right)^{K-1}\left(\frac{e^{\frac{-1}{P_{SMB}}(b_{SR})}}{P_{SMB}^{\;2}}\left(b_{SR}\right)\right)$$

$$\frac{\partial P_{totMB}}{\partial P_{SMB}} = \left(P_{outSR}\right)^K \frac{\xi}{\eta} - \frac{\xi}{\eta} K\left(P_{outSR}\right)^{K-1}\left(\frac{e^{\frac{-1}{P_{SMB}}(b_{SR})}}{P_{SMB}}\left(b_{SR}\right)\right) - P_{Tx} K\left(P_{outSR}\right)^{K-1}\left(\frac{e^{\frac{-1}{P_{SMB}}(b_{SR})}}{P_{SMB}^{\;2}}\left(b_{SR}\right)\right)$$
$$- P_{Rx} K^2\left(P_{outSR}\right)^{K-1}\left(\frac{e^{\frac{-1}{P_{SMB}}(b_{SR})}}{P_{SMB}^{\;2}}\left(b_{SR}\right)\right) + \left(Z+1\right)\frac{\xi}{\eta} - \left(Z+1\right)\frac{\xi}{\eta}\left(P_{outSR}\right)^K + \left(Z+1\right)\frac{\xi}{\eta} K\left(P_{outSR}\right)^{K-1}\left(\frac{e^{\frac{-1}{P_{SMB}}(b_{SR})}}{P_{SMB}}\left(b_{SR}\right)\right)$$
$$+ K\left(K+1\right)\left(P_{outSR}\right)^{K-1}\left(\frac{e^{\frac{-1}{P_{SMB}}(b_{SR})}}{P_{SMB}^{\;2}}\left(b_{SR}\right)\right)P_{Tx} + K\left(2K+1\right)\left(P_{outSR}\right)^{K-1}\left(\frac{e^{\frac{-1}{P_{SMB}}(b_{SR})}}{P_{SMB}^{\;2}}\left(b_{SR}\right)\right)P_{Rx}$$

$$\frac{\partial P_{totMB}}{\partial P_{SMB}} = \left(Z+1\right)\frac{\xi}{\eta} - Z\frac{\xi}{\eta}\left(P_{outSR}\right)^K + ZK\frac{\xi}{\eta}\left(P_{outSR}\right)^{K-1}\left(\frac{e^{\frac{-1}{P_{SMB}}(b_{SR})}}{P_{SMB}}\left(b_{SR}\right)\right)$$
$$+ K^2\left(P_{outSR}\right)^{K-1}\left(\frac{e^{\frac{-1}{P_{SMB}}(b_{SR})}}{P_{SMB}^{\;2}}\left(b_{SR}\right)\right)P_{Tx} + K^2\left(P_{outSR}\right)^{K-1}\left(\frac{e^{\frac{-1}{P_{SMB}}(b_{SR})}}{P_{SMB}^{\;2}}\left(b_{SR}\right)\right)P_{Rx} + K\left(P_{outSR}\right)^{K-1}\left(\frac{e^{\frac{-1}{P_{SMB}}(b_{SR})}}{P_{SMB}^{\;2}}\left(b_{SR}\right)\right)P_{Rx}$$

let $e^{\frac{-1}{P_{SMB}}(b_{SR})} = 1 - Pout_{SR}$

$$\frac{\partial P_{totMB}}{\partial P_{SMB}} = \left(Z+1\right)\frac{\xi}{\eta} - Z\frac{\xi}{\eta}\left(P_{outSR}\right)^K + ZK\frac{\xi}{\eta}\left(P_{outSR}\right)^{K-1}\left(\frac{\left(1-P_{outSR}\right)}{P_{SMB}}\left(b_{SR}\right)\right)$$
$$+ K^2\left(P_{outSR}\right)^{K-1}\left(\frac{\left(1-P_{outSR}\right)}{P_{SMB}^{\;2}}\left(b_{SR}\right)\right)P_{Tx} + K^2\left(P_{outSR}\right)^{K-1}\left(\frac{\left(1-P_{outSR}\right)}{P_{SMB}^{\;2}}\left(b_{SR}\right)\right)P_{Rx} + K\left(P_{outSR}\right)^{K-1}\left(\frac{\left(1-P_{outSR}\right)}{P_{SMB}^{\;2}}\left(b_{SR}\right)\right)P_{Rx}$$

$$\frac{\partial P_{totMB}}{\partial P_{SMB}} = \left(Z+1\right)\frac{\xi}{\eta} + Z\frac{\xi}{\eta}\left(P_{outSR}\right)^{K-1}\left(K\left(b_{SR}\right)\frac{\left(1-P_{outSR}\right)}{P_{SMB}} - P_{outSR}\right) + \left(b_{SR}\right)K\left(P_{outSR}\right)^{K-1}\frac{\left(1-P_{outSR}\right)}{P_{SMB}^{\;2}}\left(KP_{Tx} + \left(K+1\right)P_{Rx}\right)$$

$$\frac{\partial\left(p_{outMB} - 1 + U\right)}{\partial P_{SMB}} = -e^{\frac{-C_1}{P_{SMB}}} * \frac{C_1}{P_{SMB}^{\;2}}\left(1 - e^{\frac{-C_2}{P_{SMB}}}\right)^K + K\left(1 - e^{\frac{-C_2}{P_{SMB}}}\right)^{K-1}\left(-e^{\frac{-C_2}{P_{SMB}}} * \frac{C_2}{P_{SMB}^{\;2}}\right)\left(1 - e^{\frac{-C_1}{P_{SMB}}}\right)$$

where $C_1 = b_{SD}$, $C_2 = b_{SR} + b_{RD}$ and $b_{SD} = \frac{\left(2^{2R_s} - 1\right)N}{|h_{SD}|^2 \gamma_{SD}}, b_{RD} = \frac{\left(2^{2R_s} - 1\right)N}{\upsilon_{RD}{}^{\alpha} |h_{RD}|^2 \gamma_{RD}}$

then

$$(Z+1)\frac{\xi}{\eta} + Z\frac{\xi}{\eta}(P_{outSR})^{K-1}\left(K(b_{SR})\frac{(1-P_{outSR})}{P_{SMB}} - P_{outSR}\right) + (b_{SR})K(P_{outSR})^{K-1}\frac{(1-P_{outSR})}{P_{SMB}{}^2}\left(KP_{Tx} + (K+1)P_{Rx}\right)$$
$$-\lambda_{MB}\left(e^{\frac{-C_1}{P_{SMB}}} * \frac{C_1}{P_{SMB}{}^2}\left(1-e^{\frac{-C_2}{P_{SMB}}}\right)^K + K\left(1-e^{\frac{-C_2}{P_{SMB}}}\right)^{K-1}\left(e^{\frac{-C_2}{P_{SMB}}} * \frac{C_2}{P_{SMB}{}^2}\right)\left(1-e^{\frac{-C_1}{P_{SMB}}}\right)\right) = 0$$

$$\lambda_{MB} = \frac{(Z+1)\frac{\xi}{\eta} + Z\frac{\xi}{\eta}(P_{outSR})^{K-1}\left(K(b_{SR})\frac{(1-P_{outSR})}{P_{SMB}} - P_{outSR}\right) + (b_{SR})K(P_{outSR})^{K-1}\frac{(1-P_{outSR})}{P_{SMB}{}^2}\left(KP_{Tx} + (K+1)P_{Rx}\right)}{\left(e^{\frac{-C_1}{P_{SMB}}} * \frac{C_1}{P_{SMB}{}^2}\left(1-e^{\frac{-C_2}{P_{SMB}}}\right)^K + K\left(1-e^{\frac{-C_2}{P_{SMB}}}\right)^{K-1}\left(e^{\frac{-C_2}{P_{SMB}}} * \frac{C_2}{P_{SMB}{}^2}\right)\left(1-e^{\frac{-C_1}{P_{SMB}}}\right)\right)}$$

(A3 3.5)

Next, the derivatives of the total power consumption $P_{totMB}$ and the outage probability $p_{outMB}$ with respect to $\lambda_{MB}$ are given by:

$$\frac{\left(2^{2R_s} - 1\right)^{K+1} N^{K+1}}{P_{SMB}{}^{K+1} |h_{SD}|^2 \gamma_{SD}}\left(\left(\frac{1}{|h_{SR}|^2 \gamma_{SR}} + \frac{1}{\upsilon_{RD}{}^{\alpha}|h_{RD}|^2 \gamma_{RD}}\right)\right)^K - 1 + U = 0 \quad \text{(A3 3.6)}$$

$$1 - U = \frac{\left(2^{2R_s} - 1\right)^{K+1} N^{K+1}}{P_{SMB}{}^{K+1} |h_{SD}|^2 \gamma_{SD}}\left(\left(\frac{1}{|h_{SR}|^2 \gamma_{SR}} + \frac{1}{\upsilon_{RD}{}^{\alpha}|h_{RD}|^2 \gamma_{RD}}\right)\right)^K \quad \text{(A3 3.7)}$$

$$P_{SMB}{}^{K+1} = \frac{\left(2^{2R_s} - 1\right)^{K+1} N^{K+1}}{(1-U)|h_{SD}|^2 \gamma_{SD}}\left(\left(\frac{1}{|h_{SR}|^2 \gamma_{SR}} + \frac{1}{\upsilon_{RD}{}^{\alpha}|h_{RD}|^2 \gamma_{RD}}\right)\right)^K \quad \text{(A3 3.8)}$$

$$P_{MBopt} = \left(2^{2R_s} - 1\right)N\left(\frac{1}{(1-U)|h_{SD}|^2 \gamma_{SD}}\left(\left(\frac{1}{|h_{SR}|^2 \gamma_{SR}} + \frac{1}{\upsilon_{RD}{}^{\alpha}|h_{RD}|^2 \gamma_{RD}}\right)\right)^K\right)^{\frac{1}{K+1}} \quad \text{(A3 3.9)}$$

# Appendix A-Ch3-3(b)

**This is the derivation of formula (3.73)**

$$Max\sum S_{thMB} \qquad s.t.\{N_s(1-p_o)p_s(1-p_{eMB}) \geq Qs\} \tag{A3 3.10}$$

$$L(L_p, \Lambda_{MB}) = S_{thMB} + \Lambda_{MB}\left(N_s(1-p_o)p_s(1-p_{eMB}) - Qs\right) \tag{A3 3.11}$$

$$\frac{\partial S_{thMB}}{\partial L_p} + \Lambda_{MB}\frac{\partial\left(N_s(1-p_o)p_s(1-p_{eMB}) - Qs\right)}{\partial L_p} = 0 \tag{A3 3.12}$$

$$\frac{N_s(1-p_o)p_s\left(\left((1-p_{eMB}) + L_p\left((1-X_2)^K \ln(1-p_{bSD})X_1 + K*(1-X_2)^{K-1}(1-X_1)X_2(\ln(1-p_{bSR}) + \ln(1-p_{bRD}))\right)\right)*\left(T_3 + (n+1)\frac{L_p}{R_b}\right) - \frac{(n+1)L_p(1-p_{eMB})}{R_b}\right)}{\left(T_3 + (n+1)\frac{L_p}{R_b}\right)^2}$$

$$-\Lambda_{MB}\; N_s(1-p_o)p_s\left((1-X_2)^K \ln(1-p_{bSD})X_1 + K*(1-X_2)^{K-1}(1-X_1)X_2(\ln(1-p_{bSR}) + \ln(1-p_{bRD}))\right) = 0$$

where $T_3 = T_{SYNC} + T_{rts} + T_{rth} + T_{cts} + T_{Ack} + (4+n)*T_{SIFS} + T_{DIFS}$

$$\Lambda_{MB} = -\frac{(1-p_{eMB})T_3 + \left((1-X_2)^K \ln(1-p_{bSD})X_1 + K*(1-X_2)^{K-1}(1-X_1)X_2(\ln(1-p_{bSR}) + \ln(1-p_{bRD}))\right)L_p\left(T_3 + (n+1)\frac{L_p}{R_b}\right)}{\left((1-X_2)^K \ln(1-p_{bSD})X_1 + K*(1-X_2)^{K-1}(1-X_1)X_2(\ln(1-p_{bSR}) + \ln(1-p_{bRD}))\right)\left(T_3 + (n+1)\frac{L_p}{R_b}\right)^2}$$

(A3 3.13)

$$\frac{\partial S_{thMB}}{\partial \Lambda_{MB}} + \Lambda_{MB}\frac{\partial\left(N_s(1-p_o)p_s(1-p_{eMB}) - Qs\right)}{\partial \Lambda_{MB}} = 0 \tag{A3 3.14}$$

$$N_s(1-p_o)p_s(1-p_{eMB}) - Qs = 0$$

$$(1-X_1)(1-X_2)^K = \frac{Qs}{N_s(1-p_o)p_s}$$

$$\left(1-e^{L_p \ln(1-p_{bSD})}\right)\left(1-e^{L_p(\ln(1-p_{bSR})+\ln(1-p_{bRD}))}\right)^K = \frac{Qs}{N_s(1-p_o)p_s}$$

$$\left(1-L_p\ln(1-p_{bSD})\right)\left(1-L_p(\ln(1-p_{bSR})+\ln(1-p_{bRD}))\right)^K = \frac{Qs}{N_s(1-p_o)p_s}$$

$$L_p^{K+1}\left(-\ln(1-p_{bSD})\right)\left(-(\ln(1-p_{bSR})+\ln(1-p_{bRD}))\right)^K = \frac{Qs}{N_s(1-p_o)p_s}$$

$$L_{pMBopt} = \left(\frac{Qs}{N_s(1-p_o)p_s\left(-\ln(1-p_{bSD})\right)\left(-(\ln(1-p_{bSR})+\ln(1-p_{bRD}))\right)^K}\right)^{\frac{1}{K+1}} \tag{A3 3.15}$$

# Appendix A-Ch3-4(a)

**This is the derivation of formula (3.86)**

$$Min\sum E_{bMHB} \qquad s.t.\{p_{outMHB} \leq 1 - U\} \tag{A3 4.1}$$

$$L(P_{SMHB},\lambda_{MHB}) = P_{totMHB} + \lambda_{MHB}\left(p_{outMHB} - 1 + U\right) \tag{A3 4.2}$$

$$\frac{\partial P_{totMHB}}{\partial P_{SMHB}} + \lambda_{MHB}\frac{\partial\left(p_{outMHB} - 1 + U\right)}{\partial P_{SMHB}} = 0 \tag{A3 4.3}$$

where

$$P_{totMHB} = \left(pout_{SR_1}\right)^K\left(P_{AM,MHB} + P_{Tx} + K * P_{Rx}\right)$$
$$+\left(1 - \left(pout_{SR_1}\right)^K\right)\left(\sum_{l=1}^{K}\left(\sum_{i=2}^{n} X_{(R_i - 1R_i)_l} + X_{(R_nD)_l}\right) + 1\right)P_{AM,MHB} + \left(K * n + 1\right)P_{Tx} + \left(K * (n+1) + 1\right)P_{Rx}$$

$$\frac{\partial P_{totMHB}}{\partial \lambda_{MHB}} + \lambda_{MHB}\frac{\partial\left(p_{outMHB} - 1 + U\right)}{\partial \lambda_{MHB}} = 0 \tag{A3 4.4}$$

The derivatives of the total power consumption $P_{totMHB}$ and the outage probability $p_{outMHB}$ with respect to the transmit power $P_{SMHB}$ are given by:

$$\frac{\partial P_{totMHB}}{\partial P_{SMHB}} = \left(1 - e^{\frac{-1}{P_{SMHB}}\left(b_{SR_1}\right)}\right)^K \frac{\xi}{\eta} + \left(\frac{\xi}{\eta}P_{SMHB} + P_{Tx} + KP_{Rx}\right)K\left(1 - e^{\frac{-1}{P_{SMHB}}\left(b_{SR_1}\right)}\right)^{K-1}\left(\frac{-e^{\frac{-1}{P_{SMHB}}\left(b_{SR_1}\right)}}{P_{SMHB}{}^2}\left(b_{SR_1}\right)\right)$$
$$+\left(\left(\sum_{l=1}^{K}\left(\sum_{i=2}^{n} X_{(R_i - 1R_i)_l} + X_{(R_nD)_l}\right) + 1\right)\frac{\xi}{\eta}\right)\left(1 - \left(1 - e^{\frac{-1}{P_{SMHB}}\left(b_{SR_1}\right)}\right)^K\right)$$
$$+\left(\left(\sum_{l=1}^{K}\left(\sum_{i=2}^{n} X_{(R_i - 1R_i)_l} + X_{(R_nD)_l}\right) + 1\right)\frac{\xi}{\eta}P_{SMHB} + \left(K*n+1\right)P_{Tx} + \left(K*(n+1)+1\right)P_{Rx}\right)K\left(1 - e^{\frac{-1}{P_{SMHB}}\left(b_{SR_1}\right)}\right)^{K-1}\left(\frac{e^{\frac{-1}{P_{SMHB}}\left(b_{SR_1}\right)}}{P_{SMHB}{}^2}\left(b_{SR_1}\right)\right)$$

where $b_{SR_1} = \dfrac{\left(2^{2R_s} - 1\right)N}{\left|h_{SR_1}\right|^2 \gamma_{SR_1}}$

let $G = \sum_{l=1}^{K}\left(\sum_{i=2}^{n} X_{(R_i - 1R_i)_l} + X_{(R_nD)_l}\right)$ and $P_{outSR_1} = 1 - e^{\frac{-1}{P_{SMHB}}\left(b_{SR_1}\right)}$

$$\frac{\partial P_{totMHB}}{\partial P_{SMHB}} = \left(1 - e^{\frac{-1}{P_{SMHB}}\left(b_{SR_1}\right)}\right)^K \frac{\xi}{\eta} + \left(\frac{\xi}{\eta}P_{SMHB} + P_{Tx} + KP_{Rx}\right)K\left(1 - e^{\frac{-1}{P_{SMHB}}\left(b_{SR_1}\right)}\right)^{K-1}\left(\frac{-e^{\frac{-1}{P_{SMHB}}\left(b_{SR_1}\right)}}{P_{SMHB}{}^2}\left(b_{SR_1}\right)\right)$$
$$+\left((G+1)\frac{\xi}{\eta}\right)\left(1 - \left(1 - e^{\frac{-1}{P_{SMHB}}\left(b_{SR_1}\right)}\right)^K\right)$$
$$+\left((G+1)\frac{\xi}{\eta}P_{SMHB} + \left(K*n+1\right)P_{Tx} + \left(K*(n+1)+1\right)P_{Rx}\right)K\left(1 - e^{\frac{-1}{P_{SMHB}}\left(b_{SR_1}\right)}\right)^{K-1}\left(\frac{e^{\frac{-1}{P_{SMHB}}\left(b_{SR_1}\right)}}{P_{SMHB}{}^2}\left(b_{SR_1}\right)\right)$$

$$\frac{\partial P_{totMHB}}{\partial P_{SMHB}} = \left(pout_{SR_1}\right)^K \frac{\xi}{\eta} + \left(\frac{\xi}{\eta} P_{SMHB} + P_{Tx} + KP_{Rx}\right) K\left(pout_{SR_1}\right)^{K-1}\left(\frac{-e^{\frac{-1}{P_{SMHB}}\left(b_{SR_1}\right)}}{P_{SMHB}^{\,2}}\left(b_{SR_1}\right)\right)$$

$$+\left((G+1)\frac{\xi}{\eta}\right)\left(1-\left(1-e^{\frac{-1}{P_{SMHB}}\left(b_{SR_1}\right)}\right)^K\right)$$

$$+\left((G+1)\frac{\xi}{\eta} P_{SMHB} + (K*n+1)P_{Tx} + (K*(n+1)+1)P_{Rx}\right) K\left(pout_{SR_1}\right)^{K-1}\left(\frac{e^{\frac{-1}{P_{SMHB}}\left(b_{SR_1}\right)}}{P_{SMHB}^{\,2}}\left(b_{SR_1}\right)\right)$$

$$\frac{\partial P_{totMHB}}{\partial P_{SMHB}} = G\frac{\xi}{\eta} + \frac{\xi}{\eta} - \left(pout_{SR_1}\right)^K G\frac{\xi}{\eta} + G\frac{\xi}{\eta} K\left(pout_{SR_1}\right)^{K-1}\left(\frac{e^{\frac{-1}{P_{SMHB}}\left(b_{SR_1}\right)}}{P_{SMHB}^{\,2}}\left(b_{SR_1}\right)\right)$$

$$+K^2 nP_{Tx}\left(pout_{SR_1}\right)^{K-1}\left(\frac{e^{\frac{-1}{P_{SMHB}}\left(b_{SR_1}\right)}}{P_{SMHB}^{\,2}}\left(b_{SR_1}\right)\right) + K^2 nP_{Rx}\left(pout_{SR_1}\right)^{K-1}\left(\frac{e^{\frac{-1}{P_{SMHB}}\left(b_{SR_1}\right)}}{P_{SMHB}^{\,2}}\left(b_{SR_1}\right)\right)$$

$$+KP_{Rx}\left(pout_{SR_1}\right)^{K-1}\left(\frac{e^{\frac{-1}{P_{SMHB}}\left(b_{SR_1}\right)}}{P_{SMHB}^{\,2}}\left(b_{SR_1}\right)\right)$$

let $e^{\frac{-1}{P_{SMHB}}\left(b_{SR_1}\right)} = 1 - Pout_{SR_1}$

$$\frac{\partial P_{totMHB}}{\partial P_{SMHB}} = (G+1)\frac{\xi}{\eta} - G\frac{\xi}{\eta}\left(P_{outSR_1}\right)^K + GK\frac{\xi}{\eta}\left(P_{outSR_1}\right)^{K-1}\left(\frac{\left(1-P_{outSR_1}\right)}{P_{SMHB}}\left(b_{SR_1}\right)\right)$$

$$+K^2\left(P_{outSR_1}\right)^{K-1}\left(\frac{\left(1-P_{outSR_1}\right)}{P_{SMHB}^{\,2}}\left(b_{SR_1}\right)\right)P_{Tx} + K^2\left(P_{outSR_1}\right)^{K-1}\left(\frac{\left(1-P_{outSR_1}\right)}{P_{SMHB}^{\,2}}\left(b_{SR_1}\right)\right)P_{Rx}$$

$$+K\left(P_{outSR_1}\right)^{K-1}\left(\frac{\left(1-P_{outSR_1}\right)}{P_{SMHB}^{\,2}}\left(b_{SR_1}\right)\right)P_{Rx}$$

$$\frac{\partial P_{totMHB}}{\partial P_{SMHB}} = (G+1)\frac{\xi}{\eta} + G\frac{\xi}{\eta}\left(P_{outSR_1}\right)^{K-1}\left(K\left(b_{SR_1}\right)\frac{\left(1-P_{outSR_1}\right)}{P_{SMHB}} - P_{outSR_1}\right)$$

$$+\left(b_{SR_1}\right)K\left(P_{outSR_1}\right)^{K-1}\frac{\left(1-P_{outSR_1}\right)}{P_{SMHB}^{\,2}}\left(nKP_{Tx} + (nK+1)P_{Rx}\right)$$

$$\frac{\partial\left(p_{outMHB}-1+U\right)}{\partial P_{SMHB}} = -e^{\frac{-C_1}{P_{SMHB}}} * \frac{C_1}{P_{SMHB}^{\,2}}\left(1-e^{\frac{-C_3}{P_{SMHB}}}\right)^K + K\left(1-e^{\frac{-C_3}{P_{SMHB}}}\right)^{K-1}\left(-e^{\frac{-C_3}{P_{SMHB}}} * \frac{C_3}{P_{SMHB}^{\,2}}\right)\left(1-e^{\frac{-C_1}{P_{SMHB}}}\right)$$

where $C_1 = b_{SD},\ C_3 = b_{SR1} + b_{R_{i-1}R_i} + b_{R_nD}$

and $b_{SD} = \frac{\left(2^{2R_s}-1\right)N}{\left|h_{SD}\right|^2\gamma_{SD}}, b_{R_{i-1}R_i} = \frac{\left(2^{2R_s}-1\right)N}{\upsilon_{R_{i-1}R_i}{}^{\alpha}\left|h_{R_{i-1}R_i}\right|^2\gamma_{R_{i-1}R_i}}, b_{R_nD} = \frac{\left(2^{2R_s}-1\right)N}{\upsilon_{R_nD}{}^{\alpha}\left|h_{R_nD}\right|^2\gamma_{R_nD}}$

then

$$(G+1)\frac{\xi}{\eta}+\left(P_{outSR_1}\right)^{K-1}\left(G\frac{\xi}{\eta}\left(K\left(b_{SR_1}\right)\frac{\left(1-P_{outSR_1}\right)}{P_{SMHB}}-P_{outSR_1}\right)+\left(b_{SR_1}\right)K\frac{\left(1-P_{outSR_1}\right)}{P_{SMHB}^{2}}\left(nKP_{Tx}+(nK+1)P_{Rx}\right)\right)$$

$$-\lambda_{MB}\left(e^{\frac{-C_1}{P_{SMHB}}}*\frac{C_1}{P_{SMHB}^{2}}\left(1-e^{\frac{-C_3}{P_{SMHB}}}\right)^{K}+K\left(1-e^{\frac{-C_3}{P_{SMHB}}}\right)^{K-1}\left(e^{\frac{-C_3}{P_{SMHB}}}*\frac{C_3}{P_{SMHB}^{2}}\right)\left(1-e^{\frac{-C_1}{P_{SMHB}}}\right)\right)=0$$

$$\lambda_{MHB}=\frac{(G+1)\frac{\xi}{\eta}+\left(P_{outSR_1}\right)^{K-1}\left(\begin{array}{l}G\frac{\xi}{\eta}\left(K\left(b_{SR_1}\right)\frac{\left(1-P_{outSR_1}\right)}{P_{SMHB}}-P_{outSR_1}\right)\\+\left(b_{SR_1}\right)K\frac{\left(1-P_{outSR_1}\right)}{P_{SMHB}^{2}}\left(nKP_{Tx}+(nK+1)P_{Rx}\right)\end{array}\right)}{\left(e^{\frac{-C_1}{P_{SMHB}}}*\frac{C_1}{P_{SMHB}^{2}}\left(1-e^{\frac{-C_3}{P_{SMHB}}}\right)^{K}+K\left(1-e^{\frac{-C_3}{P_{SMHB}}}\right)^{K-1}\left(e^{\frac{-C_3}{P_{SMHB}}}*\frac{C_3}{P_{SMHB}^{2}}\right)\left(1-e^{\frac{-C_1}{P_{SMHB}}}\right)\right)}$$

(A3 4.5)

Next, the derivatives of the total power consumption $P_{totMHB}$ and the outage probability $p_{outMHB}$ with respect to $\lambda_{MHB}$ are given by:

$$\frac{\left(2^{2R_s}-1\right)^{K+1}N^{K+1}}{P_{SMHB}^{K+1}\left|h_{SD}\right|^{2}\gamma_{SD}}\left(\left(\frac{1}{\left|h_{SR_1}\right|^{2}\gamma_{SR_1}}+\sum_{i=2}^{n}\frac{1}{\upsilon_{R_{i-1}R_i}^{\alpha}\left|h_{R_{i-1}Ri}\right|^{2}\gamma_{R_{i-1}R_i}}+\frac{1}{\upsilon_{R_nD}^{\alpha}\left|h_{R_nD}\right|^{2}\gamma_{R_nD}}\right)\right)^{K}-1+U=0 \quad \text{(A3 4.6)}$$

$$1-U=\frac{\left(2^{2R_s}-1\right)^{K+1}N^{K+1}}{P_{SMHB}^{K+1}\left|h_{SD}\right|^{2}\gamma_{SD}}\left(\left(\frac{1}{\left|h_{SR_1}\right|^{2}\gamma_{SR_1}}+\sum_{i=2}^{n}\frac{1}{\upsilon_{R_{i-1}R_i}^{\alpha}\left|h_{R_{i-1}Ri}\right|^{2}\gamma_{R_{i-1}R_i}}+\frac{1}{\upsilon_{R_nD}^{\alpha}\left|h_{R_nD}\right|^{2}\gamma_{R_nD}}\right)\right)^{K} \quad \text{(A3 4.7)}$$

$$P_{SMHB}^{K+1}=\frac{\left(2^{2R_s}-1\right)^{K+1}N^{K+1}}{(1-U)\left|h_{SD}\right|^{2}\gamma_{SD}}\left(\left(\frac{1}{\left|h_{SR_1}\right|^{2}\gamma_{SR_1}}+\sum_{i=2}^{n}\frac{1}{\upsilon_{R_{i-1}R_i}^{\alpha}\left|h_{R_{i-1}Ri}\right|^{2}\gamma_{R_{i-1}R_i}}+\frac{1}{\upsilon_{R_nD}^{\alpha}\left|h_{R_nD}\right|^{2}\gamma_{R_nD}}\right)\right)^{K} \quad \text{(A3 4.8)}$$

$$P_{MHBopt}=\left(2^{2R_s}-1\right)N\left(\frac{1}{(1-U)\left|h_{SD}\right|^{2}\gamma_{SD}}\left(\left(\frac{1}{\left|h_{SR_1}\right|^{2}\gamma_{SR_1}}+\sum_{i=2}^{n}\frac{1}{\upsilon_{R_{i-1}R_i}^{\alpha}\left|h_{R_{i-1}Ri}\right|^{2}\gamma_{R_{i-1}R_i}}+\frac{1}{\upsilon_{R_nD}^{\alpha}\left|h_{R_nD}\right|^{2}\gamma_{R_nD}}\right)\right)^{K}\right)^{\frac{1}{K+1}}$$

(A3 4.9)

## Appendix A-Ch3-4(b)

### This is the derivation of formula (3.96)

$$Max \sum S_{thMHB} \qquad s.t. \{ N_s (1 - p_o) p_s (1 - p_{eMHB}) \geq Qs \} \tag{A3 4.10}$$

$$L(L_p, \Lambda_{MHB}) = S_{thMHB} + \Lambda_{MHB} \left( N_s (1 - p_o) p_s (1 - p_{eMHB}) - Qs \right) \tag{A3 4.11}$$

$$\frac{\partial S_{thMHB}}{\partial L_p} + \Lambda_{MHB} \frac{\partial \left( N_s (1 - p_o) p_s (1 - p_{eMHB}) - Qs \right)}{\partial L_p} = 0 \tag{A3 4.12}$$

$$\frac{N_s (1-p_o) p_s \left( \left( (1-p_{eMHB}) + L_p \left( (1-X_3)^K \ln(1-p_{bSD}) X_1 + K*(1-X_3)^{K-1} (1-X_1) X_3 \left( \ln(1-p_{bSR_1}) + (n-1) \prod_{i=2}^{n} \ln(1-p_{bR_{i-1}R_i}) + \ln(1-p_{bR_nD}) \right) \right) \right) * \left( T_4 + (n+1) \frac{L_p}{R_b} \right) - \frac{(n+1) L_p (1-p_{eMHB})}{R_b} \right)}{\left( T_4 + (n+1) \frac{L_p}{R_b} \right)^2}$$

$$- \Lambda_{MHB} \; N_s (1-p_o) p_s \left( (1-X_3)^K \ln(1-p_{bSD}) X_1 + K*(1-X_3)^{K-1} (1-X_1) X_3 \left( \ln(1-p_{bSR_1}) + (n-1) \prod_{i=2}^{n} \ln(1-p_{bR_{i-1}R_i}) + \ln(1-p_{bR_nD}) \right) \right) = 0$$

where $T_4 = T_{SYNC} + T_{rts} + T_{rth} + T_{cts} + T_{Ack} + (4+n) * T_{SIFS} + T_{DIFS}$

$$\Lambda_{MHB} = - \frac{(1-p_{eMHB}) T_4 + \left( (1-X_3)^K \ln(1-p_{bSD}) X_1 + K*(1-X_3)^{K-1} (1-X_1) X_3 \left( \ln(1-p_{bSR_1}) + (n-1) \prod_{i=2}^{n} \ln(1-p_{bR_{i-1}R_i}) + \ln(1-p_{bR_nD}) \right) \right) L_p \left( T_4 + (n+1) \frac{L_p}{R_b} \right)}{\left( (1-X_3)^K \ln(1-p_{bSD}) X_1 + K*(1-X_3)^{K-1} (1-X_1) X_3 \left( \ln(1-p_{bSR_1}) + (n-1) \prod_{i=2}^{n} \ln(1-p_{bR_{i-1}R_i}) + \ln(1-p_{bR_nD}) \right) \right) \left( T_4 + (n+1) \frac{L_p}{R_b} \right)^2}$$

(A3 4.13)

$$\frac{\partial S_{thMHB}}{\partial \Lambda_{MHB}} + \Lambda_{MHB} \frac{\partial \left( N_s (1 - p_o) p_s (1 - p_{eMHB}) - Qs \right)}{\partial \Lambda_{MHB}} = 0 \tag{A3 4.14}$$

$$N_s (1 - p_o) p_s (1 - p_{eMHB}) - Qs = 0$$

$$(1 - X_1)(1 - X_3)^K = \frac{Qs}{N (1 - p_o) p_s}$$

$$\left( 1 - e^{L_p \ln(1-p_{bSD})} \right) \left( 1 - e^{L_p \left( \ln(1-p_{bSR_1}) + (n-1) \prod_{i=2}^{n} \ln(1-p_{bR_{i-1}R_i}) + \ln(1-p_{bR_nD}) \right)} \right)^K = \frac{Qs}{N_s (1 - p_o) p_s}$$

$$\left( 1 - L_p \ln(1-p_{bSD}) \right) \left( 1 - L_p \left( \ln(1-p_{bSR_1}) + (n-1) \prod_{i=2}^{n} \ln(1-p_{bR_{i-1}R_i}) + \ln(1-p_{bR_nD}) \right) \right)^K = \frac{Qs}{N_s (1 - p_o) p_s}$$

$$L_p^{K+1} \left( -\ln(1-p_{bSD}) \right) \left( - \left( \ln(1-p_{bSR_1}) + (n-1) \prod_{i=2}^{n} \ln(1-p_{bR_{i-1}R_i}) + \ln(1-p_{bR_nD}) \right) \right)^K = \frac{Qs}{N_s (1 - p_o) p_s}$$

$$L_{pMHBopt} = \left( \frac{Qs}{N_s (1-p_o) p_s \left( -\ln(1-p_{bSD}) \right) \left( - \left( \ln(1-p_{bSR_1}) + (n-1) \prod_{i=2}^{n} \ln(1-p_{bR_{i-1}R_i}) + \ln(1-p_{bR_nD}) \right) \right)^K} \right)^{\frac{1}{K+1}}$$

(A3 4.15)

# Appendix A-Ch4-1(a)

## This is the derivation of formula (4.13)

$$R_{CBCM} = B\log_2\left(1+\frac{P_C\left|h_{CB}\right|^2\gamma_{CB}}{N_oB}\right)$$

$$\left(2^{\frac{R_{CBCM}}{\delta B}}-1\right)=\frac{P_C\left|h_{CB}\right|^2\gamma_{CB}}{N_oB}$$

$$P_{Creq}=\frac{\left(2^{\frac{R_{CBCM}}{\delta B}}-1\right)N_oB}{\left|h_{CB}\right|^2\gamma_{CB}} \tag{A4 1.1}$$

$$R_{BDRx}=\frac{1}{2}(1-\delta)B\log_2\left(1+\frac{P_D\left|h_{DTxB}\right|^2\gamma_{DTxB}}{N_oB}\right)$$

$$\left(2^{\frac{2R_{BDRx}}{(1-\delta)B}}-1\right)=\frac{P_D\left|h_{DTxB}\right|^2\gamma_{DTxB}}{N_oB}$$

$$P_{Dreq}=\frac{\left(2^{\frac{2R_{BDRx}}{(1-\delta)B}}-1\right)N_oB}{\left|h_{DTxB}\right|^2\gamma_{DTxB}} \tag{A4 1.2}$$

# Appendix A-Ch4-1(b)

## This is the derivation of formulas (4.17) and (4.18)

$$Max \Sigma EE_{CM} \qquad s.t. \{P_{Creq} \le P_{C\max}; P_{Dreq} \le P_{D\max}\} \tag{A4 1.3}$$

$$L(P_{Creq}, P_{Dreq}, \psi_{CCM}, \psi_{DCM}) = EE_{CM} + \psi_{CCM}(P_{C\max} - P_{Creq}) + \psi_{DCM}(P_{D\max} - P_{Dreq}) \tag{A4 1.4}$$

where $P_{Cmax}$ and $P_{Dmax}$ are CUE-BS and D2D maximum transmitted power, respectively. $\psi_{CCM}$ and $\psi_{DCM}$ denote Lagrangian factor for CUE-BS and D2D power constraint for CM, respectively.

$$\frac{\partial EE_{CM}}{\partial P_{Creq}} + \psi_{CCM}\frac{\partial(P_{C\max} - P_{Creq})}{\partial P_{Creq}} + \psi_{DCM}\frac{\partial(P_{D\max} - P_{Dreq})}{\partial P_{Creq}} = 0 \tag{A4 1.5}$$

$$\frac{\delta B(P_{Creq} + P_o)|h_{CB}|^2 \gamma_{CB}}{(P_{Creq} + P_o)^2 (N_o B + P_{Creq}|h_{CB}|^2 \gamma_{CB})} - \frac{\delta B \log_2\left(1 + \frac{P_{Creq}|h_{CB}|^2 \gamma_{CB}}{N}\right)}{(P_{Creq} + P_o)^2} - \psi_{CCM} = 0$$

$$\psi_{CCM} = \delta B\left(\frac{|h_{CB}|^2 \gamma_{CB}}{(P_{Creq} + P_o)(N_o B + P_{Creq}|h_{CB}|^2 \gamma_{CB})} - \frac{\log_2\left(1 + \frac{P_{Creq}|h_{CB}|^2 \gamma_{CB}}{N}\right)}{(P_{Creq} + P_o)^2}\right) \tag{A4 1.6}$$

$$\frac{\partial EE_{CM}}{\partial P_{Dreq}} + \psi_{CCM}\frac{\partial(P_{C\max} - P_{Creq})}{\partial P_{Dreq}} + \psi_{DCM}\frac{\partial(P_{D\max} - P_{Dreq})}{\partial P_{Dreq}} = 0 \tag{A4 1.7}$$

$$\frac{1}{2}(1-\delta)\frac{B(P_B + P_{Dreq} + 2P_o)|h_{DTxB}|^2 \gamma_{DTxB}}{(P_B + P_{Dreq} + 2P_o)^2 (N_o B + P_{Dreq}|h_{DTxB}|^2 \gamma_{DTxB})} - \frac{1}{2}(1-\delta)\frac{B \log_2\left(1 + \frac{P_{Dreq}|h_{DTxB}|^2 \gamma_{DTxB}}{N}\right)}{(P_B + P_{Dreq} + 2P_o)^2} - \psi_{DCM} = 0$$

$$\psi_{DCM} = \frac{1}{2}(1-\delta)B\left[\frac{|h_{DTxB}|^2 \gamma_{DTxB}}{(P_B + P_{Drew} + 2P_o)(N_o B + P_{Dreq}|h_{DTxB}|^2 \gamma_{DTxB})} - \frac{\log_2\left(1 + \frac{P_{Drea}|h_{DTxB}|^2 \gamma_{DTxB}}{N}\right)}{(P_B + P_{Dreq} + 2P_o)^2}\right]$$

(A4 1.8)

$$\frac{\partial EE_{CM}}{\partial \psi_{CCM}} + \psi_{CCM}\frac{\partial(P_{C\max} - P_{Creq})}{\partial \psi_{CCM}} + \psi_{DCM}\frac{\partial(P_{D\max} - P_{Dreq})}{\partial \psi_{CCM}} = 0$$

$$P_{C\max} = P_{Creq} \tag{A4 1.9}$$

$$\frac{\partial EE_{CM}}{\partial \psi_{DCM}} + \psi_{CCM}\frac{\partial(P_{C\max} - P_{Creq})}{\partial \psi_{DCM}} + \psi_{DCM}\frac{\partial(P_{D\max} - P_{Dreq})}{\partial \psi_{DCM}} = 0$$

$$P_{D\max} = P_{Dreq} \tag{A4 1.10}$$

## Appendix A-Ch4-1(c)

### This is the derivation of formulas (4.22) and (4.23)

$$Max \Sigma DR_{CM} \qquad s.t. \{P_{Creq} \le P_{C\max}; P_{Dreq} \le P_{D\max}\} \qquad \text{(A4 1.11)}$$

$$L(P_{Creq}, P_{Dreq}, \psi_{CCM}, \psi_{DCM}) = DR_{CM} + \Omega_{CCM}\left(P_{C\max} - P_{Creq}\right) + \Omega_{DCM}\left(P_{D\max} - P_{Dreq}\right) \quad \text{(A4 1.12)}$$

where $\Omega_{CCM}$ and $\Omega_{DCM}$ denote the Lagrangian factors for power constraint of CUE-BS and D2D links in CM, respectively.

$$\frac{\partial DR_{CM}}{\partial P_{Creq}} + \Omega_{CCM}\frac{\partial\left(P_{C\max} - P_{Creq}\right)}{\partial P_{Creq}} + \Omega_{DCM}\frac{\partial\left(P_{D\max} - P_{Dreq}\right)}{\partial P_{Creq}} = 0$$

$$\frac{\delta B|h_{CB}|^2 \gamma_{CB}}{N_o B + P_{Creq}|h_{CB}|^2 \gamma_{CB}} - \Omega_{CCM} = 0$$

$$\Omega_{CCM} = \frac{\delta B|h_{CB}|^2 \gamma_{CB}}{N_o B + P_{Creq}|h_{CB}|^2 \gamma_{CB}} \qquad \text{(A4 1.13)}$$

$$\frac{\partial DR_{CM}}{\partial P_{Dreq}} + \Omega_{CCM}\frac{\partial\left(P_{C\max} - P_{Creq}\right)}{\partial P_{Dreq}} + \Omega_{DCM}\frac{\partial\left(P_{D\max} - P_{Dreq}\right)}{\partial P_{Dreq}} = 0$$

$$\frac{(1-\delta)B|h_{DTxB}|^2 \gamma_{DTxB}}{2\left(N_o B + P_{Dreq}|h_{DTxB}|^2 \gamma_{DTxB}\right)} - \Omega_{DCM} = 0$$

$$\Omega_{DCM} = \frac{(1-\delta)B|h_{DTxB}|^2 \gamma_{DTxB}}{2\left(N_o B + P_{Dreq}|h_{DTxB}|^2 \gamma_{DTxB}\right)} \qquad \text{(A4 1.14)}$$

$$\frac{\partial DR_{CM}}{\partial \Omega_{CCM}} + \Omega_{CCM}\frac{\partial\left(P_{C\max} - P_{Creq}\right)}{\partial \Omega_{CCM}} + \Omega_{DCM}\frac{\partial\left(P_{D\max} - P_{Dreq}\right)}{\partial \Omega_{CCM}} = 0$$

$$P_{C\max} = P_{Creq} \qquad \text{(A4 1.15)}$$

$$\frac{\partial DR_{CM}}{\partial \Omega_{DCM}} + \Omega_{CCM}\frac{\partial\left(P_{C\max} - P_{Creq}\right)}{\partial \Omega_{DCM}} + \Omega_{DCM}\frac{\partial\left(P_{D\max} - P_{Dreq}\right)}{\partial \Omega_{DCM}} = 0$$

$$P_{D\max} = P_{Dreq} \qquad \text{(A4 1.16)}$$

## Appendix A-Ch4-2(a)

### This is the derivation of formula (4.35)

$$R_{CBDM} = B\log_2\left(1+\frac{P_C|h_{CB}|^2\gamma_{CB}}{P_D|h_{DB}|^2\gamma_{DB}+N_oB}\right)$$

$$\left(2^{\frac{R_{CBDM}}{B}}-1\right)=\frac{P_C|h_{CB}|^2\gamma_{CB}}{P_D|h_{DB}|^2\gamma_{DB}+N_oB}$$

$$P_D=\frac{P_C|h_{CB}|^2\gamma_{CB}}{\left(2^{\frac{R_{CBCM}}{B}}-1\right)|h_{DB}|^2\gamma_{DB}}-\frac{N_oB}{|h_{DB}|^2\gamma_{DB}} \quad \text{(A4 2.1)}$$

$$R_{D2DDM} = B\log_2\left(1+\frac{P_D|h_{DD}|^2\gamma_{DD}}{P_C|h_{CD}|^2\gamma_{CD}+N_oB}\right)$$

$$\left(2^{\frac{R_{D2DDM}}{B}}-1\right)=\frac{P_D|h_{DD}|^2\gamma_{DD}}{P_C|h_{CD}|^2\gamma_{CD}+N_oB}$$

$$P_D=\frac{\left(2^{\frac{R_{D2DDM}}{B}}-1\right)N_oB}{|h_{DD}|^2\gamma_{DD}}+\frac{\left(2^{\frac{R_{D2DDM}}{B}}-1\right)P_C|h_{CD}|^2\gamma_{CD}}{|h_{DD}|^2\gamma_{DD}} \quad \text{(A4 2.2)}$$

By solving Equation (A4 2.1) with Equation (A4 2.2) the required transmitted power ($P_{CDMreq}$) of CUE-BS link can be obtained as follows:

$$\frac{P_C|h_{CB}|^2\gamma_{CB}}{\left(2^{\frac{R_{CBCM}}{B}}-1\right)|h_{DB}|^2\gamma_{DB}}-\frac{N_oB}{|h_{DB}|^2\gamma_{DB}}=\frac{\left(2^{\frac{R_{D2DDM}}{B}}-1\right)N_oB}{|h_{DD}|^2\gamma_{DD}}+\frac{\left(2^{\frac{R_{D2DDM}}{B}}-1\right)P_C|h_{CD}|^2\gamma_{CD}}{|h_{DD}|^2\gamma_{DD}}$$

$$P_{CDMreq}=\frac{\left(2^{\frac{R_{D2DDM}}{B}}-1\right)\left(2^{\frac{R_{CBCM}}{B}}-1\right)|h_{DB}|^2\gamma_{DB}N_oB+\left(2^{\frac{R_{CBCM}}{B}}-1\right)N_oB|h_{DD}|^2\gamma_{DD}}{|h_{CB}|^2\gamma_{CB}|h_{DD}|^2\gamma_{DD}-\left(2^{\frac{R_{CBCM}}{B}}-1\right)\left(2^{\frac{R_{D2DDM}}{B}}-1\right)|h_{DB}|^2\gamma_{DB}|h_{CD}|^2\gamma_{CD}} \quad \text{(A4 2.3)}$$

The required transmission power of the D2D link in DM can be obtained by substituting Equation (A4 2.3) in Equation (A4 2.2). Then $P_{DDMreq}$ can be expressed as follows:

$$P_{DDMreq}=\frac{\left(2^{\frac{R_{D2DDM}}{B}}-1\right)N_oB}{|h_{DD}|^2\gamma_{DD}}+\frac{\left(2^{\frac{R_{D2DDM}}{B}}-1\right)P_{CDMreq}|h_{CD}|^2\gamma_{CD}}{|h_{DD}|^2\gamma_{DD}} \quad \text{(A4 2.4)}$$

# Appendix A-Ch4-2(b)

## This is the derivation of formulas (4.39) and (4.40)

$$Max \Sigma EE_{DM} \qquad s.t.\left\{P_{CDMreq} \le P_{C\max}; P_{DDMreq} \le P_{D\max}\right\} \qquad \text{(A4 2.5)}$$

$$L(P_{CDMreq}, P_{DDMreq}, \psi_{CDM}, \psi_{DDM}) = EE_{DM} + \psi_{CDM}\left(P_{C\max} - P_{CDMreq}\right) + \psi_{DDM}\left(P_{D\max} - P_{DDMreq}\right) \text{ (A4 2.6)}$$

where $\psi_{CDM}$ and $\psi_{DDM}$ denote Lagrangian factor for CUE-BS and D2D power constraint for DM, respectively.

$$\frac{\partial EE_{DM}}{\partial P_{CDMreq}} + \psi_{CDM}\frac{\partial\left(P_{C\max} - P_{CDMreq}\right)}{\partial P_{CDMreq}} + \psi_{DDM}\frac{\partial\left(P_{D\max} - P_{DDMreq}\right)}{\partial P_{CDMreq}} = 0 \qquad \text{(A4 2.7)}$$

$$\frac{B\left(P_{CDMreq} + P_o\right)\left|h_{CB}\right|^2\gamma_{CB}}{\left(P_{CDMreq} + P_o\right)^2\left(N_oB + P_{CDMreq}\left|h_{CB}\right|^2\gamma_{CB} + P_{DDMreq}\left|h_{DB}\right|^2\gamma_{DB}\right)} - \frac{B\log_2\left(1 + \frac{P_{CDMreq}\left|h_{CB}\right|^2\gamma_{CB}}{N_oB + P_{DDMreq}\left|h_{DB}\right|^2\gamma_{DB}}\right)}{\left(P_{CDMreq} + P_o\right)^2}$$
$$- \frac{BP_{DDMreq}\left|h_{CD}\right|^2\gamma_{CD}\left|h_{DD}\right|^2\gamma_{DD}}{\left(P_{DDMreq} + P_o\right)\left(P_{CDMreq}\left|h_{CD}\right|^2\gamma_{CD} + N_oB\right)\left(P_{CDMreq}\left|h_{CD}\right|^2\gamma_{CD} + P_{DDMreq}\left|h_{DD}\right|^2\gamma_{DD} + N_oB\right)} - \psi_{CDM} = 0$$
$$\text{(A4 2.8)}$$

$$\psi_{CDM} = \frac{B\left|h_{CB}\right|^2\gamma_{CB}}{\left(P_{CDMreq} + P_o\right)\left(N_oB + P_{CDMreq}\left|h_{CB}\right|^2\gamma_{CB} + P_{DDMreq}\left|h_{DB}\right|^2\gamma_{DB}\right)} \quad \frac{B\log_2\left(1 + \frac{P_{CDMreq}\left|h_{CB}\right|^2\gamma_{CB}}{N_oB + P_{DDMreq}\left|h_{DB}\right|^2\gamma_{DB}}\right)}{\left(P_{CDMreq} + P_o\right)^2}$$
$$\frac{BP_{DDMreq}\left|h_{CD}\right|^2\gamma_{CD}\left|h_{DD}\right|^2\gamma_{DD}}{\left(P_{DDMreq} + P_o\right)\left(P_{CDMreq}\left|h_{CD}\right|^2\gamma_{CD} + N_oB\right)\left(P_{CDMreq}\left|h_{CD}\right|^2\gamma_{CD} + P_{DDMreq}\left|h_{DD}\right|^2\gamma_{DD} + N_oB\right)}$$

$$\frac{\partial EE_{DM}}{\partial P_{DDMreq}} + \psi_{CDM}\frac{\partial\left(P_{C\max} - P_{CDMreq}\right)}{\partial P_{DDMreq}} + \psi_{DDM}\frac{\partial\left(P_{D\max} - P_{DDMreq}\right)}{\partial P_{DDMreq}} = 0 \qquad \text{(A4 2.9)}$$

$$\psi_{DDM} = \frac{-BP_{CDMreq}\left|h_{CB}\right|^2\gamma_{CB}\left|h_{DB}\right|^2\gamma_{DB}}{\left(P_{CDMreq} + P_o\right)\left(N_oB + P_{DDMreq}\left|h_{DB}\right|^2\gamma_{DB}\right)\left(N_oB + P_{DDMreq}\left|h_{DB}\right|^2\gamma_{DB} + P_{CDMreq}\left|h_{CB}\right|^2\gamma_{CB}\right)}$$
$$- \frac{B\log_2\left(1 + \frac{P_{DDMreq}\left|h_{DD}\right|^2\gamma_{DD}}{N_oB + P_{CDMreq}\left|h_{CD}\right|^2\gamma_{CD}}\right)}{\left(P_{DDMreq} + P_o\right)^2} - \frac{B\left|h_{DD}\right|^2\gamma_{DD}}{\left(P_{DDMreq} + P_o\right)\left(N_oB + P_{DDMreq}\left|h_{DD}\right|^2\gamma_{DD} + P_{CDMreq}\left|h_{CD}\right|^2\gamma_{CD}\right)}$$
$$\text{(A4 2.10)}$$

$$\frac{\partial EE_{DM}}{\partial \psi_{CDM}} + \psi_{CDM}\frac{\partial\left(P_{C\max} - P_{CDMreq}\right)}{\partial \psi_{CDM}} + \psi_{DDM}\frac{\partial\left(P_{D\max} - P_{DDMreq}\right)}{\partial \psi_{CDM}} = 0$$

$$P_{C\max} = P_{CDMreq} \qquad \text{(A4 2.11)}$$

$$\frac{\partial EE_{CM}}{\partial \psi_{DDM}} + \psi_{CDM}\frac{\partial\left(P_{C\max} - P_{CDMreq}\right)}{\partial \psi_{DCM}} + \psi_{DDM}\frac{\partial\left(P_{D\max} - P_{DDMreq}\right)}{\partial \psi_{DDM}} = 0$$

$$P_{D\max} = P_{DDMreq} \qquad \text{(A4 2.12)}$$

## Appendix A-Ch4-2(c)

**This is the derivation of formulas (4.44) and (4.45)**

$$Max \Sigma DR_{DM} \qquad s.t.\{P_{CDMreq} \le P_{C\max} ; P_{DDMreq} \le P_{D\max}\} \quad \text{(A4 2.13)}$$

$$L(P_{CDMreq}, P_{DDMreq}, \psi_{CDM}, \psi_{DDM}) = DR_{DM} + \Omega_{CDM}\left(P_{C\max} - P_{CDMreq}\right) + \Omega_{DDM}\left(P_{D\max} - P_{DDMreq}\right) \quad \text{(A4 2.14)}$$

where $\Omega_{CDM}$ and $\Omega_{DDM}$ denote the Lagrangian factors for power constraint of CUE-BS and D2D links in DM, respectively.

$$\frac{\partial DR_{DM}}{\partial P_{CDMreq}} + \Omega_{CDM}\frac{\partial\left(P_{C\max} - P_{CDMreq}\right)}{\partial P_{CDMreq}} + \Omega_{DDM}\frac{\partial\left(P_{D\max} - P_{DDMreq}\right)}{\partial P_{CDMreq}} = 0$$

$$\frac{B|h_{CB}|^2\gamma_{CB}}{N_oB + P_{CDMreq}|h_{CB}|^2\gamma_{CB} + P_{DDMreq}|h_{DB}|^2\gamma_{DB}} - \frac{B\,P_{DDMreq}|h_{DD}|^2\gamma_{DD}|h_{CD}|^2\gamma_{CD}}{\left(N_oB + P_{CDMreq}|h_{CD}|^2\gamma_{CD} + P_{DDMreq}|h_{DD}|^2\gamma_{DD}\right)\left(N_oB + P_{CDMreq}|h_{CB}|^2\gamma_{CB}\right)} - \Omega_{CDM} = 0$$

$$\Omega_{CDM} = \frac{B|h_{CB}|^2\gamma_{CB}}{N_oB + P_{CDMreq}|h_{CB}|^2\gamma_{CB} + P_{DDMreq}|h_{DB}|^2\gamma_{DB}} - \frac{B\,P_{DDMreq}|h_{DD}|^2\gamma_{DD}|h_{CD}|^2\gamma_{CD}}{\left(N_oB + P_{CDMreq}|h_{CD}|^2\gamma_{CD} + P_{DDMreq}|h_{DD}|^2\gamma_{DD}\right)\left(N_oB + P_{CDMreq}|h_{DB}|^2\gamma_{DB}\right)} \quad \text{(A4 2.15)}$$

$$\frac{\partial DR_{DM}}{\partial P_{DDMreq}} + \Omega_{CDM}\frac{\partial\left(P_{C\max} - P_{CDMreq}\right)}{\partial P_{DDMreq}} + \Omega_{DDM}\frac{\partial\left(P_{D\max} - P_{DDMreq}\right)}{\partial P_{DDMreq}} = 0$$

$$\frac{-B\,P_{CDMreq}|h_{CB}|^2\gamma_{CB}|h_{DB}|^2\gamma_{DB}}{\left(N_oB + P_{CDMreq}|h_{CB}|^2\gamma_{CB} + P_{DDMreq}|h_{DB}|^2\gamma_{DB}\right)\left(N_oB + P_{DDMreq}|h_{DB}|^2\gamma_{DB}\right)} + \frac{B|h_{DD}|^2\gamma_{DD}}{\left(N_oB + P_{CDMreq}|h_{CD}|^2\gamma_{CD} + P_{DDMreq}|h_{DD}|^2\gamma_{DD}\right)} - \Omega_{DDM} = 0$$

$$\Omega_{DDM} = \frac{-B\,P_{CDMreq}|h_{CB}|^2\gamma_{CB}|h_{DB}|^2\gamma_{DB}}{\left(N_oB + P_{CDMreq}|h_{CB}|^2\gamma_{CB} + P_{DDMreq}|h_{DB}|^2\gamma_{DB}\right)\left(N_oB + P_{DDMreq}|h_{DB}|^2\gamma_{DB}\right)} + \frac{B|h_{DD}|^2\gamma_{DD}}{\left(N_oB + P_{CDMreq}|h_{CD}|^2\gamma_{CD} + P_{DDMreq}|h_{DD}|^2\gamma_{DD}\right)} \quad \text{(A4 2.16)}$$

$$\frac{\partial DR_{DM}}{\partial \Omega_{CDM}} + \Omega_{CDM}\frac{\partial\left(P_{C\max} - P_{CDMreq}\right)}{\partial \Omega_{CDM}} + \Omega_{DDM}\frac{\partial\left(P_{D\max} - P_{DDMreq}\right)}{\partial \Omega_{CDM}} = 0$$

$$P_{C\max} = P_{CDMreq} \quad \text{(A4 2.17)}$$

$$\frac{\partial DR_{DM}}{\partial \Omega_{DDM}} + \Omega_{CDM}\frac{\partial\left(P_{C\max} - P_{CDMreq}\right)}{\partial \Omega_{DDM}} + \Omega_{DDM}\frac{\partial\left(P_{D\max} - P_{DDMreq}\right)}{\partial \Omega_{DDM}} = 0$$

$$P_{D\max} = P_{DDMreq} \quad \text{(A4 2.18)}$$

## Appendix A-Ch4-3(a)

### This is the derivation of formula (4.54)

$$R_{CBCoopD2D} = B\log_2\left(1+\frac{P_C|h_{CB}|^2\gamma_{CB}}{\sum_{j=1}^{K}\sum_{l=1}^{n}P_D|h_{DjlB}|^2\gamma_{DjlB}+N_oB}\right)$$

$$\left(2^{\frac{R_{CBCoopD2D}}{B}}-1\right)=\frac{P_C|h_{CB}|^2\gamma_{CB}}{\sum_{j=1}^{K}\sum_{l=1}^{n}P_D|h_{DjlB}|^2\gamma_{DjlB}+N_oB}$$

$$P_D=\frac{P_C|h_{CB}|^2\gamma_{CB}}{\left(2^{\frac{R_{CBCoopD2D}}{B}}-1\right)\sum_{j=1}^{K}\sum_{l=1}^{n}P_D|h_{DjlB}|^2\gamma_{DjlB}}-\frac{N_oB}{\sum_{j=1}^{K}\sum_{l=1}^{n}P_D|h_{DjlB}|^2\gamma_{DjlB}} \quad \text{(A4 3.1)}$$

$$R_{D2DCoop}=\frac{B}{((K*n)+1)}\log_2\left(1+\frac{P_D|h_{DD}|^2\gamma_{DD}}{P_C|h_{CD}|^2\gamma_{CD}+N_oB}+\sum_{j=1}^{K}\frac{P_{DD}|h_{rjDRx}|^2\gamma_{rjDRx}}{P_C|h_{CDRx}|^2\gamma_{CDRx}+N_oB}\right)$$

For simplicity, assuming $P_D=P_{DD}$

$$\left(2^{\frac{((K*n)+1)*R_{CoopD2D}}{B}}-1\right)=\frac{P_D|h_{DD}|^2\gamma_{DD}}{P_C|h_{CD}|^2\gamma_{CD}+N_oB}+\sum_{j=1}^{K}\frac{P_D|h_{rjDRx}|^2\gamma_{rjDRx}}{P_C|h_{CDRx}|^2\gamma_{CDRx}+N_oB}$$

$$P_D=\frac{\left(2^{\frac{((K*n)+1)*R_{CoopD2D}}{B}}-1\right)P_C}{\left[\frac{|h_{DD}|^2\gamma_{DD}}{|h_{CD}|^2\gamma_{CD}+N_oB}+\sum_{j=1}^{K}\frac{|h_{rjDRx}|^2\gamma_{rjDRx}}{|h_{CDRx}|^2\gamma_{CDRx}+N_oB}\right]} \quad \text{(A4 3.2)}$$

By solving Equation (A4 3.1) with Equation (A4 3.2) the required transmitted power ($P_{CCDreq}$) of CUE-BS link can be obtained as follows:

$$\frac{\left(2^{\frac{(((K*n)+1)+1)*R_{CoopD2D}}{B}}-1\right)P_C}{\left[\frac{|h_{DD}|^2\gamma_{DD}}{|h_{CD}|^2\gamma_{CD}+N_oB}+\sum_{j=1}^{K}\frac{|h_{rjDRx}|^2\gamma_{rjDRx}}{|h_{CDRx}|^2\gamma_{CDRx}+N_oB}\right]}=\frac{P_C|h_{CB}|^2\gamma_{CB}}{\left(2^{\frac{R_{CBCoopD2D}}{B}}-1\right)\sum_{j=1}^{K}\sum_{l=1}^{n}P_D|h_{DjlB}|^2\gamma_{DjlB}}-\frac{N_oB}{\sum_{j=1}^{K}\sum_{l=1}^{n}P_D|h_{DjlB}|^2\gamma_{DjlB}}$$

$$P_{CCDreq} = \frac{\frac{N_o B}{\sum_{j=1}^{K}\sum_{l=1}^{n} P_D \left|h_{DjlB}\right|^2 \gamma_{DjlB}} \left[\left(2^{\frac{R_{CBCoopD2D}}{B}} - 1\right) \sum_{j=1}^{K}\sum_{l=1}^{n} P_D \left|h_{DjlB}\right|^2 \gamma_{DjlB}\right] \left[\frac{\left|h_{DD}\right|^2 \gamma_{DD}}{\left|h_{CD}\right|^2 \gamma_{CD} + N_o B} + \sum_{j=1}^{K} \frac{\left|h_{rjDRx}\right|^2 \gamma_{rjDRx}}{\left|h_{CDRx}\right|^2 \gamma_{CDRx} + N_o B}\right]}{\left[\left[\frac{\left|h_{DD}\right|^2 \gamma_{DD}}{\left|h_{CD}\right|^2 \gamma_{CD} + N_o B} + \sum_{j=1}^{K} \frac{\left|h_{rjDRx}\right|^2 \gamma_{rjDRx}}{\left|h_{CDRx}\right|^2 \gamma_{CDRx} + N_o B}\right] \left|h_{CB}\right|^2 \gamma_{CB} - \left[\left(2^{\frac{R_{CBCoopD2D}}{B}} - 1\right) \sum_{j=1}^{K}\sum_{l=1}^{n} P_D \left|h_{DjlB}\right|^2 \gamma_{DjlB}\right] \left(2^{\frac{((K*n)+1)*R_{CoopD2D}}{B}} - 1\right)\right]}$$

(A4 3.3)

The required transmission power of the D2D link in CoopD2D by substituting Equation (A4 3.3) in Equation (A4 3.2), then $P_{DCDreq}$ can be expressed as follows:

$$P_{DCDreq} = \frac{\left(2^{\frac{((K*n)+1)*R_{CoopD2D}}{B}} - 1\right) P_{CCDreq}}{\left[\frac{\left|h_{DD}\right|^2 \gamma_{DD}}{\left|h_{CD}\right|^2 \gamma_{CD} + N_o B} + \sum_{j=1}^{K} \frac{\left|h_{rjDRx}\right|^2 \gamma_{rjDRx}}{\left|h_{CDRx}\right|^2 \gamma_{CDRx} + N_o B}\right]} \quad \text{(A4 3.4)}$$

## Appendix A-Ch4-3(b)

### This is the derivation of formulas (4.58) and (4.59)

$$Max \Sigma EE_{CD} \qquad s.t.\{P_{CCDreq} \le P_{C\max}; P_{DCMreq} \le P_{D\max}\} \qquad \text{(A4 3.5)}$$

$$L(P_{CCDreq}, P_{DCDreq}, \psi_{CCD}, \psi_{DCD}) = EE_{CD} + \psi_{CCD}(P_{C\max} - P_{CCDreq}) + \psi_{DCD}(P_{D\max} - P_{DCDreq}) \qquad \text{(A4 3.6)}$$

where $\psi_{CCD}$ and $\psi_{DCD}$ denote Lagrangian factor for CUE-BS and D2D power constraint for CoopD2D, respectively.

$$\frac{\partial EE_{CD}}{\partial P_{CCDreq}} + \psi_{CDM}\frac{\partial(P_{C\max} - P_{CCDreq})}{\partial P_{CCDreq}} + \psi_{DCD}\frac{\partial(P_{D\max} - P_{DCDreq})}{\partial P_{CCDreq}} = 0 \qquad \text{(A4 3.7)}$$

$$\frac{B(P_{CCDreq}+P_o)|h_{CB}|^2\gamma_{CB}}{(P_{CCDreq}+P_o)^2\left(N_oB + P_{CCDreq}|h_{CB}|^2\gamma_{CB} + P_{DCDreq}\sum_{j=1}^{K}\sum_{l=1}^{n}|h_{DjlB}|^2\gamma_{DjlB}\right)} - \frac{B\log_2\left(1+\frac{P_{CCDreq}|h_{CB}|^2\gamma_{CB}}{N_oB+\sum_{j=1}^{K}\sum_{l=1}^{n}P_D|h_{DjlB}|^2\gamma_{DjlB}}\right)}{(P_{CCDreq}+P_o)^2}$$
$$-\frac{B\left(\frac{P_{DCDreq}|h_{DD}|^2\gamma_{DD}|h_{CD}|^2\gamma_{CD}}{(P_{CCDreq}|h_{CD}|^2\gamma_{CD}+N_oB)^2} + \sum_{j=1}^{K}\frac{P_{DCDreq}|h_{rjDRx}|^2\gamma_{rjDRx}|h_{CDRx}|^2\gamma_{CDRx}}{(P_{CCDreq}|h_{CDRx}|^2\gamma_{CDRx}+N_oB)^2}\right)}{((K*n)+1)^2(P_{DCDreq}+P_o)\left(1+\frac{P_{DCDreq}|h_{DD}|^2\gamma_{DD}}{P_{CCDreq}|h_{CD}|^2\gamma_{CD}+N_oB} + \sum_{j=1}^{K}\frac{P_{DCDreq}|h_{rjDRx}|^2\gamma_{rjDRx}}{P_{CCDreq}|h_{CDRx}|^2\gamma_{CDRx}+N_oB}\right)} - \psi_{CCD} = 0$$

$$\psi_{CCD} = \frac{B|h_{CB}|^2\gamma_{CB}}{(P_{CCDreq}+P_o)\left(N_oB + P_{CCDreq}|h_{CB}|^2\gamma_{CB} + P_{DCDreq}\sum_{j=1}^{K}\sum_{l=1}^{n}|h_{DjlB}|^2\gamma_{DjlB}\right)} - \frac{B\log_2\left(1+\frac{P_{CCDreq}|h_{CB}|^2\gamma_{CB}}{N_oB+\sum_{j=1}^{K}\sum_{l=1}^{n}P_D|h_{DjlB}|^2\gamma_{DjlB}}\right)}{(P_{CCDreq}+P_o)^2}$$
$$\frac{B\left(\frac{P_{DCDreq}|h_{DD}|^2\gamma_{DD}|h_{CD}|^2\gamma_{CD}}{(P_{CCDreq}|h_{CD}|^2\gamma_{CD}+N_oB)^2} + \sum_{j=1}^{K}\frac{P_{DCDreq}|h_{rjDRx}|^2\gamma_{rjDRx}|h_{CDRx}|^2\gamma_{CDRx}}{(P_{CCDreq}|h_{CDRx}|^2\gamma_{CDRx}+N_oB)^2}\right)}{((K*n)+1)^2\left(1+\frac{P_{DCDreq}|h_{DD}|^2\gamma_{DD}}{P_{CCDreq}|h_{CD}|^2\gamma_{CD}+N_oB} + \sum_{j=1}^{K}\frac{P_{DCDreq}|h_{rjDRx}|^2\gamma_{rjDRx}}{P_{CCDreq}|h_{CDRx}|^2\gamma_{CDRx}+N_oB}\right)}$$

(A4 3.8)

$$\frac{\partial EE_{CD}}{\partial P_{DCDreq}} + \psi_{CCD}\frac{\partial(P_{C\max} - P_{CCDreq})}{\partial P_{DCDreq}} + \psi_{DCD}\frac{\partial(P_{D\max} - P_{DCDreq})}{\partial P_{DCDreq}} = 0 \qquad \text{(A4 3.9)}$$

$$\frac{-P_{CCDreq}|h_{CB}|^2\gamma_{CB}\left(\sum_{j=1}^{K}\sum_{l=1}^{n}|h_{DjlB}|^2\gamma_{DjlB}\right)}{\left(P_{CCDreq}+P_o\right)\left(\sum_{j=1}^{K}\sum_{l=1}^{n}P_{DCDreq}|h_{DjlB}|^2\gamma_{DjlB}+N_oB+P_{CCDreq}|h_{CB}|^2\gamma_{CB}\right)}$$
$$+\frac{B\frac{|h_{DD}|^2\gamma_{DD}}{P_C|h_{CD}|^2\gamma_{CD}+N_oB}+\sum_{j=1}^{K}\frac{|h_{rjDRx}|^2\gamma_{rjDRx}}{P_C|h_{CDRx}|^2\gamma_{CDRx}+N_oB}}{((K*n)+1)^2\left(P_{DCDreq}+P_o\right)\left(1+\frac{P_{DCDreq}|h_{DD}|^2\gamma_{DD}}{P_{CCDreq}|h_{CD}|^2\gamma_{CD}+N_oB}+\sum_{j=1}^{K}\frac{P_{DCDreq}|h_{rjDRx}|^2\gamma_{rjDRx}}{P_{CCDreq}|h_{CDRx}|^2\gamma_{CDRx}+N_oB}\right)}$$
$$-\frac{B\log_2\left(1+\frac{P_D|h_{DD}|^2\gamma_{DD}}{P_C|h_{CD}|^2\gamma_{CD}+N_oB}+\sum_{j=1}^{K}\frac{P_D|h_{rjDRx}|^2\gamma_{rjDRx}}{P_C|h_{CDRx}|^2\gamma_{CDRx}+N_oB}\right)}{((K*n)+1)\left(P_{DCDreq}+P_o\right)^2}-\psi_{DCD}=0$$

$$\psi_{DCD}=\frac{-P_{CCDreq}|h_{CB}|^2\gamma_{CB}\left(\sum_{j=1}^{K}\sum_{l=1}^{n}|h_{DjlB}|^2\gamma_{DjlB}\right)}{\left(P_{CCDreq}+P_o\right)\left(\sum_{j=1}^{K}\sum_{l=1}^{n}P_{DCDreq}|h_{DjlB}|^2\gamma_{DjlB}+N_oB+P_{CCDreq}|h_{CB}|^2\gamma_{CB}\right)}$$
$$+\frac{B\frac{|h_{DD}|^2\gamma_{DD}}{P_C|h_{CD}|^2\gamma_{CD}+N_oB}+\sum_{j=1}^{K}\frac{|h_{rjDRx}|^2\gamma_{rjDRx}}{P_C|h_{CDRx}|^2\gamma_{CDRx}+N_oB}}{((K*n)+1)^2\left(P_{DCDreq}+P_o\right)\left(1+\frac{P_{DCDreq}|h_{DD}|^2\gamma_{DD}}{P_{CCDreq}|h_{CD}|^2\gamma_{CD}+N_oB}+\sum_{j=1}^{K}\frac{P_{DCDreq}|h_{rjDRx}|^2\gamma_{rjDRx}}{P_{CCDreq}|h_{CDRx}|^2\gamma_{CDRx}+N_oB}\right)}$$
$$-\frac{B\log_2\left(1+\frac{P_D|h_{DD}|^2\gamma_{DD}}{P_C|h_{CD}|^2\gamma_{CD}+N_oB}+\sum_{j=1}^{K}\frac{P_D|h_{rjDRx}|^2\gamma_{rjDRx}}{P_C|h_{CDRx}|^2\gamma_{CDRx}+N_oB}\right)}{((K*n)+1)\left(P_{DCDreq}+P_o\right)^2}$$

(A4 3.10)

$$\frac{\partial EE_{CD}}{\partial\psi_{CCD}}+\psi_{CCD}\frac{\partial\left(P_{C\max}-P_{CCDreq}\right)}{\partial\psi_{CCD}}+\psi_{DCD}\frac{\partial\left(P_{D\max}-P_{DCDreq}\right)}{\partial\psi_{CCD}}=0$$

$$P_{C\max}=P_{CCDreq} \qquad \text{(A4 3.11)}$$

$$\frac{\partial EE_{CD}}{\partial\psi_{DCD}}+\psi_{CCD}\frac{\partial\left(P_{C\max}-P_{CCDreq}\right)}{\partial\psi_{DCD}}+\psi_{DDM}\frac{\partial\left(P_{D\max}-P_{DCDreq}\right)}{\partial\psi_{DCD}}=0$$

$$P_{D\max}=P_{DCDreq} \qquad \text{(A4 3.12)}$$

## Appendix A-Ch4-3(c)

### This is the derivation of formulas (4.63) and (4.64)

$$Max \Sigma DR_{CD} \qquad s.t. \{P_{CCDreq} \le P_{C\max}; P_{DCDreq} \le P_{D\max}\} \qquad \text{(A4 3.13)}$$

$$L(P_{CCDreq}, P_{DCDreq}, \psi_{CCD}, \psi_{DCD}) = DR_{CD} + \Omega_{CCD}\left(P_{C\max} - P_{CCDreq}\right) + \Omega_{DCD}\left(P_{D\max} - P_{DCDreq}\right) \qquad \text{(A4 3.14)}$$

where $\Omega_{CDM}$ and $\Omega_{DDM}$ denote the Lagrangian factors for power constraint of CUE-BS and D2D links in DM, respectively.

$$\frac{\partial DR_{CD}}{\partial P_{CCDreq}} + \Omega_{CCD}\frac{\partial\left(P_{C\max} - P_{CCDreq}\right)}{\partial P_{CCDreq}} + \Omega_{DCD}\frac{\partial\left(P_{D\max} - P_{DCDreq}\right)}{\partial P_{CCDreq}} = 0$$

$$\frac{B|h_{CB}|^2\gamma_{CB}}{\sum_{j=1}^{K}\sum_{l=1}^{n} P_{DCDreq}|h_{DjlB}|^2\gamma_{DjlB} + N_oB + P_{CCDreq}|h_{CB}|^2\gamma_{CB}} - \frac{B\left(\frac{P_{DCDreq}|h_{DD}|^2\gamma_{DD}|h_{CD}|^2\gamma_{CD}}{\left(P_{CCDreq}|h_{CD}|^2\gamma_{CD} + N_oB\right)^2} + \sum_{j=1}^{K}\frac{P_{DCDreq}|h_{rjDRx}|^2\gamma_{rjDRx}|h_{CDRx}|^2\gamma_{CDRx}}{\left(P_{CCDreq}|h_{CDRx}|^2\gamma_{CDRx} + N_oB\right)^2}\right)}{\left((K*n)+1\right)\left(1 + \frac{P_{DCDreq}|h_{DD}|^2\gamma_{DD}}{P_{CCDreq}|h_{CD}|^2\gamma_{CD} + N_oB} + \sum_{j=1}^{K}\frac{P_{DCDreq}|h_{rjDRx}|^2\gamma_{rjDRx}}{P_{CCDreq}|h_{CDRx}|^2\gamma_{CDRx} + N_oB}\right)} - \Omega_{CDM} = 0$$

$$\Omega_{CDM} = \frac{B|h_{CB}|^2\gamma_{CB}}{\sum_{j=1}^{K}\sum_{l=1}^{n} P_{DCDreq}|h_{DjlB}|^2\gamma_{DjlB} + N_oB + P_{CCDreq}|h_{CB}|^2\gamma_{CB}} - \frac{B\left(\frac{P_{DCDreq}|h_{DD}|^2\gamma_{DD}|h_{CD}|^2\gamma_{CD}}{\left(P_{CCDreq}|h_{CD}|^2\gamma_{CD} + N_oB\right)^2} + \sum_{j=1}^{K}\frac{P_{DCDreq}|h_{rjDRx}|^2\gamma_{rjDRx}|h_{CDRx}|^2\gamma_{CDRx}}{\left(P_{CCDreq}|h_{CDRx}|^2\gamma_{CDRx} + N_oB\right)^2}\right)}{\left((K*n)+1\right)\left(1 + \frac{P_{DCDreq}|h_{DD}|^2\gamma_{DD}}{P_{CCDreq}|h_{CD}|^2\gamma_{CD} + N_oB} + \sum_{j=1}^{K}\frac{P_{DCDreq}|h_{rjDRx}|^2\gamma_{rjDRx}}{P_{CCDreq}|h_{CDRx}|^2\gamma_{CDRx} + N_oB}\right)} \qquad \text{(A4 3.15)}$$

$$\frac{\partial DR_{CD}}{\partial P_{DCDreq}} + \Omega_{CCD}\frac{\partial\left(P_{C\max} - P_{CCDreq}\right)}{\partial P_{DCDreq}} + \Omega_{DCD}\frac{\partial\left(P_{D\max} - P_{DCDreq}\right)}{\partial P_{DCDreq}} = 0$$

$$\frac{-BP_{CCDreq}|h_{CB}|^2\gamma_{CB}|h_{DjlB}|^2\gamma_{DjlB}}{\left(\sum_{j=1}^{K}\sum_{l=1}^{n} P_{DCDreq}|h_{DjlB}|^2\gamma_{DjlB} + N_oB + P_{CCDreq}|h_{CB}|^2\gamma_{CB}\right)} + \frac{B\frac{|h_{DD}|^2\gamma_{DD}}{P_{CCDreq}|h_{CD}|^2\gamma_{CD} + N_oB} + \sum_{j=1}^{K}\frac{|h_{rjDRx}|^2\gamma_{rjDRx}}{P_{CCDreq}|h_{CDRx}|^2\gamma_{CDRx} + N_oB}}{\left(1 + \frac{P_{DCDreq}|h_{DD}|^2\gamma_{DD}}{P_{CCDreq}|h_{CD}|^2\gamma_{CD} + N_oB} + \sum_{j=1}^{K}\frac{P_{DCDreq}|h_{rjDRx}|^2\gamma_{rjDRx}}{P_{CCDreq}|h_{CDRx}|^2\gamma_{CDRx} + N_oB}\right)} - \Omega_{DDM} = 0$$

$$\Omega_{DDM} = \frac{-BP_{CCDreq}\left|h_{CB}\right|^2 \gamma_{CB}\left|h_{DjlB}\right|^2 \gamma_{DjlB}}{\left(\sum_{j=1}^{K}\sum_{l=1}^{n} P_{DCDreq}\left|h_{DjlB}\right|^2 \gamma_{DjlB} + N_o B + P_{CCDreq}\left|h_{CB}\right|^2 \gamma_{CB}\right)}$$

$$+ \frac{B\dfrac{\left|h_{DD}\right|^2 \gamma_{DD}}{P_{CCDreq}\left|h_{CD}\right|^2 \gamma_{CD} + N_o B} + \sum_{j=1}^{K} \dfrac{\left|h_{rjDRx}\right|^2 \gamma_{rjDRx}}{P_{CCDreq}\left|h_{CDRx}\right|^2 \gamma_{CDRx} + N_o B}}{\left(1 + \dfrac{P_{DCDreq}\left|h_{DD}\right|^2 \gamma_{DD}}{P_{CCDreq}\left|h_{CD}\right|^2 \gamma_{CD} + N_o B} + \sum_{j=1}^{K} \dfrac{P_{DCDreq}\left|h_{rjDRx}\right|^2 \gamma_{rjDRx}}{P_{CCDreq}\left|h_{CDRx}\right|^2 \gamma_{CDRx} + N_o B}\right)} \quad \text{(A4 3.16)}$$

$$\frac{\partial DR_{DM}}{\partial \Omega_{CDM}} + \Omega_{CDM}\frac{\partial\left(P_{C\max} - P_{CDMreq}\right)}{\partial \Omega_{CDM}} + \Omega_{DDM}\frac{\partial\left(P_{D\max} - P_{DDMreq}\right)}{\partial \Omega_{CDM}} = 0$$

$$P_{C\max} = P_{CDMreq} \quad \text{(A4 3.17)}$$

$$\frac{\partial DR_{DM}}{\partial \Omega_{DDM}} + \Omega_{CDM}\frac{\partial\left(P_{C\max} - P_{CDMreq}\right)}{\partial \Omega_{DDM}} + \Omega_{DDM}\frac{\partial\left(P_{D\max} - P_{DDMreq}\right)}{\partial \Omega_{DDM}} = 0$$

$$P_{D\max} = P_{DDMreq} \quad \text{(A4 3.18)}$$

# Appendix A-Ch5-1

## This is the derivation of formula (5.13)

$$Min\sum E_{bVD} \qquad s.t.\{p_{outVD} \le 1-U\} \tag{A5 1.1}$$

$$L(P_{VD},\lambda_{VD}) = P_{totVD} + \lambda_{VD}\left(p_{outVD} - 1 + U\right) \tag{A5 1.2}$$

where $$P_{totVD} = P_{AM,VD} + P_C$$

$$\frac{\partial P_{totVD}}{\partial P_{VD}} + \lambda_{VD}\frac{\partial\left(p_{outVD} - 1 + U\right)}{\partial P_{VD}} = 0 \tag{A5 1.3}$$

$$\frac{\partial P_{totVD}}{\partial \lambda_{VD}} + \lambda_{VD}\frac{\partial\left(p_{outVD} - 1 + U\right)}{\partial \lambda_{VD}} = 0 \tag{A5 1.4}$$

The derivatives of the total power consumption $P_{totVD}$ and the outage probability $p_{outVD}$ with respect to the transmit power $P_{VD}$ are given by:

$$\frac{\xi}{\eta} - \lambda_{VD}\ e^{\left(\frac{-\left(2^{2R_s}-1\right)N}{P_{VD}|h_{VD}|^2\gamma_{VD}}\right)} * \frac{\left(2^{2R_s}-1\right)N}{P_{VD}{}^2|h_{VD}|^2\gamma_{VD}} = 0 \tag{A5 1.5}$$

$$\lambda_{VD} = \frac{\xi P_{VD}{}^2|h_{VD}|^2\gamma_{VD}}{\eta\left(2^{2R_s}-1\right)Ne^{\left(\frac{-\left(2^{2R_s}-1\right)N}{P_{VD}|h_{VD}|^2\gamma_{VD}}\right)}} \tag{A5 1.6}$$

Next, the derivatives of the total power consumption $P_{totVD}$ and the outage probability $p_{outVD}$ with respect to $\lambda_{VD}$ are given by:

$$0 + 1 - e^{\left(\frac{-\left(2^{2R_s}-1\right)N}{P_{VD}|h_{VD}|^2\gamma_{VD}}\right)} - 1 + U = 0 \tag{A5 1.7}$$

$$U = e^{\left(\frac{-\left(2^{2R_s}-1\right)N}{P_{VD}|h_{VD}|^2\gamma_{VD}}\right)} \tag{A5 1.8}$$

By Taking ln for both sides Equation (A5 1.8) can be rewritten as:

$$\ln(U) = \frac{-\left(2^{2R_s}-1\right)N}{P_{VD}|h_{VD}|^2\gamma_{VD}} \tag{A5 1.9}$$

$$P_{Vopt} \approx \left(\frac{-\left(2^{2R_s}-1\right)N}{\ln U|h_{VD}|^2\gamma_{VD}}\right) \tag{A5 1.10}$$

# Appendix A-Ch5-2

## This is the derivation of formula (5.30)

$$Min \sum E_{bVMH} \qquad s.t.\{p_{outVMH} \leq 1 - U\} \qquad \text{(A5 2.1)}$$

$$L(P_{VMH}, \lambda_{VMH}) = P_{totVMH} + \lambda_{VMH}\left(p_{outVMH} - 1 + U\right) \qquad \text{(A5 2.2)}$$

$$\frac{\partial P_{totVMH}}{\partial P_{VMH}} + \lambda_{MH} \frac{\partial\left(p_{outVMH} - 1 + U\right)}{\partial P_{VMH}} = 0 \qquad \text{(A5 2.3)}$$

where

$$P_{totMH} = pout_{VR_1}\left(P_{AM,VMH} + P_C\right) + \left(1 - pout_{VR_1}\right)\left(\left(\sum_{i=2}^{n} X_{R_{i-1}R_i} + X_{R_nI} + 1\right)P_{AM,VMH} + (n+1)P_C\right)$$

$$\frac{\partial P_{totVMH}}{\partial \lambda_{VMH}} + \lambda_{VMH} \frac{\partial\left(p_{outVMH} - 1 + U\right)}{\partial \lambda_{VMH}} = 0 \qquad \text{(A5 2.4)}$$

The derivatives of the total power consumption $P_{totVMH}$ and the outage probability $p_{outVMH}$ with respect to the transmit power $P_{VMH}$ are given by:

$$\frac{\partial P_{totVMH}}{\partial P_{VMH}} = \left(1 - e^{\frac{-1}{P_{VMH}}\left(b_{VR_1}\right)}\right)\frac{\xi}{\eta} + \left(\frac{\xi}{\eta}P_{VMH} + P_C\right)\left(-e^{\frac{-1}{P_{VMH}}\left(b_{VR_1}\right)}\right)\frac{1}{P_{VMH}{}^2}\left(b_{VR_1}\right)$$
$$+\left(\left(\sum_{i=2}^{n} X_{R_{i-1}R_i} + X_{R_nI} + 1\right)\frac{\xi}{\eta}\right)\left(e^{\frac{-1}{P_{VMH}}\left(b_{VR_1}\right)}\right) + \left(\left(\sum_{i=2}^{n} X_{R_{i-1}R_i} + X_{R_nI} + 1\right)\frac{\xi}{\eta}P_{VMH} + (n+1)P_C\right)\left(e^{\frac{-1}{P_{VMH}}\left(b_{VR_1}\right)} * \frac{1}{P_{VMH}{}^2}\left(b_{VR_1}\right)\right)$$

where $b_{VR_1} = \dfrac{\left(2^{2R_s} - 1\right)N}{\left|h_{VR_1}\right|^2 \gamma_{VR_1}}$

Let $Q = \sum_{i=2}^{n} X_{R_{i-1}R_i} + X_{R_nI}$

$$\frac{\partial P_{totVMH}}{\partial P_{VMH}} = \left(1 - e^{\frac{-b_{VR_1}}{P_{VMH}}}\right)\frac{\xi}{\eta} + \left(\frac{\xi}{\eta}P_{VMH} + P_C\right)\left(-e^{\frac{-b_{VR_1}}{P_{VMH}}}\right)\frac{b_{VR_1}}{P_{VMH}{}^2}$$
$$+\left((Q+1)\frac{\xi}{\eta}\right)\left(e^{\frac{-b_{VR_1}}{P_{VMH}}}\right) + \left((Q+1)\frac{\xi}{\eta}P_{VMH} + (n+1)P_C\right)\left(e^{\frac{-b_{VR_1}}{P_{VMH}}} * \frac{b_{VR_1}}{P_{VMH}{}^2}\right)$$

$$\frac{\partial P_{totVMH}}{\partial P_{VMH}} = \frac{\xi}{\eta} + Q\frac{\xi}{\eta}e^{\frac{-b_{VR_1}}{P_{VMH}}} + Q\frac{\xi}{\eta}\frac{b_{VR_1}e^{\frac{-b_{VR_1}}{P_{VMH}}}}{P_{VMH}} + n\left(P_C\right)\frac{b_{VR_1}e^{\frac{-b_{VR_1}}{P_{VMH}}}}{P_{VMH}{}^2}$$

$$\frac{\partial\left(p_{outVMH} - 1 + U\right)}{\partial P_{VMH}} = -e^{\frac{-T_1}{P_{VMH}}} * \frac{T_1}{P_{VMH}{}^2}$$

where $T_1 = b_{VR1} + b_{R_{i-1}R_i} + b_{R_nI}$ , $b_{R_{i-1}R_i} = \frac{\left(2^{2R_s} - 1\right)N}{\upsilon_{R_{i-1}R_i}{}^{\alpha}\left|h_{R_{i-1}R_i}\right|^2 \gamma_{R_{i-1}R_i}}$ and $b_{R_nI} = \frac{\left(2^{2R_s} - 1\right)N}{\upsilon_{R_nI}{}^{\alpha}\left|h_{R_nI}\right|^2 \gamma_{R_nI}}$

then $$\frac{\xi}{\eta} + Q\frac{\xi}{\eta}e^{\frac{-b_{VR_1}}{P_{VMH}}} + Q\frac{\xi}{\eta}\frac{b_{VR_1}e^{\frac{-b_{VR_1}}{P_{VMH}}}}{P_{VMH}} + n(P_C)\frac{b_{VR_1}e^{\frac{-b_{VR_1}}{P_{VMH}}}}{P_{VMH}{}^2} - \lambda_{VMH}\, e^{\frac{-T_1}{P_{VMH}}} * \frac{T_1}{P_{VMH}{}^2} = 0$$

$$\lambda_{VMH} = \frac{\frac{\xi}{\eta}P_{VMH}{}^2 + W\frac{\xi}{\eta}P_{VMH}{}^2 e^{\frac{-b_{VR_1}}{P_{VMH}}} + W\frac{\xi}{\eta}P_{VMH}b_{VR_1}e^{\frac{-b_{VR_1}}{P_{VMH}}} + n(P_C)b_{VR_1}e^{\frac{-b_{VR_1}}{P_{VMH}}}}{e^{\frac{-T_1}{P_{VMH}}}T_1} \qquad \text{(A5 2.5)}$$

Next, the derivatives of the total power consumption $P_{totVMH}$ and the outage probability $p_{outVMH}$ with respect to $\lambda_{VMH}$ are given by:

$$1 - e^{-\frac{\left(2^{2R_s}-1\right)N}{P_{VMH}}\left(\frac{1}{\left|h_{VR_1}\right|^2\gamma_{VR_1}} + \sum_{i=2}^{n}\frac{1}{\upsilon_{R_{i-1}R_i}{}^{\alpha}\left|h_{R_{i-1}Ri}\right|^2\gamma_{R_{i-1}R_i}} + \frac{1}{\upsilon_{R_nI}{}^{\alpha}\left|h_{R_nI}\right|^2\gamma_{R_nI}}\right)} - 1 + U = 0 \qquad \text{(A5 2.6)}$$

$$U = e^{-\frac{\left(2^{2R_s}-1\right)N}{P_{VMH}}\left(\frac{1}{\left|h_{VR_1}\right|^2\gamma_{VR_1}} + \sum_{i=2}^{n}\frac{1}{\upsilon_{R_{i-1}R_i}{}^{\alpha}\left|h_{R_{i-1}Ri}\right|^2\gamma_{R_{i-1}R_i}} + \frac{1}{\upsilon_{R_nI}{}^{\alpha}\left|h_{R_nI}\right|^2\gamma_{R_nI}}\right)} \qquad \text{(A5 2.7)}$$

By taking ln for both sides of Equation (5.41) can be rewritten as:

$$\ln(U) = -\frac{\left(2^{2R_s}-1\right)N}{P_{VMH}}\left(\frac{1}{\left|h_{VR_1}\right|^2\gamma_{VR_1}} + \sum_{i=2}^{n}\frac{1}{\upsilon_{R_{i-1}R_i}{}^{\alpha}\left|h_{R_{i-1}Ri}\right|^2\gamma_{R_{i-1}R_i}} + \frac{1}{\upsilon_{R_nI}{}^{\alpha}\left|h_{R_nI}\right|^2\gamma_{R_nI}}\right) \qquad \text{(A5 2.8)}$$

$$P_{VMHopt} \approx \frac{-\left(2^{2R_s}-1\right)N}{\ln U}\left(\frac{1}{\left|h_{VR_1}\right|^2\gamma_{VR_1}} + \sum_{i=2}^{n}\frac{1}{\upsilon_{R_{i-1}R_i}{}^{\alpha}\left|h_{R_{i-1}Ri}\right|^2\gamma_{R_{i-1}R_i}} + \frac{1}{\upsilon_{R_nI}{}^{\alpha}\left|h_{R_nI}\right|^2\gamma_{R_nI}}\right)$$
(A5 2.9)

# Appendix A-Ch5-3

## This is the derivation of formula (5.47)

$$Min \sum E_{bVMB} \quad s.t.\{p_{outVMB} \leq 1 - U\} \tag{A5 3.1}$$

$$L(P_{VMB}, \lambda_{VMB}) = P_{totVMB} + \lambda_{VMB}\left(p_{outVMB} - 1 + U\right) \tag{A5 3.2}$$

$$\frac{\partial P_{totVMB}}{\partial P_{VMB}} + \lambda_{VMB} \frac{\partial\left(p_{outVMB} - 1 + U\right)}{\partial P_{VMB}} = 0 \tag{A5 3.3}$$

where $P_{totVMB} = \left(pout_{VR}\right)^K \left(P_{AM,VMB} + P_{C1}\right) + \left(1 - \left(pout_{VR}\right)^K\right)\left(\left(\sum_{l=1}^{K} X_{R_l l} + 1\right) P_{AM,VMB} + P_{C2}\right)$

$$\frac{\partial P_{totVMB}}{\partial \lambda_{VMB}} + \lambda_{VMB} \frac{\partial\left(p_{outVMB} - 1 + U\right)}{\partial \lambda_{VMB}} = 0 \tag{A5 3.4}$$

The derivatives of the total power consumption $P_{totVMB}$ and the outage probability $p_{outVMB}$ with respect to the transmit power $P_{VMB}$ are given by:

$$\frac{\partial P_{totVMB}}{\partial P_{VMB}} = \left(1 - e^{\frac{-1}{P_{VMB}}(b_{VR})}\right)^K \frac{\xi}{\eta} + \left(\frac{\xi}{\eta} P_{VMB} + P_{C1}\right) K \left(1 - e^{\frac{-1}{P_{VMB}}(b_{VR})}\right)^{K-1} \left(\frac{-e^{\frac{-1}{P_{VMB}}(b_{VR})}}{P_{VMB}{}^2}(b_{VR})\right)$$

$$+ \left(\left(\sum_{l=1}^{K} X_{lD} + 1\right)\frac{\xi}{\eta}\right)\left(1 - \left(1 - e^{\frac{-1}{P_{VMB}}(b_{VR})}\right)^K\right) + \left(\left(\sum_{l=1}^{K} X_{lD} + 1\right)\frac{\xi}{\eta} P_{VMB} + P_{C2}\right) K \left(1 - e^{\frac{-1}{P_{VMB}}(b_{VR})}\right)^{K-1} \left(\frac{e^{\frac{-1}{P_{VMB}}(b_{VR})}}{P_{VMB}{}^2}(b_{VR})\right)$$

where $b_{VR} = \dfrac{\left(2^{2R_s} - 1\right)N}{\left|h_{VR}\right|^2 \gamma_{VR}}$

Let $\quad E = \sum_{l=1}^{K} X_{lD}$ and $P_{outVR} = 1 - e^{\frac{-1}{P_{VMB}}(b_{VR})}$

$$\frac{\partial P_{totVMB}}{\partial P_{VMB}} = \left(P_{outVR}\right)^K \frac{\xi}{\eta} + \left(\frac{\xi}{\eta} P_{VMB} + P_{C1}\right) K \left(P_{outVR}\right)^{K-1} \left(\frac{-e^{\frac{-1}{P_{VMB}}(b_{VR})}}{P_{VMB}{}^2}(b_{VR})\right)$$

$$+ \left((E+1)\frac{\xi}{\eta}\right)\left(1 - \left(P_{outVR}\right)^K\right) + \left((E+1)\frac{\xi}{\eta} P_{VMB} + P_{C2}\right) K \left(P_{outVR}\right)^{K-1} \left(\frac{e^{\frac{-1}{P_{VMB}}(b_{VR})}}{P_{VMB}{}^2}(b_{VR})\right)$$

let $e^{\frac{-1}{P_{VMB}}(b_{VR})} = 1 - Pout_{VR}$

$$\frac{\partial P_{totVMB}}{\partial P_{VMB}} = (P_{outVR})^K \frac{\xi}{\eta} - \left(\frac{\xi}{\eta} P_{VMB} + P_{C1}\right) K (P_{outVR})^{K-1} \left(\frac{(1-P_{outVR})}{P_{VMB}{}^2}(b_{VR})\right)$$

$$+ \left((E+1)\frac{\xi}{\eta}\right)\left(1-(P_{outVR})^K\right) + \left((E+1)\frac{\xi}{\eta} P_{VMB} + P_{C2}\right) K (P_{outVR})^{K-1} \left(\frac{(1-P_{outVR})}{P_{VMB}{}^2}(b_{VR})\right)$$

$$\frac{\partial P_{totVMB}}{\partial P_{VMB}} = K (P_{outVR})^{K-1} \left(\frac{(1-P_{outVR})}{P_{VMB}{}^2}(b_{VR})\right)(P_{C2} - P_{C1}) + E\frac{\xi}{\eta} + \frac{\xi}{\eta} - (P_{outVR})^K E \frac{\xi}{\eta}$$

$$+ E\frac{\xi}{\eta} P_{VMB} K (P_{outVR})^{K-1} \left(\frac{(1-P_{outVR})}{P_{VMB}{}^2}(b_{VR})\right)$$

$$\frac{\partial (p_{outVMB} - 1 + U)}{\partial P_{VMB}} = -e^{\frac{-T_2}{P_{VMB}}} * \frac{T_2}{P_{VMB}{}^2}\left(1 - e^{\frac{-T_3}{P_{VMB}}}\right)^K + K\left(1 - e^{\frac{-T_3}{P_{VMB}}}\right)^{K-1}\left(-e^{\frac{-T_3}{P_{VMB}}} * \frac{T_3}{P_{VMB}{}^2}\right)\left(1 - e^{\frac{-T_2}{P_{VMB}}}\right)$$

where $T_2 = b_{VI}$, $T_3 = b_{VR} + b_{RI}$ and $b_{VI} = \frac{(2^{2R_s} - 1)N}{|h_{VI}|^2 \gamma_{VI}}, b_{RI} = \frac{(2^{2R_s} - 1)N}{\upsilon_{RI}{}^{\alpha} |h_{RI}|^2 \gamma_{RI}}$

then

$$K (P_{outVR})^{K-1} \left(\frac{(1-P_{outVR})}{P_{VMB}{}^2}(b_{VR})\right)(P_{C2} - P_{C1}) + E\frac{\xi}{\eta} + \frac{\xi}{\eta} - (P_{outVR})^K E \frac{\xi}{\eta} + E\frac{\xi}{\eta} P_{VMB} K (P_{outVR})^{K-1} \left(\frac{(1-P_{outVR})}{P_{VMB}{}^2}(b_{VR})\right)$$

$$-\lambda_{VMB} \left(e^{\frac{-T_2}{P_{VMB}}} * \frac{T_2}{P_{VMB}{}^2}\left(1 - e^{\frac{-T_3}{P_{VMB}}}\right)^K + K\left(1 - e^{\frac{-T_3}{P_{VMB}}}\right)^{K-1}\left(e^{\frac{-T_3}{P_{VMB}}} * \frac{T_3}{P_{VMB}{}^2}\right)\left(1 - e^{\frac{-T_2}{P_{VMB}}}\right)\right) = 0$$

$$\lambda_{VMB} = \frac{K (P_{outVR})^{K-1} \left(\frac{(1-P_{outVR})}{P_{VMB}{}^2}(b_{VR})\right)(P_{C2} - P_{C1}) + E\frac{\xi}{\eta} + \frac{\xi}{\eta} - (P_{outVR})^K E \frac{\xi}{\eta} + E\frac{\xi}{\eta} P_{VMB} K (P_{outVR})^{K-1} \left(\frac{(1-P_{outVR})}{P_{VMB}{}^2}(b_{VR})\right)}{\left(e^{\frac{-T_2}{P_{VMB}}} * \frac{T_2}{P_{VMB}{}^2}\left(1 - e^{\frac{-T_3}{P_{VMB}}}\right)^K + K\left(1 - e^{\frac{-T_3}{P_{VMB}}}\right)^{K-1}\left(e^{\frac{-T_3}{P_{VMB}}} * \frac{T_3}{P_{VMB}{}^2}\right)\left(1 - e^{\frac{-T_2}{P_{VMB}}}\right)\right)}$$

(A5 3.5)

Next, the derivatives of the total power consumption $P_{totVMB}$ and the outage probability $p_{outVMB}$ with respect to $\lambda_{MB}$ are given by:

$$\frac{(2^{2R_s} - 1)^{K+1} N^{K+1}}{P_{VMB}{}^{K+1} |h_{VI}|^2 \gamma_{VI}}\left(\left(\frac{1}{|h_{VR}|^2 \gamma_{VR}} + \frac{1}{\upsilon_{RI}{}^{\alpha} |h_{RI}|^2 \gamma_{RI}}\right)\right)^K - 1 + U = 0 \quad \text{(A5 3.6)}$$

$$1 - U = \frac{(2^{2R_s} - 1)^{K+1} N^{K+1}}{P_{VMB}{}^{K+1} |h_{VI}|^2 \gamma_{VI}}\left(\left(\frac{1}{|h_{VR}|^2 \gamma_{VR}} + \frac{1}{\upsilon_{RI}{}^{\alpha} |h_{RI}|^2 \gamma_{RI}}\right)\right)^K \quad \text{(A5 3.7)}$$

$$P_{VMB}{}^{K+1} = \frac{(2^{2R_s} - 1)^{K+1} N^{K+1}}{(1-U) |h_{VI}|^2 \gamma_{VI}}\left(\left(\frac{1}{|h_{VR}|^2 \gamma_{VR}} + \frac{1}{\upsilon_{RI}{}^{\alpha} |h_{RI}|^2 \gamma_{RI}}\right)\right)^K \quad \text{(A5 3.8)}$$

$$P_{VMBopt} = (2^{2R_s} - 1)N\left(\frac{1}{(1-U)|h_{VI}|^2 \gamma_{VI}}\left(\left(\frac{1}{|h_{VR}|^2 \gamma_{VR}} + \frac{1}{\upsilon_{RI}{}^{\alpha} |h_{RI}|^2 \gamma_{RI}}\right)\right)^K\right)^{\frac{1}{K+1}} \quad \text{(A5 3.9)}$$

# Appendix A-Ch5-4

## This is the derivation of formula (5.61)

$$Min \sum E_{bVMHB} \quad s.t.\{p_{outVMHB} \leq 1\text{-}U\} \tag{A5 4.1}$$

$$L(P_{VMHB}, \lambda_{VMHB}) = P_{totVMHB} + \lambda_{VMHB}\left(p_{outVMHB} - 1 + U\right) \tag{A5 4.2}$$

$$\frac{\partial P_{totVMHB}}{\partial P_{VMHB}} + \lambda_{VMHB} \frac{\partial\left(p_{outVMHB} - 1 + U\right)}{\partial P_{VMHB}} = 0 \tag{A5 4.3}$$

where

$$P_{totVMHB} = \left(pout_{VR_1}\right)^K \left(P_{AM,VMHB} + P_{C3}\right) + \left(1 - \left(pout_{VR_1}\right)^K\right)\left(\sum_{l=1}^{K}\left(\sum_{i=2}^{n} X_{(R_i - 1R_i)_l} + X_{(R_n I)_l}\right) + 1\right) P_{AM,VMHB} + P_{C4}$$

$$\frac{\partial P_{totVMHB}}{\partial \lambda_{VMHB}} + \lambda_{VMHB} \frac{\partial\left(p_{outVMHB} - 1 + U\right)}{\partial \lambda_{VMHB}} = 0 \tag{A5 4.4}$$

The derivatives of the total power consumption $P_{totVMHB}$ and the outage probability $p_{outVMHB}$ with respect to the transmit power $P_{VMHB}$ are given by:

$$\frac{\partial P_{totVMHB}}{\partial P_{VMHB}} = \left(1 - e^{\frac{-1}{P_{VMHB}}\left(b_{VR_1}\right)}\right)^K \frac{\xi}{\eta} + \left(\frac{\xi}{\eta} P_{VMHB} + P_{C3}\right) K \left(1 - e^{\frac{-1}{P_{VMHB}}\left(b_{VR_1}\right)}\right)^{K-1} \left(\frac{-e^{\frac{-1}{P_{VMHB}}\left(b_{VR_1}\right)}}{P_{VMHB}{}^2}\left(b_{VR_1}\right)\right)$$

$$+\left(\left(\sum_{l=1}^{K}\left(\sum_{i=2}^{n} X_{(R_i - 1R_i)_l} + X_{(R_n I)_l}\right) + 1\right)\frac{\xi}{\eta}\right)\left(1 - \left(1 - e^{\frac{-1}{P_{VMHB}}\left(b_{VR_1}\right)}\right)^K\right)$$

$$+\left(\left(\sum_{l=1}^{K}\left(\sum_{i=2}^{n} X_{(R_i - 1R_i)_l} + X_{(R_n I)_l}\right) + 1\right)\frac{\xi}{\eta} P_{VMHB} + P_{C4}\right) K \left(1 - e^{\frac{-1}{P_{VMHB}}\left(b_{VR_1}\right)}\right)^{K-1} \left(\frac{e^{\frac{-1}{P_{VMHB}}\left(b_{VR_1}\right)}}{P_{VMHB}{}^2}\left(b_{VR_1}\right)\right)$$

where $b_{VR_1} = \dfrac{\left(2^{2R_s} - 1\right)N}{\left|h_{VR_1}\right|^2 \gamma_{VR_1}}$

Let $F = \sum_{l=1}^{K}\left(\sum_{i=2}^{n} X_{(R_i - 1R_i)_l} + X_{(R_n I)_l}\right)$ and $P_{outVR_1} = 1 - e^{\frac{-1}{P_{VMHB}}\left(b_{VR_1}\right)}$

$$\frac{\partial P_{totVMHB}}{\partial P_{VMHB}} = \left(P_{outVR_1}\right)^K \frac{\xi}{\eta} - \left(\frac{\xi}{\eta} P_{VMHB} + P_{C3}\right) K \left(P_{outVR_1}\right)^{K-1} \left(\frac{\left(1 - P_{outVR_1}\right)}{P_{VMHB}{}^2}\left(b_{VR_1}\right)\right)$$
$$+\left((F+1)\frac{\xi}{\eta}\right)\left(1 - \left(P_{outVR_1}\right)^K\right) + \left((F+1)\frac{\xi}{\eta} P_{VMHB} + P_{C4}\right) K \left(P_{outVR_1}\right)^{K-1} \left(\frac{\left(1 - P_{outVR_1}\right)}{P_{VMHB}{}^2}\left(b_{VR_1}\right)\right)$$

$$\frac{\partial P_{totVMHB}}{\partial P_{VMHB}} = K\left(P_{outVR_1}\right)^{K-1}\left(\frac{\left(1 - P_{outVR_1}\right)}{P_{VMHB}{}^2}\left(b_{VR_1}\right)\right)\left(P_{C4} - P_{C3}\right) + \frac{\xi}{\eta}\left(1 + F\left(1 - \left(P_{outVR_1}\right)^K + P_{VMHB} K \left(P_{outVR_1}\right)^{K-1}\left(\frac{\left(1 - P_{outVR_1}\right)}{P_{VMHB}{}^2}\left(b_{VR_1}\right)\right)\right)\right)$$

$$\frac{\partial\left(p_{outVMHB}-1+U\right)}{\partial P_{VMHB}}=-e^{\frac{-T_2}{P_{VMHB}}}*\frac{T_2}{P_{VMHB}{}^2}\left(1-e^{\frac{-T_4}{P_{VMHB}}}\right)^K+K\left(1-e^{\frac{-T_4}{P_{VMHB}}}\right)^{K-1}\left(-e^{\frac{-T_4}{P_{VMHB}}}*\frac{T_4}{P_{VMHB}{}^2}\right)\left(1-e^{\frac{-T_2}{P_{VMHB}}}\right)$$

where $T_2=b_{VI}$, $T_4=b_{VR_1}+b_{R_{i-1}R_i}+b_{R_nI}$

and $b_{VI}=\frac{\left(2^{2R_s}-1\right)N}{\left|h_{VI}\right|^2\gamma_{VI}}, b_{R_{i-1}R_i}=\frac{\left(2^{2R_s}-1\right)N}{\upsilon_{R_{i-1}R_i}{}^{\alpha}\left|h_{R_{i-1}R_i}\right|^2\gamma_{R_{i-1}R_i}}, b_{R_nI}=\frac{\left(2^{2R_s}-1\right)N}{\upsilon_{R_nI}{}^{\alpha}\left|h_{R_nI}\right|^2\gamma_{R_nI}}$

then

$$K\left(P_{outVR_1}\right)^{K-1}\left(\frac{\left(1-P_{outVR_1}\right)}{P_{VMHB}{}^2}\left(b_{VR_1}\right)\right)\left(P_{C4}-P_{C3}\right)$$
$$+\frac{\xi}{\eta}\left(1+F\left(1-\left(P_{outVR_1}\right)^K+P_{VMHB}K\left(P_{outVR_1}\right)^{K-1}\left(\frac{\left(1-P_{outVR_1}\right)}{P_{VMHB}{}^2}\left(b_{VR_1}\right)\right)\right)\right)$$
$$-\lambda_{VMHB}\left(e^{\frac{-T_2}{P_{VMHB}}}*\frac{T_2}{P_{VMHB}{}^2}\left(1-e^{\frac{-T_4}{P_{VMHB}}}\right)^K+K\left(1-e^{\frac{-T_4}{P_{VMHB}}}\right)^{K-1}\left(e^{\frac{-T_4}{P_{VMHB}}}*\frac{T_4}{P_{VMHB}{}^2}\right)\left(1-e^{\frac{-T_2}{P_{VMHB}}}\right)\right)=0$$

$$\lambda_{VMHB}=\frac{K\left(P_{outVR_1}\right)^{K-1}\left(\frac{\left(1-P_{outVR_1}\right)}{P_{VMHB}{}^2}\left(b_{VR_1}\right)\right)\left(P_{C4}-P_{C3}\right)+\frac{\xi}{\eta}\left(1+F\left(1-\left(P_{outVR_1}\right)^K+P_{VMHB}K\left(P_{outVR_1}\right)^{K-1}\left(\frac{\left(1-P_{outVR_1}\right)}{P_{VMHB}{}^2}\left(b_{VR_1}\right)\right)\right)\right)}{\left(e^{\frac{-T_2}{P_{VMHB}}}*\frac{T_2}{P_{VMHB}{}^2}\left(1-e^{\frac{-T_4}{P_{VMHB}}}\right)^K+K\left(1-e^{\frac{-T_4}{P_{VMHB}}}\right)^{K-1}\left(e^{\frac{-T_4}{P_{VMHB}}}*\frac{T_4}{P_{VMHB}{}^2}\right)\left(1-e^{\frac{-T_2}{P_{VMHB}}}\right)\right)}$$

(A5 4.5)

Next, the derivatives of the total power consumption $P_{totVMHB}$ and the outage probability $p_{outVMHB}$ with respect to $\lambda_{VMHB}$ are given by:

$$\frac{\left(2^{2R_s}-1\right)^{K+1}N^{K+1}}{P_{VMHB}{}^{K+1}\left|h_{VI}\right|^2\gamma_{VI}}\left(\left(\frac{1}{\left|h_{VR_1}\right|^2\gamma_{VR_1}}+\sum_{i=2}^{n}\frac{1}{\upsilon_{R_{i-1}R_i}{}^{\alpha}\left|h_{R_{i-1}Ri}\right|^2\gamma_{R_{i-1}R_i}}+\frac{1}{\upsilon_{R_nI}{}^{\alpha}\left|h_{R_nI}\right|^2\gamma_{R_nI}}\right)\right)^K-1+U=0$$

(A5 4.6)

$$1-U=\frac{\left(2^{2R_s}-1\right)^{K+1}N^{K+1}}{P_{VMHB}{}^{K+1}\left|h_{VI}\right|^2\gamma_{VI}}\left(\left(\frac{1}{\left|h_{VR_1}\right|^2\gamma_{VR_1}}+\sum_{i=2}^{n}\frac{1}{\upsilon_{R_{i-1}R_i}{}^{\alpha}\left|h_{R_{i-1}Ri}\right|^2\gamma_{R_{i-1}R_i}}+\frac{1}{\upsilon_{R_nI}{}^{\alpha}\left|h_{R_nI}\right|^2\gamma_{R_nI}}\right)\right)^K \quad \text{(A5 4.7)}$$

$$P_{VMHB}{}^{K+1}=\frac{\left(2^{2R_s}-1\right)^{K+1}N^{K+1}}{\left(1-U\right)\left|h_{VI}\right|^2\gamma_{VI}}\left(\left(\frac{1}{\left|h_{VR_1}\right|^2\gamma_{VR_1}}+\sum_{i=2}^{n}\frac{1}{\upsilon_{R_{i-1}R_i}{}^{\alpha}\left|h_{R_{i-1}Ri}\right|^2\gamma_{R_{i-1}R_i}}+\frac{1}{\upsilon_{R_nI}{}^{\alpha}\left|h_{R_nI}\right|^2\gamma_{R_nI}}\right)\right)^K \quad \text{(A5 4.8)}$$

$$P_{VMHBopt}=\left(2^{2R_s}-1\right)N\left(\frac{1}{\left(1-U\right)\left|h_{SD}\right|^2\gamma_{SD}}\left(\left(\frac{1}{\left|h_{SR_1}\right|^2\gamma_{SR_1}}+\sum_{i=2}^{n}\frac{1}{\upsilon_{R_{i-1}R_i}{}^{\alpha}\left|h_{R_{i-1}Ri}\right|^2\gamma_{R_{i-1}R_i}}+\frac{1}{\upsilon_{R_nD}{}^{\alpha}\left|h_{R_nD}\right|^2\gamma_{R_nD}}\right)\right)^K\right)^{\frac{1}{K+1}}$$

(A5 4.9)

# Appendix B

# NETWORK SIMULATION

# TCL for V2I

```
#Start simulation
#=======================================================================
#     Define options
#=======================================================================

set val(chan)        Channel/WirelessChannel     ;# channel type
set val(prop)         Propagation/Shadowing       ;# radio-propagation model
set val(netif)        Phy/WirelessPhy             ;# network interface type
set val(mac)          Mac/802_11                  ;# MAC type
set val(ifq)          Queue/DropTail/PriQueue    ;# interface queue type
set val(ll)           LL                          ;# link layer type
set val(ant)          Antenna/OmniAntenna         ;# antenna model
set val(ifqlen)       50                          ;# max packet in ifq
set val(nn)           51                          ;# number of mobilenodes
set val(rp)           AODV                        ;# routing protocol
set val(cp)          "/home/aya/tcp-50-1"
set val(sc)          "/home/aya/m1-50"
set val(nsource)     50                           ;#number of source nodes
set val(coverage)   250                           ;#coverage
set val(x)            300
set val(y)            300
set val(seed)         3.0
set val(stop)          1000                       ;# simulation time

#=======================================================================

set ns_  [new Simulator]
set tracefd     [open user-50-1.tr w]
set nf    [open User-50-1.nam w]
$ns_ trace-all $tracefd
$ns_ namtrace-all-wireless $nf $val(x) $val(y)

#=======================================================================
#Configure RF model parameter
#=======================================================================

Propagation/Shadowing set pathlossExp_ 3.0  ;# path loss exponent
Propagation/Shadowing set std_db_ 4.0          ;# shadowing deviation (dB)
Propagation/Shadowing set dist0_ 1.0           ;# reference distance (m)
Propagation/Shadowing set seed_ 1.0            ;# seed for RNG
#=======================================================================
#define antenna options
#=======================================================================

Antenna/OmniAntenna set Gt_ 1                             ;# transmit antenna gain
Antenna/OmniAntenna set Gr_ 1                              ;# receive antenna gain
Antenna/OmniAntenna set X_ 0
```

```
Antenna/OmniAntenna set Y_ 0
Antenna/OmniAntenna set Z_ 1.5
#=====================================================================
# power of the antennas
#=====================================================================

proc SetPt { coverage } {
set Gt [Antenna/OmniAntenna set Gt_]
set Gr [Antenna/OmniAntenna set Gr_]
set ht [Antenna/OmniAntenna set Z_]
set hr [Antenna/OmniAntenna set Z_]
set RXThresh [Phy/WirelessPhy set RXThresh_]
set d3 [expr pow($coverage,3)]
set Pt [expr ($RXThresh*$d3)/($Gt*$Gr*$ht*$ht*$hr*$hr)]
return $Pt
}

#=====================================================================
# 802.11p simulation parameter setup
#=====================================================================

Phy/WirelessPhyExt set CSThresh_ 3.9810717055349694e-13 ;# -94 dBm wireless interface
sensitivity
#Phy/WirelessPhyExt set RXThresh_ 3.41828e-08
Phy/WirelessPhyExt set Pt_ 0.00001 ;# equals 20dBm when considering antenna gains of 1.0
Phy/WirelessPhyExt set freq_ 5.9e+9
Phy/WirelessPhyExt set  Rb_ 2*1e4
Phy/WirelessPhyExt set noise_floor_ 1.26e-13 ;# -99 dBm for 10MHz bandwidth
Phy/WirelessPhyExt set L_ 1.0 ;# default radio circuit gain/loss
Phy/WirelessPhyExt set Pt_consume_ 0.00009823 ;# // power consumption for transmission (W)
Phy/WirelessPhyExt set Pr_consume_ 0.00001125 ;# // power consumption for reception (W)
Phy/WirelessPhyExt set P_idle_  1.0;        # // idle power consumption (W)
Phy/WirelessPhyExt set P_sleep_ 0.00005; #// sleep power consumption (W)
Phy/WirelessPhyExt set PowerMonitorThresh_ 6.310e-14 ;# -102 dBm power monitor sensitivity
(=level of gaussian noise)
Phy/WirelessPhyExt set HeaderDuration_ 0.000040 ;# 40 us
Phy/WirelessPhyExt set BasicModulationScheme_ 0
Phy/WirelessPhyExt set PreambleCaptureSwitch_ 1
Phy/WirelessPhyExt set DataCaptureSwitch_ 0
Phy/WirelessPhyExt set SINR_PreambleCapture_ 3.1623; ;# 5 dB
Phy/WirelessPhyExt set SINR_DataCapture_ 100.0; ;# 10 dB
Phy/WirelessPhyExt set trace_dist_ 1e6 ;# PHY trace until distance of 1 Mio. km ("infinity")
Phy/WirelessPhyExt set PHY_DBG_ 0
Mac/802_11Ext set CWMin_ 15
Mac/802_11Ext set CWMax_ 1023
Mac/802_11Ext set SlotTime_ 0.000013
Mac/802_11Ext set SIFS_ 0.000032
Mac/802_11Ext set ShortRetryLimit_ 7
Mac/802_11Ext set LongRetryLimit_ 4
Mac/802_11Ext set HeaderDuration_ 0.000040
Mac/802_11Ext set SymbolDuration_ 0.000008
Mac/802_11Ext set BasicModulationScheme_ 0
Mac/802_11Ext set use_802_11a_flag_ true
Mac/802_11Ext set RTSThreshold_ 2346
Mac/802_11Ext set MAC_DBG 0
set P [Phy/WirelessPhy set Pt_]
```

```
#=======================================================================
# set up topography object
#=======================================================================

set topo	[new Topography]
$topo load_flatgrid 300 300

#=======================================================================
# Create God
#=======================================================================

set god_ [create-god $val(nn)]

#=======================================================================
# Mobile node configuration parameter setup
#=======================================================================

#  Create the specified number of mobilenodes [$val(nn)] and "attach" them
#  to the channel.
	$ns_ node-config -adhocRouting $val(rp) \
				-llType $val(ll) \
				-macType $val(mac) \
				-ifqType $val(ifq) \
				-ifqLen $val(ifqlen) \
				-antType $val(ant) \
				-propType $val(prop) \
				-phyType $val(netif) \
				-channelType $val(chan) \
				-topoInstance $topo \
				-agentTrace ON \
				-routerTrace ON \
				-macTrace ON \
				-movementTrace ON

		for {set i 0} {$i < $val(nn) } {incr i} {
			set node_($i) [$ns_  node]
			$node_($i) random-motion 0		;# disable random motion
}

#=======================================================================
# Define node movement model
#=======================================================================

puts "Loading connection pattern..."
source $val(cp)

#=======================================================================
# Define traffic model
#=======================================================================

puts "Loading scenario file..."
source $val(sc)

#=======================================================================
# Define node initial position in nam
#=======================================================================
```

```
for {set i 0} {$i < $val(nn)} {incr i} {
        # 20 defines the node size in nam, must adjust it according to your
        # scenario size.
        # The function must be called after mobility model is defined
      $ns_ initial_node_pos $node_($i) 5
}

#=====================================================================
# Setting node colors
#=====================================================================

$node_(0) color "Brown"
$ns_ at 1.0 "$node_(0) color Brown"
$ns_ at 1.0 "$node_(0) label Bs1"
$node_(1) color "Blue"
$ns_ at 1.0 "$node_(1) color Blue"
$ns_ at 1.0 "$node_(1) label V1"
$node_(2) color "red"
$ns_ at 1.0 "$node_(2) color red"
$ns_ at 1.0 "$node_(2) label V2"
$node_(3) color "grey"
$ns_ at 1.0 "$node_(3) color grey"
$ns_ at 1.0 "$node_(3) label V3"
$node_(4) color "Green"
$ns_ at 1.0 "$node_(4) color Green"
$ns_ at 1.0 "$node_(4) label V4"
$node_(5) color "Purple"
$ns_ at 1.0 "$node_(5) color Purple"
$ns_ at 1.0 "$node_(5) label V5"
$node_(6) color "Yellow"
$ns_ at 1.0 "$node_(6) color Yellow"
$ns_ at 1.0 "$node_(6) label V6"
$node_(7) color "Pink"
$ns_ at 1.0 "$node_(7) color Pink"
$ns_ at 1.0 "$node_(7) label V7"
$node_(8) color "Black"
$ns_ at 1.0 "$node_(8) color Black"
$ns_ at 1.0 "$node_(8) label V8"
$node_(9) color "Brown"
$ns_ at 1.0 "$node_(9) color Brown"
$ns_ at 1.0 "$node_(9) label V9"
$node_(10) color "Blue"
$ns_ at 1.0 "$node_(10) color Blue"
$ns_ at 1.0 "$node_(10) label V10"
$node_(11) color "red"
$ns_ at 1.0 "$node_(11) color red"
$ns_ at 1.0 "$node_(11) label V11"
$node_(12) color "Grey"
$ns_ at 1.0 "$node_(12) color Grey"
$ns_ at 1.0 "$node_(12) label V12"
$node_(13) color "Green"
$ns_ at 1.0 "$node_(13) color Green"
$ns_ at 1.0 "$node_(13) label V13"
$node_(14) color "Purple"
$ns_ at 1.0 "$node_(14) color Purple"
$ns_ at 1.0 "$node_(14) label V14"
$node_(15) color "Yellow"
```

```
$ns_ at 1.0 "$node_(15) color Yellow"
$ns_ at 1.0 "$node_(15) label V15"
$node_(16) color "Pink"
$ns_ at 1.0 "$node_(16) color Pink"
$ns_ at 1.0 "$node_(16) label V16"
$node_(17) color "Black"
$ns_ at 1.0 "$node_(17) color Black"
$ns_ at 1.0 "$node_(17) label V17"
$node_(18) color "Brown"
$ns_ at 1.0 "$node_(18) color Brown"
$ns_ at 1.0 "$node_(18) label V18"
$node_(19) color "Blue"
$ns_ at 1.0 "$node_(19) color Blue"
$ns_ at 1.0 "$node_(19) label V19"
$node_(20) color "red"
$ns_ at 1.0 "$node_(20) color red"
$ns_ at 1.0 "$node_(20) label V20"
$node_(21) color "Grey"
$ns_ at 1.0 "$node_(21) color Grey"
$ns_ at 1.0 "$node_(21) label V21"
$node_(22) color "Green"
$ns_ at 1.0 "$node_(22) color Green"
$ns_ at 1.0 "$node_(22) label V22"
$node_(23) color "Purple"
$ns_ at 1.0 "$node_(23) color Purple"
$ns_ at 1.0 "$node_(23) label V23"
$node_(24) color "Yellow"
$ns_ at 1.0 "$node_(24) color Yellow"
$ns_ at 1.0 "$node_(24) label V24"
$node_(25) color "Pink"
$ns_ at 1.0 "$node_(25) color Pink"
$ns_ at 1.0 "$node_(25) label V25"
$node_(26) color "Blue"
$ns_ at 1.0 "$node_(26) color Blue"
$ns_ at 1.0 "$node_(26) label V26"
$node_(27) color "red"
$ns_ at 1.0 "$node_(27) color red"
$ns_ at 1.0 "$node_(27) label V27"
$node_(28) color "grey"
$ns_ at 1.0 "$node_(28) color grey"
$ns_ at 1.0 "$node_(28) label V28"
$node_(29) color "Green"
$ns_ at 1.0 "$node_(29) color Green"
$ns_ at 1.0 "$node_(29) label V29"
$node_(30) color "Purple"
$ns_ at 1.0 "$node_(30) color Purple"
$ns_ at 1.0 "$node_(30) label V30"
$node_(31) color "Yellow"
$ns_ at 1.0 "$node_(31) color Yellow"
$ns_ at 1.0 "$node_(31) label V31"
$node_(32) color "Pink"
$ns_ at 1.0 "$node_(32) color Pink"
$ns_ at 1.0 "$node_(32) label V32"
$node_(33) color "Black"
$ns_ at 1.0 "$node_(33) color Black"
$ns_ at 1.0 "$node_(33) label V33"
$node_(34) color "Brown"
```

```
$ns_ at 1.0 "$node_(34) color Brown"
$ns_ at 1.0 "$node_(34) label V34"
$node_(35) color "Blue"
$ns_ at 1.0 "$node_(35) color Blue"
$ns_ at 1.0 "$node_(35) label V35"
$node_(36) color "red"
$ns_ at 1.0 "$node_(36) color red"
$ns_ at 1.0 "$node_(36) label V36"
$node_(37) color "Grey"
$ns_ at 1.0 "$node_(37) color Grey"
$ns_ at 1.0 "$node_(37) label V37"
$node_(38) color "Green"
$ns_ at 1.0 "$node_(38) color Green"
$ns_ at 1.0 "$node_(38) label V38"
$node_(39) color "Purple"
$ns_ at 1.0 "$node_(39) color Purple"
$ns_ at 1.0 "$node_(39) label V39"
$node_(40) color "Yellow"
$ns_ at 1.0 "$node_(40) color Yellow"
$ns_ at 1.0 "$node_(40) label V40"
$node_(41) color "Pink"
$ns_ at 1.0 "$node_(41) color Pink"
$ns_ at 1.0 "$node_(41) label V41"
$node_(42) color "Black"
$ns_ at 1.0 "$node_(42) color Black"
$ns_ at 1.0 "$node_(42) label V42"
$node_(43) color "Brown"
$ns_ at 1.0 "$node_(43) color Brown"
$ns_ at 1.0 "$node_(43) label V43"
$node_(44) color "Blue"
$ns_ at 1.0 "$node_(44) color Blue"
$ns_ at 1.0 "$node_(44) label V44"
$node_(45) color "red"
$ns_ at 1.0 "$node_(45) color red"
$ns_ at 1.0 "$node_(45) label V45"
$node_(46) color "Grey"
$ns_ at 1.0 "$node_(46) color Grey"
$ns_ at 1.0 "$node_(46) label V46"
$node_(47) color "Green"
$ns_ at 1.0 "$node_(47) color Green"
$ns_ at 1.0 "$node_(47) label V47"
$node_(48) color "Purple"
$ns_ at 1.0 "$node_(48) color Purple"
$ns_ at 1.0 "$node_(48) label V48"
$node_(49) color "Yellow"
$ns_ at 1.0 "$node_(49) color Yellow"
$ns_ at 1.0 "$node_(49) label V49"
$node_(50) color "Pink"
$ns_ at 1.0 "$node_(50) color Pink"
$ns_ at 1.0 "$node_(50) label V50"
puts $tracefd "M 0.0 nn $val(nn) x $val(x) y $val(y) rp $val(rp)"
puts $tracefd "M 0.0 sc $val(sc) cp $val(cp) seed $val(seed)"
puts $tracefd "M 0.0 prop $val(prop) ant $val(ant)"
for {set i 0} {$i < $val(nn) } {incr i} {
    $ns_ at $val(stop).0 "$node_($i) reset";
}
```

```
$ns_ at $val(stop).0 "stop"
$ns_ at $val(stop).001 "puts \"NS EXITING...\" ; $ns_ halt"
proc stop {}  {
   global ns_ nf tracefd
   $ns_ flush-trace
   close $tracefd
   close $nf
   exec nam Userr-50-1.nam &
   exit 0

}
puts "Starting Simulation..."
$ns_ run
```

# Appendix C

# AWK Script

```
BEGIN {
recvdSize1 = 0
recvdSize2 = 0
startTime = 0
stopTime = 0
seqno = -1;
sentPackets = 0;
droppedPackets = 0;
receivedPackets = 0;
count = 0;
sum=0;
recvnum=0
}
{
action = $1;
time = $2;
node_id = $3;
layer = $4;
flags = $5;
packet_id = $6;
type = $7;
size = $8;
a = $9;
b = $10;
c = $11;
d = $12;
   if($4 == "AGT" && $1 == "s" && packet_id <$6) {
         packet_id = $6;
}
          else if(($4 == "AGT") && ($1 == "s")) {

       if (time < startTime) {
          startTime = time
          }
         sentPackets++;
         sent_bytes=sent_bytes+size;
   }
          else if(($4 == "AGT") && ($1 == "r")) {
     if (time > stopTime) {
          stopTime = time
          }
         receivedPackets++;
         received_bytes=received_bytes+size;
   } #else if ($1 == "D" && $7 == "cbr" && $8 > 512)
else if ($1 == "D" && $7 == "tcp"){
         droppedPackets++;
  }
   #Average end-to-end delay
   if ( start_time[packet_id] == 0 )  start_time[packet_id] = time;
  if (( $1 == "r") && ( $4=="AGT" )) {  end_time[packet_id] = time;  }
      else {  end_time[packet_id] = -1;  }
}
END {
```

```
 for ( i in end_time )
 {
 start = start_time[i];
 end = end_time[i];
 packet_duration = end - start;
 if ( packet_duration > 0 )
 {    sum += packet_duration;
      recvnum++;
 }
 }
    delay=(sum/recvnum)*1000;if ( start_time[packet_id] == 0 )  start_time[packet_id] = time;
 if (( $1 == "r") && ( $4=="AGT" )) {  end_time[packet_id] = time;  }
      else {  end_time[packet_id] = -1;  }
}
END {
   for ( i in end_time )
 {
 start = start_time[i];
 end = end_time[i];
 packet_duration = end - start;
 if ( packet_duration > 0 )
 {    sum += packet_duration;
      recvnum++;
 }
 }
    delay=(sum/recvnum)*1000;
   print "\n";
   print "GeneratedPackets            = " packet_id;
   print "ReceivedPackets             = " receivedPackets;
   print "SentPackets             = " sentPackets;
   print "Sentbytess             = " sent_bytes;
   print "Receivedbytes             = " received_bytes;
"%";
   print "Total Dropped Packets = " droppedPackets;
   print "Dropped Packets Ratio = " droppedPackets/sentPackets;
   print "Total Packet Loss = " ((sentPackets-receivedPackets)/sentPackets);
   print "Packet Loss Rate= " ((sentPackets-receivedPackets)/sentPackets)*100;
   print "Average Throughput = "((received_bytes)/(stopTime-startTime))*(8/1000),
startTime,stopTime;
   print "Data Throughput = "(receivedPackets/sentPackets)*100;
   printf("%.2f\n",delay);
   print "\n";
}
```