DOCTORAL THESIS

Traffic based energy consumption optimisation to improve the lifetime and performance of ad hoc wireless sensor networks

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Traffic based Energy Consumption Optimisation to Improve the Lifetime and Performance of Ad Hoc Wireless Sensor Networks

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Declarations

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, as accepted by my examiners.

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Abstract

Ad hoc wireless sensor networks (WSNs) are formed from self-organising configurations of distributed, energy constrained, autonomous sensor nodes. The service lifetime of such sensor nodes depends on the power supply and the energy consumption, which is typically dominated by the communication subsystem. One of the key challenges in unlocking the potential of such data gathering sensor networks is conserving energy so as to maximize their post deployment active lifetime

This thesis described the research carried on the continual development of the novel energy efficient Optimised grids algorithm that increases the WSNs lifetime and improves on the QoS parameters yielding higher throughput, lower latency and jitter for next generation of WSNs. Based on the range and traffic relationship the novel Optimised grids algorithm provides a robust traffic dependent energy efficient grid size that minimises the cluster head energy consumption in each grid and balances the energy use throughout the network. Efficient spatial reusability allows the novel Optimised grids algorithm improves on network QoS parameters. The most important advantage of this model is that it can be applied to all one and two dimensional traffic scenarios where the traffic load may fluctuate due to sensor activities. During traffic fluctuations the novel Optimised grids algorithm can be used to re-optimise the wireless sensor network to bring further benefits in energy reduction and improvement in QoS parameters. As the idle energy becomes dominant at lower traffic loads, the new Sleep Optimised grids model incorporates the sleep energy and idle energy duty cycles that can be implemented to achieve further network lifetime gains in all wireless sensor network models.

Another key advantage of the novel Optimised grids algorithm is that it can be implemented with existing energy saving protocols like GAF, LEACH, SMAC and TMAC to further enhance the network lifetimes and improve on QoS parameters. The novel Optimised grids algorithm does not interfere with these protocols, but creates an overlay to optimise the grids sizes and hence transmission range of wireless sensor nodes.

Keywords

Wireless Sensor Networks, Energy conservation, Simulation, Optimal transmission range, QoS, Spatial reusability

Dedications

This thesis is dedicated to my late father, Raja Mohammed Iqbal, my mother Zahida Anwar Iqbal, my wife Farheen and our three wonderful children, Zara, Abdul-Sallam and Samiullah

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Glossary of Terms

Abbreviations

ACK:	Acknowledgement
AWSNs:	Ad hoc Wireless Sensor Networks
BMAC:	Berkeley Medium Access Control
CDMA:	Code Division Multiple Access
CSMA/CA:	Carrier Sense Multiple Access /Collision Avoidance
COTS:	Commercial off the shelf
CTS:	Clear to Send
DCF:	Distributed Coordination Function
FDMA:	Frequency Division Multiple Access
GAF:	Geographical Adaptive Fidelity
LAPAR:	Location-Aided-Power-Aware Routing
LILT:	Local Information and Link-State Topology
MAC:	Medium Access Control
MBCR:	Minimal Battery Cost Routing
MDR:	Minimum Drain Rate
MIP:	Multicast Incremental Power
MSR:	Maximum Survivability Routing
OPNET:	Optimised Network Engineering Tools
NAM:	Network Animator
NAV:	Network Allocation Vector
NOAH:	No Ad hoc Routing Protocol
NS2:	Network Simulator 2
PARO:	Power-Aware Routing Optimization
QoS:	Quality of Service
RTS:	Request to Send
SMAC:	Sensor MAC

Glossary of Terms

TDMA:	Time Division Multiple Access
T-MAC:	Timeout MAC
WSN:	Wireless Sensor Networks
WAHN:	Wireless Ad Hoc Network
WLAN:	Wireless Local Area Networks

Nomenclature

λ : Wavelength

A: Total Traffic

B: Bandwidth

d_c : Crossover distance

d_{char}: Characteristic distance

E_t : Total Transmission Energy per Second

E_r : Power is required to capture the incoming radio signal

e_t : Energy/bit consumed by the transmitter electronics

e_r : Energy/bit consumed by the node's receiver electronics

$e_d r^n$: Energy dissipated in the transmit op-amp

k: Number of hops

d: Distance

r_{opt}: Optimal range

$P_r(d)$: Power received by the receiver

G_t : Gain of the transmitter antenna

G_r : Gain of the receiver antenna

L: Path loss

h_t : Transmit antenna height

h_r : Receive antenna height

Chapter 1

Introduction

In the last few years, wireless sensor networks have moved from being objects of academic research interest to a technology that is frequently being deployed in real-life applications and rapidly being commercialized. However energy consumption still remains the biggest challenge in many wireless sensor network applications that require long lifetime (Raghunathan, Ganeriwal et al. 2006). Keeping wireless sensor nodes small in form factor results in them having limited energy storage capability. The WINS (Vardhan, Wilczynski et al. 2000) and SmartDust (Kahn, Katz et al. 1999) projects, have integrated sensing, computing, and wireless communication capabilities into a small form factor to enable low-cost production of these tiny nodes in large numbers. Many universities across USA and Europe are researching on efficient hardware / software system designs, improving on signal processing and data aggregation algorithms, and network protocols for wireless sensor networks.

Sensor nodes are driven by batteries and hence operate on low energy budget. In some environments, they must have a lifetime on the order of months to years, since battery replacement is impossible for networks with hundreds of physically scattered and embedded nodes. Previous low-power design and hardware design techniques (Broderson and Chandrakasan 1995) only provide simple solutions which are insufficient for these highly energy-constrained systems. Optimizing the energy for sensor networks is very complicated, as it involves not only reducing the energy consumption of a single sensor node but also increasing the lifetime of an entire network. The network lifetime can only be increased by including energy awareness into every stage of wireless sensor network design and operation, thus empowering the system with the ability to make dynamic trade-offs between energy consumption, system performance, and operational fidelity (Raghunathan and Srivastava 2002).

1.1 Statement of the Problems and Direction of the Research

The purpose of this research effort is to continue on the development and improvement of novel energy efficient Optimised grids algorithm developed by (Gao, Blow et al. 2006) to extend the network lifetime and QoS parameters for wireless sensor networks. The previous work has been carried out using system-level Matlab simulations. This research includes the enhanced network simulation tools that perform packet-level simulations and model in detail the communication protocols including the actual data transmission, recording events such as medium access, packet delivery, collisions, retransmissions and energy consumptions of individual nodes. This research also improves the model by adding a sleep state that further enhances the cluster head as well as network lifetimes.

A wireless ad hoc network has no pre-existing infrastructure e.g. like routers in wired networks or access points in managed wireless networks. Minimal configuration and quick deployment make ad hoc WSN's suitable for emergency situations like natural disasters or military conflicts.

WSNs applications can be divided into two categories: *Monitoring and Tracking*. Monitoring applications include indoor/outdoor monitoring e.g. security detection, structural, factory, inventory & machine monitoring. Environmental monitoring includes earthquake zones, volcanic, climate, weather, temperature and pressure monitoring. Habitat monitoring includes Animal monitoring (Zebra, birds, Cane etc). The health and wellness involves applications for infant monitoring, alerting the deaf, blood pressure monitoring and fire-fighter vital signs monitoring. Tracking applications include tracking objects, animals, humans (enemy tracking) and vehicles (traffic, car, bus).

Ad hoc wireless sensor networks (WSNs) are formed from self-organising configurations of distributed, energy-constrained, autonomous sensor nodes. The nodes are miniaturised microelectronics devices equipped with heavily integrated sensing, processing, and wireless communication capabilities and are equipped with an independent power source, such as a small battery. When these nodes are networked together in an ad-hoc fashion, they form a sensor network. The nodes gather data via their sensors, process it locally or coordinate amongst neighbours, and forward the information to the user or, in general, a data sink. The service life of such nodes depends on the power supply and the energy consumption, which is typically dominated by the communication subsystem. One of the key challenges in unlocking the potential of such data gathering sensor networks is conserving energy so as to maximize their post-deployment active lifetime.

Research has been carried out in many different areas of WSNs from enhancing medium access control (MAC) protocols to improving topology management schemes where energy can be reduced. Many of the efficient MAC routing protocols try to increase the network lifetime by transitioning the idle nodes to sleep state. This not only increases the overhead cost of introducing synchronisation packets, but also has detrimental effects on the network QoS parameters that introduce latency, jitter and results in decreased throughput.

The purpose of putting nodes to sleep is more useful for nodes that are furthest away from the base station. In the case of the nodes nearest to the base station, having much higher traffic to forward at peak rates these nodes cannot actually share the same sleep-awake schedule that is designed for the rest of the WSN. In energy efficient routing protocols, lot of emphasis is given on minimising the transmission energy consumption, by either introducing multi-hop in the network, or finding the minimum energy route, where the message will be sent via a calculated multi-hop route. These protocols fail to scale the size of the networks. The majority of these protocols find the minimum path and then always choose that path regardless of the amount of traffic. Hence nodes required to forward messages in that minimum energy path list will always die first. These protocols fail to address the issue of energy consumption based on traffic. In many wireless sensor networks, the nodes nearest the base station will always be the busiest as traffic will be approaching these nodes from all directions of the sensor fields. These nodes provide the last hop for a successful transmission. One of the significant differences between the new Sleep Optimised grids algorithm introduced in this research and the existing energy saving protocols is that the new Sleep Optimised grids algorithm balances the energy use based on network traffic and also introduces sleep mode that further extends network lifetime by saving idle energy consumption. The previous Optimised grids algorithm (Gao, Blow et al. 2006) calculates the best transmission range at a given point in the network for the nodes in that grid based on traffic. This balances the energy consumption of sensor nodes at all stages of the network. At a point furthest away from the base station, the transmission distance is longer as the traffic is much lower and the nodes can afford to transmit at a longer distance. For nodes nearest to the base station, where the traffic is higher, the transmission range is intelligently calculated to be shorter, so more data can be forwarded to the base station without consuming all the cluster head energy. This research explores into detail the benefits provided by the Optimised grids algorithm and the new Sleep Optimised grids algorithm and in addition implements these models in 2-D WSN's using packet level simulation.

1.2 Principal Aims

The principal aims of this research are as follows.

1. To develop and compare network models for 1-D and 2-D Optimised grids network with Commercial off the Shelf (COTS) products at packet level simulation.
2. To study the benefits of Optimised grids networks (Gao, Blow et al. 2006) and the new Sleep Optimised grids Network in terms of cluster head lifetime and network lifetime.
3. To evaluate the QoS parameters in terms of packet delivery, throughput, latency and jitter for Optimised grids network and new Sleep Optimised grids network as compared to existing Equal grids and COTS network.
4. Improve on the existing Optimised grids algorithm by implementing the sleep mode to further enhance the cluster head and network lifetimes.
5. To evaluate the advantages of Optimised grids network in two-dimensional networks with idle and sleep modes.

1.3 Significant Contributions

The major contributions of this research are

1. Through packet level simulation using enhanced NS2, the Optimised grids algorithms proves to be much superior in terms of energy efficiency at cluster head level by improving the cluster head lifetimes between 30% and 50% compared to Equal grids and COTS network.

2. The Optimised grids algorithm provides much better throughput as compared to similar networks based on existing protocols and using COTS network. An increase in throughput of up to 25% is achieved at 100% traffic load.
3. The latency and jitter for the Optimised grids network are much lower as compared to similar Equal grids and COTS networks. The latency falls by an order of magnitude and jitter reduced by over 55%.
4. The Optimised grids network has much better spatial re-usability as compared to existing Equal grids and COTS networks. This helps in avoiding collisions, by reducing the hidden node problem, therefore improving on packet delivery and throughput.
5. The new Sleep Optimised grids algorithm further improves the network lifetime as compared to conventional network. At lower traffic rates, by using the Sleep Optimised grids algorithm, the network lifetime improved by 500%.
6. In 2-D network scenarios including sensor traffic, the 2-D Optimised grids network has superior performance in terms of network lifetime and QoS parameters including higher throughput, lower latency and jitter.

1.4 Thesis Layout

This thesis is comprised of seven chapters, covering a background of literature, a description of studies undertaken, presentation of results and a conclusion.

Chapter 2 reviews many different components that comprise a wireless sensor node. It then explores many different energy saving theories and algorithms. It highlights many of the design challenges faced by existing wireless sensor network protocols related to energy efficiency. Many active and passive energy saving protocols are investigated.

Chapter 3 explores the existing network simulation tools and compares their advantages and disadvantages. A simulation tool is then chosen that forms the basis of the investigation carried out in this research. The performance and accuracy of this simulation tool is measured and modifications are added. This allows modelling and simulating

varying transmission range and energy consumption of WSN’s that are required in this research.
Chapter 4 starts with a simple wireless sensor network radio power model. This model lays the basis in developing the Optimised grids algorithm. Active and passive topology management scheme allows the formulation of Optimised grids algorithm. Several 1-D wireless sensor networks are modelled with various traffic configuration settings to evaluate and validate the performance of the Optimised grids algorithm. Analytical and simulated results verify the energy and throughput gains achieved by the networks based on the Optimised grids algorithm compared with existing topology management protocols and Commercial of the Shelf products (COTS).

Chapter 5 discusses the adoption of the Sleep mode in the existing 1-D Optimised grids wireless sensor networks. The existing Optimised grids algorithm is further modified to add the sleep and idle duty cycles and renamed the new Sleep Optimised grids algorithm. Again several 1-D wireless sensor networks are modelled using the enhanced NS2 simulation tool and results are compared to identify the performance and energy gains achieved by the new Sleep Model.

Chapter 6 introduces two dimensional wireless sensor networks based on the Optimised grids algorithm. Sensor network traffic is added to the existing models. Energy efficiency and QoS parameters are compared with existing protocols to highlight the advantages offered by the Optimised grids algorithm.

Chapter 7 presents the conclusions generated by the current work and discusses possible future directions for this research.

Chapter 2

Background of Studies

Some of the performance metrics required by wireless sensor network are described below

- *Energy Efficiency*. The sensors are equipped with irreplaceable batteries and hence have limited lifetime. Proper network design is required to maximize node as well as network lifetime.
- *Latency*. Nearly all the Sensor network applications required delay-guaranteed service. Sensor network protocols need to ensure that the sensed data will be delivered within the certain time frame. This is a very important requirement for sensor-actuator networks.
- *Accuracy*. The received sensor data needs to be accurate to some degree to be useful.
- *Fault tolerance*. The network needs to be robust to link failure or other hardware failures and needs to be self-healing.
- *Scalability*. A wireless sensor network may contain hundreds or thousands of nodes, scalability becomes a critical issue that guarantees that as network size or node density increase, the network performance does not decrease considerably
- *Transport Capacity & Throughput*. In majority of wireless sensor networks, sensors send data to a single base station. The area near the base station becomes critical as all the sensors in that region not only have to send their information but also are required to forward data received from the sensors further away from the base station. Hence the traffic load in those sensors is heavy even though if the data rate is low. This area has a paramount influence on the network lifetime, packet end to end delay, throughput and scalability.

2.1 Energy Efficient Hardware Challenges

Energy efficiency is the most important issue in wireless sensor networks and determines the network's lifetime. For many wireless sensor networks, that perform repetitive tasks, the higher the energy efficiency is, the longer the network lifetime will be. The initial step in designing an energy aware wireless sensor networks involves the power consumption analysis of the wireless sensor node. A typical wireless sensor node architecture shown in Figure 2.1 (Raghunathan and Srivastava 2002) consist of four main components

Figure 2.1: Schematic of a simple wireless sensor node.

1) A microprocessor or microcontroller.
2) A short range radio for wireless communication.
3) A group of sensors and actuators.
4) A power supply system, which houses the battery and the dc-dc converter.

DC to DC converters are important in portable electronics that are supplied with power from batteries. Such electronic devices often contain several sub-circuits, each with its own voltage level requirement different from that supplied by the battery (sometimes higher or lower than the supply voltage). Additionally, the battery voltage declines as its stored power is drained. DC to DC converters offer a method to increase voltage from a partially lowered battery voltage thereby saving space instead of using multiple batteries to accomplish the same thing.

2.1.1 Choosing a Low Power Microcontroller Unit

The microcontroller is the brain of the wireless sensor node. It controls all the operations of the node, from gathering the data from the sensors, to processing, storing, discarding and forwarding the required data. Many different types of microcontrollers have been used for WSNs, the most common are from Intel's StrongARM that are used for heavy sensing duties to ATMEL AtMega128L range used for low sensing duties. Many researchers have studied power-performance characteristics of MCUs in great detail and many techniques have been established to estimate the power consumption of micro-controllers (Tiwari, Malik et al. 1996), (Sinha and Chandrakasan). The total computing energy consists of two parts, the switching energy when the microcontroller is executing the instructions and the leakage energy when no computation is being carried out. Research has shown that the leakage energy consumption can reach upto 50% of computation energy, and hence it is critical to reduce this energy (Tiwari, Malik et al. 1996) to increase node lifetime.

In (Conner, Chhabra et al. 2003), the researchers show that the processor itself dissipates 35% of the total energy budget of the MICA2 platform while running *Surge*, a TinyOS monitoring application. In (Madden, Franklin et al. 2005), the authors claim similar energy values when running a TinyDB query reporting light and accelerometer readings once every minute. In (Polastre), the researchers find that the energy consumption of the processor/memory component for raw data compression is higher than the energy consumption of raw data transmission.

Majority of WSN nodes vendors are currently using commercial of the shelf (COTS) microcontrollers such as ATMEL AtMega128L, the AT90LS8535, and the Texas Instruments MSP430. These microcontrollers are not specifically designed for the wireless sensor networks and hence despite using low energy, are still not energy efficient. The power consumption of a micro-controller can significantly affect the node's lifetime. For applications that rely on large data sensing and gathering, using a StongARM microprocessor, used in high-end sensor nodes, dissipates 400mW of power while executing instructions, while a low end microcontroller developed by Atmel as used in Mica2 motes consumes only 8mW of power while executing instructions . Many microcontrollers also support various operating modes e.g. Active, Idle and Sleep modes for better power management. A StrongArm processor dissipates 50mW in idle mode and

0.16mW in sleep mode, while the Atmel processor used in Mica2 motes only consumes 10mW in idle/receive mode and less than 1uA in sleep mode.

Some researchers have optioned to develop their own microcontrollers aimed at wireless sensor network. These include the sensor network asynchronous processor (SNAP/LE) (Ekanayake, Clinton Kelly et al.), Lutonium (Martin, Nystrom et al. 2003), CHARM (Sheets, Burghardt et al.), CoolRisc (Piguet, Masgonty et al. 1997) and ASPRO (Renaudin, Vivet et al. 1998). Table 2.1 compares some of the important features and energy costs of the existing COTS & WSN application specific microcontrollers.

Table 2-1 Comparing the specifications of COTS and WSN Application Specific Microcontrollers

Processor	Clocked	Speed (MIPS)	Datapath (bits)	Memory	Voltage (V)	Energy/Ins (pJ)
Atmel Mega 128L (used in MICA2 Mote, MEDUSA II)	Yes	4	8	4-8K	3	1500
Intel XScale High end ARM cores, used in Rockwell sensors, Intel Mote	Yes	200-400	8	16-32M	1.3-1.65	890-1028
Dynamic Voltage Scaled Microprocessor Custom ARM8	Yes	7-84	32	16K	1.3-1.8	540-5600
CoolRISC XE88 microcontroller	Yes	1	8	22K	2.4	720
Lutonium 8051 compatible 0.18μm	No	200	8	8K	1.8	500
Aspro-216 [28] Custom async. Micro-STM 0.25μm	No	25-140	16	64K	1.0-2.5	1000-3000
SNAP/LE - 0.18μm	No	28	16	8K	0.6	24
Charm - 0.18μm	No	240	16	8K	1.8	288

At the moment a large amount of research is being focused on developing energy saving microcontrollers similar to SNAPL/LE YUPPIE and CHARM etc. These have relatively high processing speeds, much more than what are required by WSN applications and yet use much lower energy compared to other COTS products. As the fabrication techniques are improving, the processors are becoming smaller and faster and their energy consumption is becoming lesser and lesser.

Other techniques to improve the energy consumption as described by (Küçük and Basaran 2007) is by processor optimization. In a wireless sensor network, majority of the time, the sensed data is similar and does not change, hence the authors create a cache which stores the initial data, if the new data is similar to the earlier one, then the processor does not read or write the new data to the registers, hence resulting in an overall energy saving between 20% to 25%.

This concludes that despite many COTS microcontrollers available, none of them are really targeted for the wireless sensor network market. Large silicon chip manufacturers like ST-Microelectronics and Freescale can see the huge opportunity and have started to work jointly with researchers to make microcontrollers dedicated for wireless sensor networks.

2.1.2 Transceiver

The radio of the sensor node enables wireless communication with the neighbouring nodes. The power consumption of the radio is affected by many factors including the data rates, duty cycle, transmit power and the type of modulation schemes used. Radios normally operate in one of the four states, Transmit, Receive, Idle, and Sleep. However for many wireless transceivers the energy consumption during the idle state is not much different from the energy consumed while in receiving state. Thus, it is an energy saving mechanism to shut down the radio rather than changing to idle state when it is not transmitting or receiving data. Another cause for significant power consumption in the radio is when it changes from one state to another e.g. a radio spends a significant amount of energy changing from sleep state to transmit state by switching on the transmitter when it wants to send a packet and hence it might not be feasible to make the radio sleep.

Other mechanism to reduce radio energy consumption is by creating multi hop topologies. Multi-hopping converts a long-range single-hop communication into several short-distance ones, with intermediate nodes acting as repeaters to forward the messages. The benefits achieved by multi-hop are twofold, initially it requires less transmit energy and secondly (Tseng, Tsai et al. 2009) it avoids the need of designing high-power power amplifiers (PAs) for long-range transmission. However, the networking overhead and the added repeaters have their own additive power cost, therefore, it is important that these should be optimised. While majority of wireless sensor nodes only have a single radio, Figure 2.2 shows a block diagram and an image of BTnode rev 3 designed by Swiss Federal Institute of Technology (ETH). This wireless sensor node is based on Mica2 platform consisting of two radios, a low power Chipcon CC1000 transceiver and a Zeevo Bluetooth transceiver.

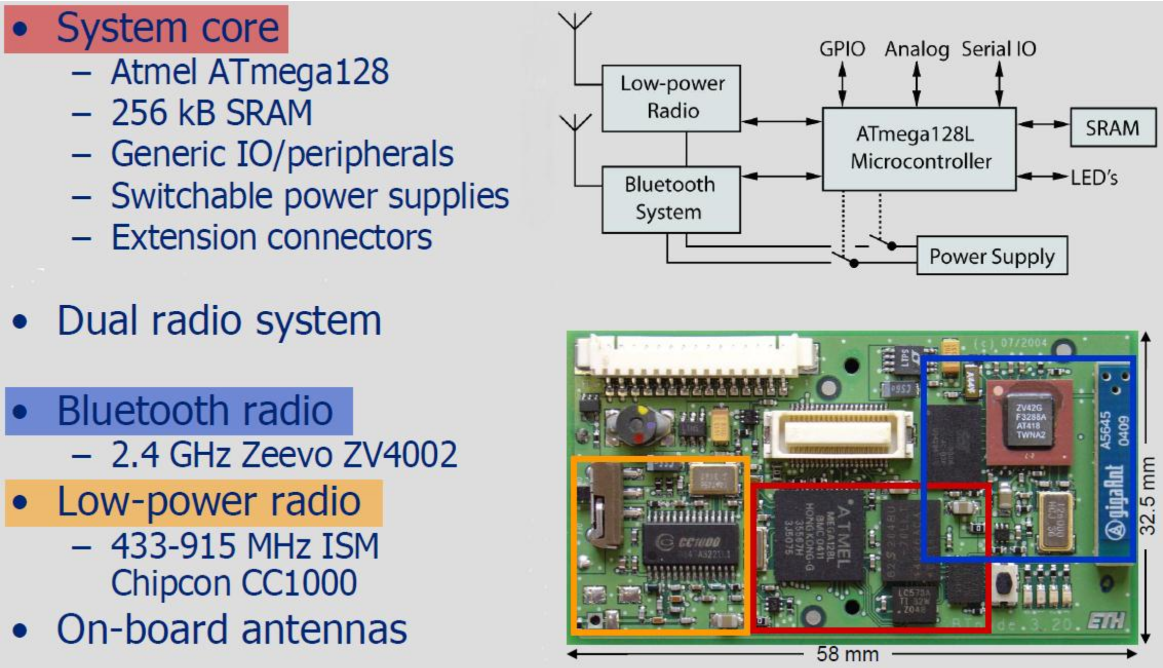

Figure 2.2: BTnode Rev 3, A Dual Radio platform with CC1000 and Bluetooth.

Table 2-2 summarises the energy consumption characteristics of most commonly used radio interfaces in existing wireless sensor platforms.

Table 2-2 COTS Radio Receiver characteristics used in WSN applications

Radio	Platform	Data Rate	Transmision	Reception/Idle	Sleep
CC1000 Chipcon	MICA2, CRICKET	38.6 kb/s	6.6-26.7 mA	7.3mA	0.2mA
TI CC2420 (Zigbee) Texas Instruments	MICAZ, TELOS, IMOTE, IMOTE2.NET	250kb/s	8.5-17.5 mA	19.7mA	1μA
ZV4002 + CC1000 Zeevo + Chipcon	BT-NODE Rev 3	>750kb/s Bluetooth	35.2 mA Bluetooth	30.8/45 mA 1 / 2 radios	3.3 mA
RF230 (Zigbee) Atmel	IRIS	250kb/s	6.1-17mA	15mA	<1μA

Table 2.2 shows two important characteristics of COTS receivers. First, the transmission energy consumption has a wide changeable range, providing opportunities for good energy

savings. Secondly, the sleep energy consumption state is several orders of magnitude lower than in other states. The transmission power control can be used to adjust the power required by the node to send messages to its neighbouring nodes and hence reducing the energy consumption, while a sleep mode can be introduced to turn off the radio when the nodes are neither transmitting nor receiving.

As there are many different variations of wireless sensor platforms, efforts are in progress to standardise the various layers (including the MAC and Physical) of Wireless Sensor Network communication protocols. The success of wireless sensor networks as a technology rests on the success of these standardisation efforts to unify the market, leading to large numbers of low cost, interoperable devices, and avoiding the proliferation of proprietary, incompatible protocols that, although perhaps optimal in their individual market niches, will limit the size of the overall wireless sensor market. Two of these standards being drafted for Wireless Sensor Networks are the IEEE 802.15.4 Low Rate Wireless Personal Area Network (WPAN) with the ZigBee Alliance, (a marketing and compliance certification organization) and the IEEE 1451.5 Wireless Smart Transducer Interface standard.

2.1.3 Sensors and Transducers

Sensor are transducers that record physical phenomena and change them to electrical signals. They can be divided into two groups either analogue or digital depending on their output. There are many different types of sensors that measure surrounding parameters e.g. temperature, light intensity, sound, acceleration, etc. Energy is required by sensors for many reasons, including i) signal sampling and conversion of physical signals to electrical ones, ii) signal conditioning, and iii) analogue-to-digital conversion. As there is a large variety of sensors available in the market, it is impossible to quantify the power consumption of the sensors. However, passive sensors e.g. temperature, seismic, etc., consume negligible power compared to other components of sensor node. But, active sensors such as sonar rangers, imagers, and narrow field-of-view sensors that require repositioning such as cameras can use a lot more power (Stemm and Katz 1997).

Again one of the key problems is the connectivity of the sensors. Majority of the available sensors are only compatible with other wireless products manufactured by the same manufacturer and there is no interoperability.

2.1.4 Battery Life & Energy Harvesting Techniques

The Battery module is the most important component in the wireless node. Battery lifetime has considerably improved over the last couple of years. The usable lifetime of a battery depends on many factors, including the size of battery, type, e.g. alkaline or lithium, and the diffusion rate of chemicals in the electrolyte. The lifetime of the battery is significantly reduced if the current drawn from the battery is higher than the manufacturer's rated value and results in battery becoming useless even though still having active ingredients in the electrolyte. This is due to the fact that the speed at which the chemicals diffuse through the electrolytes falls behind the speed at which they are used at the electrodes. Therefore to extend the battery life to maximum, the amount of current drawn from the battery needs to be under tight control. The effect of high discharge can be reversed by battery relaxation effect. Thus if the battery discharges high current while the node is in transmission state and after transmitting a packet, the node switches off by going into the sleep state, this will cause the diffusion and transport rate of the active material to catch up with the depletion caused by the discharge.

Some researchers have been trying to extend the network lifetime by introducing energy harvesting technologies to collect energy from ambient sources. Solar cells use the photovoltaic effect to convert sunlight into electricity. (Voigt, Dunkels et al.) and (Kansal and Srivastava 2003) have attached solar panels in addition to batteries to extend the node's lifetime. (Glynne-Jones, Tudor et al. 2004) have shown how a tiny piezoelectric generator can convert ambient vibration energy in to electrical energy for powering wireless sensor nodes. Thermoelectric devices can also generate energy when a temperature gradient exist across the device and are much superior to vibration based devices as they do not have any moving parts as demonstrated in the Glacsweb project (Martinez, Ong et al. 2004).

In this section different technologies have been reviewed that are either under investigation or being implemented by researchers across the globe to enable them to reduce the energy consumptions of the different hardware components that are required to assemble the next generation of wireless sensor nodes. The next section will focus on the data link layer of the OSI reference model and compare and contrast some of the key issues that are being investigated by the research community.

2.2 Energy Minimisation challenges for Medium Access Control

In Wireless Ad Hoc Network (WAHN), in the data link layer, the medium access control (MAC) sub layer and Error Control can play an important role in reducing the energy consumption of the wireless node. Two of the most important requirements of the MAC protocol in a multi-hop wireless sensor network are to establish data communication links for creating basic network infrastructure required for multi-hop wireless communication and to regulate the access of shared channel so that the available bandwidth is fairly and efficiently available to all the sensor nodes. The key requirements for these networks are high throughput and low latency. Network life is not considered to be an important issue as energy sources can be recharged or replaced. However in Wireless Ad hoc Sensor Networks, energy conservation is the most important issue as in most cases these networks are placed in inaccessible terrains, e.g. earthquake zones, forest fires or even behind enemy lines, where operator access is not available and hence batteries are not inter-changeable or rechargeable.

Compared to WAHNs, the nodes in WSNs can remain idle for a very long time waiting for some external event to happen and therefore can be put to sleep, compared to those nodes acting as cluster heads or gateways that have to transfer lot more data and need to remain active all the time. This will also result in unequal bandwidth allowance for cluster header nodes that have more data to transport as compared to leaf level nodes that only transmit to the cluster head every once so often.

For a Wireless Ad Hoc Network (WAHN) some of the main sources of energy waste (Ye, Heidemann et al. 2002) by the MAC layer are caused by retransmission of data or control packets due to collisions or congestion. If a node receives two or more packets from different sources at the same time due to hidden node problem, then none of these received packets get decoded properly and all are destroyed. When these packets are retransmitted, this not only result in more energy consumption by the concerned nodes but also the retransmitted packets cause more congestion on the network. Another cause for energy consumption in the MAC layer is idle channel sensing. If the nodes receive scheduling packets or want to transmit a message they need to sense the channel very often and wait until the channel is sensed idle, and that consumes energy. In a shared medium, the data transmitted by one node is received by all nodes within that transmission range; hence a node may waste energy in receiving packets that are not destined for it. Nearly all the MAC protocols operate by sending control packets of different types e.g. synchronisation, scheduling, RTS, CTS, ACK etc, this results in more energy consumption for resource limited wireless sensor nodes. From above it can be concluded that not only is the energy consumption and network lifetime an important issue, but network throughput can also be not ignored. However a balance needs to be made between network lifetime and throughput based on requirements of the application.

For WSNs increasing the network lifetime is one of the biggest challenges and energy needs to be conserved at each node. To tackle all or some of the above mentioned problems, a large amount of research has been carried out and still going in the design of energy efficient MAC protocols. The simplest way to conserve energy by the MAC layer protocols is by turning off the radio whenever the node is not transmitting hence leaving the node in sleep mode. The wireless MAC protocols can be divided generally in three main categories, Centralised, Distributed & Hybrid MAC Protocols as shown in Figure 2.3

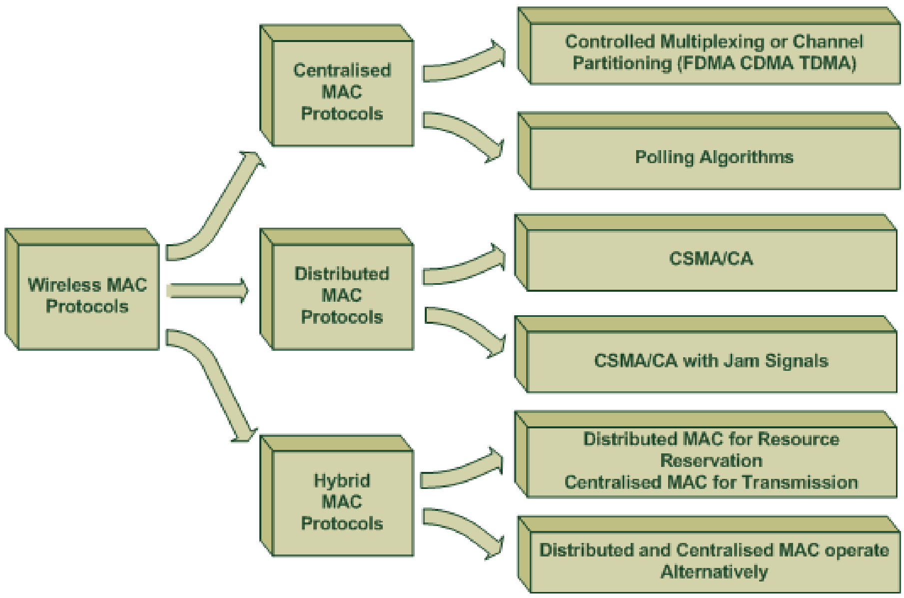

Figure 2.3: Classification of Wireless MAC Protocols.

2.2.1 Centralised MAC Protocols

In centralised MAC protocols, it is the responsibility of a single controller to allocate the channel access for all the nodes in the sensor field to provide a collision free environment. Channel multiplexing techniques similar to Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA) and Code Division Multiple Access (CDMA) have been mentioned by (Pottie and Kaiser 2000).

However drawbacks of TDMA scheme include the central controller consuming a lot more energy compared to other nodes. Also as the size of WSN keeps varying with time as nodes are added or replaced, complicated hardware components and software algorithms are required to maintain an effective working schedule. Another key problem is to maintain clock synchronisation among several hundreds or thousands of nodes, this result in adding more control packets to the limited channel and hence introducing further congestion and burden to the energy scarce sensor nodes. Due to limited channel bandwidth and very large number of nodes, when implementing FDMA, it becomes impractical for each node to have a unique operating frequency. Also due to low duty cycle, bandwidth wastage will occur as all nodes will be assigned to frequencies while very few will use them. Frequency assignment problems will also occur if there is a rapid increase in the size of the network as all the frequencies might have already been allotted. In CDMA all the nodes can transmit as required, however, each node will have its unique data encoding algorithm and will require highly complex transmitter and receiver designs.

2.2.2 Distributed MAC Protocols

These MAC protocols allow multiple channel access to all the participating nodes based on some rules. The prime example of this protocol is CSMA/CA, where all the participants regularly sense the medium to see if it is idle. If the channel is found to be busy, the transmission is deferred until the channel becomes idle. The probability of collisions are avoided by introducing a time delay procedure e.g. random back-off procedure as employed in IEEE 802.11 distributed coordination function (DCF) (Wu, Cheng et al. 2002). However the packet collision cannot be completely avoided in distributed MAC protocols due to the "hidden" and "exposed" node problem which has a very large impact on the network QoS. A hidden node is usually within the range of the intended receiver, but not in the range of the sender and hence does not know of the on-going transmission. An exposed node is within the range of the sender and out of range from the receiver, will be improperly precluded from sending in order to avoid collision. To overcome this problem the DCF uses RTS and CTS control messages to reserve the transmission time between two nodes.

The key advantages of distributed MAC schemes are that they are very flexible and easy to implement in large sensor networks. However they are not collision free and listen before talk schemes require the channel to be sensed all the time hence consuming that scarce energy reserves.

2.2.3 Hybrid MAC Protocols

The existing centralised and distributed MAC protocols do not provide optimised energy saving and network scalability for WSNs. An ideal protocol would exhibit the controllability of centralised protocols and the flexibility of distributed protocols. WSNs have unique characteristics e.g. low energy reserves, compact hardware, small transmission ranges, event or task driven and have high redundancy. IEEE 802.11 is designed for WLAN applications. It consumes significant amount of energy because the nodes are listening to the channel most of the time. A power saving mode also exists in IEEE 802.11, but does not implement a strict policy on sleep-awake schedule. Also in IEEE 802.11 the node in many cases is only a single hop away from the base station and there is no central controller. If the network becomes large and multi-hopping is introduced, then clock synchronisation will become a big problem as control packets will suffer variable delays due to node mobility and radio interference. Bluetooth (Haartsen, Bv et al. 2000) is another short-range wireless communication protocol used in many consumer devices using a TDMA/CDMA hybrid scheduling scheme. In Bluetooth, a Piconet is formed among maximum of 8 devices with one device acting as the master and the rest as slaves. Several Piconets can join together to form large networks known as ScatterNets. However for Bluetooth devices to grow to a scale of WSNs, it becomes impossible for TDMA to schedule and synchronise all the nodes, hence the scalability in Bluetooth is not as good as in contention based protocols.

2.2.4 Designing Energy Saving MAC Protocols for WSNs

Many modifications have been made to the existing WAHN protocols to accommodate for WSNs and some of the popular WSN MACs are as follows
The Sensor MAC (SMAC) (Ye, Heidemann et al. 2002) is specifically designed to prolong the life of the wireless sensor network by scheduling the nodes to enter periodic sleep mode when they are not transmitting as shown in Figure 2.4.

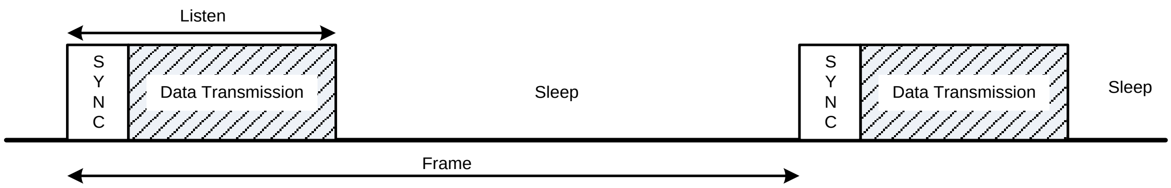

Figure 2.4: Sleep-Awake duty cycle in S-MAC.

For all the nodes, one complete frame consists of one listen and one sleep period. The duty cycle i.e. the listen period can be increased or decreased depending upon the amount of traffic. During initialisation a node stays awake for a random period to listen to a sleep-awake schedule from its neighbouring nodes. If it hears a schedule then it will follow it. However if the node does not hear a schedule broadcast, it becomes a synchroniser node and will broadcast its message. The neighbouring nodes that hear a schedule will tend to adopt the schedule and will become the follower nodes. This results in forming virtual clusters. As the sensor network can be very large, it is impossible to have a single cluster, hence there can be many virtual clusters at any one time. The nodes that are near the boundary of the cluster may hear two or more different sleep-awake schedules and tend to adopt multiple schedules so that they can transmit the message successfully between different clusters. The schedule packets are transmitted periodically so that any new node joining the network can be accommodated easily. Relative timestamps are used in SYNC packets to overcome the clock drift that can cause errors in the coordination of schedules, between neighbouring nodes.

When the nodes are awake, they all listen for the SYNC period apart from the leader node. Similar to the IEEE802.11, the SMAC also uses the RTS/CTS packets to avoid collision. It employs the physical carrier sense and virtual carrier sense. Using the physical carrier sense, the nodes can detect if the channel is busy and hence not to transmit during that time and can only receive the packet. As shown in Figure 2.5 node 1 and node 3 are synchronised to schedule of node 2 by receiving the SYNC packet which is shown by the shaded rectangular shape during the “Listen for Sync” period. Using virtual carrier sense, when node 3 wants to transmit the message to node 1, it will send a RTS packet as shown by shaded rectangular box during the “For RTS” period of node 3. The RTS packet will contain the address of recipient and the duration of the packet. Node 1 will then send a CTS packet as shown by the rectangular shaded box during the “Send CTS” period The non-recipient nodes will then set their timer (Network Allocation Vector) NAV for that time period and will go to sleep and will stay sleep until the NAV is non-zero. Therefore while node 1 and node 3 are communicating, node 2 has gone to sleep.

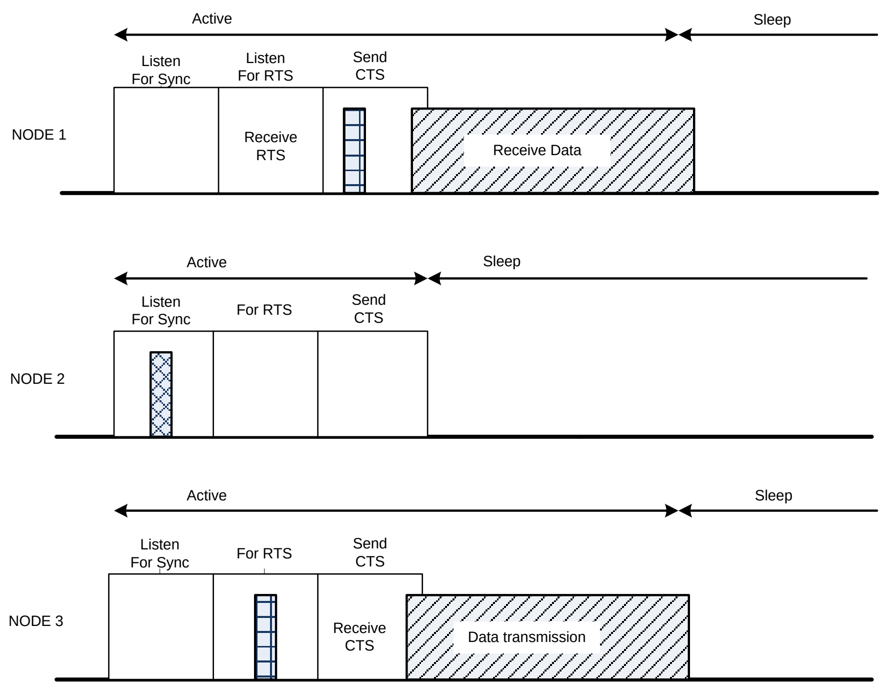

Figure 2.5: Timing schedules among different nodes.

If the data to be sent is more than one packet, then SMAC breaks down the data to small fragments to send multiple packets, but with only one RTS packet.

However the energy saving in the nodes comes from the expense of increased latency. A packet travelling across the network will have to pause after every few hops due to the sleep period of intermediate nodes.

Adaptive listening has been introduced in (Ye, Heidemann et al. 2004) to overcome the problem of increased network traffic and also to decrease latency. If for some reason the network becomes busy, the nodes will increase their duty-cycle, therefore staying awake longer to accommodate for transmission and relaying of network traffic. Another case of adaptive listening will be if a node ‘A’ overhears the RTS/CTS transmission from its neighbour, during its listen period, it will receive the estimated time of the completion of the data. Node A will go to sleep and will just wakeup before the transmission completes between neighbouring nodes, so if node A is the next intended hop, then its neighbour can pass off the message to it instead of waiting for the next awake schedule, and hence minimising congestion and latency in the network.

While SMAC is good for saving energy, it has its limitations. It uses the principles of TDMA scheduling to put the nodes to sleep and the sleeping patterns are co-ordinated to minimise the latency, however having a fixed duty cycle hinders the performance considerably if the network traffic increases rapidly in case of an external event. Also a large number of nodes will belong to two or more clusters and hence will be staying awake considerably longer and relaying a lot more traffic compared to leaf nodes in the network belonging to only one virtual cluster. These nodes will consume their energy reserves a lot quicker and will become useless. Another problem could be due to the non-presence of physical clusters instead of virtual cluster as the topology may become bigger and bigger it will be impossible to implement a perfect minimal energy consumption routing protocol in the network as the virtual cluster will keep changing and hence will result in more overhead with routing packets.

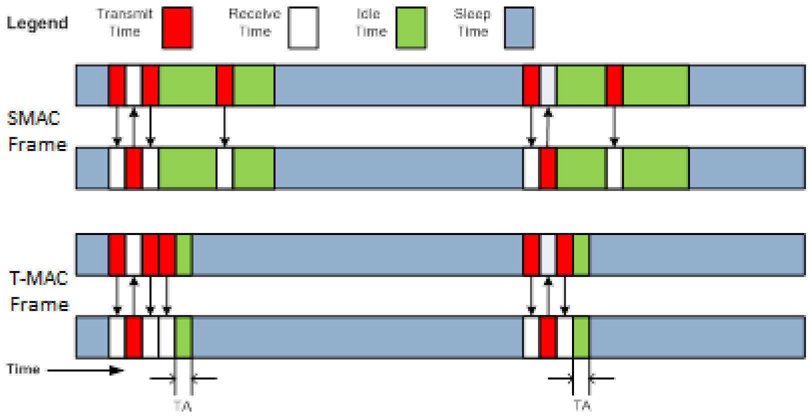

Figure 2.6: Comparing T-MAC and SMAC Frames.

The Timeout MAC (T-MAC) (van Dam and Langendoen 2003) is a similar protocol to SMAC and also involves a duty cycle than can adapt to the changes in the network traffic unlike SMAC in which it has to be done manually. The advantage of T-MAC is that it is more resilient to traffic fluctuation and can cope well if the traffic increases. The length of each frame is fixed, but at the end of the listen period there is a timeout Interval (TA). This timer keeps the node awake to see if the receiver gets any messages either control or data during the timeout, if it doesn't then the node is put to sleep. If a packet is received, the timer starts afresh. This renewal mechanism allows T-MAC to adapt easily with the change in traffic. Figure 2.6 compares the SMAC and T-MAC frames. It can be seen in SMAC, that the node remains awake even after it has received a message until the listen period is not over. In case of T-MAC after a node receives a packet, a time out (TA) counter is started and the node only remains awake until it is non-zero hence saving energy. T-MAC normally sends queued messages in a burst, hence decreasing latency for multihop messages.

One drawback of T-MAC is that it suffers from early sleep syndrome which can decrease the throughput. If some node has to be silent because of contention in a given cycle, it cannot send any message to its intended receiver to interrupt its timeout. When the sender can send after the end of contention period, the intended receiver is already in sleep mode.

2.3 Energy Efficient Routing Protocols

This research is primarily based on finding new and effective routing algorithms to minimise the energy consumption of wireless sensor networks. Ad hoc wireless networks do not have any network infrastructure. The wireless nodes in the ad hoc network try to maintain connectivity via wireless communication. Over the past few years, many efficient energy saving routing protocols have been devised and these have been analysed by the authors of (Lindsey, Sivalingam et al.). In (Li, Cordes et al. 2005) the authors base the routing protocols in two basic classifications; Activity based routing protocols and Connectivity based protocols. Figure 2.7 shows the classification of energy efficient ad hoc routing protocols.

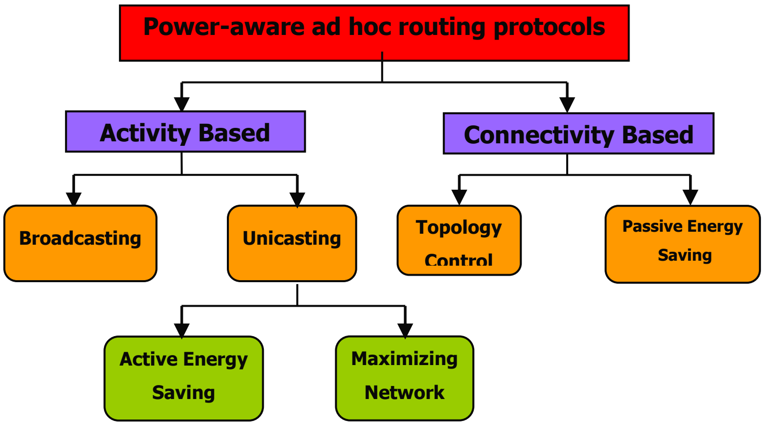

Figure 2.7: The classification of energy efficient ad hoc routing .

The energy efficient routing protocols can broadly be divided into five categories, active energy saving protocols, maximizing network lifetime protocols, passive energy saving protocols, topology control protocols and broadcasting protocols.

2.3.1 Active Energy Saving Protocols

In active energy saving protocols the aim is to find the routing path with the minimum energy consumption. The simple objective is to minimize the energy consumed per packet (Singh, Woo et al. 1998). A simple example is given by using the Power-Aware Routing Optimization protocol (PARO) (Gomez, Campbell et al. 2003) as shown in Figure 2.8. If node ‘a’ wants to transmit a message to node ‘e’, it will work out which multi-hop route requires total minimum energy consumption and will choose that path. This is to avoid large energy consumption in transmitting directly to the recipient node. In the below example it can be seen the source calculates the transmission energy between two different routes i.e. a→c→e and a→b→c→d→e and then uses the path with minimum energy consumption.

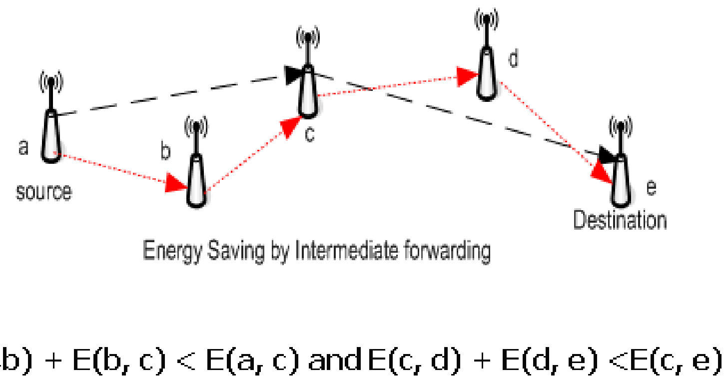

Figure 2.8: The PARO protocol implementation.

In (Xue and Li 2001) the author suggest Location-Aided-Power-Aware Routing protocol (LAPAR) based on a localized greedy algorithm that uses relay regions. In this protocol, each node is aware of its location and its neighbour's location. The relay region $R_{(s,r)}$ of the source node *s* and relay node *r* is defined as a group of destination node locations where relaying through node *r* is more energy saving then transmitting directly from *s*. Therefore if the destination node is in the relay region, then node *r* is used to forward the message to the destination node than transmitting directly. If the destination node lies in the intersection of relay regions for multiple neighbours, a greedy approach is used to find the next hop with the least energy consumption. Figure 2.9 represents LAPAR.

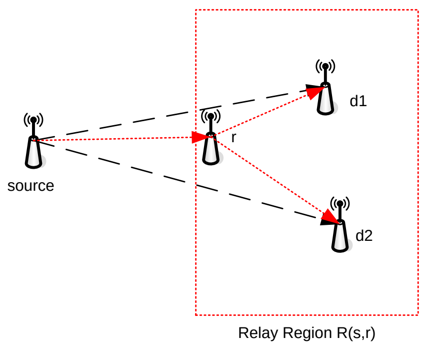

Figure 2.9: LAPAR using relay regions for forwarding packets.

There are several other protocols such as Minimum Power Routing (Banerjee and Misra 2002), that finds multi-hop minimum energy routes and is able to alter the radio's transmission power so only the necessary power is utilized to maintain an acceptable SNR at the receiver.

One of the problems associated with active power-aware routing is that nodes which are often used to forward a message run out of energy a lot more quickly. It can be seen in Figure 2.10 node C uses node A to forward a message to node B and node D.

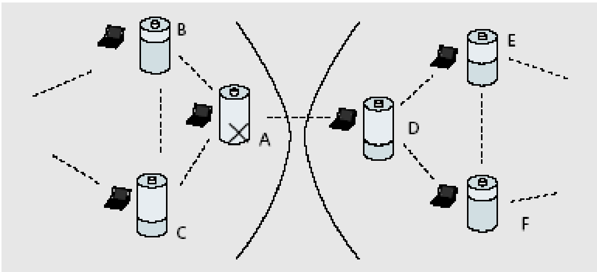

Figure 2.10: Network failure due to overuse of relay nodes

Node B also uses node A to forward the message to node C and node D. After a while node A ends up using all its energy and thus the network becomes un-operational.

2.3.2 Maximizing Network Lifetime Protocols

The protocols associated with maximizing the network lifetime try to balance the energy consumption of all the nodes in the network to overcome the problem of overuse of some nodes. One way to minimize energy consumption is to use the Minimal Battery Cost Routing (MBCR) (Toh 2001). In this routing protocol the total energy consumption of different routes is calculated adding the battery cost for each hop until the packets reaches destination. The aim is again to find the lowest energy consumption path.

In Maximum Survivability Routing (MSR) (Marbukh and Subbarao 2000), the cost for the route is calculated using the nodes that have the battery energy above a certain threshold. Nodes with battery energy lower than a certain threshold are not used in forwarding any messages.

In Minimum Drain Rate (MDR) (Kim, Garcia-Luna-Aceves et al.) routing algorithm, not only considers the minimum transmit power required but also the general node battery consumption. Therefore the nodes that have high battery consumption (not only in transmission but in carrying out other sensing and data optimization functions) are not included in the forwarding path. An example of that is 2 nodes, one having a passive sensor like a temperature, will consume less energy and will have less battery drain rate compared to a node that has an active sensor, e.g. an imaging device, or motor controlled device that will drain extra energy from the battery.

2.3.3 Passive Energy Saving Protocols

In passive energy protocols, the energy is saved by sending the nodes radio in sleep state. In sleep state the radio consumes far less energy. An example is of a Chipcon transceiver used by Mica2 motes. In the idle state the radio consume 22.2mW and in the sleep state it consumes 0.03mW that is 740 times less power.

Figure 2.11 represents a simple state diagram that can be implemented in protocols that set the node to sleep (Li, Cordes et al. 2005) and is commonly used is protocols like GAF (Xu, Heidemann et al. 2001), SPAN (Chen, Jamieson et al. 2002) SMAC (Ye, Heidemann et al. 2002) and Z-MAC (Injong, Ajit et al. 2005).

Figure 2.11: An example of a state diagram used by nodes is GAF, SPAN and SMAC.

In Geographical Adaptive Fidelity (GAF) algorithms, the network is divided into virtual grids. In each grid a cluster head node is selected by election based on the maximum energy remaining in the node, and all the rest of the nodes are put to sleep. The cluster head rotation takes place in each virtual grid so all the nodes at some time in the grid become cluster heads and this greatly increases the network lifetime. The cluster head node in any grid can communicate with the neighbouring grid cluster head and enough nodes are chosen to be cluster head so network connectivity is maintained. Span is based on similar principles as GAF.

2.3.4 Topology Management

The Wireless communication links between the nodes setup the network topology. The network topology changes rapidly with the increase or decrease of nodes transmission power. Figure 2.12 represents a network of four wireless nodes. At certain transmit power node A can transmit directly to node B and C and cannot transmit to node D and vice versa, Node B cannot transmit directly to C and vice versa. This is a set topology.

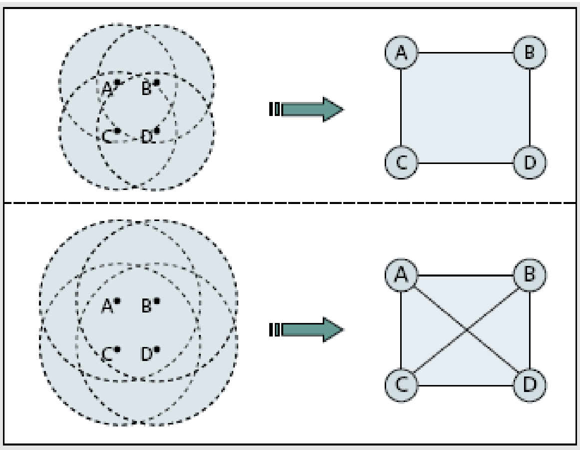

Figure 2.12: Represents the change in network topology as the transmission range increase.

If the transmit power is increased for all the nodes, each node can now communicate directly with each other and the topology has changed as shown on lower part of Figure 2.13. Thus the topology control is maintained by the transmission power of the nodes. The network energy consumption can be reduced if the power of the node is set so that all the duplicate and unnecessary links are removed from the topology and is shown by (Ramanathan and Rosales-Hain 2000) in protocols like Local Information No Topology (LINT) and Local Information and Link-State Topology (LILT). In LINT each node keeps the information of the maximum threshold number and the minimum threshold number of its neighbours. If the number of neighbours go above the threshold value, then the transmit power is decreased, but network partition is not detected. This problem is overcome by using LILT that uses global link state information as well as transmission power (Ramanathan and Rosales-Hain 2000).

2.3.5 Broadcasting and Multicasting Protocols

In Broadcasting, messages are sent from one node to all the other nodes in the network. In an energy efficient broadcasting algorithm, Broadcasting Incremental Power (BIP) (Wieselthier, Nguyen et al. 2002) builds a minimum-energy broadcast tree rooted at the source node. At the beginning the tree only has one node i.e. the source. The source transmit with the minimum power to see which node can be reached, if a node is found, that is added to the list, otherwise, it broadcasts with a slightly higher transmit power until a new node discovered. The new node is added to the tree. This procedure is repeated by adding additional transmit power to the node already in the tree to discover new nodes that are added in the tree. The procedure continues until all the nodes are added to the broadcast tree.

In Multicast Incremental Power (MIP) algorithm, an extension of BIP, a broadcast tree is constructed using BIP. After the tree is complete, all the unwanted nodes are removed from the list while only the nodes of interest are left behind in the tree.

2.4 Conclusions

This chapter has defined some of the key requirements and challenges that are posed by the current wireless sensor networks in terms of energy efficiency, latency and throughput. A brief overview has been given for some of the existing MAC and Routing protocols that have been designed for wireless sensor networks. It has highlighted some of the key features and the disadvantages associated with these existing protocols. One of the key advantages of the Optimised grids algorithm introduced in chapter 4.0 is that it tries to overcome some of the limitations found in these active energy saving protocols by calculating the minimum transmission range based on the amount of traffic passing at that particular section in the network. It has to be realised that there will be gradual increase in sensor traffic as it approaches the base station. While protocols like Power Aware Routing Protocols (PARO), Minimal Battery Cost Routing (MBCR) will find the shortest route, with minimum energy consumption, they do not take into account that the traffic will be gradually increasing and will also be arriving from all directions of the wireless sensor field. This large amount of traffic will have to be forwarded by these fixed number of few cluster head nodes that are nearest to the base station. Despite using minimum energy for packet transmission, the energy is not balanced based on excessive traffic and these nodes will soon consume all their energy making the network useless.

Chapter 3

Software Tools for Developing Wireless Sensor Networks for Research and Industry

Simulation can be described as a method of designing a model of a real system under investigation and performing experiments to understand the behaviour and response of the system under different conditions and changing parameters (Banks 1999). For the simulations to be useful, the behaviour of the model is expected to closely mimic the response of the system being observed. Discrete event simulation is the most widely used tool to study the behaviour of communication networks and also to predict the behaviour of complex stochastic dynamic systems modelling real world applications of practical interest.

3.1 Modelling WSNs using Simulation Tools

Simulation is a very powerful and flexible tool. A large number of system configurations can be controlled to study the complexity and reality that can be achieved by the simulation model. The objectives of a simulation are to draw conclusions that are meaningful, and of practical importance. The actual definition of what aspects of the system under investigation should be included in the simulation model and the required level of detail are the central design choices constraining the quality of the final output and of the derived conclusions.

Research work carried out by (Pawlikowski 2003) has shown that over 51% of the research results published in major journals and proceedings over the last years were based on the use of MANET simulation tools. A recent review on wireless network research papers conducted by (Kurkowski, Camp et al.) from an ACM symposium based on 151 articles from a five-year-period reported that 76% of the accepted work used network simulation. These facts prove the wide usage of simulation in wireless network research. This situation has arisen not only because of the increase in computational power and resources to run extensive simulations but also due to the fact that theoretical analysis and direct experimentation have limited application. In fact, direct experimentation of theoretical results is very costly and difficult to achieve and can only be carried out making working assumptions or for limit cases that make them unrealistic for worldly applications. Telecommunication systems are highly complex and consist of a large number of interacting components of different nature e.g. transmission lines, medium, mobility models, processing, routing, and communication protocols.

While there are a large number of researchers that use of simulation tools to examine or verify their theoretical models, the simulation community is not complete without its critics. The authors (Kotz, Newport et al.) and (Andel and Yasinsac 2006) claim that simulation doesn't reflect an important aspect of reality, it can't give insight into the operating characteristics of the system that is under observation. Oversimplifying the models and lack of rigor can produce inaccurate data, which can result in wrong conclusions or inappropriate implementation decisions.

Many researchers typically use only one simulation package as network simulation packages are complex and have a steep learning curve, either they are commercial, open source or independently developed. This does not allow them to compare their results with other simulators to get a much better idea (Andel and Yasinsac 2006) and try to prove that many of the network simulators have inconsistencies between results while running the same model.

David Cavin, Yoav Sasson, and Andre Schiper (Cavin, Sasson et al. 2002) run a simple flooding protocol on three widely used network simulation software packages, OPNET, Network Simulator (NS2), and Global Mobile Information Systems Simulation Library (GloMoSim), to compare the achieved results. In theory all the three simulators should give similar results, but the results from all the three simulators were found to be quite different.

Making all of the simulators agree for a given scenario won't resolve this problem. The whole purpose of simulating a protocol is to produce results that would resemble real life implementations. If a simulator is to be valid, the simulated results should correlate with real-life performance. (Andel and Yasinsac 2006).

The research work carried out by (Ivanov, Herms et al.) in 2007 tries to fill this knowledge-gap by providing experimental results on the accuracy of an NS2 wireless model for different network performances. They constructed a wireless network model and implemented it on NS2, a network emulator and a real wireless network. The NS2 radio model was calibrated to the real network and they had used the same routing protocol implementation and the same application data traffic in all the compared networks. The results showed that the packet delivery ratios, and the connectivity graphs, were represented in the model with an average error of 0.3%, 10% respectively. Based on these results they concluded that when the simulation parameters are properly adjusted, the packet delivery ratios and the network topologies were accurately represented in NS2. The mean packet latencies were found to be lower by 50% for the simulation compared to that achieved by the emulator and the real network. This was due to the fact that the runtime environment in the real network adds some delays to the normal propagation and routing delays.

One of the advantages of NS2 is that during its development, Josh Broch (Broch, Maltz et al. 1998) and his colleagues invited the experts to validate radio propagation models and the 802.11 MAC implementations during the development of their NS2 MANET extensions. The routing protocols were also validated by their original authors. Using these experts in their fields increased confidence of the work carried out by NS2 user research community when real-life implementations are not possible.

NS2 is considered to be the most popular simulator within the research community and research carried out by (Kurkowski, Camp et al. 2005) shows that it accounted for 45% of the papers then on second place came the self-developed simulators. Research carried out using NS2 is also mentioned in many other IEEE/ACM journals and conferences, confirms its popularity and reliability among the research community. Figure 3.1 shows the most commonly used simulators by the MANET research community.

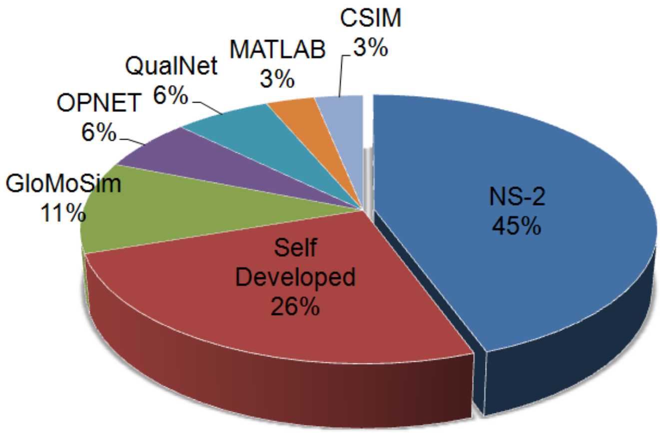

Figure 3.1: Simulator usage summary from proceeding of ACM Mobihoc

This chapter considers the use of simulation and compares different simulators (QualNet, NS2, OPNET, etc.) for the specific case of wireless sensor networks. The ultimate purpose of this chapter is to identify the simulation environment which appears to be the most appropriate to study the performance and behaviour of wireless sensor networks.

3.1.1 Components of a Wireless Ad hoc Sensor network

In order to fully understand the characteristics and behaviour of wireless sensor networks, we need to define all the components that can be considered vital in the abstract simulation model. The following is the list of the important components that will constitute our simulation model.

- There will be fixed or immobile devices, called nodes that have data processing and data transmission capabilities. These nodes will be powered by on-board batteries that have limited energy. The nodes may also need be equipped with geographic localisation devices e.g. GPS units or other devices depending on their nature of use.
- As nodes will have communication capabilities, e.g. either with the base station or with other nodes within their vicinity, they will closely follow the rules and algorithms defined by the OSI protocol stack. Hence all the nodes will have their communications regulated by the characteristics associated to the OSI protocol layers: application, presentation, session, transport, network, data link, (MAC), and physical layer.

- Node energy power relies on the use of on board batteries. Every action involving the use of the radio has energy cost. As the nodes will be communicating with the base station or with their neighbours, they will be consuming energy in the transmission or reception of packets. This requires the energy consumption of radio to be closely monitored. Every action involving the use of the radio channel, or even when device is switched on or off, consumes energy, hence affecting the available energy and node life.
- The transmission model also need to be dynamic as the transmission range will need to be varied depending on the amount of traffic at different parts of the network.
- Radio propagation is affected by the adverse environmental conditions in which the network is placed. The network is usually embedded in an environment and the physical characteristics of that environment greatly influence the propagation of the radio signals as well as the mobility pattern of the nodes. Path loss ratios ranging between 2 and 4 will be incorporated in the models.
- The traffic load varies at different locations in the network. Different traffic loads can be created using Constant Bit Rate sources (CBRs). CBR sources needs to be incorporated with the abstract simulation model.

3.1.2 Requirements for Wireless Ad hoc Sensor network Simulations

Great care needs to be taken in modelling wireless networks. Small difference in a model's architecture can result in significance difference in results and hence lead to different conclusions. Even though some researchers (Andel and Yasinsac 2006) claim that simulation can be of limited use because some results can be misleading. Despite all criticism simulation is still one of the most powerful and cost effective tools to investigate the behaviour of communication networks. It follows that extreme care is required when selecting/discarding and modifying or implementing network parameters.

This research explores the behaviour of energy consumption as well as QoS parameters in wireless sensor networks. This will involve reshaping the network traffic to improve the node's and hence the network lifetime. A study will be carried out to learn about network characteristics like packet delivery, latency and jitter and how these can be improved. This will require a simulator which is easy and flexible to modify and also to accommodate different levels of detail. The simulator also needs to be modular and open, so that new modules/component can be easily added or modified for example adding an energy model or modifying the energy consumption rates of the energy model at different transmission distances. Many researchers (Figure 3.1) develop their own simulators, these simulators are usually task specific and sometimes there is no evidence to show that they have been tested rigorously to confirm that the results are correct. Developing and testing a simulator is a very time consuming job especially when there are many excellent network simulators already available in the public and commercial domain. Therefore it is more convenient to use a tried and tested simulator that can easily be programmed and modified to implement or test models.

According to (Banks 1998) "Discrete-Event Simulation Model can be defined as a model in which the state variable change only at those discrete points in time at which the events occur. Events occur as the consequences of activity times and delays. Entities may compete for system resources, possibly joining queues, while waiting for an available resource. Activities and delay time may hold entities for the duration of time. The discrete-event simulation model is conducted over time ("run") by a mechanism that moves the simulated time forward. The system state is updated at each event, along with the capturing and freeing of resources that may occur at that time"

There are two different types of Discrete-Event simulators for telecommunication networks, a) those designed to simulate the models that can later be mapped to actual hardware e.g. emulators or in some cases models that can access the actual hardware to pass the messages, and b) those that are specifically designed as network simulators. The network simulators can be highly detailed and have major components like nodes, agents, protocols, links, network addresses, packet representation, transport and routing protocols already implemented in them. While it is a great advantage to have as many protocols available in a good simulator, it is sometimes more difficult, or impossible to modify or extend the available protocols for specific needs of user defined models. Therefore while choosing a simulator, a trade-off is generally made between the flexibility, the modifiability and the presence or availability of tools and components.

3.1.3 Selection criteria for wireless sensor network simulators

This research involves the discrete-event simulations of the performance of ad hoc wireless sensor networks, including the use of energy which determines the life of the network. Therefore there is a need for selection criteria for the type of simulator that will be required. Different simulators, either open source or commercial have many modules that are essential for our research e.g. the energy model, while others that don't have the required models or are only available as purchasable modules. The simulator needs to be customisable as it may also be required to run the simulations with some of the trace options turned on while others trace options switched off e.g. if the packet delivery is only being monitored at the MAC layer, then there is no need for the traces of packet handling at network and transport layer. Also in another case we may only want to monitor the network energy consumption, then we will not be interested in the rest of the OSI reference model, and hence the trace support for them modules can be switched off (even though all those events would be taking place, but to reduce the size of the trace file, and to increase the speed of the simulation, they will not be recorded). Another key advantage is to have a simulator that can run on multiple platforms, e.g. Windows and Linux. Many simulators are written for Linux OS as they are open source and can easily be modified and also execute much faster in that environment as compared to when they are transported in Windows OS. Many network simulators come with some sort of topology creation tools that allow the researcher to create large network topologies using simple script or configuration languages. As the simulation networks become larger we will require the use of such tools to create large topologies, hence having such support in the simulator will enhance our work.

As the simulations will try to mimic real life sensor network deployment, the main requirement of the simulator is to have a real implementation of the OSI modules in all the layers. One of the key layers of interest will be the MAC layer where the sleep mode and synchronisation algorithms will be introduced. Node mobility is not required in the first instance; even though it is useful feature as in this research we are more interested in fixed node and multi-hop communication. At the application and session layer, a simple ftp module or CBR module can perform the required task. At transport layer we are only working on wireless sensor networks, it not a key requirement to have TCP transport protocol, a best effort UDP service is sufficient to carry out the task required. All the wirelesses sensor nodes are only required to send the data to the base station e.g. in case of a forest monitoring wireless sensor network, the base station would only be interested to know the temperature at certain locations in the forest.

The physical layer is also of importance as much of the research will be focused on the effect of transmission power on node energy and how the network could be as energy efficient as possible. There are many radio wave propagation models implemented within simulators ranging from the simple Friss- space attenuation model which assume that the transmitter and receiver are in line of sight to the more complicated shadowing and Rayleigh fading models. However it is not only the number of models that are included, but the characteristics and quality of those models is far more important if accurate results are required. This research incorporates the Two Ray Ground Model that is the most accepted model used by the research community. The simulator should also have a set of good traffic generation modules that follow a specific target distribution e.g. Poisson or that can easily be configured as required by the user to model the traffic in the network.

Monitoring support is of extreme importance as that will only allow studying the dynamics of the simulated model. The monitoring has to be based on per node as well as per flow model. It is of vital importance to record the energy consumption of the communications module while each node is either sleep/awake or transmitting/receiving and the energy consumed in the transition from sleep to wake including re-synchronisation energy. Also for network QoS analysis a flow model is essential. The monitoring module needs to be very flexible so that only the desired level of detail is recorded while other components can be turned off depending on the simulation, e.g. when trying to trace the energy consumption of each node we will not want to record the QoS parameters. Recording the QoS and energy parameters simultaneously will not only prolong the simulation run time, but also generate trace files in the size of gigabytes that use up all the system space memory. In that case the analysis of data will be automated.

Therefore to summarise, what is required, is a simulator architecture that is open, very flexible and modifiable. A simulator that allows the user to add new models and edit existing models. It also allows the user to select a desired level of detail so components can easily be switched on or off. A simulator that has the popular routing protocols, and allows scalability so that the number of nodes can be increased easily as required by the model application. The researcher needs to be familiar with the software design of the simulator and the programming languages and tools required to use the simulator. This will help in building prototype models much efficiently, confidently and effectively. It will also reduce time in testing and debugging the new modules and software. The documentation of the simulator should also be of good quality so that the user can easily learn how to use the software.

One of the most important factors to consider is the acceptability of the simulator by the research community. As mentioned earlier, results produced can be very specific to a simulator and may not be nearly the same as results achieved from other simulators. Hence a simulator that produce results that can be compared easily with the present literature and that can easily be reproduced by other researchers is more likely to be accepted by the research community. Many of the public domain simulators are more convenient to use and modify and of course are free. However if commercial simulator provide some modules that are necessary and provide some clear advantage over the free simulator, then they need to be considered.

3.2 Selection of Network simulators for WSNs

Figure 3.1 at the beginning of Chapter 3.0 represents the most commonly used mobile ad-hoc network simulators used by the research community. It can be seen that the four most popular simulators from the commercial or public domain are GloMoSim, QualNeT, OPNET and NS2. In this section we discuss the above four mentioned simulators and conclude which one will be the ideal candidate for our research work.

3.2.1 GloMoSim

According to survey conducted by (Kurkowski, Camp et al. 2005), Global Mobile Information System Simulation library [GloMoSim] (Bajaj, Takai et al. 1999) is used by 11% of the research community and is placed in the third position after self-developed simulators and NS2. This simulation library was designed and developed by UCLA Parallel Computing Laboratory in order to study extremely large networks with the number of nodes ranging from several hundreds to million. It was designed for wired and wireless networks but only supports wireless protocols. GloMoSim has many libraries written in C-based parallel discrete-event simulation language PARSEC (Bagrodia, Meyer et al. 1998). PARSEC has the unique characteristics to execute discrete-event simulation models using many asynchronous parallel simulation protocols on many different parallel computers. A common Application Programming Interface (API) is used for the communication of variables between two different layers. This allows for rapid development of new protocols that can easily be swapped with the existing ones, if the APIs defined between each layer are strictly followed. This sort of composition makes GloMoSim a very modular simulator.

Figure 3.2 summarises the protocols that have been developed at each layer. Models of these protocols or layers can be deployed at different levels of detail.

Figure 3.2: Showing the protocols developed at each layer for GloMoSim (Bajaj, Takai et al. 1999)

GloMoSim uses a platform independent visualisation tool written in JAVA for both real-time and trace based monitoring and debugging.

One of the key design challenges in any network simulator is the scalability issue. In general the common approach is to map each node as a single simulation object; hence each node is a node entity instance. The drawback of this approach is that as the number of entities increases the simulation overhead increases rapidly and such design is not practically scalable. In case of a network with 100,000 or more nodes, at least 100,000 entity instances will have to be created which is not only untenable but also impractical.

GloMoSim is specifically designed to simulate very large scalable networks consisting of thousands to millions of heterogeneous nodes that can easily be ported on parallel or distributed computer environments. To overcome the scalability problem, designing the GloMoSim library was a challenging issue.

GloMoSim (Bajaj, Takai et al. 1999) assumes that the network is divided into a number of partitions and a single entity is defined to simulate a single layer of the complete protocol stack for all the network nodes that belong to the same partition. Communications among the entities obey the corresponding common APIs. Syntactically, the interactions may be specified using messages, function calls, or entity parameters as appropriate. This method supports modularity because a PARSEC library entity representing a layer of the protocol stack is completely self-contained. It encapsulates the complexity of specific network behaviour independently from other ones. This method also supports scalability because node aggregation inside one entity will be able to reduce the total number of entities, which also improves the sequential performance other than the parallel ones.

GloMoSim is not public domain, but is freely available for educational and research use. To summarise, GloMoSim has many models and protocols that are implemented for mobile ad hoc networks. Another key advantage is that it has the ability to scale up to several hundred and thousands of nodes that is quite unique as many other simulators can at most only simulate a few hundred nodes. It is based on PARSEC language and needs a PARSEC compiler every time to run the simulation. Small modifications can easily be made to protocols by using the standard C programming, however to add new components, modify modules, need good programming skills in C and in PARSEC language. The analysis and visualisation tools are very basic, and the documentation is also not very helpful.

3.2.2 QualNet

QualNet (Quality Networks) work from Scalable Network Technologies (a spin out company from UCLA) is a commercial product that is an improved modelling tool derived from GloMoSim. It has a dedicated and fully implemented protocols and modules for both the wired and wireless scenarios including ad hoc, cellular and satellite models. It also has an excellent manual with numerous examples for configuration and running of new simulation networks as well as tweaking parameters in the provided network models and protocols (Manual).

The basic version of QualNet software comes with the standard library which offers the most common models and protocols necessary for both wired and wireless network modelling for research and industrial purposes. Many other libraries can be purchased separately including the MANET library which provides specific components for ad hoc networks, energy and mobility models other than those already present in the standard library; and, a QoS library which includes specialised protocols for implementing quality-of-service. The authors of QualNet claim it to be the most complete network simulator, in terms of available protocols, models and tools for mobile ad hoc networks. Another key advantage is that the authors provide the C source code for all the components, modules, models and protocols; this allows the customers to fully modify or tweak the models as well as to better understand the working of models.

The QualNet Developer software suite consist of five different components put together to form a complete solution for any type of network analysis. The components are as follows:

a) The Animator is a graphical tool that allows the user to rapidly setup or develops new topologies, add layers, traffic and protocols, to an existing or new model and run the animations. Figure 3.3 shows the GUI features of QualNet Developer software.

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Figure 3.3: QualNet GUI demonstration of the animator module (Simulator 2006)

b) The Designer is a finite state machine tool that allows customised protocol modelling and involves a state based visualisation tool that is used to define the events and processes of a new protocol model.

c) The Analyser is a statistical graphing tool that plots the statistics related to hundreds of inbuilt or custom performance metrics.

d) The Tracer is a full packet level visualisation tool that allows the viewing of the contents of a packet as it goes up and down the network protocol stack.

e) The Simulator, this component is designed to include high fidelity models of networks of tens of thousands of nodes with heavy traffic and high mobility.

QualNet is the commercial version of GloMoSim. It has all the protocols and models for Wireless and Wired networks and comes with excellent planning, analysis and visualisation tools. QualNet also supports network emulation and allows for realistic 3D environmental modelling. It has excellent documentation and online help. In simple words, QualNet is a complete commercial simulator.

3.2.3 Optimised Network Engineering Tools (OPNET)

Optimised Network Engineering Tools (OPNET) was first developed at Massachusetts Institute of Technology (MIT) in 1987, and is now commercial software provided from OPNET Technologies Inc (OPNET_Technologies. 2008) for modelling and simulation of communications protocols, devices and networks.

OPNET is widely accepted to be a state of the art network simulator and is used by many large companies and a limited trial version is free for educational purposes. OPNET comes with a good editor and very useful graphical tools for design, implementation and animation of new protocols or networks. Figure 3.4 shows an OPNET Modeler graphical user interface.

Figure 3.4: OPNET GUI demonstrating the network and results (OPNET_Technologies. 2008).

The OPNET software is divided into three main categories that provide nearly all the features for effectively designing, simulating, deployment and past deployment optimisation and troubleshooting of the network. Table 3.1 shows the summary of tools available from OPNET.

Table 3-1 Summary of all the Network Modelling tools available from OPNET

Application Performance & Management Solutions	ACE Live (not free)	Delivers an end-to-end solution, that spans monitoring, measurement and detection of application performance
	OPNET Panorama	Performance Management tool for critical Java and .NET applications.
	IT Guru System Planner (not free)	Useful for server capacity planning and analysing system configurations and workloads.
Network Planning, Engineering & Operations	IT Guru Network Planner (limited)	This software analyses "what if " scenarios for intelligent, risk-mitigated, and cost effective decision making
	OPNET nCompass (not free)	This tool pinpoints critical network performance problems in real time by providing 24/7 consolidated view of network topology, traffic and status information.
	IT Sentinel (not free)	This tool stops network configuration issues from turning into critical problems. Diagnosis device configuration errors, security breaches
Network Research & Development	OPNET Modeler Suite (not free)	Allows developing, testing and optimising new protocols and technologies using discrete event simulation for WANS, MANS.
	OPNET Modeler Wireless Suit (not free)	Modelling and design of wireless networks and use of many new protocols including technologies as MANET, IEEE 802.11 WLAN, 3G/4G, Ultra Wide Band, IEEE 802.16 WiMAX, Bluetooth, and Satellite.

OPNET Modeller is the main tool for network modelling and simulation. OPNET is based on C/C++ programming language. The simulation network is setup using a hierarchical graphical user interface allowing the user to select the required options. OPNET can simulate all types of wired and wireless networks. It comes with a full implementation of 802.11 compliant protocols, and has many of the ad hoc routing protocols. OPNET optimisations tool are used by many companies for network modelling, design and to diagnose and fix problems as well as to re-organise their networks.

The OPNET Modeller has three main components, the OPNET Planner, the Model Library and the Analysis tool. The OPNET Planner analyse the performance and the behaviour of the network by discrete event simulations. OPNET Planner allows the use of hierarchical editors to create communication networks without the need of programming or compiling. The project editor graphically shows the network topology, created by the user by adding nodes, and link objects. The network topology parameters can be easily be configured using the dialog boxes. The note editor shows the internal architecture of the network device or system, by capturing the flow of data between the functional elements known as “modules”. The modules are typically network protocols or algorithms and are assigned a process model that is developed using the process editor.

Figure 3.5: OPNET Process Editor (OPNET_Technologies. 2008)

The last level of editors is the process editor that allows the user to design and customise the protocols, resources, applications, algorithms and queuing policies. Processes are modelled as finite state machines (FSMs) as shown in Figure 3.5 above. The states and transitions can be graphically added in the editor, whereas conditions that specify the function and output of each state are programmed C/C++.

The Model library has many of the devices, protocols, applications and environments (e.g., TCP, IP, FTP, ATM, Frame Relay, Ethernet, IEEE 802.11, support for wireless), link models including point-to-point and bus topology, many queuing disciplines such as First-in-First-Out (FIFO), Last-In-First-Out (LIFO), priority non-pre-emptive queuing , pre-empt and resume or round-robin.

The analysis tool is integrated with the modeller and has many built-in statistics for easy analysis of the simulation. Graphs and charts are automatically generated based on pre-selected options and do not require any pre-scripting nor post processing is necessary (OPNET_Technologies. 2008).

To summarise, OPNET is a well-established commercial product that supports both wired and wireless networks. It has nearly all the components, models, and protocols available to model and research high performance networks in great detail. The graphical user interface simplifies the network design process, and new models can be developed using FSMs which can be difficult to grasp in the beginning but become easier with experience.

At the moment the student licence comes with very few protocols and models and no help or technical support at all. It is also required to be renewed every six months with OPNET technologies.

OPNET is not without its critics, e.g. the authors (Malowidzki 2004) claim to have found OPNET modules implementations to be complex and fragile. They also claimed adding new protocols and modules are not only difficult, but also error-prone and thus require significant effort and a lot of time.

3.2.4 Network Simulator 2 (NS2)

Network simulator 2 (NS2) (NS_2) is an object oriented discrete event simulator that has its origin from U.C. Berkeley. NS2 is open source and freely available. The first version "NS1" was based on REAL network simulator (Keshav 1988) and was developed by the Network Research Group at the Lawrence Berkeley National Laboratory (LBNL), USA. NS version 2 was later released with the effort of the VINT project (Bajaj, Breslau et al. 1998) that was supported by DARPA, at LBNL, Xerox PARC, and UCB. The idea of the VINT project was not to create a new network simulator but to bring together the joint efforts of all the people working on network research under one unified simulator hence NS2.

As shown in Figure 3.1, NS2 is the most popular simulator in the research community with the overall acceptance rate over 45%. Based on the success of NS2, the National Science Foundation (NSF) CISE program and the French government (INRIA) have provided the research grant from (2006-2010) for the next generation of NS2 , called the

NS3 project (NS-3). At the moment a development version of NS3 has been released containing only few protocols while a full version is intended to be released by the end of 2009.

NS2 has many of the protocols that are required for the simulation of wired and wireless networks (ad hoc local and satellite). Transport protocols, routing algorithms, traffic shaping, queuing, congestion control for nearly all sizes of networks can be simulated and studied. NS2 can also be used as an emulator where it can be introduced into the live network to inject the required amount of live traffic.

NS2 is based on the OSI reference model where a network is composed of many interconnecting elements. The interconnecting elements are nodes, links, traffic generators, statistical traffic generators, agents, routing protocols, queues, MAC protocols, propagation models etc.

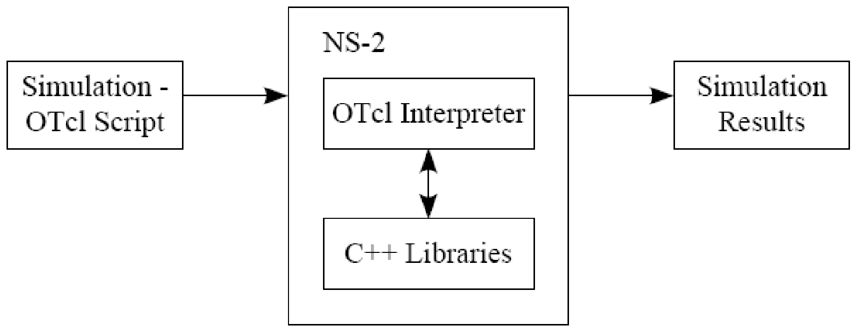

Figure 3.6: The Tcl/Otcl and C++ interface

NS2's is written in two different languages, its core engine is written in C++, and the OTcl (Wetheral) scripting language is used for the configuration of simulation networks as shown in Figure 3.6. The combination of two languages provides a compromise between the performance of the simulator and its ease of use. The simulator comes precompiled as a class hierarchy of protocols and modules written in C++ and an interpreted class hierarchy of components written in Otcl that are related to the compiled modules.

Using Tcl, the researchers can rapidly set up models that are also easier to debug. Tcl provides the control over the simulation as in starting, stopping of events, network configuration, link failures network failures and information gathering.

In NS2, a new model or protocol can be added by writing the functionality of the protocol in C++, and a common variable programming interface is provided, where the variables are declared both in C++ and in OTcl. The variables are linked together, and thus the new protocol can be set up or called from the simulation scripts written in OTcl. The results of the simulations are stored in trace files, and can be analysed later. For each individual packet, a record is kept when it arrives, leaves, or is dropped at each layer, link or queue. The Network Animator (NAM), is a simple animation tool based on Tcl/Tk that allows the user to view NS2 trace files for post-processing, analysis and replay of simulations.

NS2 provides Network Animator (NAM) as shown in Figure 3.7 that allows the simulation results to be viewed in a graphical format.

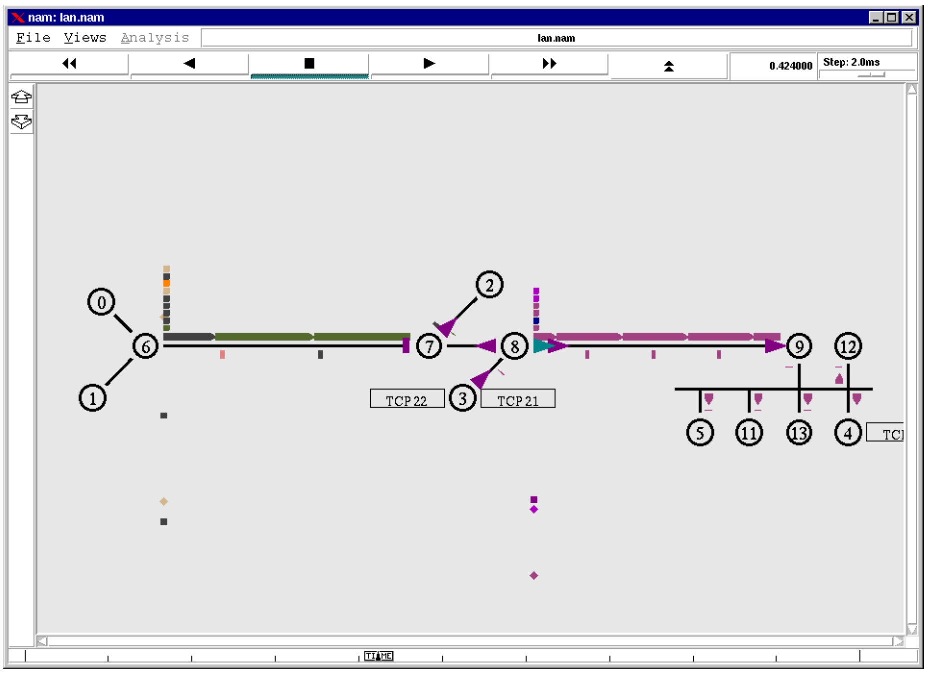

Figure 3.7: Network animator (NAM) representing a simple network in graphical format

The OTcl class called ‘Simulator’ provides the configuration interface to control and operate the simulation. The Simulator class provides the methods to create and manage a new topology, to initialise the packet format and to choose the scheduler. The Simulator object also internally stores the reference to all the elements in the topology.

When a node receives packets, it examines its destination address and its sources address. It then maps the values read from the packet to an outgoing interface object that is the next downstream recipient of this packet. In NS2 this job carried out by the “classifier” object. In a node there are many classifier objects that look at different parts of the packets as they forward the packet through the node.

The main task of the classifier is to provide a match against some logical criteria and retrieve a reference to another simulation object based on the match results. A classifier normally contains a table of simulation objects indexed by slot number. Once a slot number is determined for the received packet, it forwards the received packet to the object referenced by that particular slot.

Agents are also important components of a node as they model the endpoints of the network, where the packets are constructed, processed or consumed. The agent creates new sources like TCP, UDP and new sinks. There are many types of links available including simplex, duplex, point to point, broadcast and wireless that can have predefined capacity, delay and queuing discipline. Link failures can also be simulated. There are many different type of queues like drop-tail (FIFO), random early detection (RED), buffer management, weighted fair queuing (WFQ), stochastic fair queuing (SFQ) and deficit round robin (DRR). NS2 also has all the popular routing protocols built in it including DSDV, DSR, AODV CBRP, OLSR and TORA. It also comes with many of the applications including FTP, Telnet, and HTTP, which use TCP as an underlying transport protocol, and applications requiring a constant bit rate (CBR) traffic pattern, that use the UDP transport protocol.

To summarise, NS2 is the most popular simulator used by the mobile and ad hoc networks research community. It comes with a large number of models, algorithms and protocols and a fairly useful NS2 manual. Because of the very large research community, there is a free NS user’s mailing list that dates back to nearly a decade of archived items and a large number of online tutorials that are based on wired and wireless technology, hence there is some information for everyone. On the downside, NS2 has very complex software architecture with steep learning curve. Adding new components or modifying existing ones requires to user the write the code in C++ as well as OTcl. Even though it might not be easy to add new components or modules, the simulator itself is very easy to use.

The graphical tool NAM only allows the visualisation of results and therefore a lot of scripting is required to extract the required data from trace files. The advantage is that NS2 can run on many platforms including Windows and linux.

3.2.5 The choice of Simulator for this Research

After reviewing several simulators, NS2 has been chosen as the best tool to carry out this research. The selection of NS2 has been based on several factors as listed below

First and foremost is that NS2 is the most popular network simulator. It is widely used by the mobile and ad hoc research community and is also the most trusted among all the network simulators. NS2 is also considered by some researchers as a reference simulator and has much larger scientific acceptance (Andel and Yasinsac 2006).

Another great feature of NS2 is that it is free to download and can run on different platforms and has nearly all the pre-built components, incorporates modularity, scalability, and modifiability with all the source code unlike OPNET and QualNET that come along with very heavy licensing fees. However the learning curve of NS2 is slightly steep and requires ability to program in C++. NS2 has got a very large online research and developer's community that is readily available via the free mailing list. In the case of OPNET, a heavy fee is required for any mailing list access or help. While QualNet and OPNET have excellent graphical user interface for easy deployment of simulation networks, the core source code is not provided, and hence the inbuilt models cannot be modified as compared to NS2, which provides the code for all the modules. On the other hand the GloMoSim simulator is also free, but lacks some of the protocols that are required for this research. GloMoSim also has an outdated user manual and no technical support or user mailing list. New modules and protocols are not being written for GloMoSim as all resources are being used for QualNet.

OPNET and QualNet have excellent tools to analyse and visualise results obtained from the simulation, in which case NS2 lags significantly behind. However with the use of simple scripting language like awk and perl, the researcher can tease out results from large trace files and use normal plotting software like gnuplot or matlab to display the results in the desired form.

3.3 Wireless Model in NS2

This research is primarily based on wireless sensor networks, hence the wireless model in NS2 is of primary importance. The wireless node in NS2 is defined by the class mobilenode that inherits its basic features from the base class node and adds extra features like mobility to a node to move in a given topology and the ability to transmit and receive signals by an antenna. The main difference is that the wireless nodes are not connected with other wireless nodes or fixed nodes via links e.g. wired. Figure 3.8 shows the basic components making a wireless mobilenode in NS2 (Delaney and Meenaghan).

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Figure 3.8: Portrait of a Wireless node

As mentioned earlier the classifier's duty is to match a packet against some predefined criteria and obtain a reference to the next simulation object based on the match results. (NS2_Manual 2008). There are many routing agents implemented in NS2, the most commonly used routing protocols are DSDV, DSR, TORA, AODV and NOAH.

The link layer (LL) serves as simulating the data link protocols, that are responsible for packet fragmentation and reassembly and also providing a reliable link protocol. In the wireless node the link layer has an Address Resolution Protocol (ARP) module which resolves all the IP to hardware (MAC) address conversion. All the outgoing packets (into the channel) are passed down to the LL by the routing agents that passes is down to the interface queue. All the incoming packets are passed by the MAC layer to LL which then forwards them to the node entry point.

When the LL receives an outgoing packet for which it does not have the address, it sends the query to Address Resolution Protocol Module (ARP) to retrieve the address for the destination of the packet. If the ARP has the hardware address of the destination, it writes it into the MAC header of the packet. Otherwise it broadcasts an ARP query, and caches the packet temporarily. For each unknown destination hardware address, there is a buffer for a single packet. In case additional packets to the same destination are sent to ARP, the earlier buffered packet is dropped. Once the hardware address of a packet's next hop is known, the packet is inserted into the interface queue. The Interface queue gives priority to routing protocol packets, inserting them at the head of the queue. NS2 has several different queuing models.

Carnegie Mellon University have implemented the full 802.11 distributed coordination function (DCF) MAC protocol that uses a RTS/CTS/DATA/ACK pattern for all unicast packets and can also send data for broadcast packets. The implementation uses both physical and virtual carrier sense. Other forms of MAC layer implementations are SMAC (Ye, Heidemann et al. 2004), that includes sleep cycles and Simple MAC, that does the contains the RTS/CTS procedures of 802.11 MAC

The physical layer behaves as a hardware interface which is used by the wireless node to access the channel. This interface is subject to collisions and the radio propagation model receives packets transmitted by other wireless node interfaces to the channel. The interface stamps each transmitted packet with the meta-data related to the transmitting interface like the transmission power, wavelength etc. This meta-data in the packet header is used by the propagation model in the receiving network interface to determine if the packet has minimum power to be received and/or captured and/or detected (carrier sense) by the receiving node. The model approximates the DSSS radio interface (Lucent WaveLan direct-sequence spread-spectrum) (NS2_Manual 2008).

The wireless node use the Friss-space attenuation (line of sight model, that gives the power received by one antenna under idealized conditions given another antenna some distance away transmitting a known amount of power) for sending packets to nodes that are in the near vicinity and an approximation to Two ray Ground model (Rappaport 1999) for packets that need to be transmitted farther. The approximation assumes specular reflection off a flat ground plane. The shadowing model takes a probabilistic approach. The antenna used by wireless node is omni-directional with unity gain. The function of the channel is to send the packets to all its neighbours. It duplicates the packets to all the wireless nodes attached to the channel except the sender .The term duplicate means that if the channel has 'n' number of wireless nodes attached to the channel, then it will make 'n' number of copies of that packet and send one copy of this packet to each wireless node. It is the receiver's responsibility to accept the packet and how to handle the collisions. If the channel quality is poor, it will calculate using receiver threshold level to either accept or discard the packet.

The first version of the energy model was implemented by Carnegie Mellon University. This model only calculated the energy consumption during the transmission and reception of the packet and also the idle energy consumed by the wireless node. Further research led to the addition of sleep energy and the transition time and energy calculations between sleep and idle state by University of Southern California (USC) while developing SMAC.

3.4 Creating Simple Networks with NS2 and Fixing Bugs

NS2 is freely available network simulation software that has many inbuilt protocols and models. The simulator is composed of two different programming languages, C++ and OTcl. The networks are setup using tool command language (tcl), a scripting language that is a lot simpler to use compared to C++. However if they uses requires to modify any of the protocols for research purpose, then they make the changes in the corresponding C++ module and recompile the whole code, for the changes to take effect in the simulations.

During this research the NS2 version 2.29 was installed on Linux openSUSE 10.0 operating system. The NS2 package comes along with its own Tcl/Tk development tools and all the libraries. The following script shows a very simple program using tcl script to print out one statement "Hello NS2 user".

The script file is saved as simple.tcl.

#File simple.tcl begins………………	// comments
set ns_ [new Simulator]	// creating a new object type 'simulator' with instance name ns_
$ns_ at 1 "puts \"Hello NS2 USER…\""	// After 1 second print the required statement on the screen
$ns_ at 1.5 "exit"	// After 1.5 second exit the program
$ns_ run	// Run the program now
#File simple.tcl ends………………..	// comments

To run the script file, we just type 'ns' at the prompt followed by the filename 'simple.tcl' as shown in Figure 3.9 using a KDE advanced text editor (Kate). The left window shows the directory structure, the top right windows shows the simple.tcl script file and the lower right window shows the execution and the output of the file.

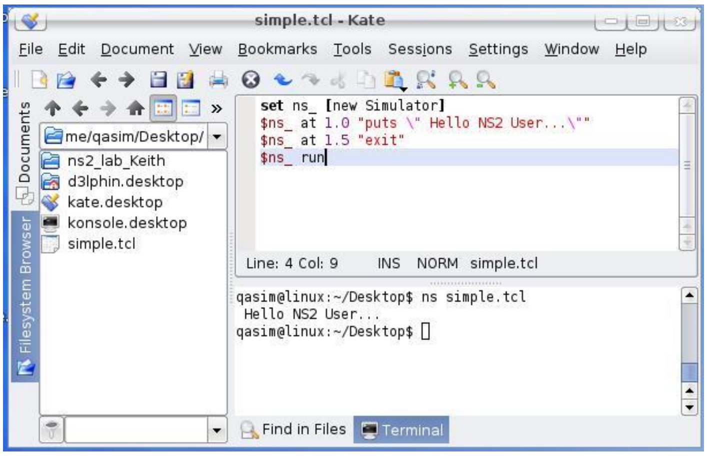

Figure 3.9: Showing output of simple.tcl in Kate

3.4.1 Simulating a basic two node Wireless Sensor Network

Simulation of any type of wireless network in NS2 requires following a systematic procedure for creation and declaration of network components as represented by the flow diagram in Figure 3.10. In the rest of this section we are going to write the script for a simple two node wireless sensor network that uses default values setup in NS2 e.g. both nodes have identical properties,

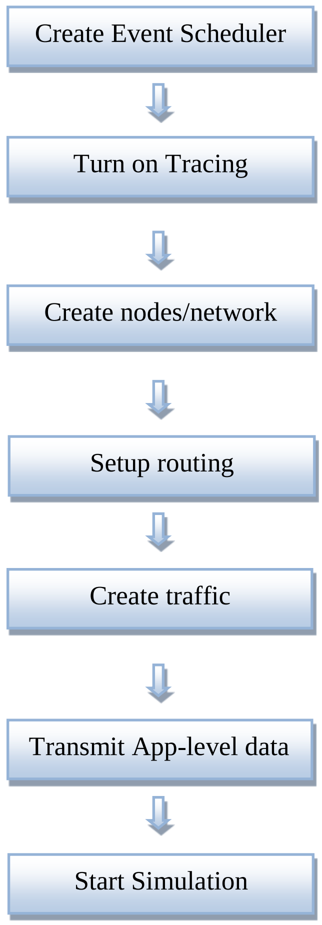

Figure 3.10: Systematic approaches in configuring wireless network simulation

The first objective is to define the global variables, create an instance of the simulator object in line 3, then in line 5 we set up variable tracefd that points to the newly created output file, simple .tr. In line 7 all the trace events are copied to variable tracefd that in turn writes it to the file. In line 8 we create a new object of the type topography that is supposed to be the network area where all the wireless sensor nodes will remain. In line 9 we set that area to be 100m by 100m.

```
1    # Define Global Variables
2    # create simulator
3    set ns_ [new Simulator]
4    # define traces
5    set tracefd     [open simple.tr w]
6    $ns_ trace-all $tracefd
7    # create a topology in a 100m x 100m area
```

```
8    set topo [new Topography]
9    $topo load_flatgrid 100 100
```

In line 11 we create a new object called general operation director (god). This object is only required in wireless networks as it keeps track of all the nodes in the simulation e.g. their co-ordinates and their respective location among other nodes. The $val(nn) is the number of nodes in that simulation. In line 13 a channel is setup for the network.

```
10   # Create god
11   create-god $opt(nn)
12   #  Create channel
13   set chan_1_ [new Channel/WirelessChannel)]
```

Lines 14 to 32 define the properties of the node and all the parameters that are required to set up the wireless nodes properly, e.g. what type of MAC, link layer, propagation channel, queue type, queue length, trace type, and energy model values are required. The Line 27 to 34 are optional and are only required if monitoring the energy, as in our research case.

```
14   $ns_ node-config -adhocRouting DSDV \          // Setting the routing protocol
15                    -llType  LL \                 // Setting the link layer
16                    -macType Mac/802_11 \         // Choosing the MAC type
17                    -ifqType $opt(ifq) \          // Setting the interface queue
18                    -ifqLen 50 \                  // Setting the queue lenght
19                    -antType $opt(ant) \          // Setting omni-directional Antenna
20                    -propType $opt(prop)          // Setting two ray ground / Freespace
21                    -phyType $opt(netif) \        // Setting the Physical layer
22                    -channelType $opt(chan) \     // Setting the number of channels
23                    -topoInstance $topo_  \       // Setting network Topology
24                    -agentTrace ON \              // Tracing the packets by agents
25                    -routerTrace ON \             // Tracing the routes of the packets
26                    -macTrace ON \                // Tracing packets in MAC layer
27                   -energyModel $opt(energymodel) \  // Creating the instance of the energy model
28                   -initialEnergy 500 \           // Initial energy in joules
29                   -idlePower     0.05 \          // power consumption (Watt) in idle state
30                   -rxPower       0.05 \          // power consumption (Watt) in receive state
```

```
-txPower       0.10  \                 // power consumption (Watt) in Transmit
-sleepPower  0.0001\                   // power consumption (Watt) in sleep state
-transitionPower  0.0025\              // power consumption from sleep to idle
-transitionTime 0.01                   // time used in state transition from sleep
```

It is important to explain the relationship between Watt and Joules. Watt is a unit of measurement of electrical power and Joule is a unit of measurement of mechanical (heat) energy. However, the equivalency can be stated as 1Joule/sec = 1 Watt.

Let's assume if the total time to transmit a single message for a wireless node is 1 second and the transmitting power of the transmitter is 0.1 Watt. Then the total energy consumed to transmit a single message is 0.1 Joule.

The next step is to create two wireless nodes themselves and to place them 50m apart in the flat grid by assigning them the XYZ coordinates as shown in the next fragment of the script.

```
#Generating only 2 nodes
for {set i 0} {$i < 2} H {
set node_($i) [$ns_ node]  }
# Provide initial (X,Y, for now Z=0) co-ordinates for wireless mobile nodes
$node_(0) set X_  10.0
$node_(0) set Y_  10.0
$node_(0) set Z_   0.0
$node_(1) set X_  10.0
$node_(1) set Y_  60.0
$node_(1) set Z_   0.0
```

The next step is to add a traffic generator to the first node and a sink to the second node as follows; the comments decipher the actions of the code, so basically node 0 has a UDP application that is sending the packets to node 1. The UDP application is connected by the traffic generator Constant Bit Rate (CBR) source. The UDP application is connected to null_(0), that acts as a sink for node 1. All traffic from udp_(0) that is connected to node 0 will be sent to node 1.

```
set udp_(0) [new Agent/UDP]                // Creating an application of type UDP
$ns_ attach-agent $node_(0) $udp_(0)       // Attaching this UDP to node 0
set null_(0) [new Agent/Null]              // Creating new application type sink
```

```
$ns_ attach-agent $node_(1) $null_(0)        // Attaching the sink  to node 1
set cbr_(0) [new Application/Traffic/CBR]    // Creating new traffic agent CBR
$cbr_(0) set packetSize_ 512                 // Setting packet size to 512 bytes
$cbr_(0) set interval_ 1.0                   // Send packet every second
$cbr_(0) set random_ 1                       // Send packet randomly between 1 second
$cbr_(0) set maxpkts_ 10000                  // The maximum packets to send is 10000
$cbr_(0) attach-agent $udp_(0)               // The traffic source is connected to the UDP app
$ns_ connect $udp_(0) $null_(0)              // The packets from this source will go to node 1
$ns_ at 5.0 "$cbr_(0) start"                 // Start sending packets 5 secs after simulation starts
```

A finish procedure can be added to stop the simulation gracefully

```
# Tell ns the simulation stop time after 200 second
$ns_ at 200.0 “$ns halt”
# Start your simulation
$ns_ run
```

Figure 3.11 shows the NAM animation of a two node wireless sensor network where node 0 is transmitting to node 1.

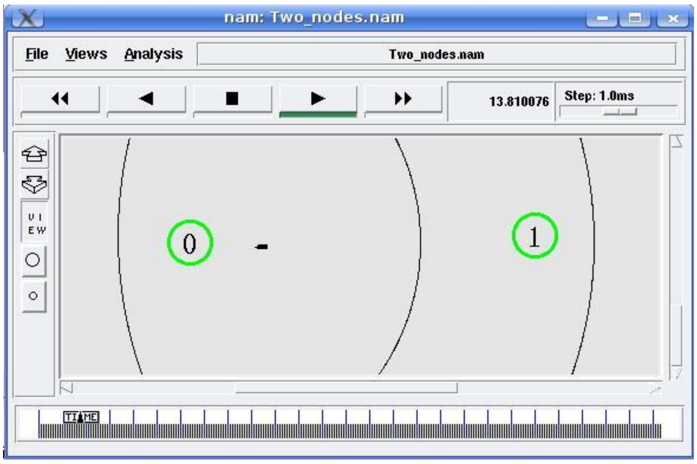

Figure 3.11: Network animation of a two node wireless sensor network

3.4.2 Upgrading and Testing the Energy Model

The Majority of the protocols and modules present in NS2 have been written and contributed by academics and researchers while carrying out their own research. This has led to some modules being specifically designed to perform a specific task. One example of that is SMAC developed by University of Southern California (USC). This is the only working MAC protocol that uses the sleep mode in NS2. So even though USC have implemented sleep mode in the energy model, that sleep mode cannot be directly used with other MAC protocols like 802.11 or SimpleMAC. This section deals with some of the shortcomings discovered while testing the energy model. It is of note that the Energy model was updated in NS2 version 2.28, with all the energy updates for SMAC. However in version 2.29 and later the energy trace was removed from the general trace file as they create an overhead for all the researchers that are not using NS2 for network energy modelling. Therefore the current default version of NS2 does not involve the full energy model output in the trace file. Since my research involves modelling network traffic to optimise network lifetime, I added the complete trace for the energy model.

This research is based on optimising the network lifetime. Hence correct energy calculations are of vital and central role to this work. One of the key requirements is to work with the existing energy model that is present in NS2 and perhaps add new functions that can give better results. The reason to test the energy model was essential to observe if the energy consumption for transmission, reception, idle and sleep state were correctly calculated for each node. Another key thing was to find out which of the existing protocols and modules are compatible and working correctly with the energy module.

To test the energy model a simple two node wireless network was setup where node 1 was sending packets to node 2. A single line fragment of the trace file showing information about a packet sent by node 0 can be seen below. Each field is separated by a blank space and I have explained each field in Table 3.2

S 134.290447179 _O_ MAC 201 cbr 100 [energy 911.441952 ei 78.946 es 0.046 et 2.820 er 6.381]

Table 3.2: Summary of Fields in an NS2 trace file

Field	Comments
S	S or s denotes a packet was sent, R o r means message received
134.290447179	Time the packet was sent
_O_	Node ID
MAC	MAC layer been traced,
201	Packet number
cbr	Source of packet is Constant Bit Rate source is used
512	Packet size 512 bytes
energy	Energy tag
911.441952	Node energy remaining
ei	Idle energy consumption
78.946	Total idle energy consumed by the node so far
es	Sleep energy consumption
0.046	Total sleep energy consumed by the node so far
et	Transmit energy consumption
2.820	Energy consumed by the node during transmission of all packets
er	Receive energy consumption
6.381	Energy consumed by the node during reception of all packets

3.4.2.1 Adding the Transmit/Receive/Idle/Sleep State Time Function

As shown below the trace file only shows the energy consumed in each state and not the total time spent in each state. Thus the total time spent in transmitting/receiving /idle and sleep is very important to prove that total consumed energy is accurately calculated.

Before modification the trace file output was as below.

S 134.290447179 _O_ MAC 201 cbr 100 [energy 911.441952 ei 78.946 es 0.046 et 2.820 er 6.381]

After adding four C++ methods in the energy model class to keep the track of total time in each state the output of trace file was changed to show the total time the node spends in each state as in the fragment below.

S 134.290447179 _O_ MAC 201 cbr 100 [energy 911.441952 ei 78.946 es 0.046 et 2.820 er 6.381 t_Id 78.946 t_Sl 1.554 t_Tr 0.247 t_Re 0.207]

Where:

t_Id = total idle time spent by the node.

t_Sl = total sleeping time spent by the node.

t_Tr = total time the nodes spends transmitting packets.

t_Re = toal time the nodes spends receiving packets.

The total energy of the wireless node at the start of the simulation was set to 1000 Joules. The idle power of the transmitter electronics was set to 1 Watt. The wireless node was idle for 78.946 seconds, hence 78.946 Joules were consumed during the idle mode. This proves the accuracy of the simulator.

3.4.2.2 Debugging Energy Update in the Energy Model

Before any of the existing protocols and models could be adopted for our research work, a thorough, proper and systematic approach was required to test them so error prone and unambiguous results could be avoided. A large number of networks were simulated to test many different protocols and models (details below) to see if the results were similar to the theoretical values obtained.

A simple simulation was setup consisting of 6 nodes making 3 pairs. In each pair one node was transmitting while the other node was only receiving (e.g. in this case node 1 was transmitting and node 2 was receiving. node 3 was transmitting and node 4 was receiving, node 5 was transmitting and node 6 was receiving). The transmit energy consumption of each node was set to be double the receive energy consumption. The receive and idle energy consumption were set to equal units. This simulation was ran for 220 seconds using 802.11 MAC protocol and different routing protocols. It can be seen from Figure 3.12 (the vertical axis shows node' energy consumption in joules and horizontal axis represent the time in seconds), that while simulating 802.11 with AODV or Dumbagent (top and bottom graph on the left) the idle energy was being computed but not being updated as it is shown from the curves, which appear to be flat. However when the transition takes place from idle state to transmit or receive state, the graphs show a sudden drop as the energy now gets updated. This bug was also present with Simple-MAC using DSDV and AODV routing protocol (top and bottom graph on the right).

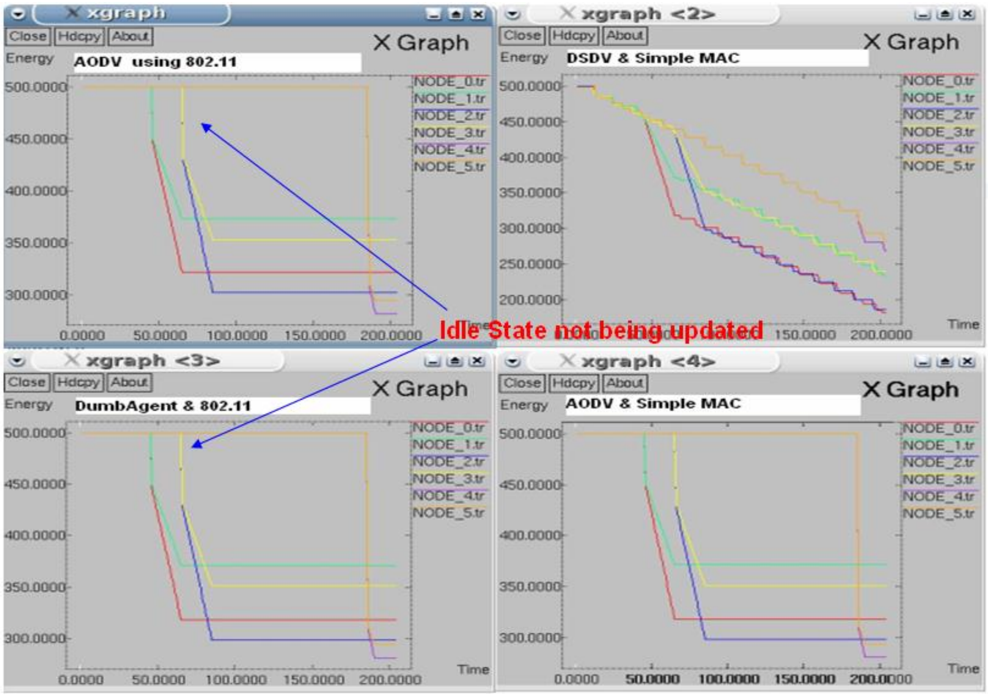

Figure 3.12: Idle energy update problem with NS2

This bug was removed by adding an idle energy update procedure in all the ad hoc routing protocols and the fix can be seen in the below Figure 3.13.

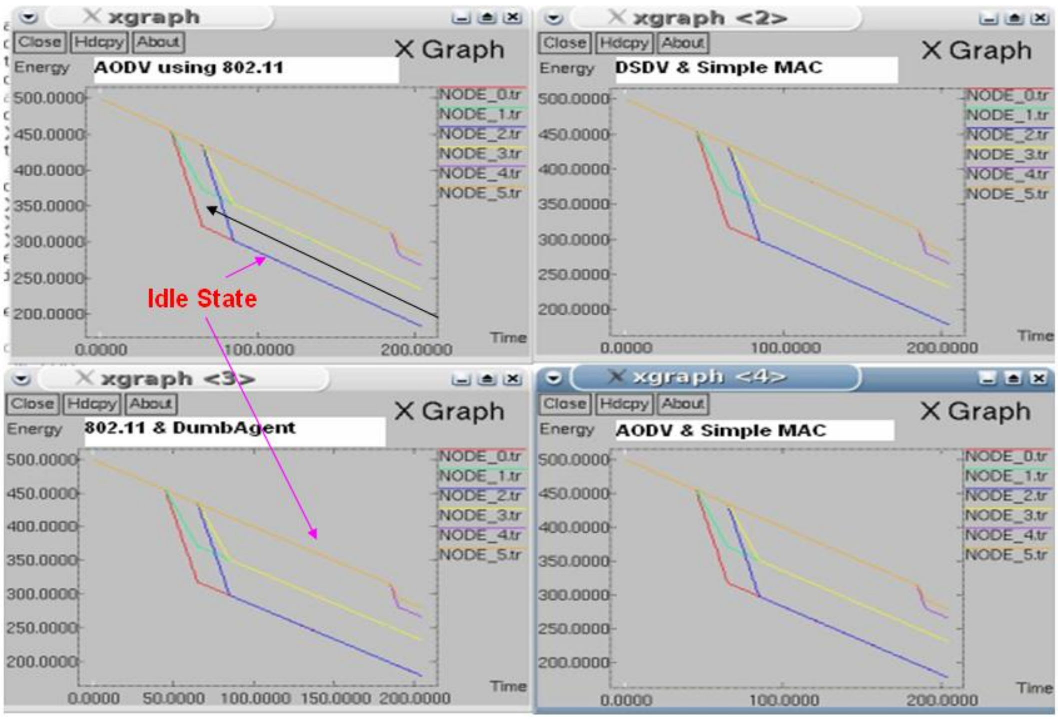

Figure 3.13: Idle energy update problem fixed

3.4.2.3 Theoretical and NS2 comparison of the Transmit and Receive Energy of Chipcon CC1000 Transceiver

The Chipcon transceiver CC1000 (Chipcon) is used on the Mica2 generations of motes developed by Crossbow Inc. The reason to use the Chipcon CC1000 transceiver was twofold, first to see if the commercial products like motes could be simulated using NS2 and secondly to compare if the theoretical transmit and receive energy-use values obtained from Chipcon's parameters matched the results obtained from simulating the Mote Chipcon transceiver characteristics using NS2.

From the Chipcon CC1000 datasheet the following values were obtained for different states.

Chipcon CC1000 Transceiver parameters

Transmit = 31.2 mW (0 dBm)

Receive = 22.2 mW

Idle = 22.2 mW

Sleep = 0.03 mW (740 times less energy)

The Mica2 Motes Characteristics.

The theoretical time and energy for sending a **100 byte** packet using a Chipcon transceiver Motes with Bandwidth **19.2 Kbps**, and the message size set to **100 byte** **<u>was calculated as follows</u>**

Time to transmit or receive 100 bytes at 19.2 Kbps = (100x8)/19200 = **0.04166 seconds**

Thus the total energy used during transmission 0.04166x31.2mW = **1.30 mJ** Total energy required to receive the message 0.04166x22.2mW = **0.925 mJ**

<u>The corresponding values obtained by NS2 simulation were derived from the simulation trace file below</u>

The blue coloured trace lines represent the activity of node _0_ while the black line represents the activity of node _1_. S=sent, R = received. In the trace below node _0_ sends a RTS packet to node _1_ which then sends a CTS packet. Node _0_ then sends a cbr packet with Id 38 and size 100 bytes. Node _1_ then sends an ACK packet after receiving the cbr packet with id 38 and size 100 byte

S 106.149201500 _0_ MAC - 0 RTS 10 [energy 35912.0160 et 66.050 er 21.934 t_Tr 2.117 t_Re 0.988]
S 106.160201600 _1_ MAC - 0 CTS 10 [energy 35921.9328 et 30.826 er 47.242 t_Tr 0.988 t_Re 2.128]
S 106.171201700 _0_ MAC - 38 cbr 100 [energy 35911.4286 et 66.394 er 22.178 t_Tr 2.128 t_Re 0.999]
R 106.214201800 _1_ MAC - 38 cbr 100 [energy 35920.2918 et 31.512 er 48.196 t_Tr 1.010 t_Re 2.171]
S 106.214201800 _1_ MAC - 0 ACK 10 [energy 35920.6350 et 31.169 er 48.196 t_Tr 0.999 t_Re 2.171]
S 106.255921179 _0_ MAC - 0 SYNC 9 [energy 35909.8428 et 67.735 er 22.422 t_Tr 2.171 t_Re 1.010]

Therefore total time to transmit 2.171 – 2.128 = **0.043 seconds**

Total energy used = 0.043 x 31.2mW = **1.34 mJ**

Total Time to receive is 2.171 – 2.128 = **0.043 seconds**

Total energy used is 0.043 x 22.2mW = **0.954 mJ**

The outputs of the simulation can be validated as:

Total energy used to transmit = 67.735 – 66.394 = **1.341 mJ**

Total energy used to receive = 48.196 – 47.242 = **0.954 mJ**

It is observed that the **theoretical** and the **simulated** values for the Chipcon transceiver lie very close to each other. The reason that the simulated values are slightly higher is that the calculations performed by NS2 are up to 8 significant digits accurate after the decimal point. However in this case it is a good enough approximation.

3.4.2.4 Comparing the Theoretical and Simulated SMAC Sleep and Idle Energy Consumption with Chipcon CC1000 Parameters

SMAC was designed by Dr Wei Yei at USC. The main objective of SMAC is to save energy by putting the node to sleep when it does not have to transmit a message for a long time. Figure 3.14 represents the SMAC duty cycle. The entire transmission and reception take place in the active period. In the sleep state the radio consumes very little energy. SMAC is based on 802.11 and hence the message is sent as RTS→ CTS→DATA→ACK. In SMAC an additional SYN packet is sent so that all the nodes in a cluster sleep and awake in the same time period

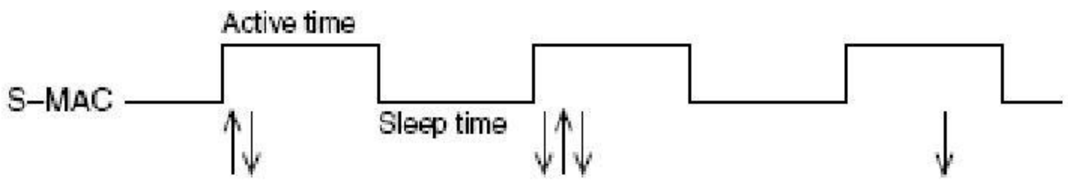

Figure 3.14: The SMAC duty cycle with active and sleep state

The **SMAC sleep energy consumption** values were obtained theoretically and by simulation. Again the Chipcon CC1000 parameters were set the same as section 3.4.2.4 The total simulation runtime was 200 seconds. As the duty cycle of SMAC was varied from 10 % to 100%, the energy consumption values for sleep state are shown in Figure 3.15. The reason for lower sleep energy value compared to theoretical is due to the fact for the first 40 sec of the simulation the nodes do not go to sleep as they are trying to establish a sleep-awake schedule. The theoretical values are very much close towards the simulated values (shown by the Actual column 4).

Duty Cycle	sleep sec	Theoretical mJ	Actual Sleep	Actual mJ
10 %	180	5.4	148.27	4.48
20 %	160	4.8	140.07	4.20
30 %	140	4.2	128.35	3.85
50 %	100	3.0	92.144	2.76
70 %	60	1.8	56.446	1.69
90 %	20	0.6	19.617	0.58

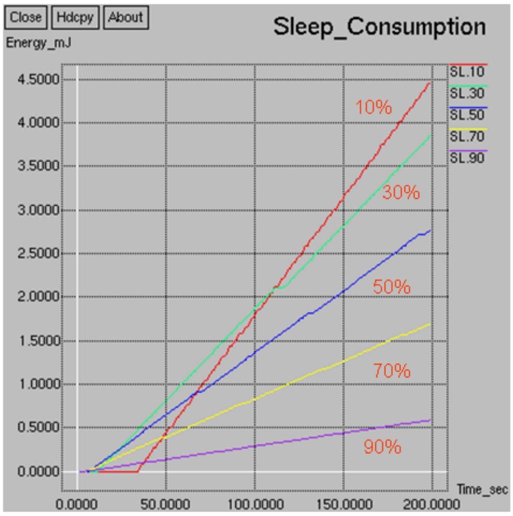

Figure 3.15: The sleep state energy consumption for 200 seconds

The **SMAC Idle energy consumption** values were obtained theoretically and by simulation as shown in Figure 3.16.

Total Simulation runtime 200 seconds

Duty Cycle	Idle sec	Theoretical mJ	Actual Idle Time sec	Actual mJ
100%	200	4440	200.00	4440
90 %	180	3996	178.64	3965
80 %	160	3552	160.28	3552.62
70 %	140	3108	141.75	3151.84
50 %	100	2220	106.45	2363.08
30 %	60	1332	70.39	1562.76
10 %	20	444	49.48	1098.66

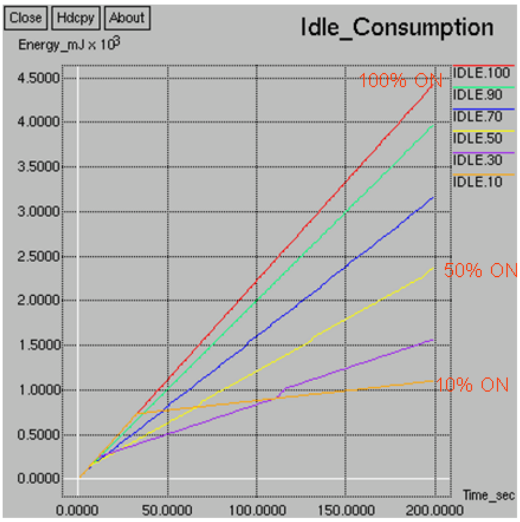

Figure 3.16: The Idle state energy consumption for 200 seconds

Again the theoretical and the simulated idle energy consumption values for SMAC are very close to each other.

3.4.2.5 Testing SMAC Latency in Multihop Scenario.

A simulation scenario was setup in NS2 that contained a linear network of 11 nodes as described by (Ye, Heidemann et al. 2004). The reason to perform this test was to simulate and achieve the results published in the paper by using NS2. The setting for the simulation was kept very similar as described in the publication (Ye, Heidemann et al. 2004). The results given in the publication were achieved by programming 11 motes with SMAC and running the tests while our results are based on NS2 simulation.

Simulation Settings

Total nodes 11

Inter node distance 3m

Message size 100 byte

1 Message sent every 100 second

From Figure 3.17 the left hand graph is obtained from (Ye, Heidemann et al. 2004) and shows that when the duty cycle is set to 10%, the maximum latency is approximately 11 seconds for the message to travel from base station to its destination. This latency is reduced to 3 seconds when adaptive listening is introduced. Adaptive listening prevents the node from going into sleep state when it has messages in the buffer that need to be transmitted. However when no sleep cycle is introduced in SMAC, the total time taken by the message to reach its destination is less than 2 seconds.

The right graph in Figure 3.17 represents the results obtained by my simulation. There is very high latency about 40 seconds. The latency hardly decreases (only 2 seconds approximately) when adaptive listening is introduced. However when no sleep cycle is applied the latency decreases to approximately 4 seconds.

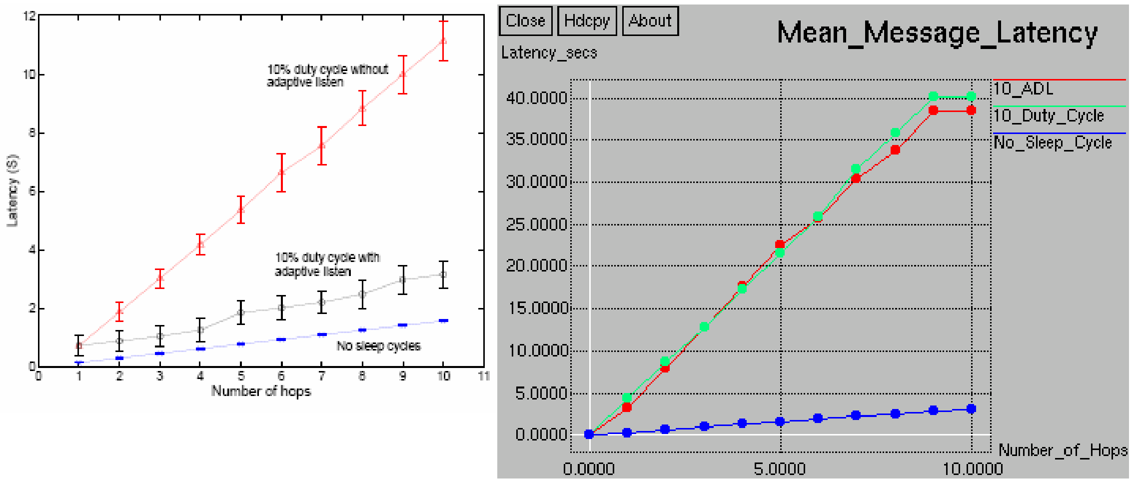

Figure 3.17: The Latency problems with SMAC

From this simulation it can be seen that some discrepancy exist in the NS2 model of SMAC. One reason is that using SMAC each node spends a lot of time sending SYNC packets to its neighbours. After sending and receiving SYNC packets the node goes to sleep. The adaptive listening module clearly does not work as required.

It was noted that by increasing the duty cycle from 10% to 50% and 90% the latency should fall dramatically. However this is not the case for all the different duty cycles implemented, the latency does not change as shown in Figure 3.18.

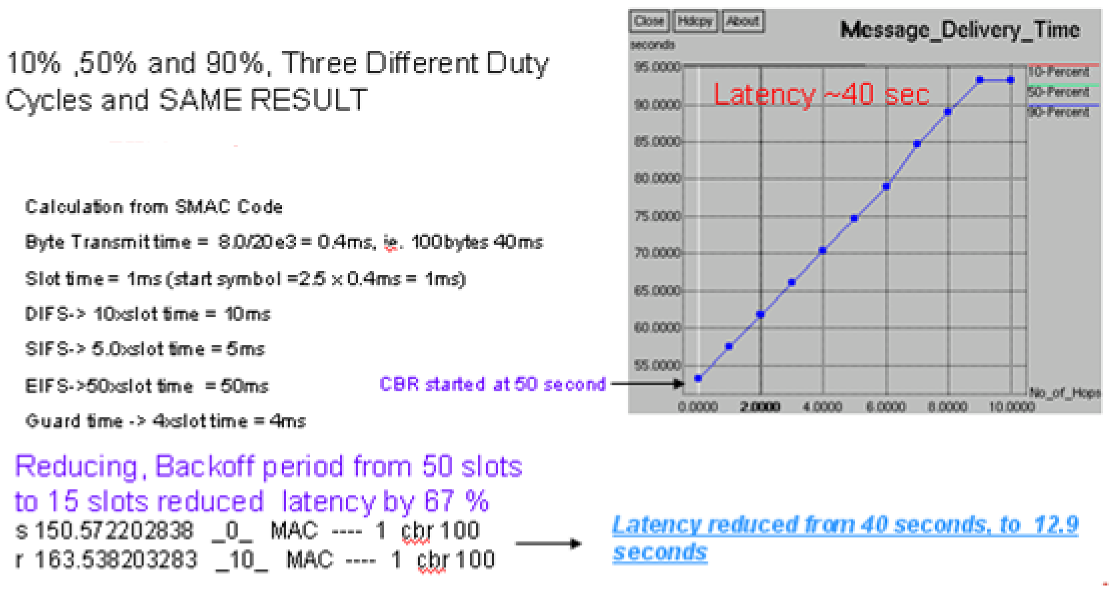

Figure 3.18: The Latency does not decrease as the duty cycle is increased

However when the backoff period for SMAC was reduced from 50 slots (as implemented in TinyOS) to 15 slots, the latency reduced by 67%.

A key point to note is that when the EIFS values are reduced, the latency values do match. But due to the unpredictable behaviour of SMAC implementation and its use of TDMA MAC protocol in NS2, it was not used in this research.

3.5 Modifying NS2 to Accommodate for Different Transmission Ranges

A point to be noted is that while running wireless simulation in NS2, each node cannot have an individual range. The reason for this was to make the simulator more efficient and to avoid excessive calculations. In a simple case where three wireless nodes are set for simulation, if the first node is to have the transmission range of 10m, the second node having transmission range of 20m and the third node having a transmission range of 30m, NS2 will assign the transmission range of the first node i.e. 10m to the second and third node as well. This causes a major hindrance as in this research, each node has an individual transmission range.

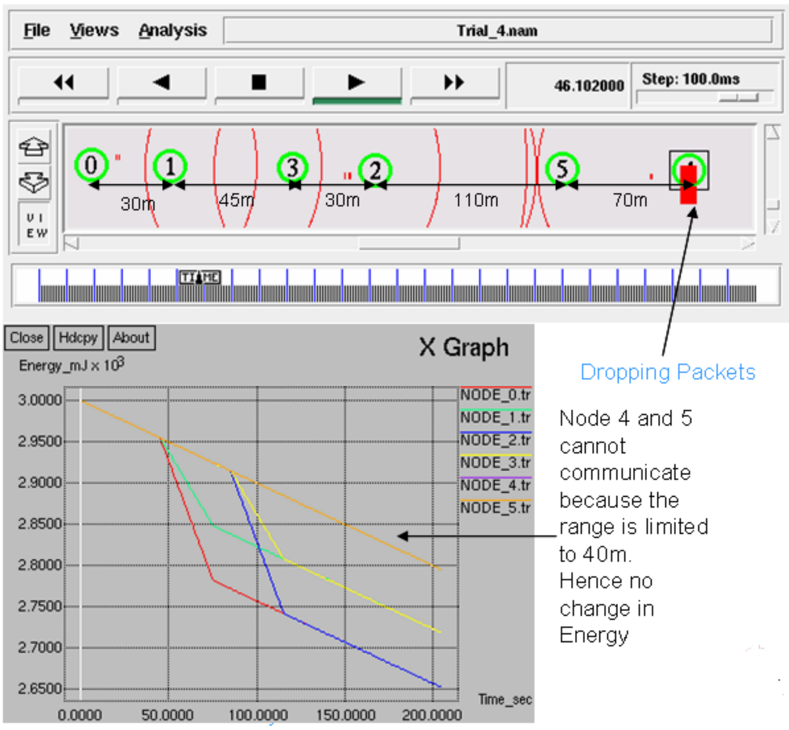

Figure 3.19: Node 4 and 5 are not communicating and dropping packets

A simple simulation was set up using three pairs of wireless nodes. The transmission range and carrier sense threshold for node pair 0, 1, and 2, 3 were set to 40m each. The transmission range and carrier sense threshold for node pair 4, 5 was set to 100m. The distance between each node pair was kept greater than the pair's transmission range so that they did not interfere with the other pair. The actual positions of the nodes are shown in Figure 3.19. It was demonstrated by simulation that the node pairs 0,1 and 2,3 communicate with each other correctly as shown in Figure 3.18 and it was noted that they have the same range. However in the NS2 simulation it was found that node pair 4,5 despite having the transmission range of 100m and separation of 70m, cannot communicate with each other. This is because NS2 has set the transmission range for node pair 4, 5 to (i.e. 40m).

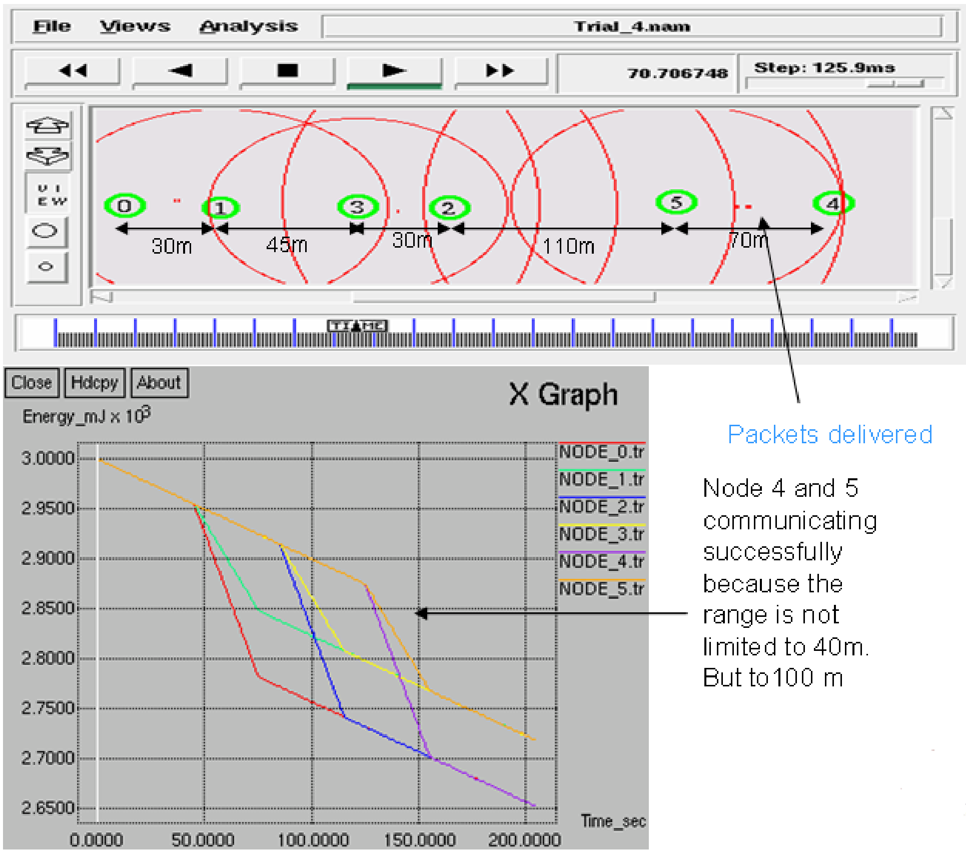

Figure 3.20: Node 4 and 5 are communicating and not dropping packets

This issue was fixed by modifying the channel properties of wireless node in NS2. In NS2 the channel is used to store the transmission range of the first node. And NS2 implements that range to all the packets sent by all the other nodes. This was not the case before where the channel used to store the transmission range of the first node and implement that range to all the packets sent by all the other nodes. Three test cases were setup. In the first case the distance between the node pair 4-5 was set to 70m. Both the nodes communicated successfully. Then the distance between the node pair was increased to 100m. The nodes pair maintained 100% throughput. The node pair was then increased to 130m. At this point, both the nodes did not communicate at all. Figure 3.20 shows the same simulation with the transmission range problem solved. Node pair 4, 5 can communicate over the distance of 100m even though their separation distance is kept to 70m in the simulation.

3.6 Conclusion

This chapter of the thesis has presented an in-depth review of the simulation tools used in the wireless research community. Four main network simulators were investigated to find a suitable candidate for this research. The selection of NS2 was based on several factors, including its acceptability and credibility among the research community. The key advantage of NS2 is its ease of modification. It includes all the necessary protocols that are required for this research. Preliminary preparations were made in NS2 and simple simulations were run to confirm its operation. The enhanced NS2 tool will be a very useful asset in this research.

Chapter 4

Modeling Wireless Sensor Networks

In this chapter the modified network simulation tool NS2 described in Chapter 3 is used to accommodate nodes with different transmission ranges, and develop simulation and energy models of such topology management schemes for three simple linear wireless sensor networks. Detailed packet-level simulations show that if the radio range is Optimised using traffic-dependent energy-based techniques then the cluster head lifetime can be improved by 30% and 50% respectively, compared with the best case where equal radio range and commercial off the shelf (COTS) systems are used. However, such improvements must not be at the expense of either the overall network lifetime or the quality of service (QoS). Using my traffic modelling approach in NS2 I show that when traffic is high the new Optimised grids network (Iqbal, Holding et al. 2007) provides a significant improvement in the key QoS parameters of packet delivery (increased by 30%), latency (reduced by an order of magnitude) and jitter (reduced by 55%) without decreasing network life.

Ad hoc WSNs are an emerging distributed sensing technology with very different characteristics to the traditional, secure, and highly-controlled wireless networks used in industrial sensing and control systems. Quantitative analysis (Iqbal, Holding et al. 2007) and (Gao, Blow et al. 2005) shows that in ad hoc WSN's there is a complex and subtle relationship between various approaches to minimising inter-node communication while maintaining an acceptable QoS and functionality. Concurrent research into energy aware networking using system-level modelling has shown that, if novel network management and network protocols are used as energy management techniques, it is feasible to extend the system life significantly (Gao, Blow et al. 2006). This work was completed using matlab and theoretical calculations were completed to extended the network lifetime. This work did not involve packet level simulation using any of the network simulators. The work only focused on cluster head energy consumption and did not focus on network QoS parameters including network throughput, latency and jitter. It also did not simulate the varying traffic loads conditions and also did not include the Sleep mode. The need is to demonstrate, through detailed modelling of the network management techniques and message-packet modelling of the protocols, that such extended life systems can be achieved. In this research, packet level simulation is used to verify the results achieved by (Gao, Blow et al. 2006). It also enhances that work by looking into the QoS parameters and including the Sleep Mode. The traffic load is also varied to see how the network lifetime is effected and a detailed comparison is made between all the networks.This chapter describes how the use of optimum node transmission ranges can increase WSN lifetimes and quality of service (QoS).

4.1 Designing an Energy Efficient Transmission Model

4.1.1 A WSN Radio Power Model

The network lifetime can be defined to be the time until the first node runs out of battery power as defined by the authors in (Chang and Tassiulas 2004). In (Giridhar and Kumar 2005) the authors define functional lifetime of a sensor network as the maximum number of times a certain data collection function or task can be carried out without any node running out of energy. In the context of those WSNs in which neighbouring nodes collaborate to forward data to a base station or sink, typically by forming clusters in which redundant nodes for routing sleep in order to save energy, the network lifetime is effectively defined by failure of the first cluster or grid that cannot provide a cluster head function.

The service life of WSN nodes depends on the capacity of their power supply and their energy consumption, where the wireless communications subsystem dominates other node functions such as sensing and local processing.

A simplified power model of radio communication (Min, Bhardwaj et al. 2002) and (Heinzelman, Chandrakasan et al. 2000), gives the energy (per second) consumed by a node in transmission as:

$$E_t = (e_t + e_d r^n)B \qquad (4.1)$$

This comprises a distance-independent term e_t that accounts for the energy/bit consumed by the transmitter electronics (including energy costs of imperfect duty cycling due to finite startup time), and a distance-dependent term $e_d r^n$ that accounts for energy dissipated in the transmit op-amp (including op-amp inefficiencies) where r is the transmission range used. The parameter n is the power index for the channel path loss; this factor depends on the RF environment and is generally between 2 and 4. The bandwidth B of the network represents the capacity of the connection. The greater the capacity, the more likely that greater performance will follow, though overall performance also depends on other factors, such as latency. On the receiving side, the fixed amount of power is required to capture the incoming radio signal is:

$$E_r = e_r B \qquad (4.2)$$

where e_r is the energy/bit consumed by the node's receiver electronics. Typical numbers for currently available radio transceivers are e_t=50x10^{-9} J/bit, e_r=50x10^{-9} J/bit, e_d=100x10^{-12} J/bit m^2 (for n=2) and B=1Mbit/s (Chen, Jamieson et al. 2002).

Since the path loss of radio transmission scales with distance in a greater-than-linear fashion, dividing a long path into several shorter ones using intermediate nodes as relays/ routers will reduce the total transmission energy, but increase the total node consumption (due to e_t), and the total receiving energy consumption. There is clearly a balancing act between reduced transmission energy and increased receive energy; hence an optimum transmission distance exists.

Following (Gao, Blow et al. 2006) I consider multihop communication in a finite one-dimensional network from the source to the base station across a distance d using k hops as shown in Figure 4.1. Let the source at $x=d$ generate traffic of A Erlang, so that each intermediate node receives and transmits the same traffic, A. Assume that the routing nodes consume no energy while idle,

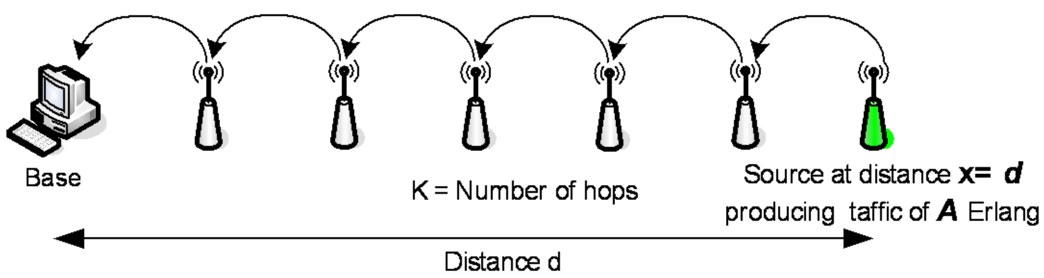

Figure 4.1: A finite one dimensional multi hop network

then the power consumed by this communication is simply the sum of the transmit and receive energies multiplied by the effective bit rate, *BA*, and is given by:

$$P = \sum_{i=1}^{k} (e_t + e_d r_i^n + e_r) BA, \quad where \quad \sum_{i=1}^{k} r_i = d \qquad (4.3)$$

Since *P* is strictly convex, Jensen's inequality can be used to minimize *P*: given *d* and *k* then *P* is minimized when all the hop distances r_i are made equal to *d/k* [3]. The minimum energy consumption for a given distance *d* has either no intervening hops or k_{opt} equidistant hops where k_{opt} is always one of the following (Gao, Blow et al. 2006),

$$k_{opt} = \lfloor d / d_{char} \rfloor \text{ or } k_{opt} = \lceil d / d_{char} \rceil \qquad (4.4)$$

The optimum transmission distance d_{char}, called the *characteristic distance*, is independent of *d* and is given by,

$$d_{char} = \sqrt[n]{(e_t + e_r) / e_d (n-1)} \qquad (4.5)$$

The characteristic distance depends only on the energy consumption of the hardware and the path loss coefficient (i.e. it is independent of the traffic); d_{char} alone determines the optimal number of hops. For typical COTS (commercial, off-the-shelf)-based sensor nodes, d_{char} is about 35 meters.

4.1.2 Topology Management

Topology management aims to match the distributed resources to the overlying applications in an energy efficient manner to achieve the service requirements for the maximum possible time. In a typical ad hoc wireless sensor network deployment, a dense network is required to ensure adequate coverage of both the sensing and multi-hop routing functionality, in addition to improving network fault-tolerance. Topology management in such networks exploits both the macro-scale redundancy of possible routes between source and destination, and the micro-scale redundancy of nodes that are essentially equivalent for the multi-hop path. The objective is to transition redundant nodes to a sleep state to save node radio energy (i.e. to reduce the node idle-mode energy consumption, which does not differ much from the node receive-mode energy consumption). The crucial issue is to intelligently manage the sleep state transitions while maintaining robust undisturbed operation.

WSN node transceivers consume power not only when sending and receiving data, but also when listening. Stemm and Katz (Stemm and Katz 1997) show idle:receive:transmit ratios are 1:1.05:1.4 by measurement, while more recent studies show ratios of 1:2:2.5 (Kasten) and 1:1.2:1.7 (Chen, Jamieson et al. 2002). Significant energy savings are only obtainable by putting as many nodes as possible to sleep.

Achieving energy saving through activation of a limited subset of nodes in an ad-hoc wireless network has been the goal of some recent research such as SPAN (Chen, Jamieson et al. 2002), ASCENT (Cerpa and Estrin 2004), CEC (Xu, Heidemann et al. 2002) , AFECA (Xu, Heidemann et al. 2000) and GAF (Xu, Heidemann et al. 2001). In SPAN, a limited set of nodes forms a multi-hop forwarding backbone that maintains the original capacity of the underlying ad-hoc network. Other nodes no longer carry the burden of acting as relays and transition to sleep states more frequently. To balance out energy consumption, the backbone functionality is rotated between nodes. In ASCENT, the decision for being active is delegated to the nodes; passive nodes keep listening all the time and assess their course of actions; stay passive or become active. The Cluster-based Energy Conservation (CEC) algorithm creates clusters and selects cluster-heads based on the highest advertised remaining energy. The Adaptive Fidelity Energy-Conserving Algorithm (AFECA) allows each node to sleep for randomized periods based on the number of (overheard) neighbours it has. The GAF algorithm is based on a division of the sensor network in a number of virtual grids of size *R* by *R*. The value of *R* is chosen such that all nodes in a grid are equivalent from a routing perspective. This means that any two nodes in adjacent grids should be able to communicate with each other. Clearly, for the worst-case node location, *R* should satisfy

$$R \leq r/\sqrt{5} \tag{4.6}$$

For the one dimension case, *R* should satisfy

$$R \leq r/2 \tag{4.7}$$

GAF only keeps one node awake in each grid, while the other nodes put their radio in the sleep mode. To balance out the energy consumption, the burden of traffic forwarding is rotated between nodes. In a high-density deployment, by increasing the radio range, *r*, there are more nodes in each grid and hence more redundant nodes can make the transition into the sleep state. However, the path loss of radio transmission scales with distance in a greater-than-linear fashion. The requirement is to determine an optimum range that provides the maximum energy saving.

Unlike CEC, where each node advertises its remaining energy and then the node with the highest energy is elected as the cluster head, the LEACH protocol (Heinzelman, Chandrakasan et al. 2002) divides a network into a small number of clusters of nodes, each of which has a cluster head node that fuses data from the other sensor nodes and forwards it directly to the base station. This gives better performance than direct transmission from the sensor nodes, and the cluster head nodes are rotated randomly within the cluster to enhance network lifetime. PEGASIS (Lindsey and Raghavendra 2002) outperforms LEACH by having a single data fusing cluster head (which eliminates the overhead of dynamic cluster formation). All non-cluster head nodes, which know their own location and that of all the other nodes, send data to the cluster head by multi-hopping via other sensor nodes. The cluster head node is rotated randomly after each round of transmission to enhance network lifetime.

In (Zhao and Erdogan 2006), a novel self-organizing energy efficient hybrid protocol based on LEACH is presented, combining cluster based architecture and multiple-hop routing for inter-cluster communication between cluster heads and the base station, in order to minimize transmission energy. In (Gupta and Younis 2003) the authors place high energy nodes called “Gateways” which know the location of all the nodes in the network, act as a data fusing cluster head, and transmit data direct to the base station.
In (Moussaoui and Naïmi 2005) the authors introduce a new Distributed Energy-efficient Clustering Hierarchy protocol (DECHP) in which the selected cluster head are uniformly placed throughout the sensor field and uses a multi-hop approach in sending traffic to the base station. This distributes the energy dissipation evenly among all sensor nodes to improve network lifetime. In (Shu, Krunz et al. 2005) the authors propose two mechanisms for achieving balanced power consumption: routing aware optimal cluster planning which is similar to DECHP, and the clustering-aware optimal random relay, similar to PEGASIS, but where a node might send the data to its neighbouring cluster

head or straight to the base station if this minimises energy use. In (Dagher, Marcellin et al.) the authors address the multi-faceted nature of minimizing energy in such networks, and use Pareto optimization to maximizing the lifetime of the unicast multi hop wireless sensor networks.

In (Lee, Kim et al. 2006) the author propose a novel MAC and physical layer method for varying transmission power according to the distance of the destination node to minimize energy consumption. In (Deng, Han et al. 2004) the authors try to find the relationship between optimal transmission ranges for various network conditions. They conclude that when the path loss exponent, see Equation (1), is high e.g. four, the optimal transmission range is nearly the same for varied number of node densities, however when the path loss exponent is set to two, then the optimal transmission range decreases noticeably as the node density increases.

It is of note that WSN's, like other wireless networks, present specific challenges in terms of maintaining a good quality of service (Chen and Varshney), and it is important that this is taken into account (particularly at higher traffic levels) when designing energy minimization schemes. In (Wang, Liu et al.) the authors outline the WSN QoS requirements for several layers which they refer to the OSI 7- Layers model. For each layer they give the definitions of QoS requirements including throughput, latency, packet loss, jitter, packet sequencing, and bit error rate. In the following I establish relationships between traffic, QoS, and energy minimization, and use these relationships in WSN network design.

4.1.3 A Theoretical Approach for a Traffic based Optimal Grid Design

The simple energy model in section 4.1.1 assumed that no energy was consumed while the node was idle. This led to a characteristic distance that was independent of traffic. If the idle state energy is included then the characteristic distance is modified. Again, following (Gao, Blow et al. 2006), consider a linear network of length d as shown in Figure 4.2 in which the traffic carried from end to end is A Erlang that is the total traffic.

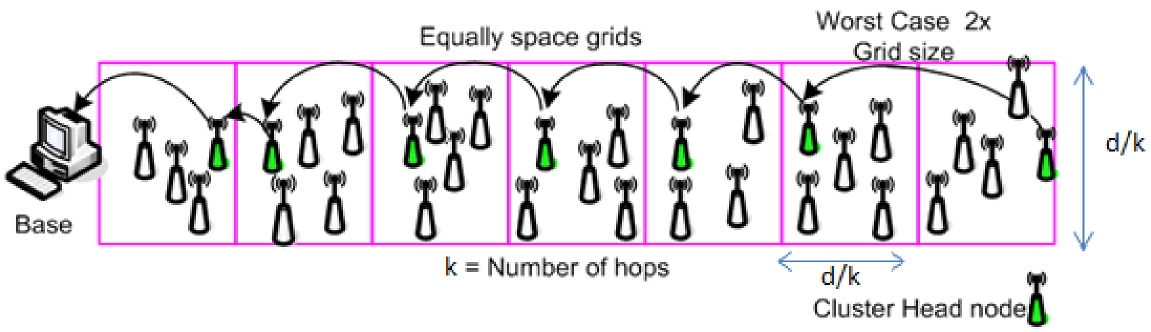

Figure 4.2: A multi-grid sensor field containing cluster head nodes forwarding data.

If the transmission route is divided into *k* grids and only one node wakes up in each grid as relay node, as in the GAF protocol, the total energy consumption per second by *k* hops is:

$$P = k[e_r BA + e_t BA + e_d (2\frac{d}{k})^n BA + ce_r (1-2A)B] \quad (4.8)$$

The last term $ce_r(1\text{-}2A)B$ in equation (4.8) represents the energy consumption when the radio neither receives nor transmits, i.e. it is in the idle state. To achieve this term, we know that the maximum traffic achievable by the network is 1 or 100%. The total traffic received by the wireless node anywhere in the linear network will be A Erlang and the total traffic the same node will forward is A Erlang. Therefore total amount of 2A Erlang traffic will pass the wireless node, and this wireless node will not be in the idle state during that time. Hence the idle time will be calculated as the total time minus the time the node was either busy transmitting or receiving a message as (1-2A). The energy consumption in the idle state is approximately equal to that in the receiving state, so that the parameter *c* is close to 1. Note that we are currently assuming (i) that nodes in the sleep state consume no energy, and (ii) the routing node in each grid can be located anywhere within that section and so the radio range is now twice the grid size that is $2\frac{d}{k}$.

We differentiate equation (4.8) with respect to k to find the maximum grid size that is required to give the most efficient cluster head life.

$$D[k((e_t + e_r)\mathrm{BA} + e_d(2\tfrac{d}{k})^n\mathrm{BA} + \mathrm{C}e_r(1-2A)B), k] \quad (4.9)$$

$$\mathrm{d}P/\mathrm{d}k = (1-2A)B\mathrm{C}e_r + 2^n\mathrm{BA}(\tfrac{d}{k})^n e_d - \frac{2^n\mathrm{BA}d(\frac{d}{k})^{-1+n} n e_d}{k} + \mathrm{BA}(e_r + e_t) \quad (4.10)$$

$1 - 2A)B\mathrm{Ce}_r + 2^n \mathrm{BA}(\frac{d}{k})^n e_d - \frac{2^n \mathrm{BA}d(\frac{d}{k})^{-1+n} n e_d}{k} + \mathrm{BA}(e_r + e_t)$ (4.11)

The following equation is reached

$$\mathrm{d}P/\mathrm{d}k = (B - 2AB)\mathrm{Ce}_r + \mathrm{BA}(-2^n (\frac{d}{k})^n (-1+n) e_d + e_r + e_t) \quad (4.12)$$

By setting dP/dk =0

$$(1 - 2A)B\mathrm{Ce}_r + -2^n \mathrm{BA}(\frac{d}{k})^n (-1+n) e_d + \mathrm{BA}(e_r + e_t) = 0 \quad (4.13)$$

and rearranging the following equation is reached

$$(\frac{d}{k}) = \sqrt[n]{\frac{A(e_r+e_t)+(1-2A)\mathrm{Ce}_r}{2^n A(n-1)e_d}} \quad \text{where} \quad R_{opt} = (\frac{d}{k}) \quad (4.14)$$

The energy efficient optimum size of the virtual grid can now be derived from equation (4.15) and is given by:

$$R_{opt} = r_{opt}/2 = \sqrt[n]{\frac{(e_r + e_t)A + ce_r(1-2A)}{2^n A(n-1)e_d}} \quad (4.15)$$

The minimum energy consumption characteristic range is no longer a constant and changes with the amount of traffic. Figure 4.3 shows the relationship between the traffic A and the optimal range r_{opt} . The optimal range decreases as the loaded traffic increases until, at the extreme point A=0.5 the transmitter spends 50% of the time transmitting and 50% receiving (I assume the node can only do one or the other), so there is no idle time and the optimal range converges to d_{char}. Under conditions of light traffic (i.e. the data transferred in the sensor network is low), the idle state dominates the energy consumption and the optimal radio range increases sharply and can be relatively large.

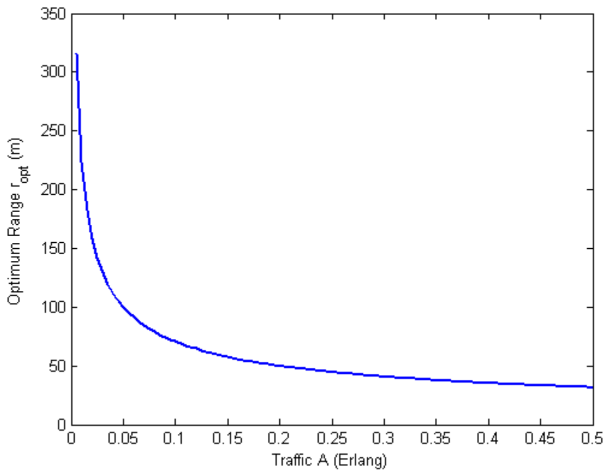

Figure 4.3: Optimum radio range as a function of the network traffic.

4.1.4 Transmission Range Adjustment

In a typical wireless sensor network application data is generated internally by multiple sensors at different locations and transmitted to a single sink node (such as a base station) where data can be stored and analyzed.

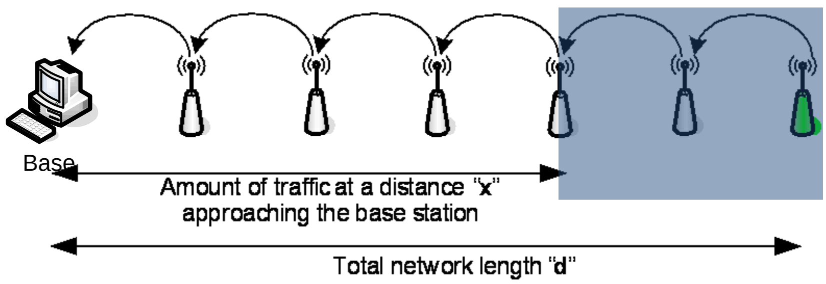

Figure 4.4: A linear network of length d.

Consider a linear network as shown in Figure 4.4, where the density of nodes is uniform. The network contains a single sink on one edge at $x = 0$. If each node produces a Erlang of data then the traffic to be forwarded at a point that is x meters away from base station is:

$$A(x) = (d - x)n_d a \qquad (4.16)$$

where d is the size of the network and n_d is the node density.

Let this network be overlaid by a virtual grid, as shown in Figure 4.5, such that traffic originating in section i of the grid is forwarded to the base station by the relay/routing node in section *i-1* of the grid. The traffic handled by the routing node in any given section of the grid is passed directly to the relay/routing node in the next section.

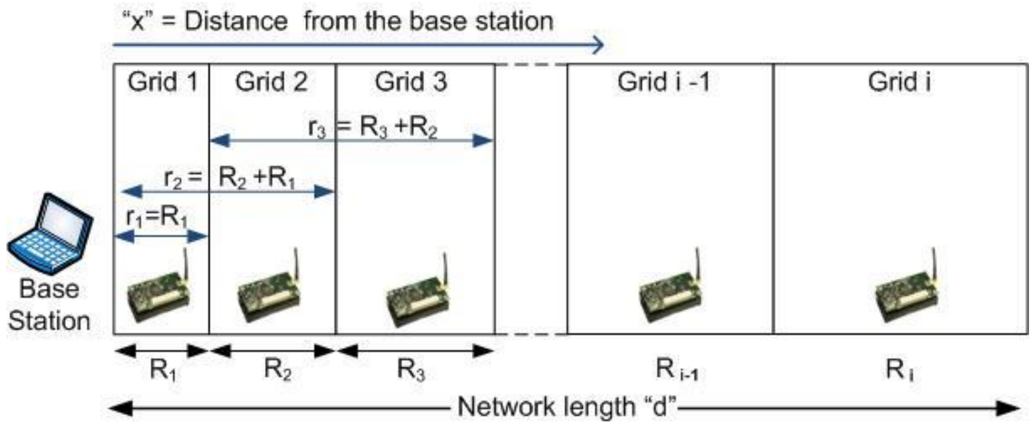

Figure 4.5 Linear network divided by virtual grids of different size

If the relay node is close to the sink there is more traffic to be forwarded than for that of the relay nodes far from the sink. For more energy efficient transmission this node can use short-range transmission. Similarly, nodes far from the sink have less data to forward and can use long-range transmission; thus a larger number of nodes that are not involved in routing can be put into the sleep state. Specifically I considered a non-uniform grid covering the network and exploit the relationship between range and loaded traffic described in the previous section (which only considered data in transit across a linear network of routing nodes) to determine the optimum grid-specific range for the efficient transmission of the actual traffic in a particular grid.

I use a heuristic algorithm developed by (Gao, Blow et al. 2004) (Gao, Blow et al. 2006), based on the range-traffic relationship (4.15), to determine the grid sizes for grid section-specific traffic levels. The grid sizes are calculated iteratively as follows:

$$R_1 = R_{opt}(x = R_1), R_2 = R_{opt}(x = R_2 + R_1), \cdots R_i = R_{opt}(x = \sum_{j=1}^{i} R_j) \qquad (4.17)$$

where R_{opt} is the optimal grid size for the regular transport network derived in section 4.1.3.

4.2 Implementing the New Optimised Cluster Head Model in NS2

Simulation has become an indispensable tool in the construction and evaluation of ad hoc WSNs. Energy-aware simulations of optimum range WSNs using system-level Matlab simulations and sensor data traffic have been used to evaluate best-case performance and energy reduction (Gao, Blow et al. 2006). These results serve as a target for system performance.

However, the need is for packet-level simulations that model in detail the communication protocols and overheads and the actual data transmission, including events such as collisions. Note that the optimum grid sizes (above) are network traffic dependent (i.e. depend on actual network traffic including overheads, rather than sensor generated data traffic alone).

4.2.1 Simulation Model Definition and Optimised grids Calculation

This section defines the simulation model that was set up to test the theory devised in section 4.1. A 600m linear network was considered with node density 1/7 nodes/m where each node generated a traffic level of 0.003 Erlangs. The traffic originating in section *i* of the grid is forwarded to the base station by the relay/routing node in section *i-1* of the grid. The traffic handled by the routing node in any given section of the grid is passed directly to the routing node in the next section. The following steps show how the grid sizes can be calculated using the Optimised grids formula equation (4.15) and traffic equation (4.16).

<u>Step 1</u>

The network length is set to 600m, the node density is 1/7 nodes/m = 0.143 nodes/m and each node produces the data of 0.003 Erlang. By using equation (4.16), I can work out that the total traffic approaching the base station where 'x' will become zero, hence total traffic is

(600-0)*0.143*0.003 = 0.2574 Erlang.

Step 2

As the maximum traffic approaching the base station will be 0.2574 Erlang. This value is added to equation (15) to work out the Optimised grids size.

$$R_{opt} = r_{opt}/2 = \sqrt[2]{\frac{(50\text{x}10\text{ -}9 + 50\text{x}10\text{ -}9)*0.2574 + 1*50\text{x}10\text{ -}9\,(1-2*0.2574)}{2^2*0.2574*(2-1)*100\text{x}10\text{ -}12}} = 22.0$$

Hence the optimised first grid size will be 22.0m for the traffic of 0.2574 Erlang reaching the base station.

Step 1 and step 2 show how the first grid size is calculated for this model. To calculate the next grid size I repeat step 1 again. This time the value of ‘x’ will be 22.0m as I already have calculated the value for the first grid. I now need to know how much traffic will be approaching 22.0m away from the base station. Hence to calculate the new value of traffic 22.0m away from the base station using equation 4.16 as before,

(600-22.0)*0.143*0.003 = 0.2478 Erlang.

The new result for the traffic is 0.2478 Erlang. Adding this value to equation (4.15) will give the size of the second grid to be

$$R_{opt} = r_{opt}/2 = \sqrt[2]{\frac{(50\text{x}10\text{ -}9 + 50\text{x}10\text{ -}9)*0.2478 + 1*50\text{x}10\text{ -}9\,(1-2*0.2478)}{2^2*0.2478*(2-1)*100\text{x}10\text{ -}12}} = 22.5m$$

So the next grid size will be 22.5m, to calculate the third grid size, the first two grids sizes are added to work out the new value of “x” that now becomes 44.5. By carrying out step 1 and step 2 the third grid size can be calculated, This process is repeated until the value of x becomes equal to the grid length “d”, in this case 600m.

Also by plotting equation (4.12) using the given network range it can be seen that when dp/dk=0, the grid size is shown to be 22 as shown in Figure 4.6

$$\text{Manipulate[Plot[}(1-2A)*1000000*50*10^{-9} - 2^2*1000000*A*(R)^2(-1+2)*100*10^{-12} + 1000000*A(50*10^{-9}+50*10^{-9}) = \\ = 0, \{R, 0,30\}], \{A, 0.003,0.2574\}]$$

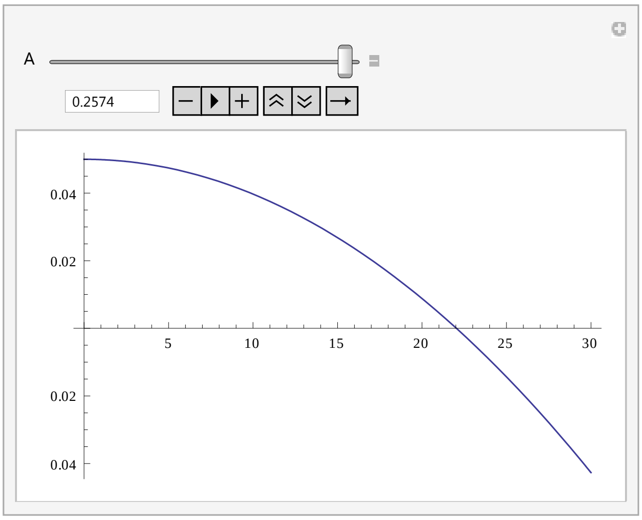

Figure 4.6: Grid size calculated for traffic of 0.2574 Erlang using Mathematica 8.0

The corresponding optimum grid sizes, radio-ranges, and the cluster head node transmission energy consumption, calculated using equations (15), (16), (17), (1) and (2) were achieved by writing a C++ program, that allows the user to add all the variables to calculate the optimum grid sizes as shown by **Optimal Grid Calculator** software "Listing 4.1". The ease of the software is that the user can add different network lengths, data rates and node densities to work out the required Optimised grids sizes. Rigorous testing has been done on the software with different parameters that have also been calculated manually to prove its reliability. It can now be readily and consistently be used to calculate the optimum grids sizes.

Listing 4.1: Optimal Grid Calculator Software Script.

```
#include <math.h>                      //Adding libraries
#include <stdlib.h>
#include <iostream.h>
#include <stdio.h>

int main (void)
{
double et = 50e-9 ;                    // Energy used transmitting a bit
double er = 50e-9 ;                    // Energy used receiving a bit
double ed =100e-12;                    // Energy used by transmit Op-Amp
double A= 0.0;                         // Declaring variable to hold the value of total traffic
double n = 2.0;                        // Power index for channel path loss
double d = 0.0;                        // Holds the value of total grid lenght
double node_density = 0.0;             // Holds the value of node density
double x= 0.0;                         // Traffic at a distance x from the base station
int i = 0;                             // Required for counting loop
char j;                                // Required for finishing the program
```

```
double data_rate = 0.0;             // Traffic in Erlangs produced by nodes 'a'
double Ans = 0.0;                   // Store the value of grid size
double Erlang_data[100];            // Holds the value of total traffic in an array
double Inc_Distance[100];
double Distance [100];
double NewGrid [100];
cout<<"==========================================================";
cout<<"\n              A Program to Calculate The Optimised Grid Size        \n";
cout<<"==========================================================";
cout<<endl<<endl;
cout<<"\n Please enter the Linear length of the d: " ;
cin>>d;
cout<<"\n Please enter Node density: " ;
cin>>node_density;
cout<<"\n Please enter the data_rate in Erlang " ;
cin>>data_rate;
printf("\n------------------------------------------------------------------");
printf("\nGrid No  \tTraffic \tGrid size \tDistance from BS ");
printf("\n------------------------------------------------------------------\n\n");
while (x <= d)                      // Start an interative loop
{
A=(d-x)*node_density*data_rate;               // Using equation___10
// Equation 9 is divided into four parts (steps)
double Part_1 =(er+et)*A;
double Part_2= 50e-9*(1-(2*A));
double Part_3 = 4*A*ed;
double Part_4= (Part_1 + Part_2)/Part_3;
Ans= sqrt(Part_4);                  // This gives the final new grid size
i++;                                // Increment to get the grid number,
x=x+Ans;                            // New value of X is old X + new grid size to cal
NewGrid[i] = Ans;                   // Holds the value of new grid size in an array
Inc_Distance[i] = x;                // Value of total distance away from the base station from grid (i)
Erlang_data[i] = A;                 // Total amount of traffic approaching the base station from grid (i)
printf(" %d\t\t %.6f\t   %.1f\t\t  %.1f \n", i, Erlang_data[i], NewGrid[i], Inc_Distance[i]);
 }                                  // End of loop
printf("\n------------------------------------------------------------------\n");
cout<<"\n Please enter 'q' to finish  " ; // Request program to exit gracefully
cin>>j;
}                                   // End of program
```

When the program is executed, it asks the user to enter the maximum length of the network ‘d’, the node density and also the data produced by node in Erlang. After that when the enter key is pressed, the program executes as shown in Figure 4.7. The last value in Figure 4.7 is greater than 600, because the Optimised grids size is based on the amount of traffic and node density and is independent of the total length of the actual grid. The grid length is entered only to have a network of certain length.

Table 4-1 also shows the results achieved for Optimised grids spacing using the software mentioned in Listing 4.1. There are a total number of 19 Optimised grids with different grid sizes. The transmit energy consumption is calculated using equation (4.1) from section 4.1.1 for grid length R_{opt}.

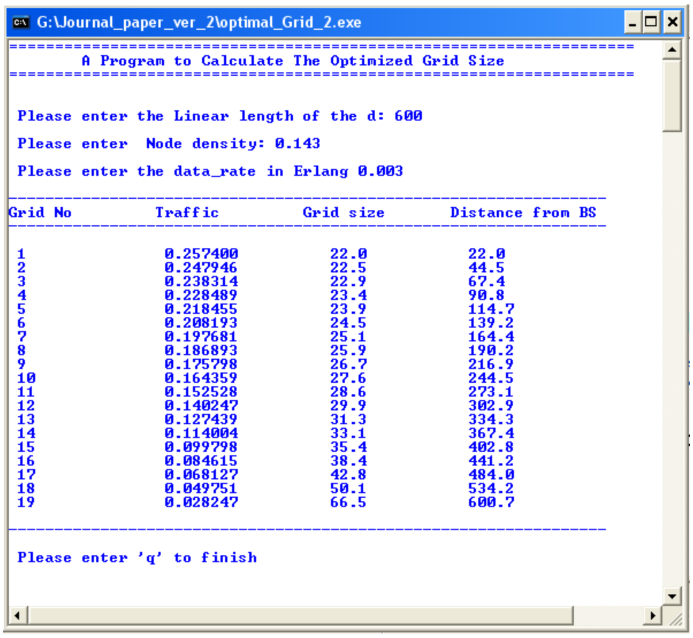

Figure 4.7: Output screen from Optimised grid software

Table 4-1 Optimised Grids size for 600m Network

Grid (i)	R (i)	r(i) = Ri+R(i-1)	Transmit energy consumption for r(i) at 1Mbit/s
	(m)	(m)	(j/s)
Base (0)	0	0	0.0000
1	22	44	0.2420
2	22.5	44.5	0.2480
3	22.9	45.4	0.2561
4	23.4	46.3	0.2644
5	23.9	47.3	0.2737
6	24.5	48.4	0.2843
7	25.1	49.6	0.2960
8	25.9	51	0.3101
9	26.7	52.6	0.3267
10	27.6	54.3	0.3448
11	28.6	56.2	0.3658
12	29.9	58.5	0.3922
13	31.3	61.2	0.4245
14	33.1	64.4	0.4647
15	35.4	68.5	0.5192
16	38.4	73.8	0.5946
17	42.8	81.2	0.7093
18	50.1	92.9	0.9130
19	65.9	116	1.3956

The routing protocol used in these simulations was NAOH (Widmer) which allows to create a preset multi-hop network where each cluster head node only transmits to its neighbour cluster node and vice versa. In NOAH, the addresses of the static neighbouring cluster head nodes are hard-coded in the simulation scripts to generate true multi-hop operation. (Note that dynamic routing protocols such as AODV, DSR and DSDV could have been used, but are not required for these simulations as all the cluster head nodes are static and hence the routing information does not change).

The data rate and basic rate for all the simulations was set to 1Mbits/sec. Every packet was sent with a preamble. Most 802.11 cards have two values for the preamble length: the long preamble is 128 bits while the short preamble is 56 bits; in each case a further 16 bits (that are not affected by the short or long distinction) are added as part of the preamble. As the majority of the modern 802.11 cards use the short preamble due to advances in electronics (Robinson, Papagiannaki et al. 2005), the MAC/802_11 preamble length was set to 72 bits in all these simulations.

Three network models: a *COTS* network, an *Equal grids* network and the *Optimised grids* network, were set up based upon the 802.11 MAC protocol. For all the three networks the receive energy consumption, calculated using equation (4.2) from section 4.1.1, was set to 0.5 j/s and the idle energy consumption was set to 0.5j/s which is same as the receive energy.

COTS Network: this comprised a linear network of 19 cluster head nodes with equal grids space based on COTS transceivers with a characteristic transmission distance of approximately 35m (the 600m linear network was divided 19 grids of 31.57m). Hence the COTS transmission energy consumption per second calculated using (equation 4.1) was 0.54j/s for the cluster head node of each grid. This is because, for all the grids the cluster head node of grid (i) might have to transmit to a cluster head at the furthest point in the grid (i-1) thus the transmission range becomes double the grid space.

Equal grids Network: this comprised a linear network of 19 cluster head nodes with an Equal grids space of 31.57m. The minimum transmit power required for this grid spacing was calculated using (equation 4.1) was 0.45j/s for the cluster head node of each grid.

Optimised grids Network: this comprised a linear network of Optimised grids spaced cluster head nodes as given in column 2 Table I. The transmit power consumption for each node is also shown in Table 1 and was calculated using equation (4.1).

In NS2 a wireless node is constructed from several units combined together. The two most important units that relate to this simulation are the radio propagation model, and the energy model. The radio propagation model uses the Friss Space attenuation model (Rappaport 1999) as shown by equation (4.18) and the Two Ray Ground model (Rappaport 1999) as shown by equation (4.19) where $P_r(d)$ is the power received by the receiver at a distance d, G_t and G_r is the gain of the transmitter and receiver antenna and is set to 1.0 in NS2. d is the distance between the transmitter and the receiver, L is the path loss also set to 1.0 in NS2, λ is the wavelength of the signal that is calculated using (speed of light / frequency). The frequency is set to 916 Mhz in this case for NS2 based on a mica2 mote. h_t and h_r are transmit and receive antenna heights set to 1.5m which are NS2 default values.

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2} \tag{4.18}$$

$$P_r(d) = \frac{P_t G_t G_r {h_t}^2 {h_r}^2}{d^4} \tag{4.19}$$

The crossover distance d_c is represented by equation (20)

$$d_c = \frac{4 h_t h_r}{\lambda} \tag{4.20}$$

The Friss- Space attenuation model is used in calculating the message received power for nodes that are near or in clear line of sight, while the Two Ray ground (Rappaport 1999) model is used for nodes that are further from the transmitting node. At crossover distance the value obtained by both the models is same. As mentioned in chapter three, NS2 does not allow the nodes to have different transmission ranges in order to speed up simulation times. During the execution of the simulation script, all the nodes are assigned the same transmission range, carrier sense threshold, and receiver threshold as the first node. This is a significant limitation and restricts the use of nodes that are required to have different transmit power to achieve different radio ranges, as in my Optimised grids network.

To overcome this limitation, I modified the NS2 channel model to enabled nodes to have different transmission powers as described is chapter 3.0 section 3.5. This integrates well with the existing NS2 radio propagation models and the existing NS2 energy model which allows the transmission, receive, sleep and idle energy consumption to be set for a given node. The modified NS tool, in which nodes with higher transmission powers send their messages further, was used to simulate all three networks, including the Optimised grids network that requires the nodes in each grid to have a unique transmission range. In the Optimised grids model the carrier sense threshold value of each grid was limited to twice it's transmit distance. This alleviates the hidden node problem and results in improved performance. The cluster head node energy consumption for each of Optimised grids is shown in Table 4-1, column 4, together with the grid location and spacing of these nodes.
It is of note that the modified NS2 tool also overcomes similar problems in modelling protocols like GAF and LEACH (where the conventional NS simulation model treats all the nodes as have the same transmit power, even though they may have different initial, transmit, receive and idle energy consumption values).

4.2.2 Modelling and Simulation of WSN traffic

Network traffic was generated using a constant bit rate (CBR) and message settings for all the cluster head nodes. For all of the simulations the packet sizes were set as follows: sensor data packet, 1000 bytes (including a preamble of 72 bytes); RTS, 44 bytes; CTS: 38 bytes; and acknowledgment, 38 bytes. Each cluster head in the grid has to transmit its own aggregated data as well as to forward the data it receives from cluster head notes further from the base station. The COTS and Equal grids networks have equally spaced grids, therefore the additional data that each cluster head in turn has to forward is increased by a constant factor only. For example, Table II shows the CBR setting for the cluster heads, the amount of traffic generated by each grid, and the traffic to be forwarded by the cluster head in each grid. To explain it further, the grid length in COTS and Equal grids network is uniform. That is 600/19 = 31.57m. As the node density is 0.143 and each node produces 0.003 Erlang of data. Therefore the traffic produced at each grid is 31.57*0.143*0.003 = 0.013544 Erlang.

As the data rate is set to 1Mbits/s, hence the total traffic produced is 0.013544 * 1e6 = 13453.53 bits/s. Now to achieve data in bytes, divide 13453.53bits/s by 8 to get the new value of 1693 bytes/s. Because each transmitted packet is 1 kBytes, therefore to convert to kBytes, I divide 1693 bytes by 1000 to get the value of packets sent by each grid per second. This equates to approximately 1.69 packets per second. Hence each grid in the COTS network will generate 1.69 packets of its own data, as well as forward the packets of the previous grid.

Table 4-2 COTS & Equal Grids Network

Grid (i)	Packets to Forward (packets/s)	Grids own Packets (packets/s)	Total Packets Transmitted (packets/s)	CBR Timer Settings (s)
Base (0)	0	0	0.0000	0.00
1	30.49	1.69	32.1800	0.59
2	28.79	1.69	30.4800	0.59
3	27.1	1.69	28.7900	0.59
4	25.4	1.69	27.1000	0.59
5	23.71	1.69	25.4000	0.59
6	22.02	1.69	23.7100	0.59
7	20.32	1.69	22.0200	0.59
8	18.63	1.69	20.3200	0.59
9	16.94	1.69	18.6300	0.59
10	15.24	1.69	16.9400	0.59
11	13.55	1.69	15.2400	0.59
12	11.86	1.69	13.5500	0.59
13	10.16	1.69	11.8600	0.59
14	8.47	1.69	10.1600	0.59
15	6.78	1.69	8.4700	0.59
16	5.08	1.69	6.7800	0.59
17	3.39	1.69	5.0800	0.59
18	1.69	1.69	3.3800	0.59
19	0	1.69	1.6900	0.59

As it can be seen from Table 4-2, column 2, grid 19 generates 1.69 packets/s of its own data and has no packets to forward from any previous grid. Grid 18 generates 1.69 packets per second of it own aggregated grid data, but also has to forward 1.69 packets/sec received from grid 19. Hence grid 18's cluster head transmits 3.38 packets per second. As

I move up the table, it can be seen that the cluster header of grid 1 has to transmit 30.49 extra packets to the base station in addition to its own grid 1.69 packets per second. The CBR packet size is set to 1 kByte per second. Hence if I want to send only one packet per second, then I will set the CBR timer to 1 (please not this is not the unit of time but percentage, 1 means 100 percent of the unit time). Hence if I want to sent 1.69 packets per second. We inverse 1.69 to get the value of 0.59, so when 59% time approaching to 1 second has passed, it will transmit a 1 kByte message packet.

For the Optimised grids network, the size of grid *i* will be smaller than *i+1*, therefore the sensor data generated in this grid is less than that generated in grid *i+1*. However, it still has to forward the messages received from grid *i+1* and all more remote grids. The total number of packets that will be transmitted by the cluster head in each grid was calculated using equation (4.16) and is shown in table 4-3.

Each node was given an initial energy of 500 joules for simulation purposes. The total simulation time was set to 1000 seconds so that the network operated in a steady state condition.

Table 4-3 Optimised Grids Network

Grid (i)	Packets to Forward (packets/s)	Grids own Packets (packets/s)	Total Packets Transmitted (packets/s)	CBR Timer Settings (s)
Base (0)	0	0	0.0000	0.00
1	31	1.18	32.1800	0.85
2	29.79	1.21	31.0000	0.83
3	28.56	1.23	29.7900	0.81
4	27.31	1.25	28.5600	0.8
5	26.02	1.28	27.3100	0.78
6	24.71	1.31	26.0200	0.76
7	23.36	1.35	24.7100	0.74
8	21.98	1.39	23.3600	0.72
9	20.54	1.43	21.9800	0.7
10	19.06	1.48	20.5400	0.68
11	17.53	1.53	19.0600	0.65
12	15.93	1.6	17.5300	0.63
13	14.25	1.68	15.9300	0.6
14	12.47	1.77	14.2500	0.56
15	10.57	1.9	12.4700	0.53
16	8.52	2.06	10.5700	0.49
17	6.22	2.3	8.5200	0.43
18	3.53	2.69	6.2200	0.37

All the cluster head nodes transmit messages towards the base station via a multi-hop route as mentioned earlier. The total message transmit time for each node was 985 seconds as all the CBR's were started 10 seconds after the start of simulation and stopped 5 seconds before the end of the simulation. Figure 4.8 and 4.9 show the network simulation animation as captured by the NS Network Animator (NS-NAM). The theoretical throughput at the base station is calculated as follows using (10), where d is 600m, the base station is at x = 0, the node density n_d is 0.143, the traffic generated by each node is 0.003 Erlang, and the bandwidth of the system is 1Mbits/s. The corresponding theoretical traffic (throughput) received by the sink node is 0.257 Mbit/s.

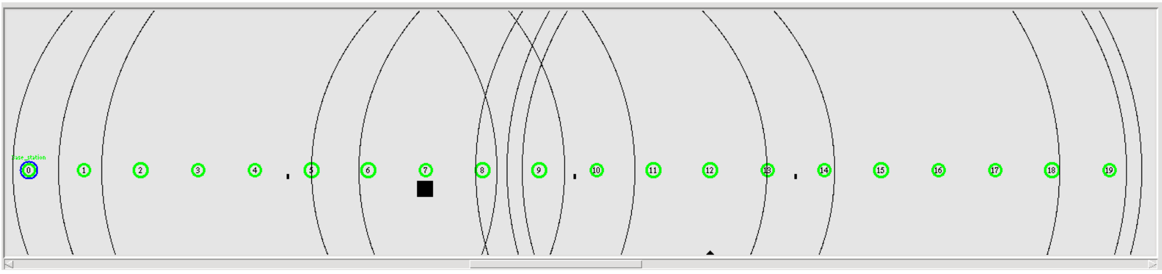

Figure 4.8 Equal grids and COTS network animation screen as shown in NS-NAM

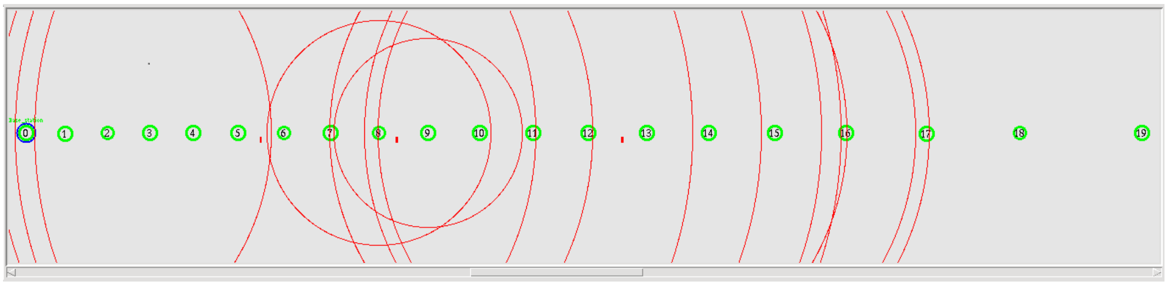

Figure 4.9 Optimised grids network's unEqual grids spacing captured on NS-NAM

Note that the COTS and Equal grids networks are symmetric: based on the mean cluster header node positions, a message sent by grid (i) in these networks is received not only by the cluster head in the intended grid (i-1) but also by cluster heads in grids (i-2), (i+1) and (i+2), thus consuming reception energy that could be saved. This is caused by overhearing and the fixed equal grid size that cannot be reduced for these networks. This also adds to network congestion and can generate unwanted collisions at grid (i+2) if the cluster head node in grid (i+3) is simultaneously forwarding a message to the cluster head node in grid (i+2); and similarly for grid (i-2). In comparison, the Optimised grid network is asymmetric: messages originated from grid (*i*) can be received by grid (*i-1*), (*i-2*) and (*i+1*) but not by grid (*i+2*) which is outside the grid-specific range of the cluster head node in grid (*i*). This improved spatial use reduces unnecessary reception energy and reduces collisions. It is shown through packet level simulation that this reduces the collisions by a third; it also improves the throughput and saves nearly a third of reception energy consumed by the grid.

4.3 *Performance Analysis of Optimised Grids vs Equal Grids and COTS Network*

4.3.1 Quality of Service: First I consider the performance and QoS of the Optimised grids, the Equal grids and the COTS networks. The enhanced NS2 simulator model was used to generate a range of QoS parameters including total network throughput, individual cluster head throughput, the packet delivery ratio for each cluster head, the latency and jitter of each cluster head within the three networks.

Simulation results of total network throughput for the first 100 seconds are shown in Figure 4.10 and Figure 4.11. The average throughput achieved over 990 seconds by the Optimised grids network is 0.242 Mbit/s (i.e. 93%). The throughputs achieved by the COTS and Equal grids networks are 0.194 Mbit/s and 0.193 Mbit/s respectively, (i.e. around 75%). The reason for the superior throughput of the Optimised grids network is its good spatial reuse as described earlier.

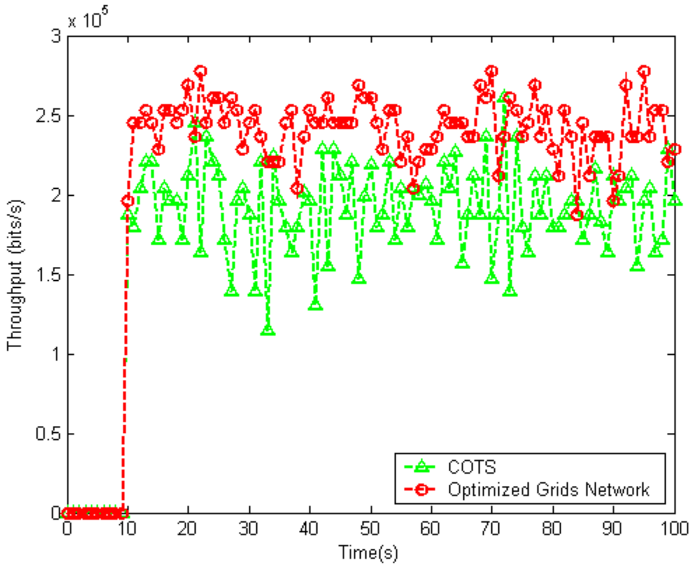

Figure 4.10: Throughput: Optimised grids and COTS networks

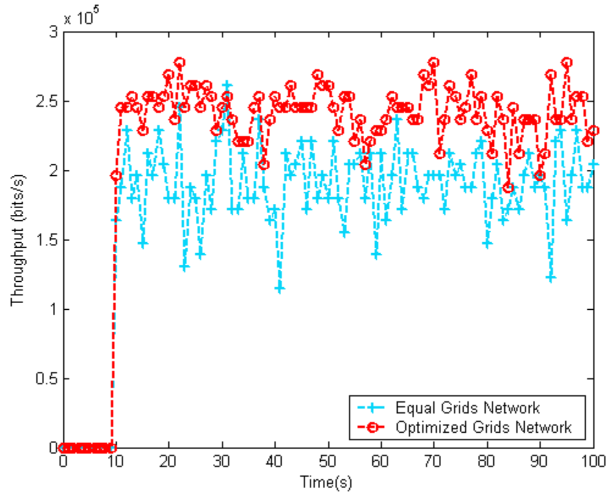

Figure 4.11: Throughput: Optimised grids and Equal grids networks

The packet delivery performance of each cluster head node in the three networks is shown in Figure 4.12. It can be seen that the Optimised grids network delivers up to 100% of the packets for the first three grids, with a relatively slow decrease in packet delivery for the grids further away from the base station. However the delivery ratio for the grids farthest away in the network is better than 86%. In the COTS and Equal grids network, the delivery performance drops much more sharply after the third grid due to a large number of collisions between the packets, and for the 40% of the network that is furthest from the base station the packet delivery falls below 65%.

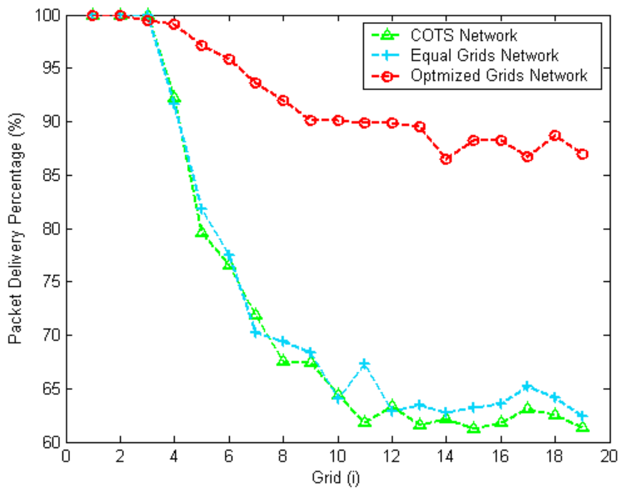

Figure 4.12: Cluster head node packet delivery performance

The latency for the three networks (i.e. the average time taken by the packets to reach the base station from each cluster head node) is shown in Figure 4.13. The Optimised grids network has an average of an order of magnitude lower latency compared to the Equal grids network and COTS networks. This is because in the Optimised grids network there is much less overhearing of redundant messages, and the cluster head nodes transceivers are freer to transit their own messages and receive messages from the previous grids, resulting in much faster packet delivery and hence reduced latency.

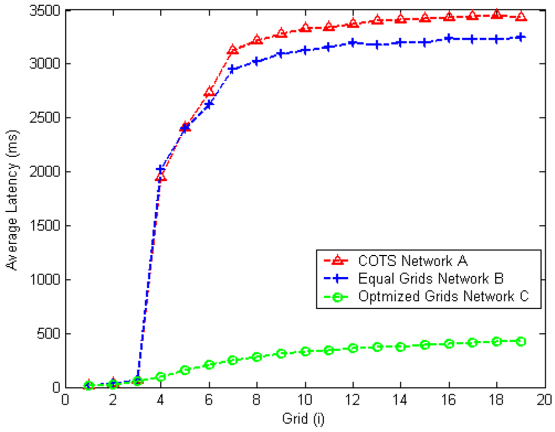

Figure 4.13: Average packet latency for the three networks

The packet inter-arrival time (jitter) in the three networks is shown in Figure 4.14. Again the Optimised grids network has superior performance with 55% less jitter than the Equal grids and COTS networks.

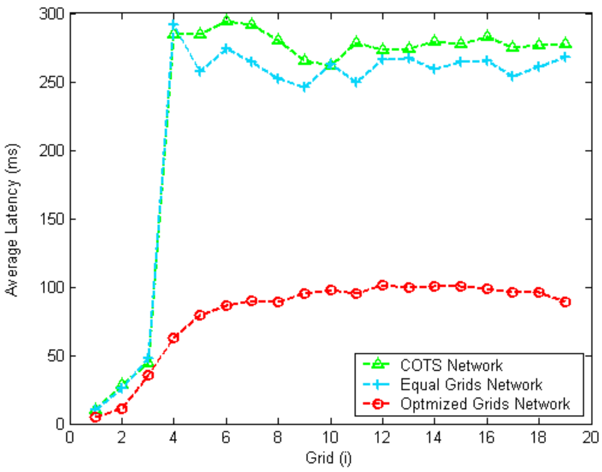

Figure 4.14: Average Jitter for the three networks

4.3.2 Cluster Head Node Energy Utilization: The second set of results focus on the energy use including the transmit, receive, idle, and total energy consumption. I compared the energy used by the cluster header nodes of the Optimised grids, Equal grids and COTS networks. I also examined the energy use of equivalent theoretical models of the three networks (the theoretical models depict an ideal situation where there are no packet collisions, re-transmission, overhearing and 100% message delivery).

Figure 4.15 shows the theoretical transmission energy consumption of the three networks. It can be seen that the energy use is balanced better among the cluster head nodes in the Optimised grids network compared to the COTS and Equal grids networks (where the cluster head nodes near the base station consume nearly twice the energy of the equivalent Optimised grids cluster head nodes). The COTS network consumes the most energy. The reason is that the COTS network has a fixed longer transmission distance as these products do not have variable transmission range and use more energy. Its transmission distance is not based on the grid size as compared to Equal grids and Optimised grids network. Thus if the grid size becomes smaller, they will still be spending the same amount of energy for a shorter distance. When the grid size is increased and becomes longer than their transmission range, they cannot be included in the simulation for comparison.

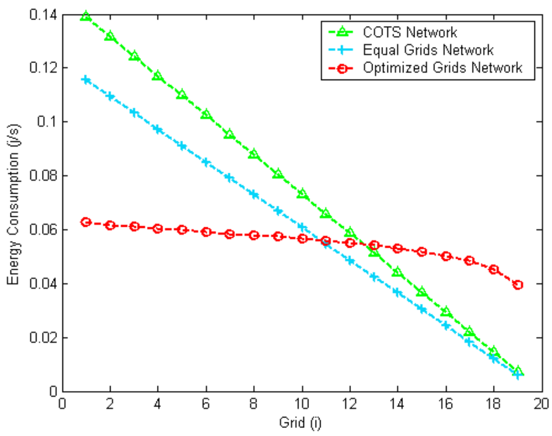

Figure 4.15: Theoretical transmission energy consumption.

The enhanced NS2 simulations generated an average transmission energy consumption results for the three networks, as shown in Figure 4.16. In the Optimised grids network the cluster head of grid 1 consumes 43.5 % and 32.4% less transmission energy than the equivalent nodes in the COTS network and Equal grids networks respectively. The transmit energy values for Optimised grids network (which averages 93% throughput) are very close to the theoretical values. However the results for the COTS and the Equal grids network (which average about 75% throughput) show lower consumption compared to the theoretical values, particularly for cluster head nodes nearer the base station. Fig 4.16 also show that small peaks for grid 5 and 7 for the Equal grids and COTS network. The peaks represent that these nodes are consuming a lot of energy, while they keep on transmitting messages and grids 4 and 6 spend more time receiving the messages, hence consume less energy. Simulation analysis shows that collisions are taking place at this point as the network is highly congested for both these networks. This also explains, beyond that point, the throughput for these grids is lower as compared to Optimised grids network as shown in Figure 4.12.

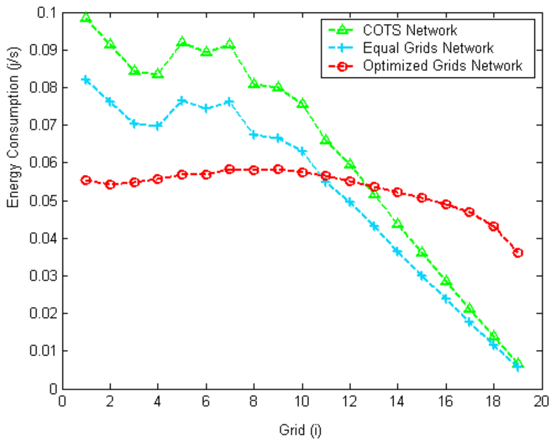

Figure 4.16: Simulated transmission energy consumption

Similarly, the enhanced NS2 simulations were used to derive the reception energy used by the cluster header nodes, as shown in Figure 4.17. This shows that the receive energy consumption in the Optimised grids network is up to 33% lower than that in the Equal grids and COTs networks. Recall that in the symmetric COTS and Equal grids networks, the cluster head node in grid (i+2) can overhear messages from cluster head node in grid (i). Note that the case of cluster header nodes near the base station (i.e. cluster header nodes 1 and 2) the reception energy is much reduced as the base station does not source or forward data.

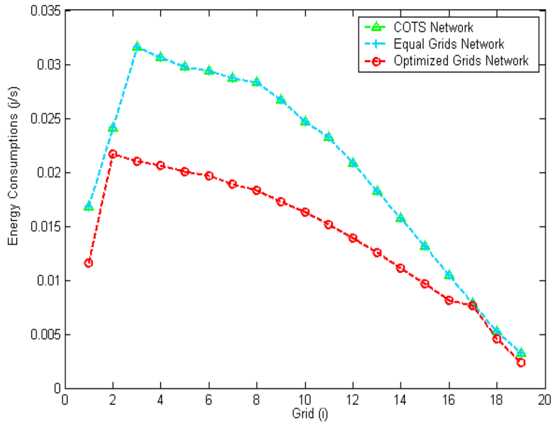

Figure 4.17: Receive energy consumption

Figure 4.18 shows the idle energy consumption for the three networks. It can be seen that as the traffic approaches the base station the nodes become more active and hence the idle energy consumption starts to decrease. The Optimised grids network has more idle energy consumption compared to the COTS and Equal grids as it is more efficient in transmitting and receiving data and hence has more times for the nodes to stay idle.

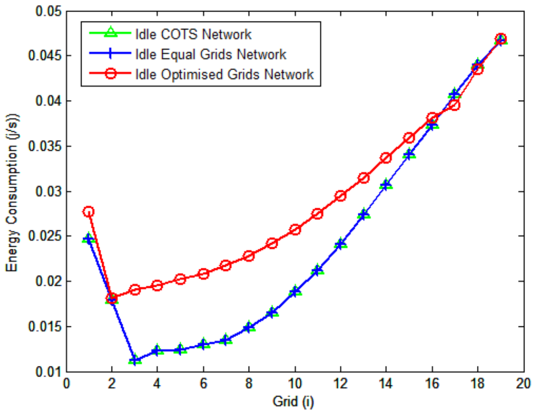

Figure 4.18: Idle energy consumption

The total cluster head energy consumption was also compared including idle, receive, and transmission energies. The enhanced NS2 simulations of the COTS, Equal grids and Optimised grids networks, Figure 4.19, show that in the COTS and Equal grids suffer from congestion in grids toward the base station is reflected in the total energy graphs, where the small peaks and troughs occur because some nodes are spending time re-transmitting messages, while their neighbouring nodes are too busy receiving useful as well as redundant messages.

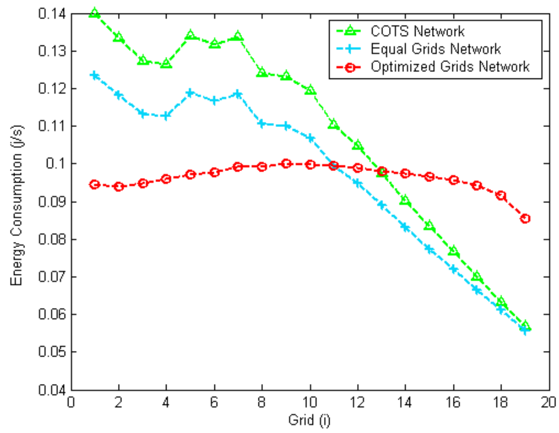

Figure 4.19: Actual total energy consumption

In contrast, the Optimised grids network, the cluster head energy use is better balanced due to energy efficient grid sizing (even though the receive energy saved by good spatial reuse was consumed by the increase idle state). Therefore in the Optimised grids network the lifetime of the cluster head nodes can be improved by at least 30% and 50% respectively compared with the best case where equal radio range and commercial off the shelf (COTS) systems are used. Implementing the Optimised grid spacing would further improve protocols such as SPAN, LEACH and SMAC.

Another important issue is to look at is the total time spent by the cluster head nodes in tranceiving data and remaining in idle state. This will allow me to see if the theory can be further improved to increase the cluster-head lifetime and also in general to improve the network lifetime.

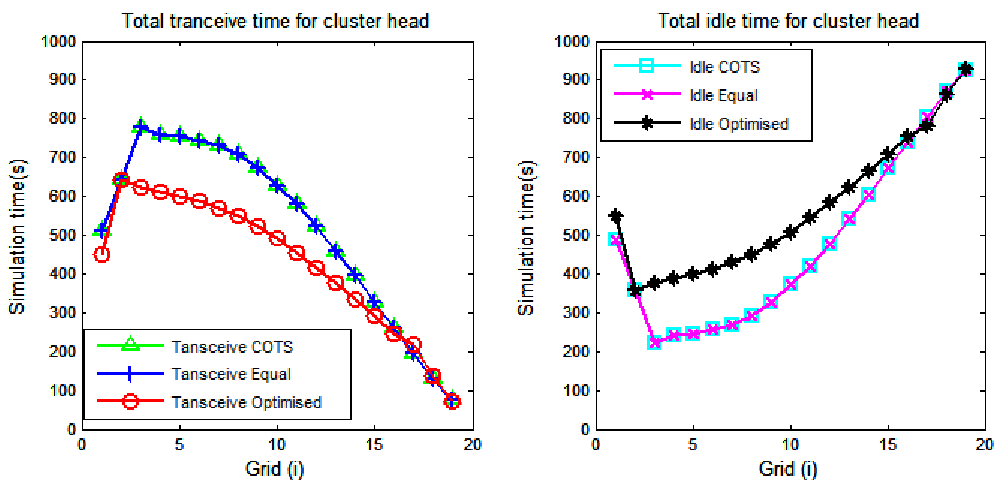

Figure 4.20: Comparison of cluster head transceiver time and idle time

Figure 4.20 shows two graphs, the LHS graph shows that as the cluster head traffic approaches the base station, the clusters spend more time in transmitting and receiving data. This is also proven by the RHS graph that the idle time for the cluster head decreases as the traffic approached the base station. The cluster head nodes in all the three networks remain idle for average of 92% of the time in the furthest grid (19). In the Optimised grids network the cluster head node of grid (2) spends 36% of the total simulation time in idle state and 64% of the time transmitting and receiving data. The cluster head node of grid (3) of COTS and Equal grids network spend 23% of total simulation time in idle state and 77% of the simulation time in transmitting and receiving data.

4.3.3 Cluster Header Life and Total Network Lifetime

Assuming cluster head rotation within each grid, I now compare the simulated total network lifetime (i.e. the time until the loss, due to energy depletion, of the cluster head store-and-forward backbone of the network) for the three networks. I assume a simple model in which each node is powered by a pair of Lithium Ion 1.5V batteries with a combined recoverable power of 32.4 kJ before reaching the minimum of 2.1 volts needed to run the transceiver. Note that particular care is required when determining the network lifetime of non-equal grids networks, because the network lifetime is not directly linked to cluster header life. The COTS and Equal grids network have a constant number of nodes in each grid. However, in the Optimised grids network, as the grid nearer the base station decrease in size, the number of nodes in each grid also decreases, and therefore there are fewer nodes among which the cluster head can rotate. As it has already been demonstrated, in the Optimised grids network it is these small grids which deliver more traffic with better QoS than the equivalent (larger) grids in the Equal grids and COTS networks. This raises the interesting question of whether this increase in performance and QoS has been at the expense of grid and network lifetime.

The enhanced NS2 simulated cluster header life for each of the grids is shown in the RHS graph of Figure 4.21.The LHS graph shows the theoretical cluster head life for the three networks. In each case it is the grid adjacent to the base station that has the shortest life. The shortest theoretical cluster head lifetime for the Optimised grids network is 50% more than that of Equal grids network and 76% more compared to the COTS network. In the simulated cluster head graph on RHS in Figure 4.19, the Optimised grids network lifetime is 31% more than the Equal grids network and 48% more than that of COTS network. Clearly from previous Figures 4.8 & 4.9 it can be seen that Optimised grids network has higher throughput compared to the other two networks and the cluster head lifetimes are much closer to theoretical values. The other two networks have lower throughput and hence their cluster head life increases compared to theoretical values.

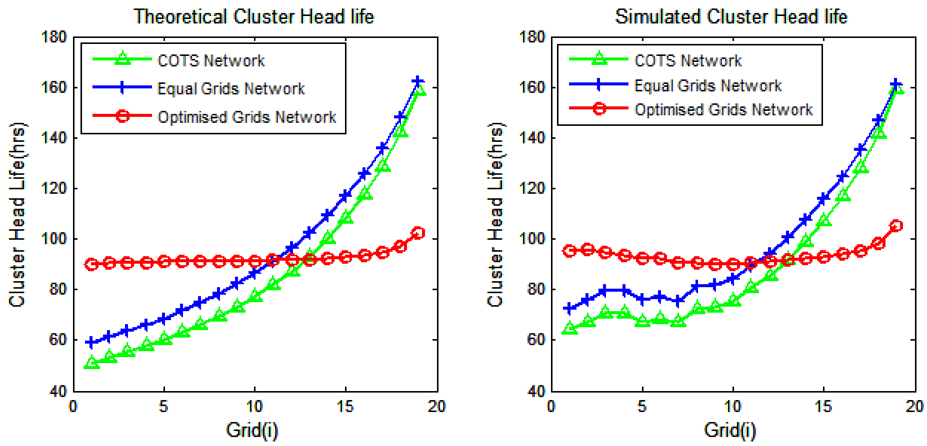

Figure 4.21: Theoretical and simulated cluster header lifetime

Figure 4.22 shows the theoretical and simulated grid life. In both the theoretical and simulated results, the grid nearest to the base station has the least life. In theoretical results the grid nearest to the base station for Optimised grids network has a lifetime of 283 hours while the Equal grids and COTS network have the grid lifetime of 266 hours and 230 hours respectively. Keeping in mind that the Equal grids network and COTS network do not have the same throughput as the Optimised grids network, the grid nearest to the base station in the simulated Optimised grids network, has the total life is 306 hours as compared to 327 hours for Equal grids network and 289 hours for COTS network.

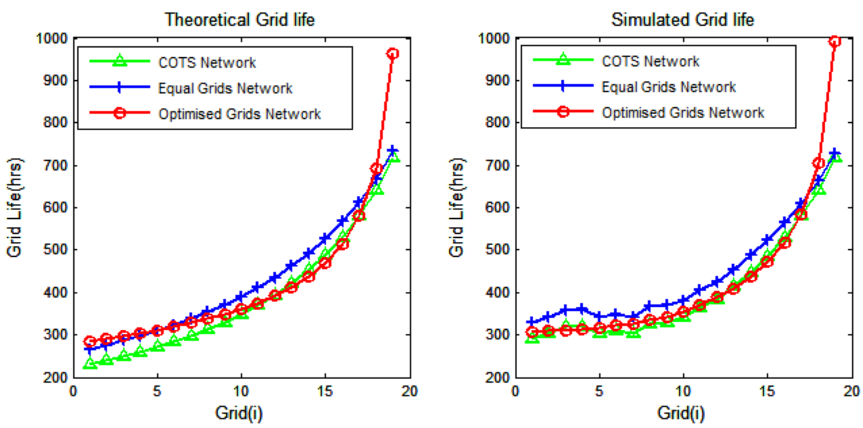

Figure 4.22: Theoretical and simulated Grid lifetime

Clearly the Optimised grid network's better quality of service at high levels of load, (throughput increased by 30%, latency reduced by an order of magnitude, jitter reduced by 30% compared to the equal range and COTS networks) has not been at the expense of network lifetime. The key question is whether the Optimised grid network holds its advantage at lower levels of sensor data traffic.

4.3.4 Energy & Throughput Analysis for 1kB and 2kB Message Size

In this section the size of packet transmitted from the cluster head nodes was changed from 1kB to 2 kB and the CBR timing values for all the three networks were doubled. This created the same amount of traffic for all the three networks but with half of the data packets. Keeping in mind that for one data packet sent there are 3 extra packets generated for RTS, CTS, ACK.

Figure 4.23 shows that when the message size is 2kB, the Equal grids and the COTS network use slightly more energy and also cause a crossover point between grid 4 and 6. This explains as the number of CTS/RTS/ACK requests is reduced, more packets can pass through as the network becomes less contentious and also less congested. This is also proved by measuring the throughput, for all the three networks, The COTS and Equal grids network has a 5% increase in network throughput, going from 75% to 80%. It can be seen that the energy consumption of the Optimised grids network drops and is again reflected by the throughput, that falls from 94% to 89%. Figure 4.24 show the throughput gain in the COTS network, while Figure 4.25 compares the drop in throughput caused by increasing the packet size from 1kB to 2kB.

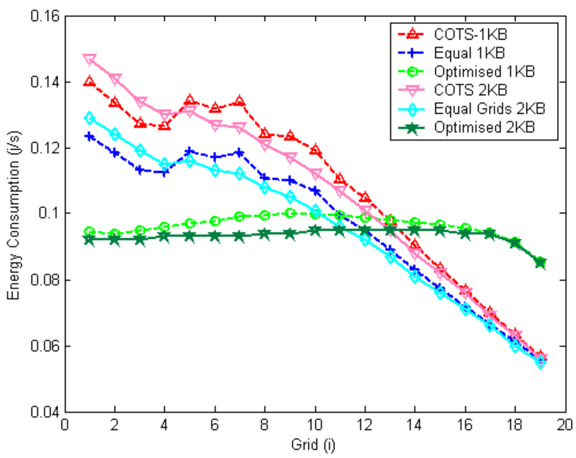

Figure 4.23 Energy comparison by replacing 1kB message with 2kB message

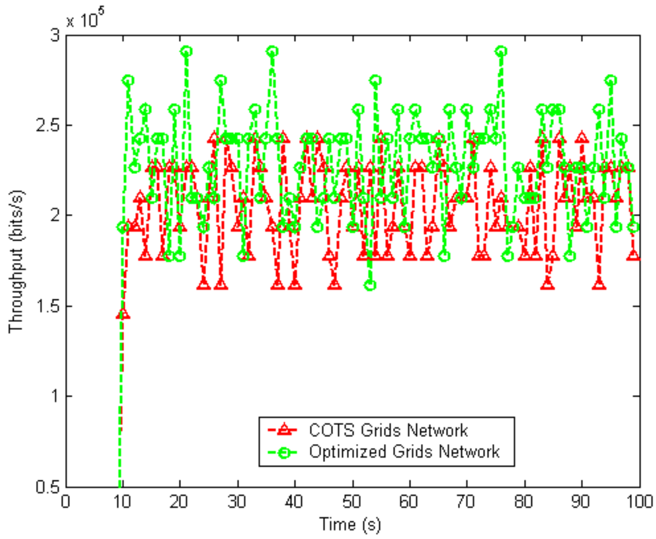

Figure 4.24 Throughput: Optimised grids compared with COTS using 2kB data packets

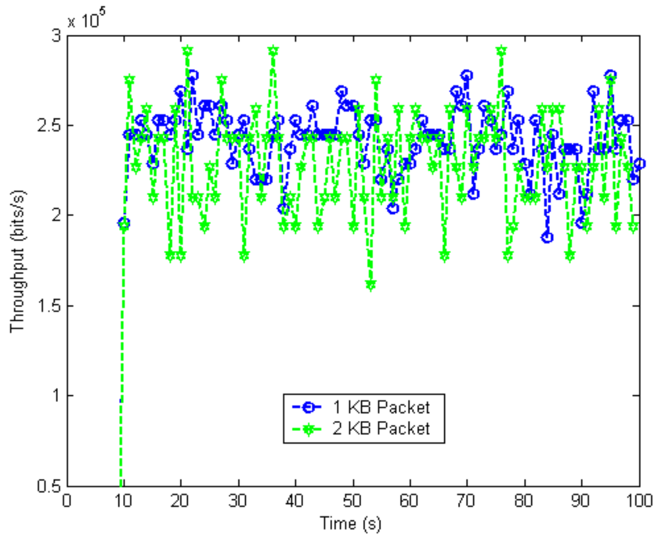

Figure 4.25 Difference in throughput by using 1kB and 2kB data packets for Optimised grids network

As the number of packets in the network has halved, the congestion has been significantly reduced because of the decrease in CTS, RTS and ACK packets that are sent for each data packet. The number of collisions has decreased for the COTS and Equal grids network, but for the Optimised grids network, the larger packet size has caused more delays in the middle of the network and packets are being dropped causing a decrease in throughput.

4.4 Network Behaviour at Higher and Lower Levels of Traffic

In section 4.2 and 4.3, a detailed packet level analysis was carried out to compare the network performance characteristics and network lifetime for the Optimised grids, Equal grids and COTS network. In this section further simulations were carried out to see the effects on sensor network throughput and lifetime by increasing the network traffic from 100% to 200% and also decreasing network traffic (from 100% to 75%, 50%, 25% and 10%). The key factor to realise is that in this section the network, length, node density and grid sizes are not changed. Only the number of packets transmitted from each cluster head is either increased or reduced.

4.4.1 Increasing the Network Traffic to 200%

In the simulation setup described in section 4.2, the CBR setting where modified according to Table 4-4 to accommodate for higher traffic in the network. The traffic produced by each node was increased from 0.003 Erlang to 0.006 Erlang. This caused the network to reach its peak operating level near the base station. By using equation (4.16) the maximum traffic approaching the base station is given below

(600-0)*0.143*0.006 = 0.5148 Erlang = 514800 Mbits/s.

Where 600 is the total network length, 0.143 is the node density and 0.006 Erlang traffic is generated by each node in the network. The network bandwidth is set to 1Mbits/s, therefore the total traffic transmitted by the cluster head node nearest to the base station will 514800 bits/s. Thus node nearest to the base station will be either in transmit or receive state. Table 4.4 shows the NS2 parameters setup for traffic generation for COTS Equal grids and Optimised grids network.

As the Optimised grids network has non-uniform grid size, the cluster heads near the base station have lower grid traffic to generate compared to the nodes that are furthest away. Therefore the Optimised grids network has individual CBR setting for each of the cluster head and is different as compared to COTS and Equal grids network that have uniform size grids and each cluster head produces the same amount of grid traffic anywhere in the network.

Table 4-4 CBR Setting for Three Networks with 0.006 Erlang Traffic per Node

Optimised Grids CBR Timings				COTS & Equal Grids CBR Timings			
Grid (i)	Grid Size (m)	Traffic Packets/s	CBR Time (s)	Grid (i)	Grid Size (m)	Traffic Packets/s	CBR Time (s)
1	22	2.4	0.42	1	31.58	3.4	0.295
2	22.5	2.4	0.41	2	31.58	3.4	0.295
3	22.9	2.5	0.41	3	31.58	3.4	0.295
4	23.4	2.5	0.40	4	31.58	3.4	0.295
5	23.9	2.6	0.39	5	31.58	3.4	0.295
6	24.5	2.6	0.38	6	31.58	3.4	0.295
7	25.1	2.7	0.37	7	31.58	3.4	0.295
8	25.9	2.8	0.36	8	31.58	3.4	0.295
9	26.7	2.9	0.35	9	31.58	3.4	0.295
10	27.6	3.0	0.34	10	31.58	3.4	0.295
11	28.6	3.1	0.33	11	31.58	3.4	0.295
12	29.9	3.2	0.31	12	31.58	3.4	0.295
13	31.3	3.4	0.30	13	31.58	3.4	0.295
14	33.1	3.5	0.28	14	31.58	3.4	0.295
15	35.4	3.8	0.26	15	31.58	3.4	0.295
16	38.4	4.1	0.24	16	31.58	3.4	0.295
17	42.8	4.6	0.22	17	31.58	3.4	0.295
18	50.1	5.4	0.19	18	31.58	3.4	0.295
19	65.9	7.1	0.14	19	31.58	3.4	0.295

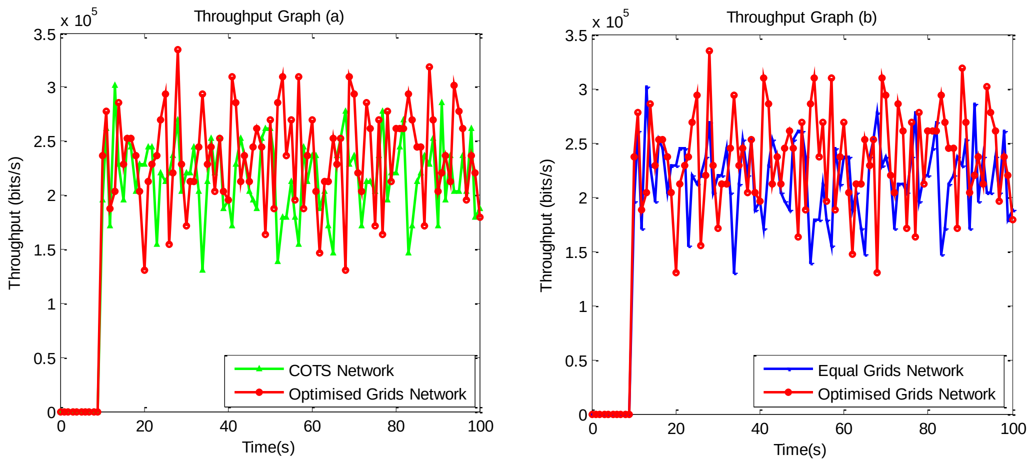

Figure 4.26 Throughput: Optimised grid compared with COTS and Equal grids networks with 200% Traffic

Figure 4.26 show that the throughput for the Optimised grids network is slightly higher compared to the other two networks. The average throughput for the first 90 seconds for the Optimised grids network is 236461 bits/s as compared to 217451 bits/s for Equal grids and 216482 bits/s for COTS network. Optimised grids network has approximately 8% more throughput than Equal grids and COTS network. All the three networks suffer from packet loss as the theoretical throughput should be somewhere near 514800 bits/s.

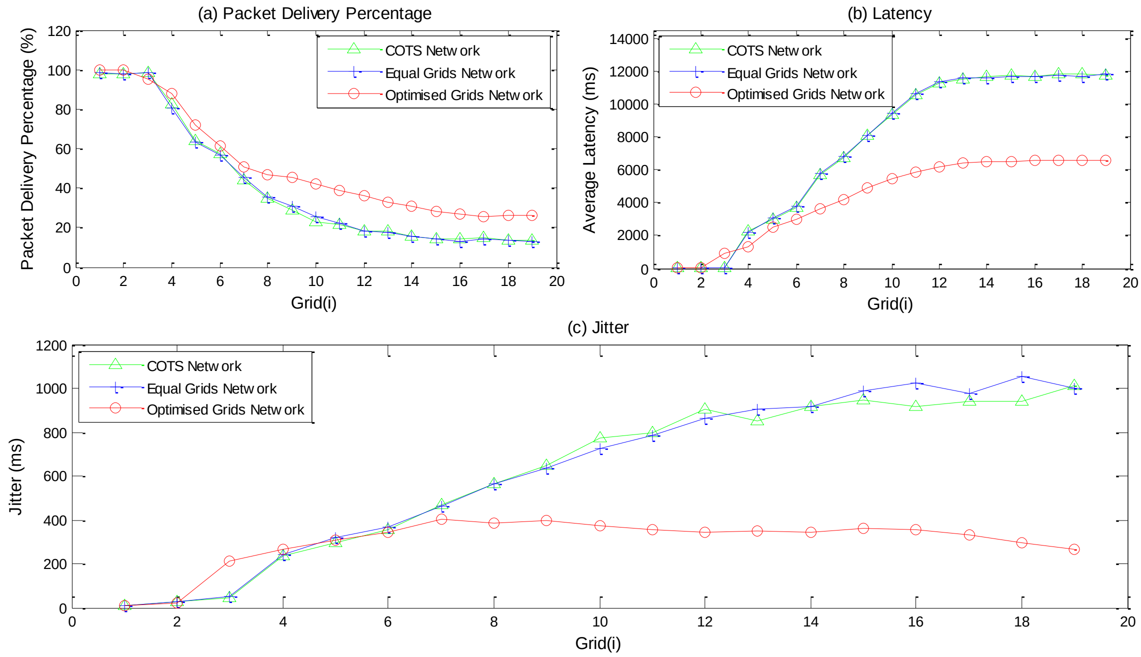

Figure 4.27 Packet Delivery, Average Latency and Jitter Graphs for 200% Network Traffic

Figure 4.27 show the actual network performance characteristics for all the three networks as the traffic is increased to 200%. Figure 4.27 (a) shows that all the three networks have nearly 100% delivery rate for the first three grids and then its starts to fall with last cluster head node for the Optimised grids network only having packet delivery rate of 26% and around 13% for Equal grids and COTS network. Figure 4.27 b shows the average latency for the three networks. The COTS and Equal grids network has nearly twice as much packet delay time from cluster head node 12-19 as compared to Optimised grids network. It can be seen from Table-4.4 that for all the three networks, the cluster head in each grid is generating a minimum of 2 packets per seconds. For the cluster head nodes that are furthest away, the latency is about 6 seconds for the Optimised grids network and around 12 seconds for Equal grids and COTS network. Therefore throughout the network channel, the nodes are dropping packets as more and more packets are being sent from previous grids that the nodes nearer to the base station cannot forward. This results in a lower throughput for all three networks as compared to theoretical values.

Figure 4.28 shows the theoretical and simulated cluster head energy consumption per second for all the three networks. The theoretical values show the ideal conditions when all the packets are delivered to the base station with no collisions or latency, however the simulated values are quite different. The graphs show that the grids furthest away from the network are transmitting and receiving all the packets and the theoretical and simulated energy consumptions values are nearly same. As the traffic goes beyond the midpoint, this is where failure starts to occur in all three networks. The channel starts to get congested and cluster heads start to drop packets that are required to be forwarded from previous grids toward the base station. In the COTS and Equal grids network, again the peak and troughs indicate that some nodes are only transmitting while others are only receiving data. The Optimised grids network shows that the cluster head nodes away from the base station are transmitting and receiving 100% of the packets, however from grid 17 and moving toward the base station, the energy consumption decreases, as cluster head nodes are sending more RTS/CTS messages and are trying to find an empty slots to send their packets, hence the throughput falls greatly and is below 50%.

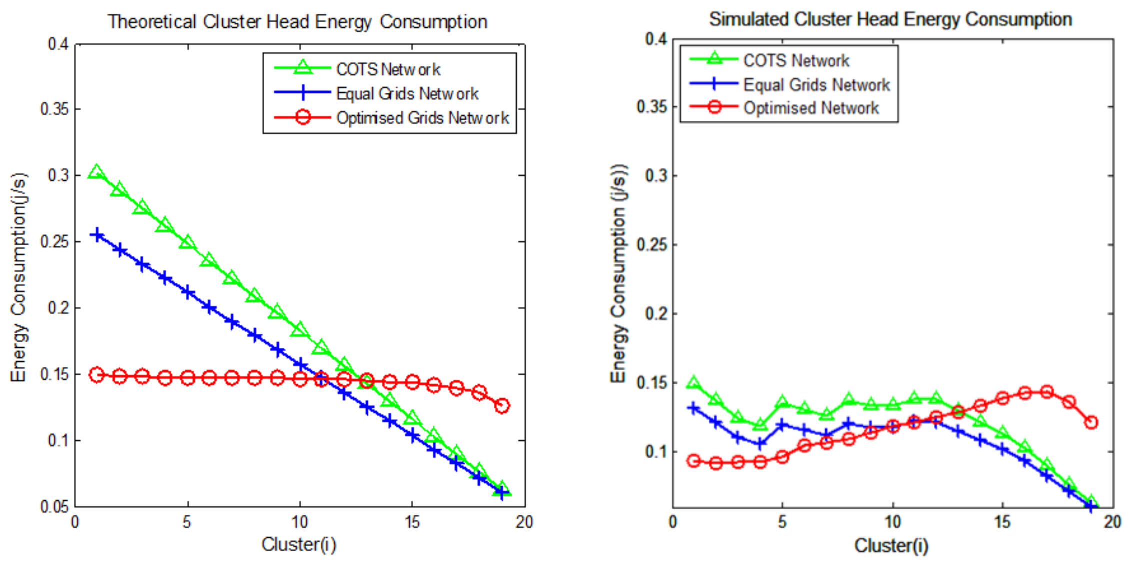

Figure 4.28 Theoretical and simulated cluster head energy consumption per second for 200% Traffic.

This causes the cluster heads to save energy by not transmitting packets from previous grids. The nodes near the base station are consuming less transmission energy, and that is reflected in the simulated cluster head energy consumption graph in Figure 4.28.

The cluster head lifetime of the nodes near to the base station is also higher in simulated network as compared to theoretical values because of the lack of delivery of all the packets from previous grids in the network as shown in Figure 4.29.

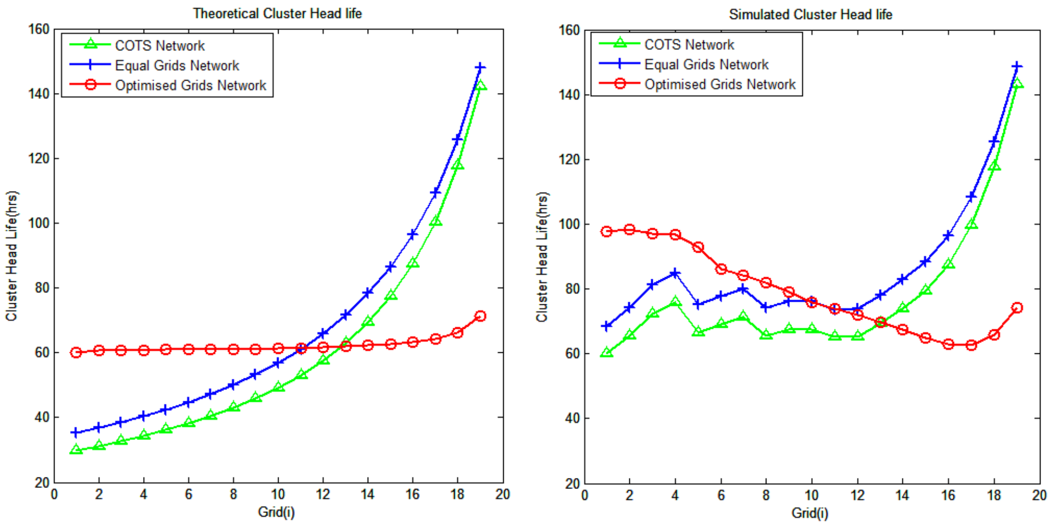

Figure 4.29 Theoretical and simulated cluster head life.

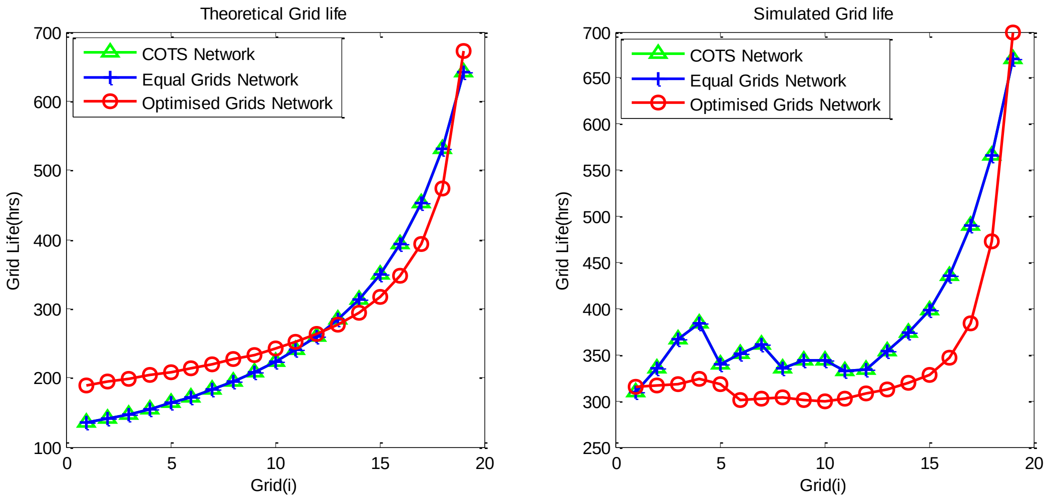

Figure 4.30 Theoretical and simulated network lifetime with 200% network traffic

The same characteristics are shown in total network lifetime graphs (Figure 4.30). In theory the Optimised grids network has 20% more lifetime than the Equal grids network and 41% more network lifetime compared to the COTS network before the first cluster head dies.

In the simulated traffic, the COTS grid and Equal grids network shows higher node lifetime because they have less packet delivery, and are saving on transmission energy. The Optimised grids node nearest to the base station in the simulated network has 2% more network lifetime compared with the two networks.

Overall the Optimised grids network has 8% higher throughput, half the latency and 80% less jitter as compared with the other two networks at higher traffic loads.

4.4.2 Decreasing the Network Traffic to 75%

To achieve a 25% reduction in traffic, the data transmitted from each node was reduced from 0.003 Erlang to 0.00225. The modified CBR values are shown in Table 4-5 to accommodate for lower traffic in the network. The total traffic reaching the base station was calculated as (600-0)*0.143*0.00225 = 0.19305 Erlangs = 193050 bits/s.

Table 4-5 CBR Setting for Three Networks with 0.00225 Erlangs Traffic per Node

	Optimised Grids CBR Timings				COTS & Equal Grids CBR Timings		
Grid	Grid Size	Traffic	CBR Time	Grid	Grid Size	Traffic	CBR Time
(i)	(m)	Packets/s	(s)	(i)	(m)	Packets/s	(s)
1	22	0.9	1.13	1	31.58	1.3	0.787
2	22.5	0.9	1.11	2	31.58	1.3	0.787
3	22.9	0.9	1.09	3	31.58	1.3	0.787
4	23.4	0.9	1.06	4	31.58	1.3	0.787
5	23.9	1.0	1.04	5	31.58	1.3	0.787
6	24.5	1.0	1.01	6	31.58	1.3	0.787
7	25.1	1.0	0.99	7	31.58	1.3	0.787
8	25.9	1.0	0.96	8	31.58	1.3	0.787
9	26.7	1.1	0.93	9	31.58	1.3	0.787
10	27.6	1.1	0.90	10	31.58	1.3	0.787
11	28.6	1.2	0.87	11	31.58	1.3	0.787
12	29.9	1.2	0.83	12	31.58	1.3	0.787
13	31.3	1.3	0.79	13	31.58	1.3	0.787
14	33.1	1.3	0.75	14	31.58	1.3	0.787
15	35.4	1.4	0.70	15	31.58	1.3	0.787
16	38.4	1.5	0.65	16	31.58	1.3	0.787
17	42.8	1.7	0.58	17	31.58	1.3	0.787
18	50.1	2.0	0.50	18	31.58	1.3	0.787
19	65.9	2.7	0.38	19	31.58	1.3	0.787

Where 600 is the total network length, 0.143 is the node density and 0.00225 Erlang traffic is generated by each node in the network. The network bandwidth is set to 1Mbits/s, therefore the total traffic that approaches the cluster head node (including its own packets) nearest to the base station will be 193050 bits/s.

Figure 4.31 shows the throughput for all the three networks. As the traffic is lowered the Equal grids and COTS network show an average throughput of 193509 bits/s while the Optimised grids network has an average throughput of 19548 bits/s.

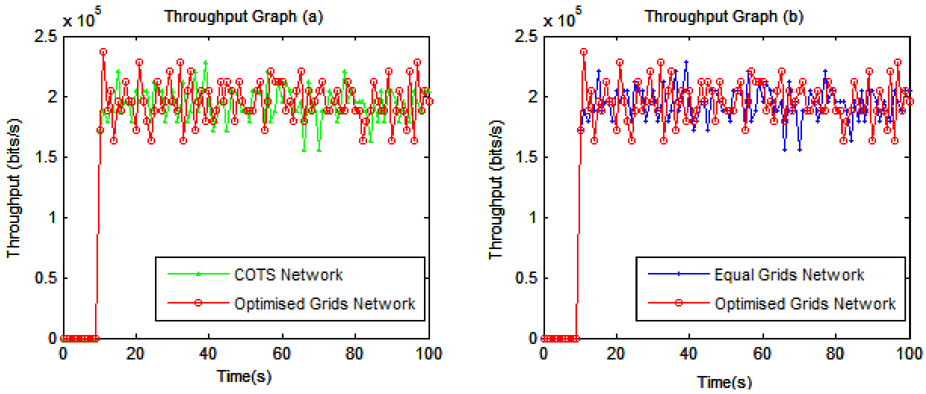

Figure 4.31 Throughput: Optimised grids compared with COTS and Equal grids networks with 75% Traffic

Figure 4.32(a) shows that the packet delivery for the Optimised grids network is still higher as compared to the other two networks, even though all the three networks have packet delivery above 95%. As the network now has much low traffic compared to its full capacity, the latency values (Figure 4.32b) for COTS and Equal grids network have considerably dropped from around 3000ms (Figure 4.13) to about 300ms for cluster head nodes furthest from the base station as compared to Optimised grids network where the latency values have dropped just under half. But the Optimised grids network already had a lower latency value compared to the other two nodes during 100% traffic (Figure 4.13).

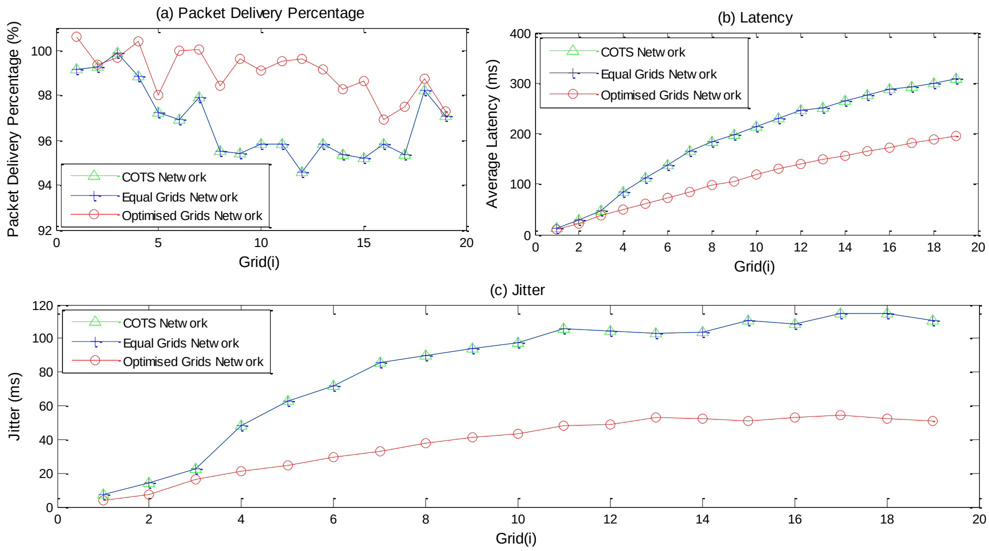

Figure 4.32 Packet Delivery, Average Latency and Jitter Graphs for 75% Network Traffic

Comparing at 75% traffic load, the Optimised grids network still has only half the latency value as compared to the other two networks for cluster head nodes furthest away from the base station. The packet delivery fluctuates as some nodes spend more time in transmitting the received packets and hence packets get lost. The jitter (Figure 4.32c) for all the three networks have also reduced to half as that compared to Figure 4.14, where the network had 100% traffic.

Figure 4.33(a) &(b) shows the tranceive and idle time for all the three networks for the first 1000 seconds of the simulation. The cluster head nodes nearest to the base station for the Equal grids and COTS network spend approx. 25% more time transmitting and receiving data as compared to the Optimised grids network. This shows that the Optimised grids network is highly efficient in transmitting and receiving data due to spatial re-usability and also has maximum throughput.

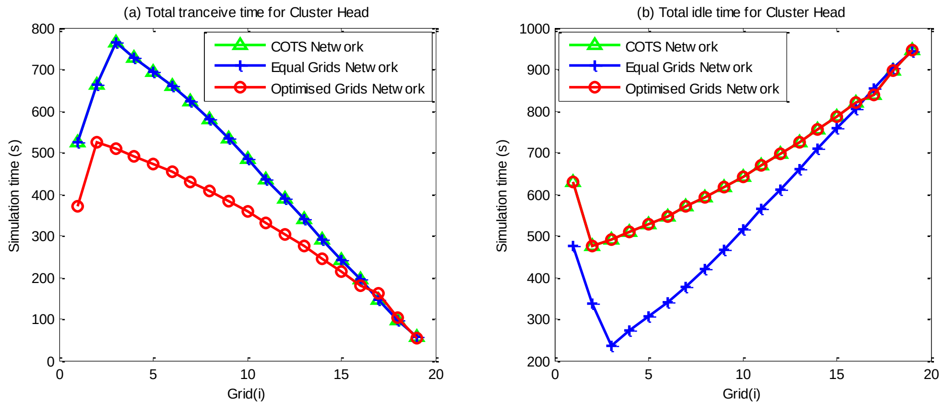

Figure 4.33 Comparison of cluster head trancieve time and idle time for 75% traffic

But as the cluster head nodes move away from the base station, the idle time starts to dominate. This results in idle energy being consumed and that is highly evident for nodes that are furthest away from the base station.

Figure 4.34 shows the simulated energy consumption for all the three networks. As the traffic load is only 20% of the network bandwidth, the Equal grids and the COTS network show a linear energy consumption througout the network with nodes nearest the base station consuming twice as much energy compared to nodes furthest away. Again the Optimised grids network has cleverly balanced the energy consumption for all all the cluster head nodes throughout the network. The cluster head node of Optmised grid 1 is consuming 33% and 49% less energy compared to the same nodes in the Equal grids & COTS network.

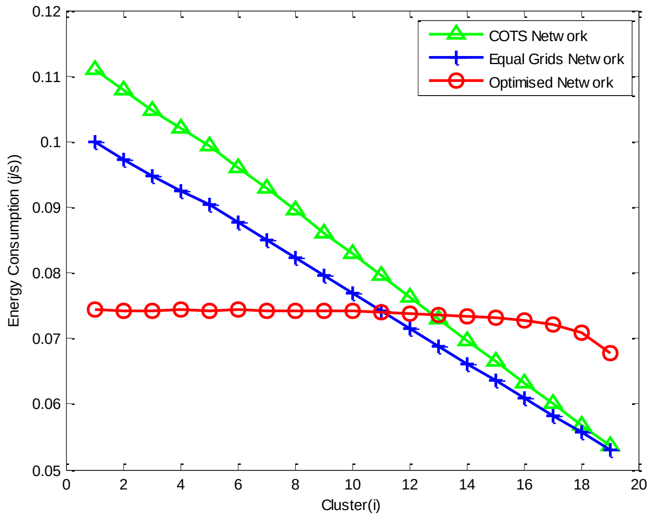

Figure 4.34 Simulated cluster head energy consumption per second for 75% traffic.

The total first grid life for the Optimised grids network and the Equal grids network is 328 hrs (Figure 4.35b as compared to COTS network, that has grid life of 290 hrs. A point to remember is that the Equal grids network have constant grid size. The grids nearest to the base station are larger than that of Optmised grids network and thus have more nodes for cluster head rotation. This results in improved network lifetime for the Equal grids network. As the network traffic becomes lower the idle time increases, it is that idle time that causes the Equal grids network to live as long as the Optmised grids network, because it has more nodes to rotate.

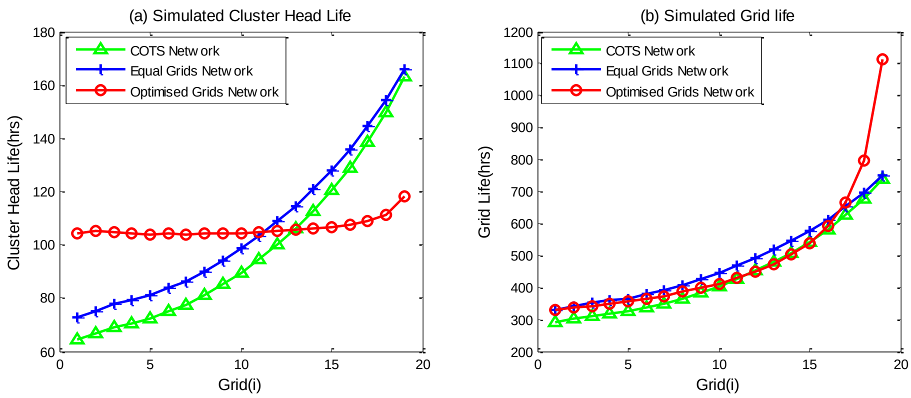

Figure 4.35 Simulated cluster head and network lifetime with 75% network traffic

4.4.3 Decreasing the Network Traffic to 50%, 25% and 10%

The next step involved in reducing the network traffic to 50%, 25% and 10% for all the three networks. Table 4-6 shows the packets transmitted by the cluster head nodes and the CBR timings for all the three networks.

At 50% reduction, the total traffic reaching the base station from each of the network was reduced to 128700 bits/s. For 25% and 10% reduction the total traffic reaching the base station was reduced to 64350 bit/s and 25740 bits/s. At lower traffic, the entire three networks achieve 100% throughput. The latency graph (4.36b) shows the inherent latency in the system that cannot be removed even if the traffic is lowered between 50% and 5%.

It shows the average time the packet takes to reach the base station from each grid via multi-hop routing. The jitter is packet inter-arrival time and is also same for all the three networks between 50% and 10% network traffic reduction.

Table 4-6 Packet Transmission Rate for Three Networks with 50%, 25% and 10% Traffic

	Optimised Grids Cluster Head Packet Transmission				COTS & Equal Grids Cluster Head Packet Transmission				
Grid	Grid Size	50% Traffic	25% Traffic	10% Traffic	Grid	Grid Size	50% Traffic	25% Traffic	10% Traffic
(i)	(m)	Packets/s	Packets/s	Packets/s	(i)	(m)	Packets/s	Packets/s	Packets/s
1	22	0.59	0.29	0.118	1	31.58	0.85	0.42	0.17
2	22.5	0.60	0.30	0.121	2	31.58	0.85	0.42	0.17
3	22.9	0.61	0.31	0.123	3	31.58	0.85	0.42	0.17
4	23.4	0.63	0.31	0.125	4	31.58	0.85	0.42	0.17
5	23.9	0.64	0.32	0.128	5	31.58	0.85	0.42	0.17
6	24.5	0.66	0.33	0.131	6	31.58	0.85	0.42	0.17
7	25.1	0.67	0.34	0.135	7	31.58	0.85	0.42	0.17
8	25.9	0.69	0.35	0.139	8	31.58	0.85	0.42	0.17
9	26.7	0.72	0.36	0.143	9	31.58	0.85	0.42	0.17
10	27.6	0.74	0.37	0.148	10	31.58	0.85	0.42	0.17
11	28.6	0.77	0.38	0.153	11	31.58	0.85	0.42	0.17
12	29.9	0.80	0.40	0.160	12	31.58	0.85	0.42	0.17
13	31.3	0.84	0.42	0.168	13	31.58	0.85	0.42	0.17
14	33.1	0.89	0.44	0.177	14	31.58	0.85	0.42	0.17
15	35.4	0.95	0.47	0.190	15	31.58	0.85	0.42	0.17
16	38.4	1.03	0.51	0.206	16	31.58	0.85	0.42	0.17
17	42.8	1.15	0.57	0.230	17	31.58	0.85	0.42	0.17
18	50.1	1.34	0.67	0.269	18	31.58	0.85	0.42	0.17
19	65.9	1.77	0.88	0.353	19	31.58	0.85	0.42	0.17
			Total packets per second transmitted from for each network						
		16.09	8.04	3.218			16.09	8.04	3.22

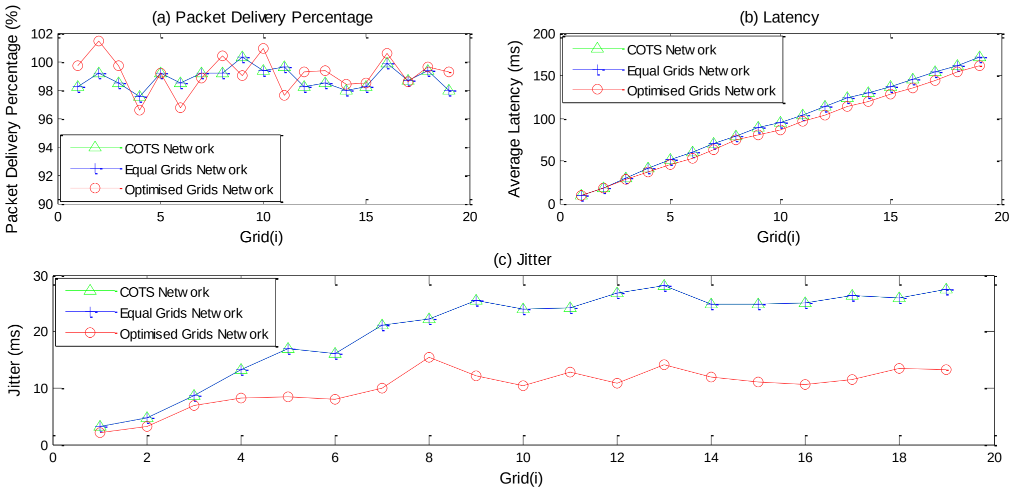

Figure 4.36 Packet Delivery, Average Latency and Jitter Graphs for Lower Network Traffic

At lower traffic, the idle energy becomes very dominant and it can be seen that during 10% network traffic (Figure 4.37), the maximum transceiver time spent by the busiest cluster head node is only 11% for COTS and Equal grids network only 7.5% for the Optimised grids network during the total simulation time of 1000 seconds. The idle energy consumption greatly decreases network lifetime for all the three networks.

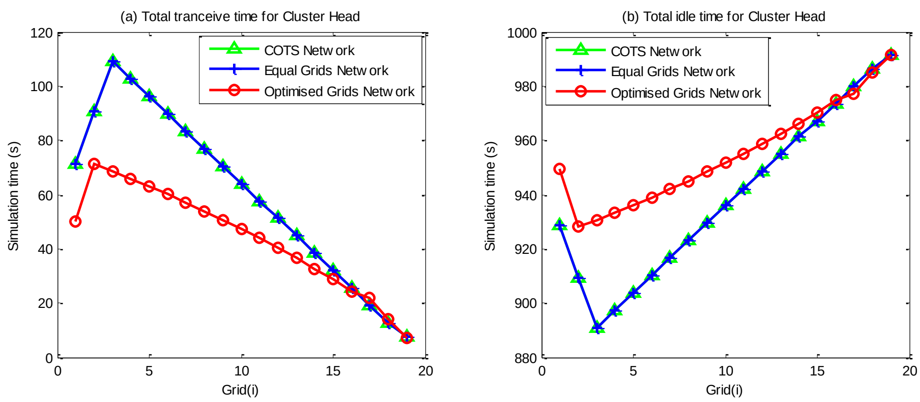

Figure 4.37 Comparison of cluster head transceiver time and idle time for 10% network traffic

Figure 4.38 and 4.39 show the cluster head and network lifetime for all the three networks. As always the cluster head life in both the 50% case and 10% case is much higher as

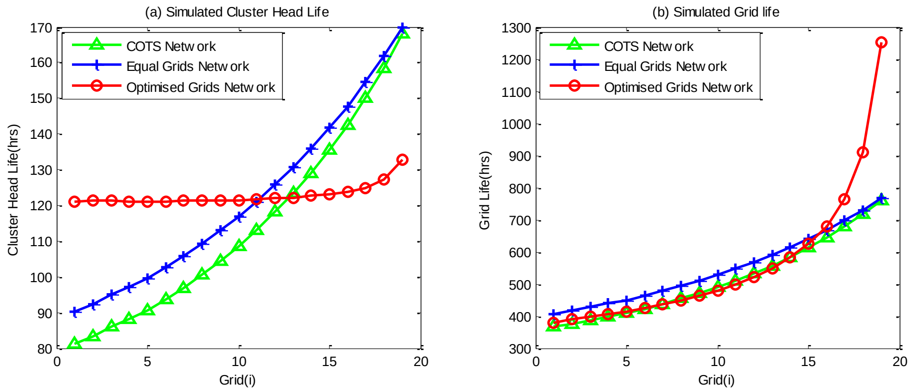

Figure 4.38 Simulated cluster head and network lifetime with 50% network traffic

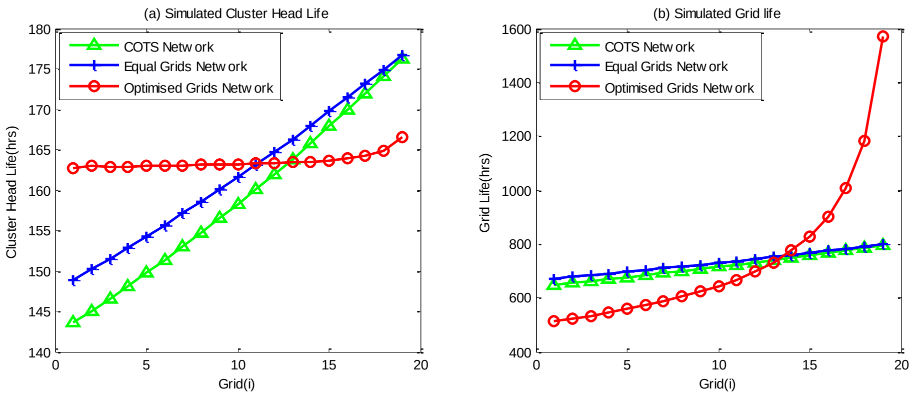

Figure 4.39 Simulated cluster head and network lifetime with 10% network traffic

compared to the Equal grids and COTS network, but the total network lifetime for the Equal grids network is higher during 50%, 25% and 10% traffic load.

The main reason for that is that the idle energy becomes dominant, and during lower network traffic, the nodes remain idle for over 90% of time. The COTS and Equal grids network have more nodes compared to Optimised grids network, and hence, there is more node rotation which causes the grid to live longer.

At lower traffic, below 75%, the Optimised grids network has the least lifetime compared to the other two networks. The whole benefit of Optimised grids network can only be realised if the grid size changes dynamically as the traffic in the network increases or decreases. The next section will show what happens to network lifetime if the Optimised grids are dynamically changed based on network traffic.

4.5 Dynamic-Optimisation of the Networks with Fluctuating Traffic Loads

Section 4.4 described the behaviour of the COTS, Equal grids and Optimised grids network with higher and lower levels of traffic without changing the grid sizes when the traffic became lower. This section studies the effects the network quality features as well as the cluster head and grid life by re-calculating the grid sizes depending on the increased or decreased levels of traffic. This term is referred as ‘Dynamic’. The network length and node density parameters are not changed, only a new grid size is calculated to re-optimise (dynamic) the Optimised grids network.

4.5.1 Dynamic Network with 200% Traffic Load

As the network traffic is doubled, equation (4-15), is used to calculate the Dynamic Optimised grids sizes for the Optimised grids network.

Table 4-7 Packet Transmission Rate for Dynamic grids with 200% Traffic

	Optimised Grids CBR Timings					COTS & Equal Grids CBR Timings		
Grid	Grid Size	Traffic	CBR Time		Grid	Grid Size	Traffic	CBR Time
(i)	(m)	Packets/s	(s)		(i)	(m)	Packets/s	(s)
1	15.6	1.7	0.60		1	22.2	2.4	0.42
2	15.8	1.7	0.59		2	22.2	2.4	0.42
3	16	1.7	0.58		3	22.2	2.4	0.42
4	16.2	1.7	0.58		4	22.2	2.4	0.42
5	16.5	1.8	0.57		5	22.2	2.4	0.42
6	16.7	1.8	0.56		6	22.2	2.4	0.42
7	17	1.8	0.55		7	22.2	2.4	0.42
8	17.3	1.9	0.54		8	22.2	2.4	0.42
9	17.6	1.9	0.53		9	22.2	2.4	0.42
10	18	1.9	0.52		10	22.2	2.4	0.42
11	18.3	2.0	0.51		11	22.2	2.4	0.42
12	18.7	2.0	0.50		12	22.2	2.4	0.42
13	19.2	2.1	0.49		13	22.2	2.4	0.42
14	19.7	2.1	0.47		14	22.2	2.4	0.42
15	20.2	2.2	0.46		15	22.2	2.4	0.42
16	20.8	2.2	0.45		16	22.2	2.4	0.42
17	21.5	2.3	0.43		17	22.2	2.4	0.42
18	22.2	2.4	0.42		18	22.2	2.4	0.42
19	23.1	2.5	0.40		19	22.2	2.4	0.42
20	24.2	2.60	0.39		20	22.2	2.4	0.42
21	25.4	2.72	0.37		21	22.2	2.4	0.42
22	27	2.90	0.35		22	22.2	2.4	0.42
23	29	3.11	0.32		23	22.2	2.4	0.42
24	31.8	3.41	0.29		24	22.2	2.4	0.42
25	36	3.86	0.26		25	22.2	2.4	0.42
26	43.8	4.70	0.21		26	22.2	2.4	0.42
27	32.4	3.47	0.29		27	22.2	2.4	0.42
	600	64.4				600.0	64.4	

Table 4-7 shows the new calculated grid size for the Dynamic Optimised grids network. It can be seen as the traffic increased to 200%, the number of grids has increased from 19 to 27. Hence the grids have become smaller in size to better handle the increased traffic. At this stage the COTS and Equal grids network is also divided into 27 grids so all the networks can be compared with and without optimisation (Section 4.4). By dividing the COTS and Equal grids network will also give a better understanding of network QoS parameters for all the three networks and a fair comparison. This could also show that some new QoS characteristics could possibly not have been visible if the network was not divided into more number of grids. As mentioned in previous section, the full benefit of Optimisation can only be achieved if the Optimised grids network is fully dynamic and re-configures the grid sizes, when the network traffic changes.

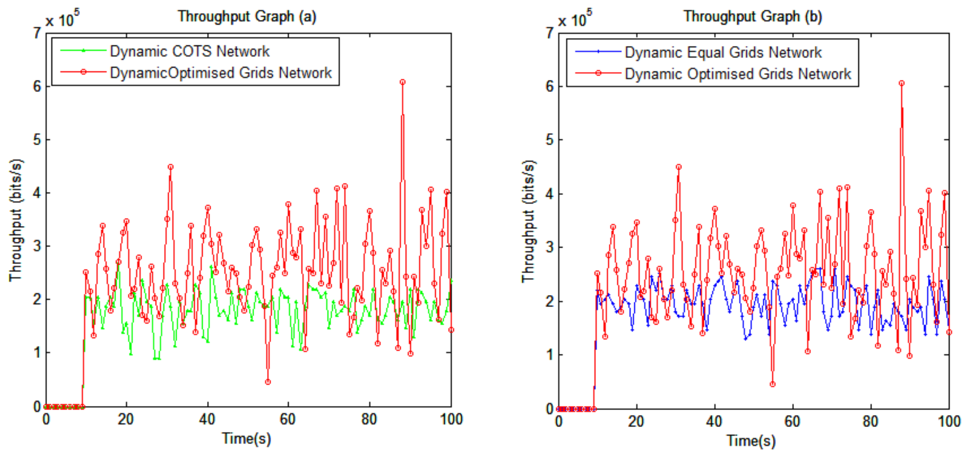

Figure 4.40 Throughput: Dynamic Optimised grids compared with Dynamic COTS and Dynamic Equal grids networks with 200% Traffic

A key point to remember is as the number of grids has increased, it means that the grids have become smaller, therefore the transmission distance for the cluster heads would have also decreased. On the other hand where the transmission distance has decreased, the number of grids transmitting packets has also increased, thus causing more congestion on the network. Figure 4.40 shows the maximum traffic reaching the base station from all the nodes in each network. The theoretical throughput value at 200% traffic is 514800 bits/s. The Dynamic Optimised grids network delivers an average throughput of 258175 bits/s, while the Dynamic Equal grids and Dynamic COTS network have an average throughput of 196647 bit/s and 183917 bits/s respectively. Thus Dynamic Optimised grids network has 31.3 % more throughput than the Dynamic Equal grids network and 40.4% more throughput than Dynamic COTS network. Comparing both the 200% traffic network from section 4.4.1 with the re-optimised grids network, the throughput for the Dynamic Optimised grids network has increased by 9.1% from 236461bits/s to 258175 bits/s. The network throughput for the other two networks has decreased.

Figure 4.41 compares the packet delivery, latency and jitter for 200% Dynamic networks. The packet delivery between cluster heads 5-15 has improved for the Dynamic Optimised grids network, while there has been little change for the other two networks. The latency values for the cluster head nodes furthest away from the base station has decreased by over 600% for Dynamic Optimised grids network and Dynamic COTS network and by 1100% for the Dynamic Equal grids network as compared to non-dynamic networks (Section 4.4, Figure 4.27). However the Dynamic Optimised grids network still has lower overall latency compared to the other two networks. The jitter have increased for all the three networks, the reason is that as the number of cluster heads have increased from 19 to 26,the number of packets that need to be delivered has also increased.

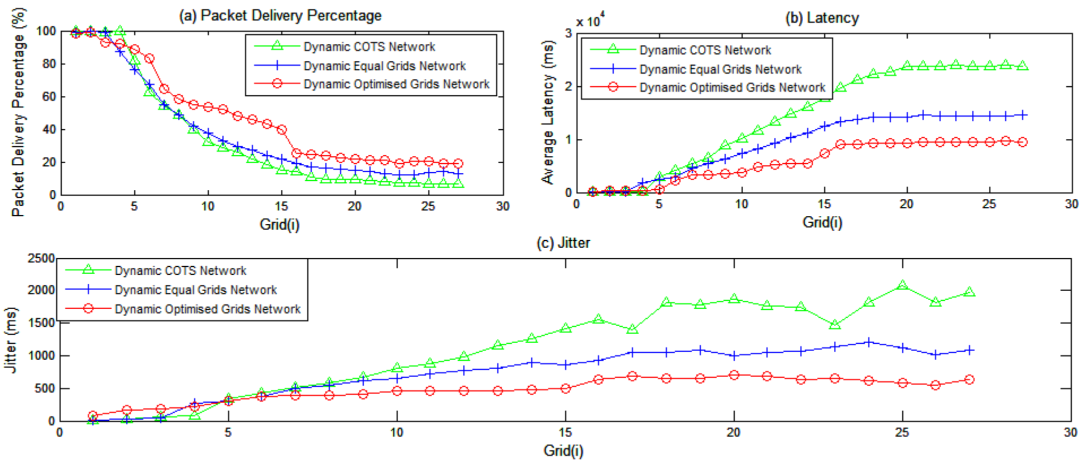

Figure 4.41 Packet Delivery, Average Latency and Jitter Graphs for 200% Dynamic Network Traffic

The cluster head lifetime (Figure 4.42a) and Grid life (Figure 4.42b) show a considerable improvement for all the three networks.

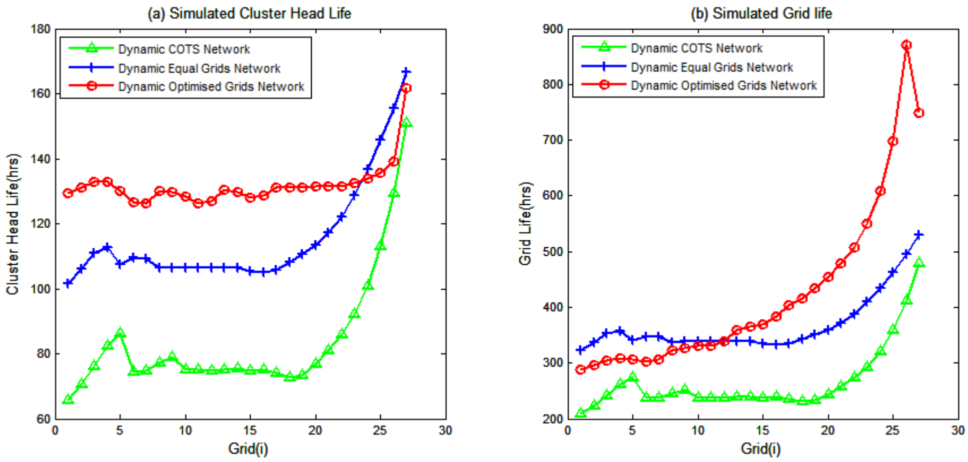

Figure 4.42 Simulated cluster head and network lifetime with 200% Dynamic network traffic

Comparing with section 4.4.1, 200% non-dynamic traffic graphs cluster life (Figure 4.28b) and Grid life (Figure 4.29b), the Dynamic cluster head life for the Optimised grids network has increased by 118% (node 17) for the cluster head node that dies first and 47% for Dynamic Equal grids network for the node that dies first. The increase in life has only been 8% for the cluster head node that dies first in the Dynamic COTS network.

The total network lifetime graphs show a 33% decrease in life for the Dynamic COTS network and around 3% decrease in life for the Dynamic Equal grids and Dynamic Optimised grids network. However the decrease in network lifetime for the Dynamic Optimised grids network has been due to a considerable increase in throughput and caused by increased expenditure during transmit energy. The key point to remember is that by adding dynamics to the networks, the latency figures have considerably improved for all the three networks and the throughput has increased by 9.1% for the Dynamic Optimised grids network. For the Dynamic COTS and Dynamic Equal grids network, throughput as well as network life has decreased when the traffic load has been increased.

4.5.2 Dynamic Networks with 75% Traffic Load

With 75% traffic, the grid number reduced from 19 to 17 as the grids became slightly bigger. Table 4-8 shows the grid sizes, traffic, packet generated per second by each grid and the CBR settings for the two networks (Dynamic Equal grids and Dynamic Optimised grids).

COTS network has been removed from this analysis as the typical range for COTS network is limited to 35m. As the network traffic becomes less, the number of Dynamic grids becomes lesser and the grid size starts to increase greater than 35m. In that case there no fixed transmission values that can be used for COTS network.

Table 4-8 Packet Transmission Rate for Dynamic grids with 75% Traffic

	Optimised Grids CBR Timings					COTS & Equal Grids CBR Timings		
Grid	Grid Size	Traffic	CBR Time		Grid	Grid Size	Traffic	CBR Time
(i)	(m)	Packets/s	(s)		(i)	(m)	Packets/s	(s)
1	25.4	1.02	0.98		1	35.3	1.4	0.70
2	26	1.05	0.96		2	35.3	1.4	0.70
3	26.6	1.07	0.93		3	35.3	1.4	0.70
4	27.3	1.10	0.91		4	35.3	1.4	0.70
5	28	1.13	0.89		5	35.3	1.4	0.70
6	28.9	1.16	0.86		6	35.3	1.4	0.70
7	29.8	1.20	0.83		7	35.3	1.4	0.70
8	30.9	1.24	0.80		8	35.3	1.4	0.70
9	32.1	1.29	0.77		9	35.3	1.4	0.70
10	33.6	1.35	0.74		10	35.3	1.4	0.70
11	35.3	1.42	0.70		11	35.3	1.4	0.70
12	37.5	1.51	0.66		12	35.3	1.4	0.70
13	40.3	1.62	0.62		13	35.3	1.4	0.70
14	44.3	1.78	0.56		14	35.3	1.4	0.70
15	50.2	2.02	0.50		15	35.3	1.4	0.70
16	61.2	2.46	0.41		16	35.3	1.4	0.70
17	42.7	1.78	0.58		17	35.3	1.5	0.70
	600.1	24.20				600.1	24.2	

Figure 4.43 shows the network performance parameter, the Dynamic Optimised and Dynamic Equal grids networks behave similar. At lower traffic load the Dynamic Optimised grids network performs slightly better in throughput, latency and jitter.

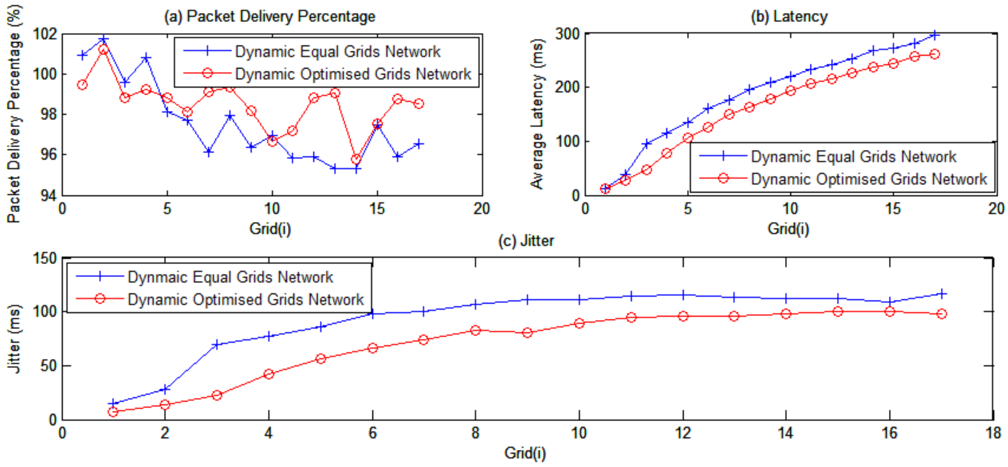

Figure 4.43 Packet Delivery, Average Latency and Jitter Graphs for 75% Dynamic Network Traffic

Figure 4.4.4 shows the simulated cluster head lifetime for the two networks. The cluster heads nearest to the base station for the Dynamic Optimised grids network are highly efficient. They have an average of 53% longer life as compared to Dynamic Equal grids network. The grid nearest to the base station for the Dynamic Optimised grids network has life of 343 hrs as compared to that of 318 hrs for Dynamic Equal grids network.

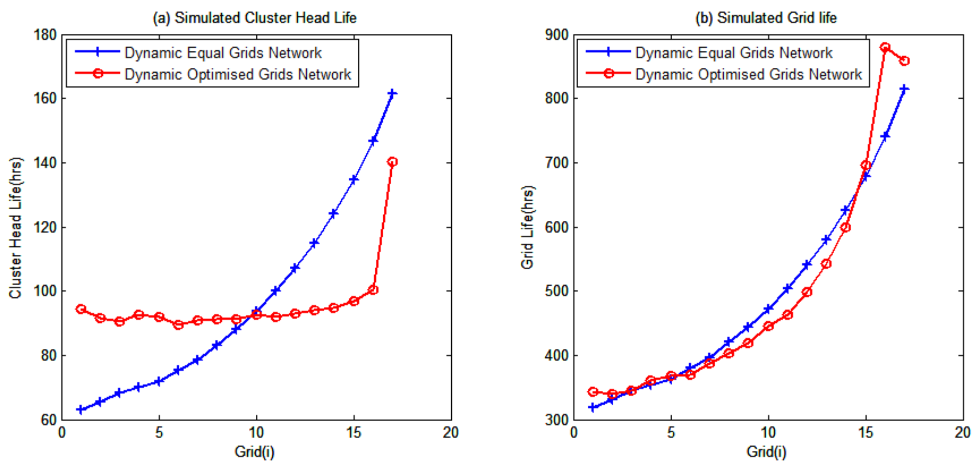

Figure 4.44 Simulated cluster head and network lifetime with 75% Dynamic network traffic

There is about 15 hours of network lifetime improvement for the Dynamic Optimised grids network compared to Section 4.4.2 (75% traffic Optimised grids network lifetime). However the Dynamic Equal grids network lifetime has decreased by 10 hrs. This clearly indicates that at lower traffics re-optimisation benefits only the Optimised grids network.

4.5.3 Dynamic Networks with 50%,25%,10% Traffic Load

Further network re-optimisation simulations were done with traffic reduced to 50%, 25% and 10%. It was noticed that as the traffic becomes lower the total number of grids becomes less and the grid size becomes larger. At 50% Dynamic traffic (Table 4-9) the total number of grids is reduced from 19 to 14.

At lower traffic, all the networks have near 100% throughput and packet delivery. The latency values become equal to that are inherent in the system and the jitter becomes near to packet transmission rate from cluster head nodes. Cluster head lifetime for the Dynamic Optimised grids network and Dynamic Equal grids network becomes less as the grid sizes are increased and hence greater transmit energy is consumed to transmit further. On the other side as the grid size in increased, so are the number of nodes in the grid. Hence from Figure 4.45, when there is 50% traffic, the network lifetime for the Dynamic Optimised grids network improves by 14% as compared to 2% decrease in Dynamic Equal grids network.

Table 4-9 Packet Transmission Rate for Dynamic grids with 50% Traffic

	Optimised Grids CBR Timings					COTS & Equal Grids CBR Timings		
Grid	Grid Size	Traffic	CBR Time		Grid	Grid Size	Traffic	CBR Time
(i)	(m)	Packets/s	(s)		(i)	(m)	Packets/s	(s)
1	31.2	0.84	1.20		1	42.86	1.1	0.87
2	32	0.86	1.17		2	42.86	1.1	0.87
3	32.9	0.88	1.13		3	42.86	1.1	0.87
4	34	0.91	1.10		4	42.86	1.1	0.87
5	35.2	0.94	1.06		5	42.86	1.1	0.87
6	36.6	0.98	1.02		6	42.86	1.1	0.87
7	38.3	1.03	0.97		7	42.86	1.1	0.87
8	40.2	1.08	0.93		8	42.86	1.1	0.87
9	42.7	1.14	0.87		9	42.86	1.1	0.87
10	45.9	1.23	0.81		10	42.86	1.1	0.87
11	50.2	1.35	0.74		11	42.86	1.1	0.87
12	56.8	1.52	0.66		12	42.86	1.1	0.87
13	68	1.74	0.57		13	42.86	1.1	0.87
14	56	1.50	0.67		14	42.82	1.1	0.87
	600	16.00				600	16.0	

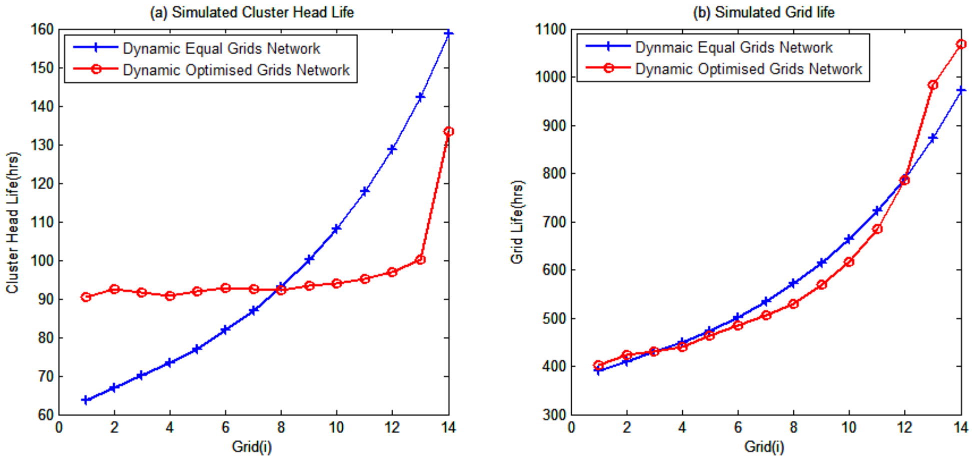

Figure 4.45 Simulated cluster head and network lifetime with 50% Dynamic network traffic

At 25% traffic, the Dynamic networks have only 10 grids as shown in Table 4-10.

Table 4-10 Packet Transmission Rate for Re-Optimised grids with 25% Traffic

	Optimised Grids CBR Timings					COTS & Equal Grids CBR Timings		
Grid	Grid Size	Traffic	CBR Time		Grid	Grid Size	Traffic	CBR Time
(i)	(m)	Packets/s	(s)		(i)	(m)	Packets/s	(s)
1	44.1	0.59	1.69		1	60	0.8	1.24
2	45.8	0.61	1.63		2	60	0.8	1.24
3	47.8	0.64	1.56		3	60	0.8	1.24
4	50.2	0.67	1.49		4	60	0.8	1.24
5	53.2	0.71	1.40		5	60	0.8	1.24
6	57	0.76	1.31		6	60	0.8	1.24
7	62.1	0.83	1.20		7	60	0.8	1.24
8	69.7	0.93	1.07		8	60	0.8	1.24
9	82.8	1.11	0.90		9	60	0.8	1.24
10	87.3	1.13	0.85		10	60	0.8	1.24
	600	8.00				600	8.0	

At lower traffic both the networks have 100% throughput and same latency and jitter.

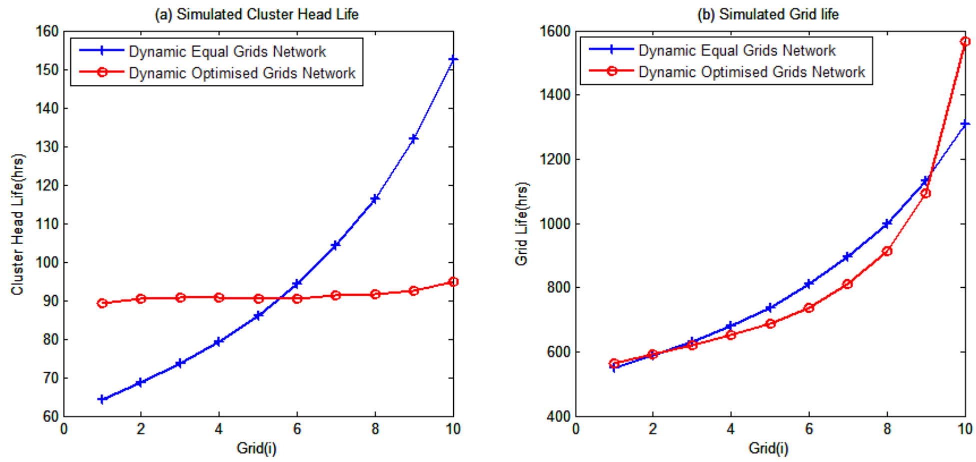

Figure 4.46 Simulated cluster head and network lifetime with 25% Dynamic network traffic

Again from Figure 4.46 the Dynamic Optimised grids cluster head nodes consumes less energy compared to Dynamic Equal grids and the cluster head life has increased from 452 hours to 563 hours (24.5% increase) as compared to Dynamic Equal grids network that has only improved 12 hours (~2%) from 539 hours to 551hours.

Table 4.11 shows the Dynamic grids size for Dynamic Optimised and Dynamic Equal grids network when the traffic is reduced to 10%. It can be seen that the number of grids has now reduced to only 7.

Table 4-11 Packet Transmission Rate for Re-Optimised grids with 10% Traffic

	Optimised Grids CBR Timings					COTS & Equal Grids CBR Timings		
Grid (i)	Grid Size (m)	Traffic Packets/s	CBR Time (s)		Grid (i)	Grid Size (m)	Traffic Packets/s	CBR Time (s)
1	69.7	0.37	2.68		1	85.71	0.46	2.18
2	74.1	0.40	2.52		2	85.71	0.46	2.18
3	79.9	0.43	2.33		3	85.71	0.46	2.18
4	88	0.47	2.12		4	85.71	0.46	2.18
5	100.5	0.54	1.86		5	85.72	0.46	2.18
6	123.6	0.67	1.50		6	85.72	0.46	2.18
7	64.2	0.32	2.91		7	85.72	0.46	2.18
	600	3.20				600	3.2	

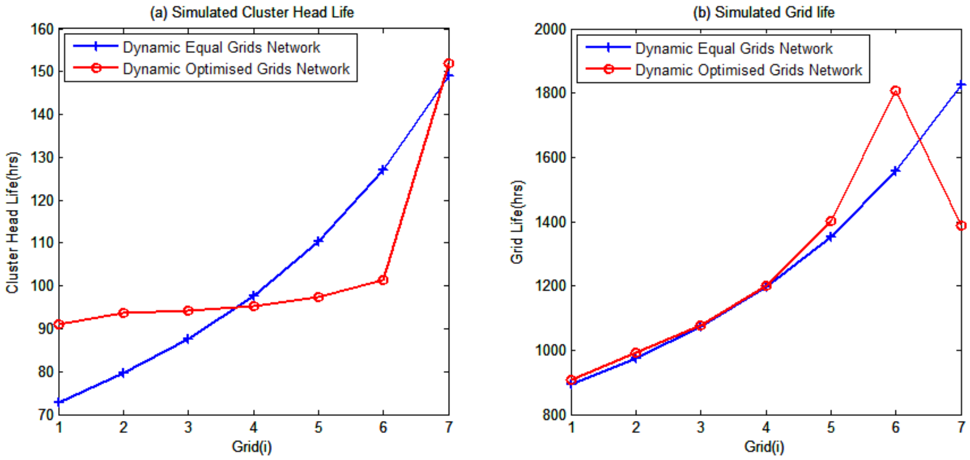

Figure 4.47 Simulated cluster head and network lifetime with 10% Dynamic network traffic

In Figure 4.47 the Dynamic Optimised grids network has the lifetime of 906 hours as compared to Dynamic Equal grids network lifetime of 893 hours. Comparing with section 4.4.3 for Dynamic Optimised grids network, the network lifetime has increased from 511 hour to 906 hours (77% increase). For Dynamic Equal grids network the network lifetime has increased from 672 to 893 (33% increase)

Despite increase in network life for both the Dynamic networks, the idle time spent by the nodes can be seen in Figure 4.48.

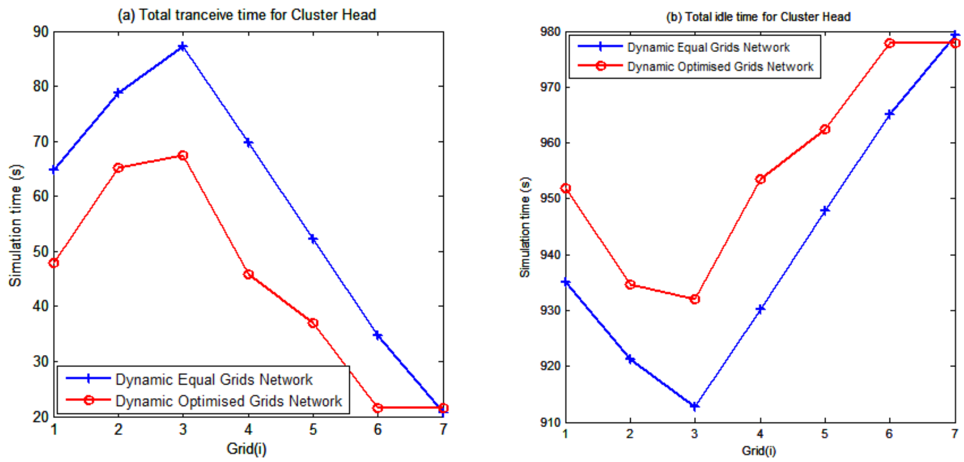

Figure 4.48 Comparison of cluster head transceiver time and idle time for 10% Dynamic network traffic

At 10 % maximum traffic, the cluster head nodes spend over 90% of the time in idle state and hence consuming idle energy. If this energy can be saved it can provide further network lifetime for all the networks.

4.6 Replacing CBR with Exponential Traffic

Exponential traffic is the most common type of traffic on wireless internet. This section looks at what benefits can be achieved by applying Optimised grids network to this type of traffic. Exponential traffic can also be generated in NS2 by setting the EXPOO Traffic. EXPOO Traffic is used to generate traffic based on Exponential On/Off distribution. The packets are only sent during ON periods and not during the Off period. The On (Burst) and Off (Idle) periods are taken from an exponential distribution.

From NS2 manual , the configuration parameters are:

PacketSize_ constant size of packets generated.
burst_time_ average on time for generator.
idle_time_ average off time for generator.
rate_ sending rate during on time.

The sending rate during the On time can be calculated as follows. In the Equal grids network and the COTS network, each cluster head node transmits at the mean datarate of 13547.82 bits/s . This is the minimum traffic that is required from the exponential traffic generator. The On time is set to be equal to Off time that is 500ms.

```
Mean datarate = rate_ * (burst_time_)/(burst_time_ + idle_time_) (4.21)
Therfore
⇨ 13547.82 = rate_ *(500/(500+500))
⇨ rate_ = 13547.82 / 0.5
⇨ rate_ = 27096 bits/s
```

The below fragment of tcl code shows how the exponential traffic generator was set up for each node.

```
###############################
## Connecting node 1 to node 0
##############################

set udp_(1) [new Agent/UDP]
$udp_(1) set class_ 1
$ns_ attach-agent $node_(1) $udp_(1)

set Exp_(1) [new Application/Traffic/Exponential]
$Exp_(1) set packetSize_ 808
$Exp_(1) set burst_time_ 500ms
$Exp_(1) set idle_time_ 500ms
$Exp_(1) set rate_ 27096
$Exp_(1) attach-agent $udp_(1)

$ns_ connect $udp_(1) $null_0
```

```
$ns_ at 10.00 "$Exp_(1) start"
$ns_ at 10000.00 "$Exp_(1) stop"
```

4.6.1 Replacing the CBR with Exponential Traffic Generator

Table 4-12 shows the calculated bit rates values for all the three networks using equation (4.21).

Table 4-12 Exponential Traffic Burst Rate Calculations for All Three Networks

	Optimised Grids Burst Timings					COTS & Equal Grids Burst Timings		
Grid	Grid Size	Traffic	Rate		Grid	Grid Size	Traffic	Rate
(i)	(m)	Packets/s	(ms)		(i)	(m)	Packets/s	(ms)
1	22	0.9	18876.0		1	31.58	1.3	27095.6
2	22.5	0.9	19305.0		2	31.58	1.3	27095.6
3	22.9	0.9	19648.2		3	31.58	1.3	27095.6
4	23.4	0.9	20077.2		4	31.58	1.3	27095.6
5	23.9	1.0	20506.2		5	31.58	1.3	27095.6
6	24.5	1.0	21021.0		6	31.58	1.3	27095.6
7	25.1	1.0	21535.8		7	31.58	1.3	27095.6
8	25.9	1.0	22222.2		8	31.58	1.3	27095.6
9	26.7	1.1	22908.6		9	31.58	1.3	27095.6
10	27.6	1.1	23680.8		10	31.58	1.3	27095.6
11	28.6	1.2	24538.8		11	31.58	1.3	27095.6
12	29.9	1.2	25654.2		12	31.58	1.3	27095.6
13	31.3	1.3	26855.4		13	31.58	1.3	27095.6
14	33.1	1.3	28399.8		14	31.58	1.3	27095.6
15	35.4	1.4	30373.2		15	31.58	1.3	27095.6
16	38.4	1.5	32947.2		16	31.58	1.3	27095.6
17	42.8	1.7	36722.4		17	31.58	1.3	27095.6
18	50.1	2.0	42985.8		18	31.58	1.3	27095.6
19	65.9	2.7	56542.2		19	31.58	1.3	27095.6
	600	24.1				600.02	24.1	

Figure 4.49 show the average throughput for the Optimised grids network to be approximately 185180 bit/s and for COTS and Equal grids network its 161523 bits/s. This is 30 % lower compared to Optimised grids throughput achieved by CBR traffic in section 4.3.1. The COTS and Equal grids throughput has also decreased by 20.5%.

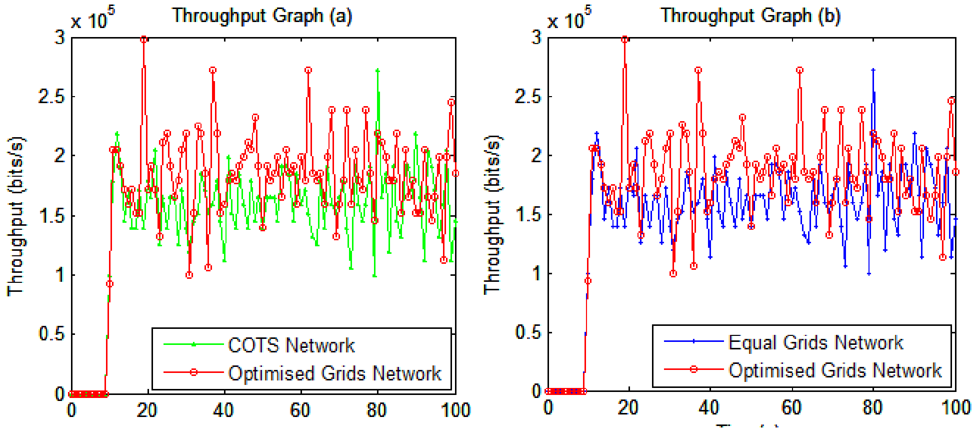

Figure 4.49 Optimised grids compared with COTS and Equal grids networks with Exponential Traffic

This lower throughput has resulted due to the bursty nature of the traffic. When the exponential source sends traffic, the nodes near the base station can store and forward their own and neighbouring node's traffic, but cannot store the packets coming from the cluster head nodes near the end of the network, and those packets are dropped in the queue. Figure 4.50 also shows reduced packet delivery for nodes that are furthest away from the base station for the entire three networks. The Optimised grids network has a packet delivery ratio of only 53% as compared to CBR traffic, where packet delivery was above 85% for all the nodes. The packet delivery for COTS and Equal grids network has also fallen from 63% to around 38% for cluster head nodes beyond grid 11. The average latency and jitter has also increased four folds for all the three networks.

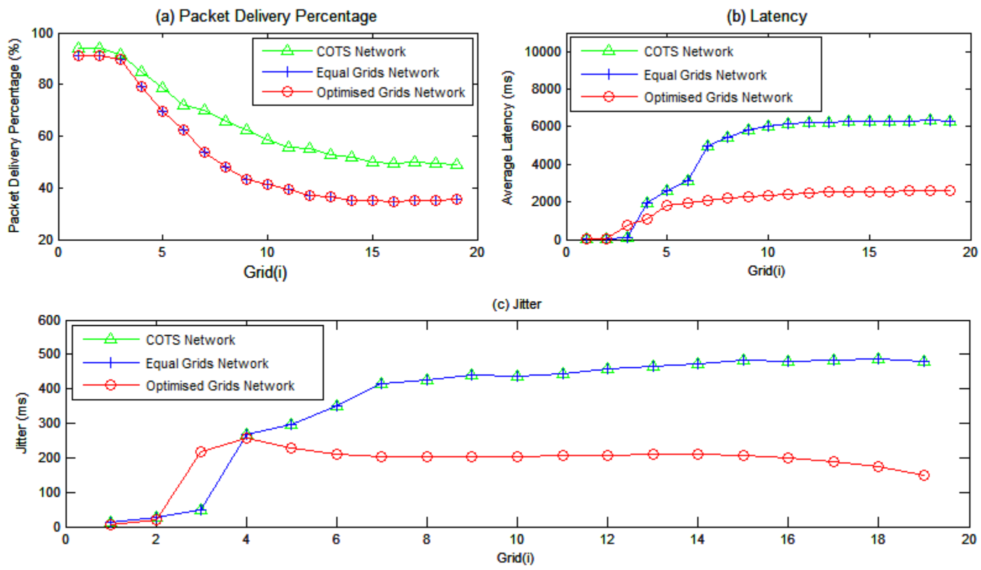

Figure 4.50 Packet Delivery, Average Latency and Jitter Graphs for Exponential Traffic

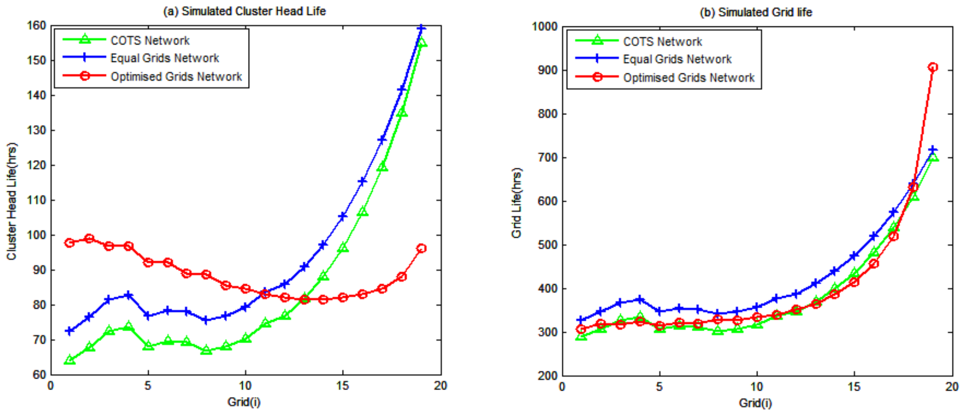

Figure 4.51 Simulated cluster head and network lifetime with Exponential network traffic

The cluster head lifetime has increased for all the three networks. This increase in cluster head has resulted from the decrease in throughput from all the three networks

Overall the Optimised grids network still has superior network performance parameters compared to the COTS and Equal grids network. It has higher throughput, lower latency and jitter. The network lifetime is 20hrs lower that Equal grids network, but this caused by fewer nodes to rotate within the grid and also greater throughput.

4.7 Conclusion

This section of the thesis has demonstrated the use of enhanced packet level simulation tool, NS2 to develop and implement a one dimensional optimal (unequal) grid network that minimises the cluster head energy use and balances the cluster head energy use throughout the network, thus extending the system lifetime.

In section 4.1 using the heuristic developed by (Gao, Blow et al. 2006) the relationship between network traffic and the Optimised grids sizes are explored. This model is then implemented in section 4.2 using the enhanced NS2 tool, where three networks were setup to study the network performance parameters and the energy consumption at a detailed packet level .

In section 4.2 the results for the Optimised grids network were compared with the Equal grids and COTS network. Using the new Optimised grids model it is seen that the cluster head lifetime can be improved by 30% and 50% respectively during 100% traffic compared with the best case scenario where equal radio range and commercial of the shelf (COTS) systems are used.

Section 4.3 also showed by using the traffic modelling approach, when traffic is high, the new Optimised grids network provided a significant improvement in the key QoS parameters. The throughput of the new Optimised grids network showed an increase by 24.7% as compared to Equal grids and COTS network. The data packet delivery of the new Optimised grids network also increased by 30%. The latency reduced by an order of magnitude and jitter was reduced by 55% without decreasing network lifetime.

In section 4.4 the traffic level was varied between 200% and 10% to see the effects on network performance and life for the three networks. In the case of 200% traffic load the new Optimised grids network again had higher throughput and reduced latency and jitter as compared to the Equal grids and COTS network. All the three networks suffered from high traffic congestion and only delivered around half the required throughput. At lower traffic between 75 % and 10%, all the three networks had near 100% throughput and much improved latency and jitter, even still the new Optimised grids network had better performance than the other two networks. The cluster head lifetime of the new Optimised grids network at lower traffics was still between 30% and 50% higher as compared to the COTS and Equal grids network. But as traffic load is lowered, the idle energy starts to dominate. As the new Optimised grids network has smaller grid size, it has lesser number of nodes that can be rotated to become cluster heads as compared to the other two networks. This caused the new Optimised grids network to have lower network life at 10% traffic.

Section 4.5 introduced re-optimisation known as “Dynamic” at higher and lower traffic for the three networks. By re-optimising at 200% traffic load, the Dynamic Optimised grids network throughput increased by 31.3 % and 40% compared with the Dynamic Equal grids and Dynamic COTS network. The throughput improved by 9.1% as compared to non-optimised new Optimised grids network in section 4.4. At lower traffic the network parameters became equal to that are inherent in the system, hence latency and jitter could not be further reduced.

The advantage of re-optimisation at lower traffic became increasingly evident as the Dynamic Optimised grids network’s life improved during lower traffic loads. In the best case scenario, when the network traffic is only 10%, the re-optimisation causes 77% increase in network lifetime for the Dynamic Optimised grids network as compared to only 33% for the Dynamic Equal grids network.

Section 4.6 investigated the behaviour of exponential traffic on the new Optimised grids network. While the average throughput is lower for all the three networks, the new Optimised grids network still had 14.6% higher throughput and nearly 50% less latency and jitter as compared to the Equal grids and COTS network. One of the key advantages of higher throughput is that if the data is being sent by using TCP where failure leads to re-transmission, then higher throughput will lead to increased network lifetime as fewer re-transmissions are required.

One of the key aspects to explore in the next chapter is how much gain can be achieved by reducing the idle energy consumption of the new Optimised grids network and how it will affect the overall network lifetime with fluctuating traffic loads.

Chapter 5

Introducing the Sleep Model in Wireless Sensor Networks

In ad hoc wireless sensor networks, energy use is in many cases the most important constraint since it corresponds directly to operational lifetime. The lifetimes can be extended by topology management schemes, such as GAF, Leach and SPAN that put the redundant nodes for routing to sleep in order to save the energy. The radio range will affect the number of neighbour nodes that collaborate to forward data to the sink. In Chapter 4.0 a one dimensional optimal (unequal) grid network was modelled that minimised cluster head node energy consumption and balanced the energy use throughout the network, thus extending the system lifetime and throughput. A selection of traffic behaviours were simulated by increasing and decreasing the traffic produced by the nodes and the results were studied.

One of the most important issues realised in Chapter 4.0 was that during lower traffic rates, idle time, became a dominant feature which caused an increase in idle energy consumption and therefore shortening the cluster head as well as the network lifetime. Even in those cases where the traffic was 100%, the cluster head nodes further away from the base station had much less traffic to forward and spent over 90% of the time in the idle state. In this chapter a Sleep Mode is introduced in the sensor network model that was developed in Chapter 4.0 section 4.1 and 4.2. This allowed comparing the increase in network lifetime that can be achieved with the Sleep Mode with respect to results achieved in section 4.3. The Sleep Mode is also introduced within higher and lower traffic loads and compared with results achieved from Chapter 4.0 section 4.4 and for all the three networks. In the second part of this chapter the Original Optimised grids model is modified by adding a sleep state in equation (4.15) and a new model is developed called the New Sleep Model. Then new grids sizes are calculated for all the three networks. This gave a detailed insight into the behaviours of network QoS parameters and also the cluster head and network lifetimes.

5.1 Simulating Sleep Mode in Existing Sensor Network Model

In the last decade, a lot of research has been carried out in maximising the lifetime of Wireless Ad Hoc Networks (WAHN). Much of the attention has gone into MAC and Routing protocols that have either been modified or redesigned based on protocols similar to 802.11. Some of the earliest protocols designed included Power-Aware Routing Optimization protocol (PARO) (Gomez, Campbell et al. 2003) in which if node 'A' wanted to transmit a message to node 'E', it would calculate a multi-hop path that required the minimum energy consumption. Several other protocols have been reviewed in Chapter 2.0 that rely on the principles of active energy saving.

In passive energy saving protocols, the node often sends the radio into a sleep state, when it's in an idle state for more than a predefined period of time. In the GAF algorithm the network is divided into virtual grids and the node with the maximum energy is chosen to be the cluster head. The chosen cluster head can talk to all its neighbouring cluster head nodes and sufficient numbers of cluster head nodes are created to achieve network connectivity. In Sensor MAC (SMAC), a 'sleep awake' schedule is set up among a group of nodes that allows them to go to sleep after a predefined wakeup time known as duty cycle. The duty cycle can be set between 10% and 100%. Nodes lying on the border of two grids have two schedules to follow so connectivity can be maintained between the whole of the network.

5.1.1 Adding Sleeping Mode to the Model Devised in Chapter 4.0

In chapter 4.0 it was noticed that the cluster head nodes nearest to the base station spent the majority of their time in either transit or receive state and hence used more energy compared to cluster head nodes that were further away from the base station. This idle time and hence idle energy was becoming larger as the network traffic was gradually reduced from 100% to 10%. A further study was carried out to see the behaviour of network lifetime by introducing a Sleep Mode. At present a sleep model is only introduced in SMAC and is not implemented in 802.11 protocols that is the most reliable protocol in NS2. The network traffic levels used by SMAC are much lower as compared to the model developed in Chapter 4.0. A way to overcome this bottleneck in NS2 was to decrease the idle energy consumption to a fixed lower level. At the moment the idle energy consumed by a node in the idle state is 0.05 joules per second. It was assumed that during the idle time the node goes to sleep for 90% of the time and only remains awake for 10% of the total idle time. This idle energy consumption was reduced to 0.005. This meant that the nodes will only consume 10% of the energy while they were awake. This also assumes that when nodes have gone to sleep (90% of the idle time) or are transitioning from idle to sleep and vice-versa, they were not consuming any energy at all.

This does not affect the network throughput, packet delivery, latency and jitter. The study is aimed to get an insight on how the network lifetime could be improved if sleep energy is introduced into the Optimised grids, Equal grids and COTS networks.

The Idle energy consumption of the Optimised grids, Equal grids and the COTS network was modified to accommodate for sleep energy and the simulations were run for 1010 seconds. To avoid confusion, the three models (Optimised, Equal and COTS) will have a prefix of ‘Sleep’ where the Sleep Mode is introduced and prefix of ‘Idle’ where there is no Sleep Mode. Figure 5.1 compares the cluster head lives of the three network models (Optimised grids, Equal grids and COTS network) with idle energy developed in Chapter 4.0 section 4.2 with the same models including the sleep energy. Apart from idle energy consumption as described earlier, nothing else is changed in the simulation run.

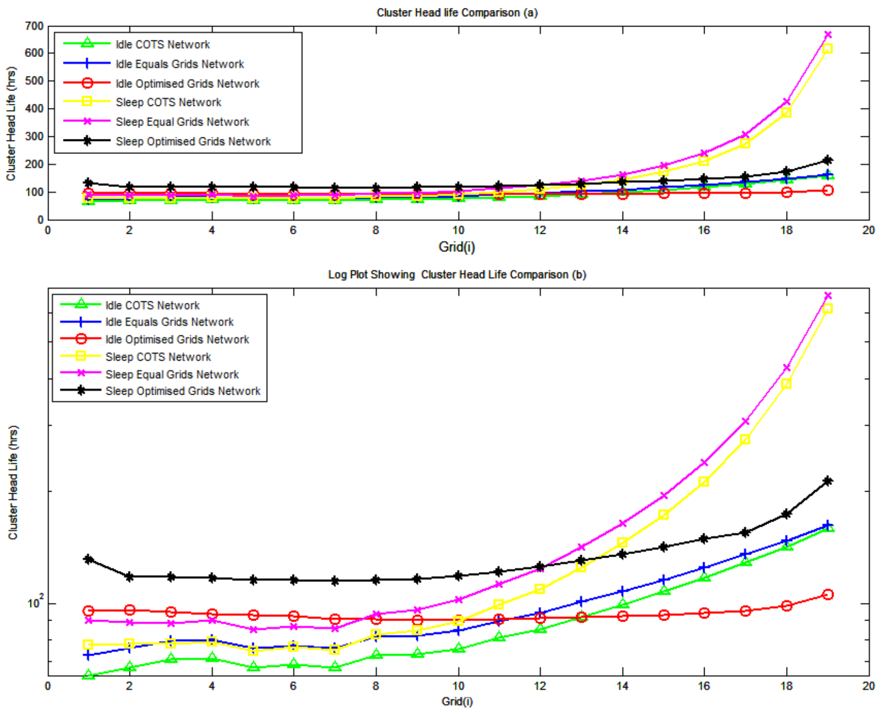

Figure 5.1 100% Traffic Cluster head life comparison with and without Sleep Mode

The lower zoomed graph of Figure 5.1 shows the cluster head lifetime of the first five nodes. It can be seen that all the three networks have an increase in cluster head lives. The Sleep Optimised grids network shows an average increase of 26% for the first five cluster head nodes, while for Sleep Equal grids and Sleep COTS network it has been 13.3% and 16.4%. Keeping in mind from Chapter 4.0 section 4.4, the Sleep Optimised grids network has approximately 24.7% higher throughput and much higher packet delivery with lower latency and jitter. As the nodes spend less time being idle, the highly efficient Sleep Optimised grids network uses the saved idle energy more efficiently, by providing extended cluster head lifetime compared to the other two networks.

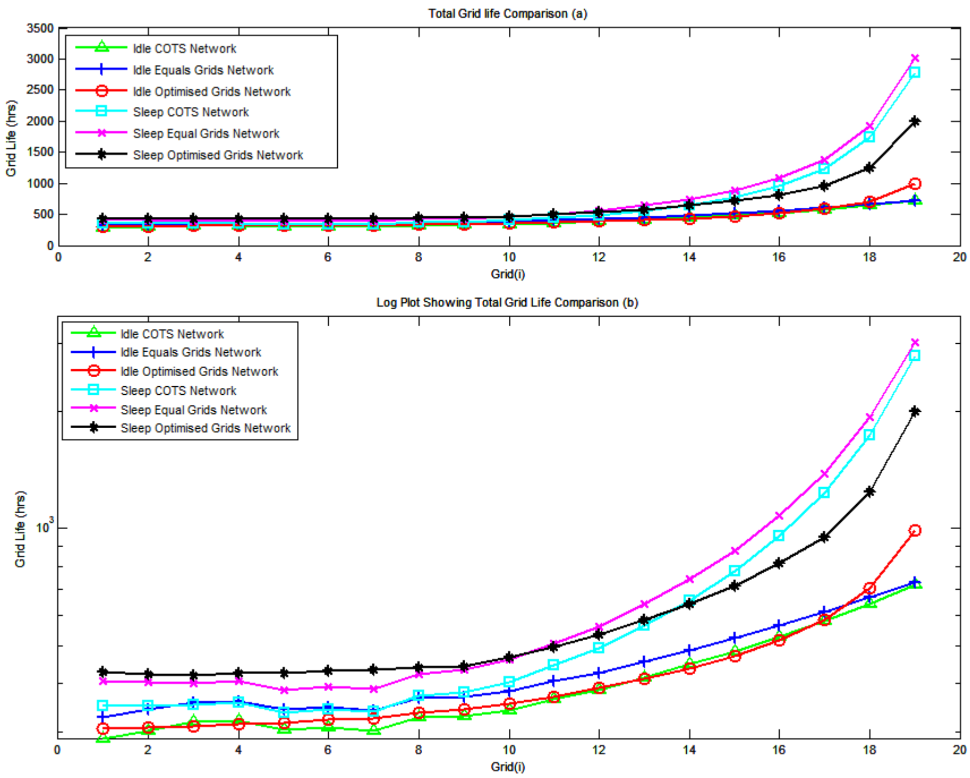

Figure 5.2 100 % Traffic Total Network lifetime comparison with and without Sleep Mode

The average total grid lifetime for the first five grids of the Sleep Optimised grids network (black line) has increased by 39% as compared to Idle Optimised grids network. It also shows that the increase in grid lifetime has only been 18.4% for the COTS and Equal grids network. Another key point noted is that without Sleep Mode, the Idle Equal grids network had overall 6.8% longer lifetime as compared with Idle Optimised grids networks. By using the Sleep Mode and intelligently utilising transmit energy, the Sleep

Optimised grids network now has at least 9.1% more network lifetime as shown by node 3 of 'Sleep Optimised grids network' compared with node 5 of 'Sleep Equal grids network'. Please note from Figure 5.2 (b) that nodes in grid 5 and grid 7 will die much quicker for both the Sleep Equal grids and Sleep COTS networks. This is because of the congestion in those networks near the base station. Cluster head nodes in grid 5 and 7 are repeatedly transmitting packets that are being lost for majority of the time to cluster head nodes of grid 4 and 6. Hence cluster head nodes of grid 5 and 7 are continuously using more transmit energy as compared to cluster head node of grid 4 and 6 that are consuming less energy as they are only receiving packets. The next section compares the effects on network lifetime for three networks when the traffic is fluctuating with the integrated sleep mode.

5.2 Effects of Traffic Fluctuation on Network Lifetime with Sleep Mode

This section compares the network lifetime with the network traffic fluctuation from 200% to 10% of the original traffic load. Three scenarios are studied, a) when the traffic approaches 200%, b) when the traffic is reduced by 50% and, c) when the traffic load goes down to 10% of the original traffic load.

5.2.1 Increasing the Network Traffic to 200% with Sleep Mode

The total network bandwidth is 1Mbits/s. By increasing the network traffic to 200%, the total theoretical data being transmitted by the cluster head node next to the base station for all the three networks is increased from 0.2574Mbits to 0.5148Mbits/s.

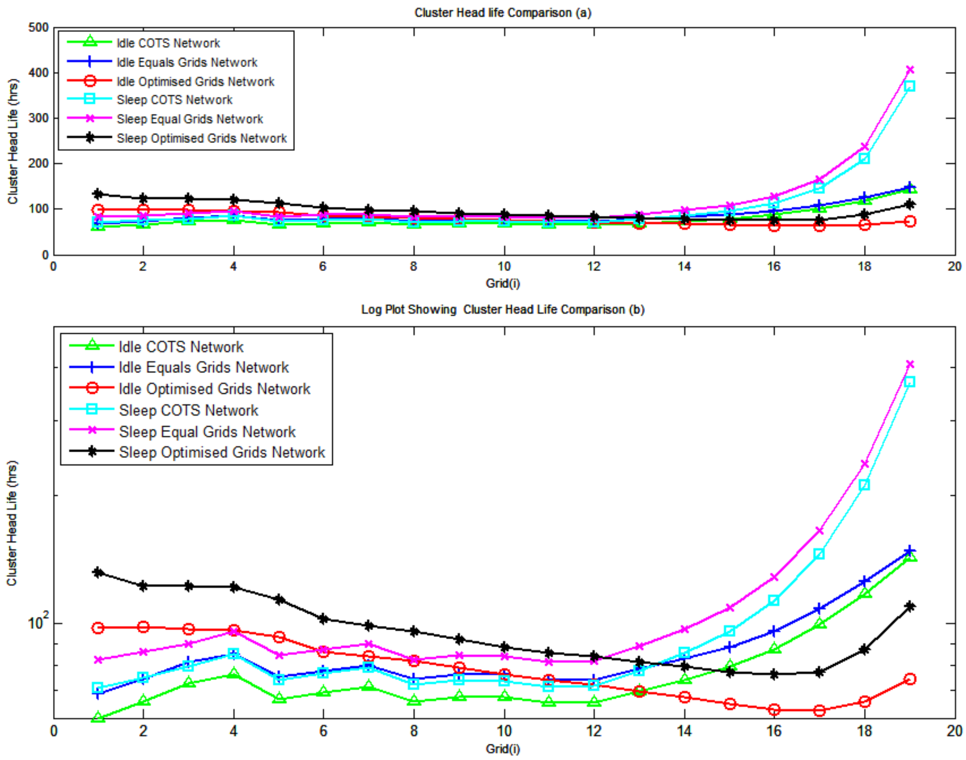

Figure 5.3 200% Traffic cluster head life comparison with Idle and Sleep Mode

Earlier in Chapter 4.0 section 4.4.1 it has been confirmed that the Idle Optimised grids network has a total throughput of 0.2364 Mbits/s as compared to 0.2174 Mbits/s achieved by the Idle Equal grids network and 0.2164 Mbits/s achieved by Idle COTS network. Table 4-4 in Chapter 4.0 shows the network grid sizes and grid traffic parameters used in this simulation.

The Sleep Optimised grids network also has 33% less average latency and jitter as compared to the other two networks. What needs to be seen now is if the Sleep Mode brings any bigger benefits compared to the other two networks.   Figure 5.3 shows that there has been a near linear gain of 13% extra cluster head lifetime from node 6 to 16 for the Sleep Optimised grids network as compared to an Idle Optimised grids network. But from node 1 to 5 this increase is around 23%. The reason is that the nodes nearest to the base station are transmitting their grid packets to the base station, but are not forwarding all the packets from previous grids (shown in Figure 4.27, Chapter 4.0), and hence are not using that amount of transmit energy consumption required to forward packets. Even though the Sleep Optimised network has the highest throughput and also the highest cluster head lifetime, it's the cluster head nodes (16,17) that have the shortest lifetime, The reason is that those grids are moving forward nearly all the packets from previous grids as well as their own grids, but these packets are not reaching the base station as they are being dropped by nodes nearest to the base station.

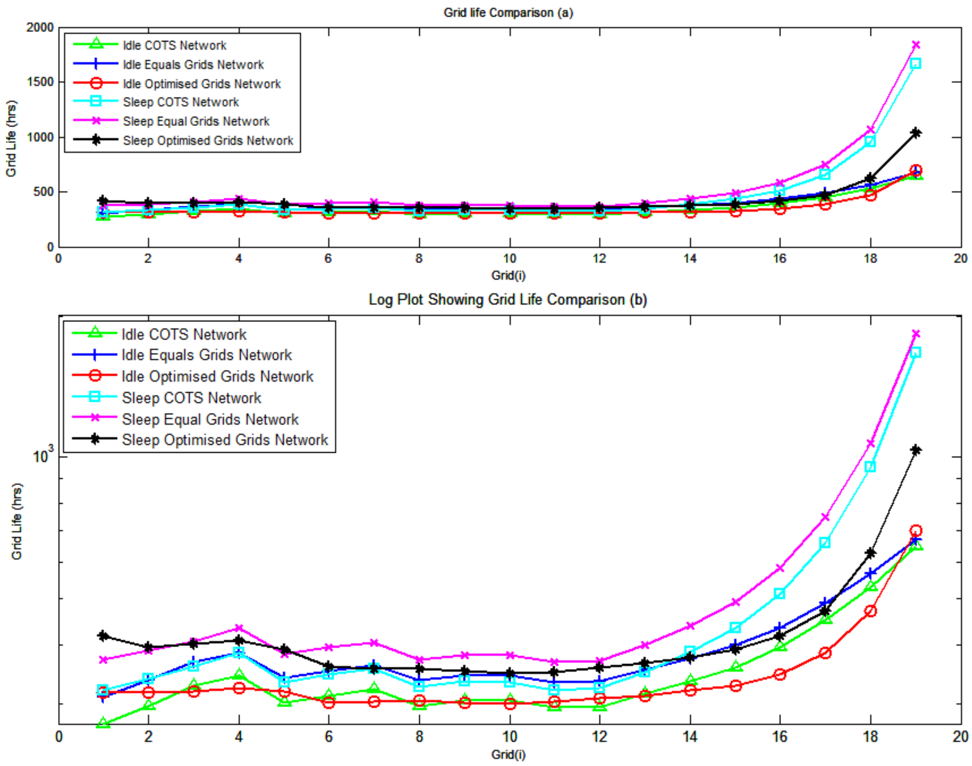

Figure 5.4 200% % Traffic Network lifetime comparison with Idle and Sleep Mode

Figure 5.4 shows that Sleep Optimised grids life is still 32% higher compared to Idle Optimised grids life. The Sleep Equal grids network shows the shortest grid life time for grid 11 to be 366 hours as to Sleep Optimised grids shortest lifetime of 347 hours for grid 10. Again the shortest lifetime is 312 hours for grid 11 of the Sleep COTS network. One thing to remember is that the Sleep Optimised grids network has nearly 9.0% higher throughput compared to the other two networks and also higher packet delivery compared to the Sleep COTS and Sleep Equal grids networks.

5.2.2 Decreasing the Network Traffic to 50% with Sleep Mode

To lower the network traffic to 50%, the data transmitted from each node was reduced from 0.003 Erlang to 0.0015 Erlang. The total throughput reaching the base station was reduced from 0.2574 Mbits/s to 0.128700 Mbits/s. Table 4-6 in Chapter 4.0 highlights the grid sizes and packets produced by each cluster head in that grid for 50% traffic. At 50% traffic all the three networks have 100% throughput. As idle energy is very dominant at lower traffic, the Sleep Optimised grids network can now efficiently use the saved energy for efficient packet transmission. Figure 5.5 shows the increased cluster head life

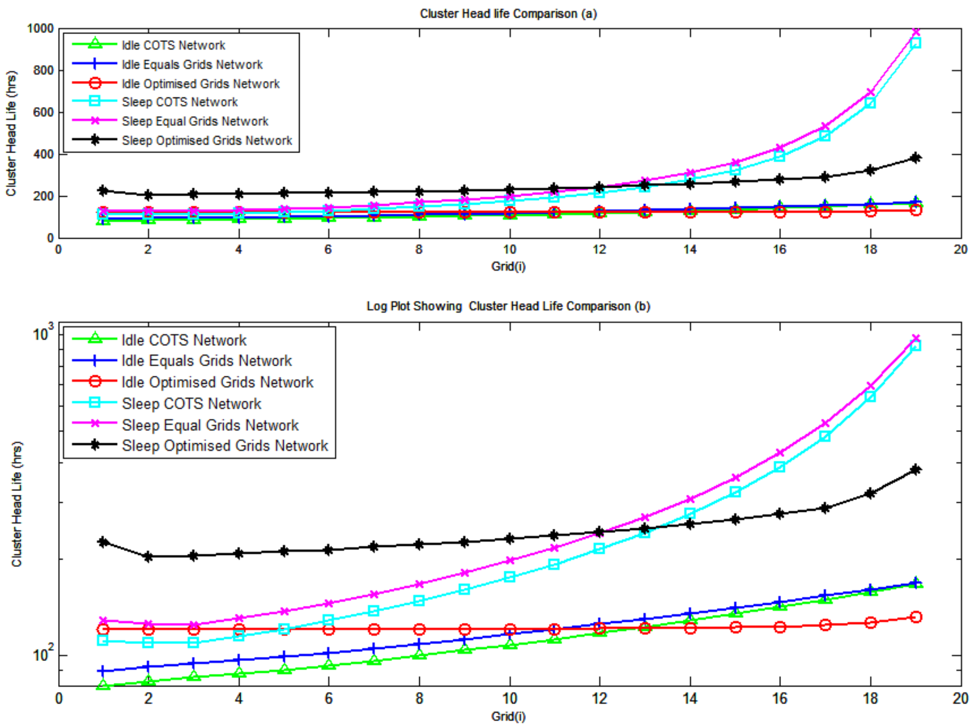

Figure 5.5 50% Traffic cluster head lifetime comparison with Idle and Sleep Mode

for all the three networks. The Sleep Optimised Grid's cluster head lifetime has increased by 87.5% for nodes nearest to the base station as compared to 44% for Sleep Equal grids and 31% for Sleep COTS grids. By using the sleep mode, huge benefits have been gained by the Sleep Optimised grids network as compared to the other two networks, due to un-Equal grids sizes.

Previously without the sleep mode, the Optimised grids network had 6% lower grid life as compared to the Equal grids network. The reason being that Equal grids and COTS networks have more nodes in each grid due to their larger grid sizes. Therefore more nodes could be rotated to become cluster heads. At low traffic, there was an advantage for COTS and Equal grids networks, as all the three networks consumed the same amount of idle energy. The energy being saved by Optimised grids network from transmission and reception of packets was being utilised or wasted in the idle state. Figure 5.6 (a,b) shows that by implementing sleep mode, Sleep Optimised grids network has an increase of 68% grid lifetime in case of grid 2 where all the nodes die first.

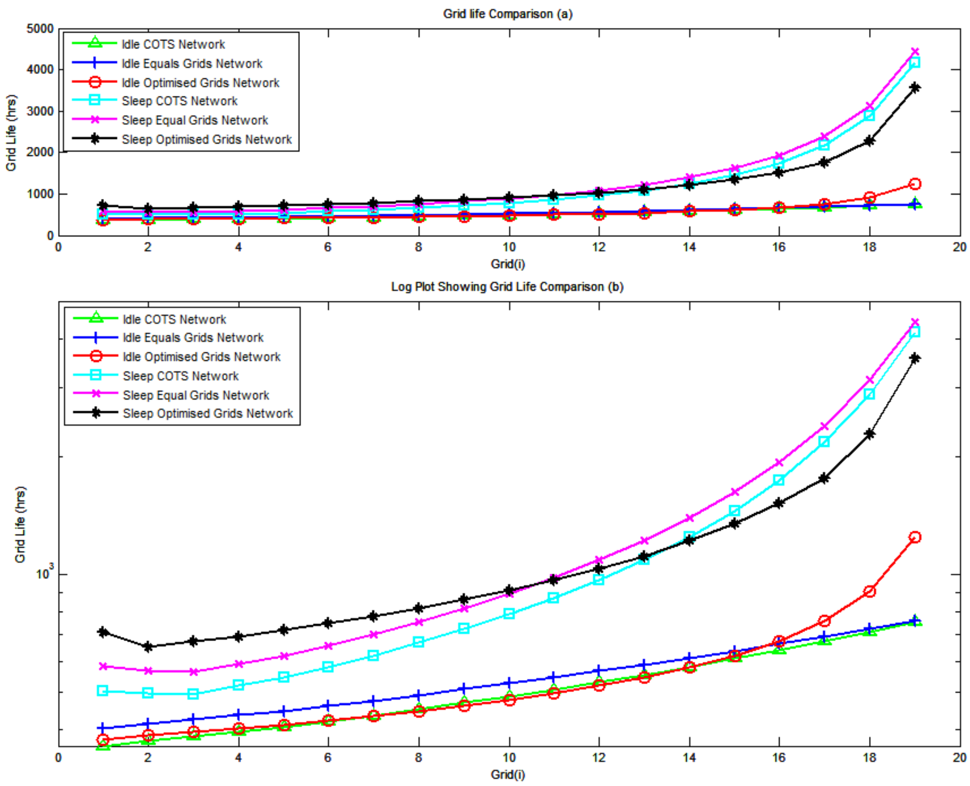

Figure 5.6 50% % Traffic Network lifetime comparison with Idle and Sleep Mode

Overall the Sleep Optimised grids network has gained around 20% more lifetime (comparing Sleep Optimised grid 2 with Sleep Equal grid 3) and 34 % more network lifetime compared to Sleep COTS network (comparing Sleep Optimised grid 2 with Sleep COTS grid 3). Thus at lower levels of traffic, the Optimised grids traffic model has a clear advantage as shown by the cluster head and grid life increase in the Sleep Optimised grids network.

5.2.3 Decreasing the Network Traffic to 10% with Sleep Mode

At 10% load, the maximum traffic being transmitted from the cluster head node nearest to the base station was reduced from 0.2574 Mbits to 0.02574 Mbits/s. Each node in the network was producing the traffic of 0.0003 Erlang. Table 4-6 in Chapter 4.0 highlights the grid sizes and packets produced by each cluster head in that grid for 10% traffic. Using the Sleep Mode with very low traffic shows a giant leap in cluster head lifetime for all the three networks (Figure 5.7). It can be seen that the cluster heads in Sleep Optimised grids network had an average increase in lifetime of 442% as compared to Sleep Equal grids and Sleep COTS network that show an average increase of 319% and 302%.

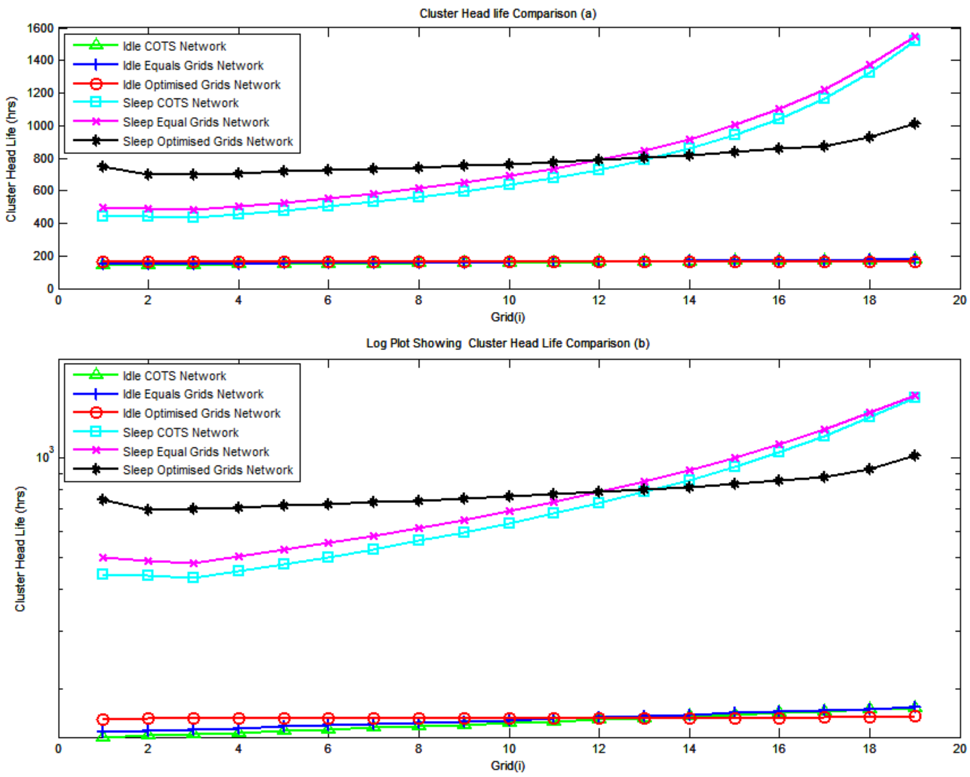

Figure 5.7 10% Traffic cluster head lifetime comparison with Idle and Sleep Mode

This increased benefit in grid lifetimes can also be seen in Figure 5.8. Previously the Idle Optimised grids network was trailing both the Idle Equal grids and Idle COTS network.

The Idle Optimised grids, Idle Equal grids and Idle COTS grids had maximum lifetimes of 530, 668 and 644 hours respectively.

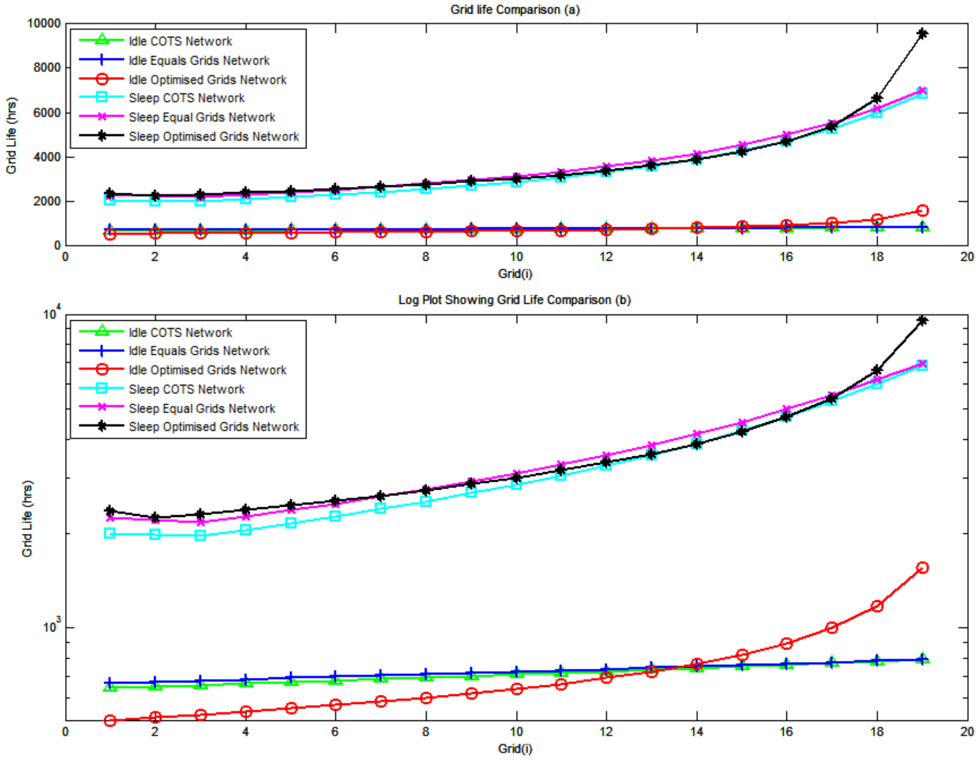

Figure 5.8 10% Traffic Network lifetime comparison with Idle and Sleep Mode

After introducing the Sleep Mode, the grid lifetimes have increased considerably as shown by Figure 5.8 (b). The Sleep Optimised, Sleep Equal grids and Sleep COTS have gone from 530 hours to 2300 hours, 668 hours to 2172 hours and 644 hours to 1964 hours. The Sleep Optimised grids network has come from behind and has gained an advantage over both Sleep Equal grids and Sleep COTS networks. This has been the result of efficient unequal grids clustering.

5.3 Re-Optimisation (Dynamic) of Networks with Fluctuating Traffic Loads with Sleep Mode.

This section of the chapter continues to see if the Network QoS parameters and Network lives can be increased if the initial Optimised grids sizes calculated in Chapter 4.0 section 4.2 are recalculated with the new fluctuating loads. In the case where there is no Sleep Mode in section 4.5 Chapter 4.0, it was made evident that re-calculating the grid sizes gave a clear advantage in both grid and network lifetime for Optimised grids network. When the traffic load is higher, the numbers of grids in the Idle Optimised grids network also increased, and when the traffic became lower, the number of grids for the Idle Optimised grids network decreased. In this section, three cases are studied where the network traffic is increased to 200% and then decreased to 50% and 10% and compared with the Dynamic-Idle Optimised network grids of Chapter 4.0 section 4.5. Another reason is to find out if the Dynamic Sleep Mode has any kind of advantage over the Non-Dynamic Sleep modes studied in section 5.2.

5.3.1 Comparing the Dynamic Sleep Mode Networks with Dynamic Idle Mode Networks with 200 % Traffic.

In this section the traffic approaching the base station is increased from 0.2574 Mbits /s (100%) to 0.5148 Mbits/s (200%). The new grid sizes are recalculated for the Sleep Optimised grids network. As the traffic is increased to 200%, the number of unequal grids increased from 19 to 27 for the Sleep Optimised grids network. The new grids sizes and data forwarded by each cluster head for all the three networks are shown in Chapter 4.0 Table 4-7. As the grids decrease in size, the cluster head nodes consume less transmit energy to send the message to the neighbouring node. On the other hand if the number of grids increases, the congestion on the network also increase as more cluster head nodes will not only be transmitting packets, but also sending more CTS/RTS/ACK packages. Hence the cluster head nodes will be stressed. For the cluster head node nearest to the base station, as traffic is just over half of the bandwidth, it will be theoretically in either transmit state or receive state. Just to recap from Chapter 4.0 section 4.5 it was concluded that the Dynamic Idle Optimised grids network has 31.3% higher throughput compared to Dynamic Idle Equal grids network and 40.4% more throughput compared to Dynamic Idle

COTS network. The QoS parameters for all the three networks had increased, but the Dynamic Idle Optimised grids network still had higher packet delivery and much lower latency and jitter as compared to the other two networks. The key question now is has the network lifetime of the Dynamic Sleep Optimised grids network increased from the Dynamic Idle Optimised grids network and Sleep Optimised grids network? Figure 5.9 holds the answers. It can be seen that compared to Dynamic Idle Optimised grids network, the Dynamic Sleep Optimised grids network has 90% more lifetime. The peaks and troughs for the Dynamic Sleep Optimised grids network show the nodes that were in constant transmit mode and those that were more of receive mode.

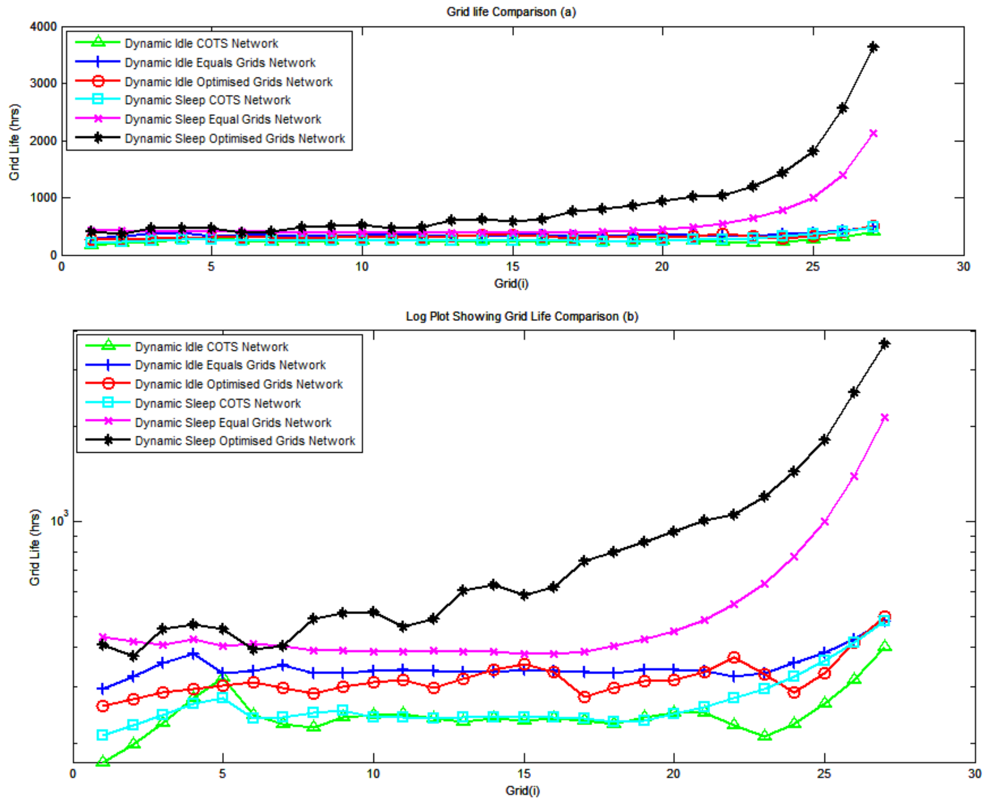

Figure 5.9 200% Network lifetime comparison with Dynamic Sleep Mode VS Dynamic Idle Mode Networks

The Dynamic Sleep Equal grids network show grid 16 and 17 run out of energy first in that network. The Dynamic Sleep Optimised grids network lifetime has increased as compared to the Dynamic Idle Optimised grids network but has it improved compared to the Sleep Optimised network of section 5.2? The answer is yes, because from Figure 5.4(b) for the Sleep Optimised grids total grid lifetime graph it can be seen that grid 9 and 10 have lives of 347 and 351 hours while the Dynamic Sleep Optimised grids shows that grid 2 has a lifetime of 376 hours. It can be seen from Figure 5.9 (b) that for the

Dynamic Equal grids network, grid 16 only has a lifetime of 381 hours and will die first in that network. The Dynamic Sleep Equal grids, grid lifetime graph (Figure 5.9b) shows 6 hours longer lifetime as compared to the Dynamic Sleep Optimised grids network. As mentioned earlier the Dynamic Sleep Optimised grids network has 31.3% more throughput compared to the other two networks hence uses more energy in transmission as compared to the other two networks. The packet delivery is also between 7-10% higher at lower end of Dynamic Sleep Optimised grids network. A fair conclusion is that if the other two networks had the same throughput and packet delivery, they would have much lower grid lifetimes. In the case when the traffic is increased in the network, the re-optimisation increases grid lifetime for Dynamic Sleep Mode networks. The next step is to see if this statement is held when the traffic is decreased.

5.3.2 Comparing the Dynamic Sleep Mode Networks with Dynamic Idle Mode with 50 % Traffic.

As the network traffic is reduced from 0.2574Mbit/s to 0.1287Mbits/s, Re-Optimising the Idle Optimised grids network results in a reduction of the number of grids from 19 to 14. This means that grid size becomes larger. The advantage it has is that now the energy that was being wasted by cluster head node by going into the idle state is being used in transmission and also the number of nodes in the grid increases as the grid area become larger. The new grid lengths were calculated for the Dynamic Sleep Optimised grids model and the values are shown in Chapter 4.0 Table 4-9.

Figure 5.10 shows the results achieved by comparing the Dynamic Sleep Optimised grids network with the Dynamic Idle Optimised grids network. The network lifetime has increased by 42.5% for Dynamic Sleep Optimised network. Dynamic Sleep Equal grids network has an increase of 29% network lifetime . The grid nearest to the base station for Dynamic Sleep Optimised grids network has a lifetime of 575.2 hours as compared to only 499.13 hours for Dynamic Sleep Equal grids network, hence having 26.7% extra network lifetime.

The key question now is to see if the Re-Optimisation has bought any benefits for Sleep Optimised grids network. Looking at Figure 5.6(b) grid 2 has the least lifetime of 663 hours for the Sleep Optimised grids network, while the Dynamic Sleep Optimised grids network has a reduced lifetime of 575 hours for grid 1 in Figure 5.10b.

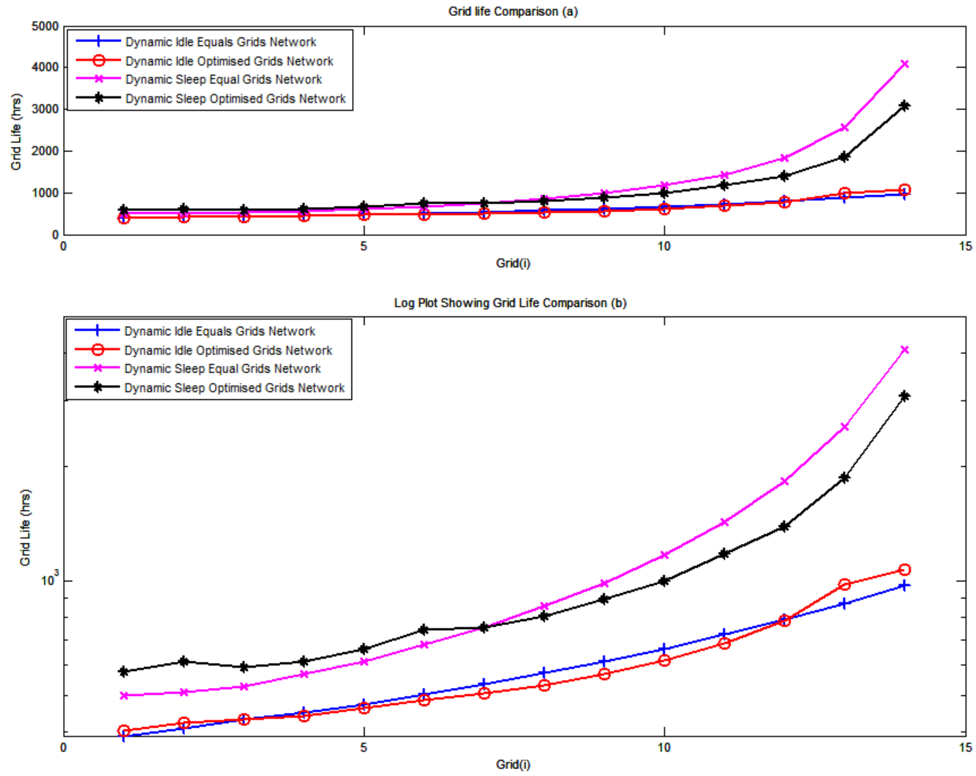

Figure 5.10 50% Network lifetime comparison with Dynamic Sleep Mode VS Sleep Mode Networks

This proves that Dynamic Sleep Optimised grids network at lower traffic does not increase its network lifetime as Re-Optimisation increases the grid size.

5.3.3 Comparing the Dynamic Sleep Mode Networks with Dynamic Idle Mode with 10 % Traffic.

This time the traffic was reduced to 0.02574 Mbits/s and the grids where re-calculated. This gave a new Dynamic grid number reduced from 19 to 7 grids only. The complete grid sizes with number of packets generated from each cluster head node are given in Chapter 4, Table 4-11. From Figure 5.11, the Dynamic Sleep Optimised grids network has an increase in lifetime from 902 to 1627 hours, an increase of 90%, while the Dynamic Sleep Equal grids network has an increase from 888.6 to 1375 hours, an increase of 55% only. Also the Dynamic Sleep Optimised grids network has 18.3 % more network lifetime as compared to Dynamic Sleep Equal grids network.

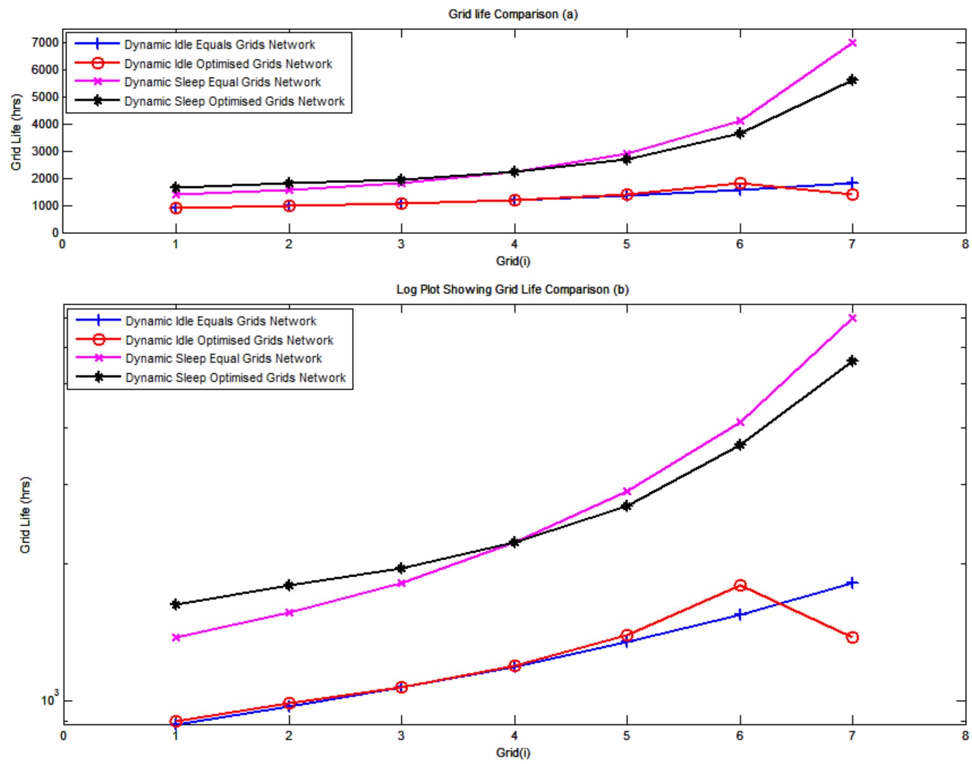

Figure 5.11 10% Network lifetime comparison with Dynamic Sleep Mode VS Sleep Mode Networks

By comparing the results achieved for 10% Traffic Dynamic Sleep Optimised grids network (minimum grid life 1627 hours) in this section, with 10% Traffic Sleep Optimised grids network (2240.7 hours) of Figure 5.8(b), also proves that at lower traffic loads, re-optimisation does not benefit when using sleep mode. This is because the grids sizes become bigger and therefore consume more transmit energy and reduce network lifetime.

When the traffic load is greater than 100% it is beneficial to re-optimise the Sleep Optimised grids networks, this reduces the grid sizes, which in return also lower the transmit power used by the Sleep Optimised grids cluster head nodes. This results in higher network lifetime.

5.4 Derivation of the New Sleep Model.

The Optimisation model described in Chapter 4.0 sections 4.2 serves well in providing highly efficient, optimised grids spacing that results in balanced energy consumption between cluster head nodes along the entire network. The Optimised grids's cluster head nodes have much higher lifetime compared to the Equal grids and COTS network. In this section we use the same model and try to add sleep energy consumption to see if further benefits can be received in increasing cluster head and network lifetimes. Equation 4.8 from Chapter 4.0 section 4.2 is modified as below to include the duty cycle for Idle time (Dt_I) and Sleep Time (Dt_S). The Sleep Energy Consumption (e_s) is also added to the equation.

$$P = k\left((e_t + e_r)\mathrm{BA} + e_d\left(2\frac{d}{k}\right)^n \mathrm{BA} + \mathrm{BCe}_r\big((1-2A)\mathrm{Dt}_I\big) + e_s\big((1-2A)\mathrm{Dt}_S\big)\right) \quad (5.1)$$

To find that most efficient grid size, equation 5.1 is differentiated with respect to k we obtain

$$\frac{dP}{dk} = \mathrm{Dt}_I(1-2A)\mathrm{BCe}_r - 2^n\mathrm{BA}\left(\frac{d}{k}\right)^n(-1+n)e_d + \mathrm{Dt}_S(1-2A)e_s + \mathrm{BA}(e_r + e_t) \quad (5.2)$$

By setting dP/dk =0 we obtain

$$\mathrm{Dt}_I(1-2A)\mathrm{BCe}_r - 2^n\mathrm{BA}\left(\frac{d}{k}\right)^n(-1+n)e_d + \mathrm{Dt}_S(1-2A)e_s + \mathrm{BA}(e_r + e_t) = 0 \quad (5.3)$$

Which can be re-arranged to give the following equation for d/k?

$$\left(\frac{d}{k}\right) = \sqrt[n]{\frac{\mathrm{Dt}_S(1-2A)e_s + \mathrm{BA}(e_r + e_t) + \mathrm{Dt}_I(1-2A)\mathrm{BCe}_r}{2^n\mathrm{BA}(n-1)e_d}} \quad (5.4)$$

Recall that $R_{opt} = (\frac{d}{k})$, so the new Optimised grids sizes with the New Sleep Model can be calculated by using equation (5.4). The term 'A' is the total data that the cluster head node has to forward at a certain distance 'x' away from the base station in the network of length 'd'. e_t is the energy/bit consumed by the transmitter electronics (including energy costs of imperfect duty cycling due to finite start-up time) and is equal to $50x10^{-9}$ J/bit , and a distance-dependent term e_d that accounts for energy dissipated in the transmit op-amp is $100x10^{-12}$ J/bit m^2 (for n=2) and depends on transmission distance . The parameter *n* is the power index for the channel path loss; this value depends on the RF environment and is generally between 2 and 4. e_r is the energy/bit consumed by the node's receiver electronics and is approximately $50x10^{-9}$ J/bit, and *Bandwidth B* =1Mbit/s (Chen, Jamieson et al. 2002).

To avoid confusion the Optimised energy model derived in Chapter 4.0 will be called Original Model, and the model given by equation (5.4) in this section will be called the New Sleep Model. All the three networks with graphs legend data starting with 'New' will refer to this New Sleep Model.

There are two key points that need to be remembered while using equation (5.4). Dt_I *and* Dt_S are the ratios of the time the cluster head node stays in idle state and sleep state. Hence the total of these two ratios always has to be equal to one.

$\mathrm{Dt}_I + \mathrm{Dt}_S = 1$

The second key point is that the sleep mode is always set to zero. This is because NS2 does not have a complete 802.11 protocol with a sleep model implemented. In NS2 what is being done, is that for all the time the node spends in the idle state, it only consumes energy for the ratio set by Dt_I for the rest of the time it does not consume energy and therefore is considered as sleeping.

The next step is to calculate the optimised grid sizes using equation (5.4). Please note these three models will be referred as i) New Sleep Optimised grids , ii) New Sleep Equal grids and iii) New Sleep COTS respectively.

The new grid sizes using the New Sleep model are calculated as below. The total data reaching the base station is 0.2574 Erlang. This value is inserted into equation (5.4) and the first grid size is calculated as R_{opt}.

The values for $\mathrm{Dt}_I$was set to 0.1 and Dt_S was set to 0.9. The sleep energy was set to zero because NS2 does not support sleep mode.

$$R_{\mathrm{opt}} = \sqrt[2]{\frac{0.9(1-2A)e_s + 1000000 * A(50 * 10^{-9} + 50 * 10^{-9}) + 0.1(1-2A) * 1000000 * 1 * 50 * 10^{-9}}{2^2 * 1000000 * A(n-1)100 * 10^{-12}}}$$

$$= 50\sqrt{\frac{0.005(1-2A)+\frac{A}{10}+0.9(1-2A)e_s}{A(-1+n)}}$$

$$= 50\sqrt{\frac{0.005(1-2A)+\frac{A}{10}+0.9(1-2A)5*10^{-4}}{A(-1+2)}}$$

$$= 50\sqrt{\frac{0.00545(1-(2*0.2574))+\frac{0.2574}{10}}{0.2574(-1+2)}}$$

$$Therefore\ for\ the\ first\ grid\ size\ \ R_{\text{opt}} = 16.6037$$

Using equation (4.16) from Chapter 4.0, the traffic approaching the second grid can now be calculated as follows

(600-16.6037)*0.143*0.003 = 0.25027 Erlang.

Table 5-1 displays the new calculated grid sizes, the amount of data that will be transmitted from each grid and the CBR timer setting for each cluster head node in each grid for all the three networks. The number of grids has increased from 19 to 32. The unequal grid sizing of the New Sleep Optimised grids indicates that as at the grids move away from the base station, the grids sizes are also increasing along with the traffic generated by each grid. Please note this not the total traffic passing that grid. It’s only the traffic produced by all the nodes in that grid including the cluster heads own sensor data.

Table 5-1 Grids sizes, Traffic and CBR setting using the New Sleep Model with 100% Traffic

	Optimised Grids CBR Timings					COTS & Equal Grids CBR Timings		
Grid	Grid Size	Traffic	CBR Time		Grid	Grid Size	Traffic	CBR Time
(i)	(m)	Packets/s	(s)		(i)	(m)	Packets/s	(s)
1	16.5400	0.8848	1.1302		1	18.75	1.0055	0.99
2	16.5810	0.8902	1.1234		2	18.75	1.0055	0.99
3	16.6250	0.8902	1.1234		3	18.75	1.0055	0.99
4	16.6720	0.8955	1.1166		4	18.75	1.0055	0.99
5	16.7210	0.8955	1.1166		5	18.75	1.0055	0.99
6	16.7740	0.9009	1.1100		6	18.75	1.0055	0.99
7	16.8300	0.9009	1.1100		7	18.75	1.0055	0.99
8	16.8910	0.9063	1.1034		8	18.75	1.0055	0.99
9	16.9550	0.9116	1.0969		9	18.75	1.0055	0.99
10	17.0250	0.9116	1.0969		10	18.75	1.0055	0.99
11	17.0990	0.9170	1.0905		11	18.75	1.0055	0.99
12	17.1800	0.9223	1.0842		12	18.75	1.0055	0.99
13	17.2680	0.9277	1.0779		13	18.75	1.0055	0.99
14	17.3640	0.9331	1.0717		14	18.75	1.0055	0.99
15	17.4690	0.9384	1.0656		15	18.75	1.0055	0.99
16	17.5840	0.9438	1.0595		16	18.75	1.0055	0.99
17	17.7120	0.9492	1.0536		17	18.75	1.0055	0.99
18	17.8540	0.9599	1.0418		18	18.75	1.0055	0.99
19	18.0140	0.9652	1.0360		19	18.75	1.0055	0.99
20	18.1940	0.9760	1.0246		20	18.75	1.0055	0.99
21	18.3990	0.9867	1.0135		21	18.75	1.0055	0.99
22	18.6360	0.9974	1.0026		22	18.75	1.0055	0.99
23	18.9120	1.0135	0.9867		23	18.75	1.0055	0.99
24	19.2400	1.0296	0.9713		24	18.75	1.0055	0.99
25	19.6360	1.0511	0.9514		25	18.75	1.0055	0.99
26	20.1260	1.0779	0.9278		26	18.75	1.0055	0.99
27	20.7520	1.1154	0.8965		27	18.75	1.0055	0.99
28	21.5850	1.1583	0.8633		28	18.75	1.0055	0.99
29	22.7650	1.2227	0.8179		29	18.75	1.0055	0.99
30	24.6050	1.3192	0.7580		30	18.75	1.0055	0.99
31	28.0260	1.5015	0.6660		31	18.75	1.0055	0.99
32	24.0000	1.2816	0.7803		32	18.75	1.0055	0.99
	600.0340	32.1750				600	32.1750	

For the New Sleep Equal grids and New Sleep COTS network, all the grid sizes are of equal length of 18.75m and all the cluster head nodes are generating the same number of packets from their own grid. Table 5.2 defines the traffic that the cluster head has to forward to its neighbouring grid cluster head node facing towards the base station. It includes its own grid data packets as well as the packets that are received from its previous grids.

Table 5-2 Total Network Traffic to Forward to Base Station from Each grid

	Optimised Grids CBR Timings					COTS & Equal Grids CBR Timings		
Grid	Traffic to Forward		Transmit E		Grid	Traffic to Forward		Transmit E
(i)	(bit/s)	Packets/s	(j/s)		(i)	(m)	Packets/s	(j/s)
1	257400	32.18	0.1589		1	257400	32.18	0.1906
2	250322	31.29	0.1596		2	249356	31.17	0.1906
3	243200	30.40	0.1602		3	241313	30.16	0.1906
4	236079	29.51	0.1609		4	233269	29.16	0.1906
5	228914	28.61	0.1616		5	225225	28.15	0.1906
6	221750	27.72	0.1622		6	217181	27.15	0.1906
7	214543	26.82	0.1629		7	209138	26.14	0.1906
8	207336	25.92	0.1636		8	201094	25.14	0.1906
9	200086	25.01	0.1649		9	193050	24.13	0.1906
10	192793	24.10	0.1656		10	185006	23.13	0.1906
11	185500	23.19	0.1663		11	176963	22.12	0.1906
12	178164	22.27	0.1676		12	168919	21.11	0.1906
13	170785	21.35	0.1690		13	160875	20.11	0.1906
14	163363	20.42	0.1704		14	152831	19.10	0.1906
15	155899	19.49	0.1718		15	144788	18.10	0.1906
16	148391	18.55	0.1732		16	136744	17.09	0.1906
17	140841	17.61	0.1746		17	128700	16.09	0.1906
18	133247	16.66	0.1767		18	120656	15.08	0.1906
19	125568	15.70	0.1789		19	112613	14.08	0.1906
20	117846	14.73	0.1810		20	104569	13.07	0.1906
21	110039	13.75	0.1840		21	96525	12.07	0.1906
22	102145	12.77	0.1869		22	88481	11.06	0.1906
23	94166	11.77	0.1906		23	80438	10.05	0.1906
24	86057	10.76	0.1952		24	72394	9.05	0.1906
25	77821	9.73	0.2005		25	64350	8.04	0.1906
26	69412	8.68	0.2076		26	56306	7.04	0.1906
27	60789	7.60	0.2173		27	48263	6.03	0.1906
28	51866	6.48	0.2298		28	40219	5.03	0.1906
29	42600	5.32	0.2471		29	32175	4.02	0.1906
30	32819	4.10	0.2747		30	24131	3.02	0.1906
31	22265	2.78	0.3267		31	16088	2.01	0.1906
32	10253	1.28	0.4856		32	8044	1.01	0.1906

Table 5-2 also lists the transmit energy in joules/sec consumed by each cluster head node while forwarding the data. As the grid size in the New Sleep Optimised grids network increases, so thus the transmit energy consumption for that grid. For New Sleep Equal and New Sleep COTS grids, the grid sizes and cluster head node energy consumptions remains constant throughout the network.

5.4.1 Quality of Service with the New Sleep Model

The three New Sleep Models as described in section 5.4.1 were set up and simulated using the Enhanced NS2 simulator. Key parameters investigated were the maximum throughput for the whole simulated network, the packet delivery from each cluster head node and average latency and jitter.

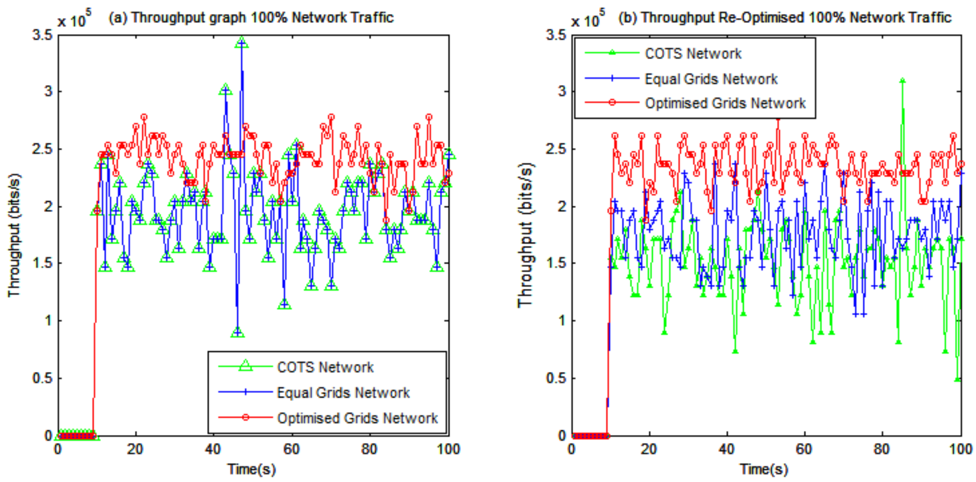

Figure 5.12 100% Traffic: Throughput difference between (a) Original and (b) New Model

In this section precedence is given to QoS parameters. Figure 5.12 compares the throughput achieved by using the Original Model (Figure 5.12 (a)) and the New Sleep Model (Figure 5.12b). The average throughput calculated for the first 90 seconds for the Original Model for Optimised grids Equal grids and COTS grids is 241440 bit/s, 194784 bit/s and 193482 bit/s respectively. Using the New Sleep Model the throughputs are 234488 bit/s, 176920 bit/s and 152260 bit/s for the New Sleep Optimised grids, New Sleep Equals grids and New Sleep COTS network. It shows that using the New Sleep Model the New Sleep COTS network has suffered a loss of 21.3%, while the New Sleep Equal grids and New Sleep Optimised grids has suffered a loss of 9.2% and 1.9%. The loss is understandable, as the grid numbers have increased and the grid distances have become smaller, the New Sleep COTS and New Sleep Equal grids networks are prone to too many collisions and packet losses due to non-optimised ineffective transmission range. Infact an important point to realise is by using the New Sleep Model, the New Sleep Optimised grids network has 32.53% more throughput compared with New Sleep Equal grids network and 54% more throughput as compared with New Sleep COTS network. The effect of this can be seen in Figure 5.13 (b) where by using the New Sleep Model, the New Sleep COTS network has suffered a significant drop in packet delivery compared to the New Sleep Equal grids and Original Sleep COTS network.

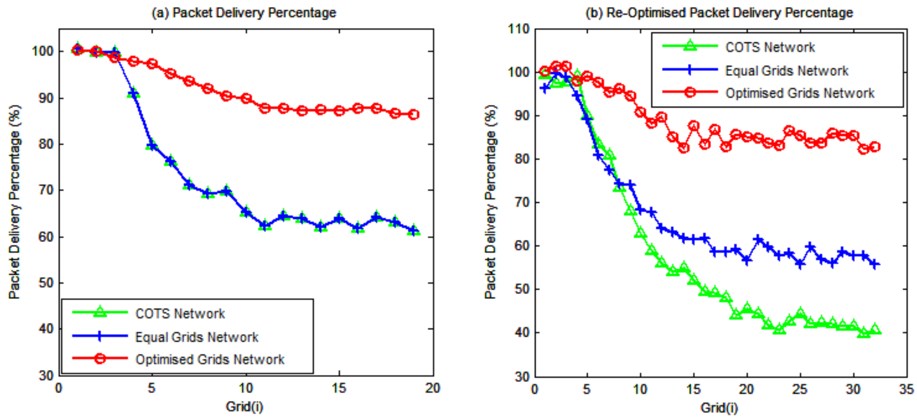

Figure 5.13 100% Traffic: Packet delivery difference between (a) Original and (b) New Model

The average latency figures have also increased slightly for the New Sleep Equal grids and New Sleep Optimised grids network by comparing values with the Original Model Figure 5.14(a) and New Sleep Model Figure 5.14(b). For the COTS network, the average latency has nearly tripled by changing from one model to the other. But the important point is that the New Sleep Optimised grids network has nearly 4 times and ten times less average latency values compared to the New Sleep Equal grids and New Sleep COTS networks.

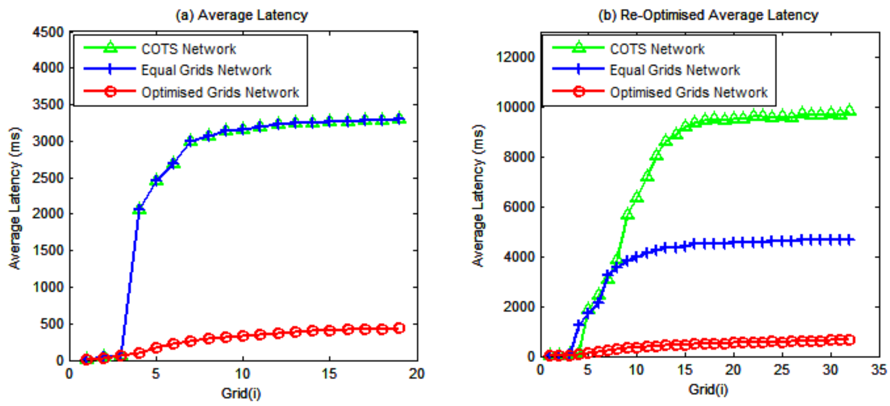

Figure 5.14 100% Traffic: Average latency difference between Original and New Model

Figure 5.15 shows the jitter for the Original Model (5.15a) and New Sleep Model (5.15b). For the New Sleep Optimised grids network, the jitter has not changed much. The jitter has increased on average by 100ms for the New Sleep Equal grids network, but for the New Sleep COTS network the jitter has more than doubled.

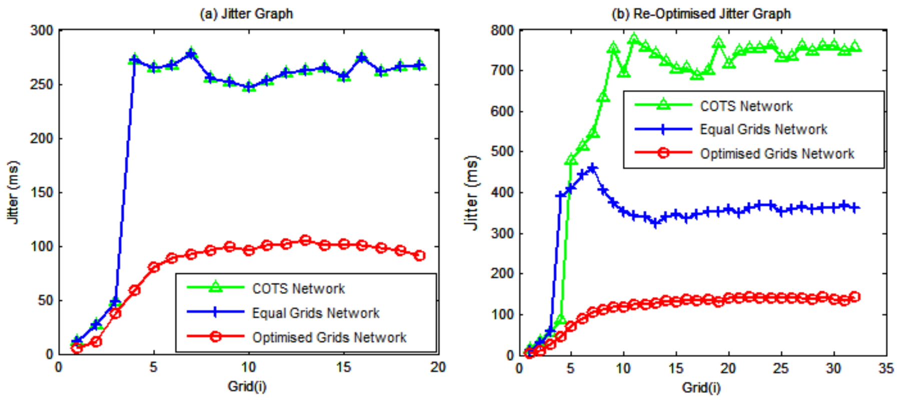

Figure 5.15 100% Traffic: Jitter difference between Original and New Model

The reason the New Sleep Model is referred as Optimised model is that it increases the cluster head lifetime for the Optimised grids network by 37% as compared to only 1.9% degradation in network throughput. Recalling that cluster head and network lifetime is the most important constraint in WSNs, this model shows that great benefits can be achieved by a very small loss in network QoS parameters, resulting in a slight increase in latency and jitter. It also predicts that if dynamic optimisation is applied using the New Sleep Model, this will further enhance the cluster head and network lifetimes for all the three networks.

5.4.2 Cluster Head & Total Grid Life Comparison with New Sleep Model

This section tries to explore if any increased cluster head or network lifetime benefits are gained by using the New Sleep Model. The results achieved are compared with the Original Model with Idle energy (graph legends starts with 'Idle') and the Original Model with Sleep Mode (graph legend starts with 'Sleep'). The graph legends for New Sleep Model begin with 'New Sleep'.

Figure 5.16(a) compares the cluster head lifetimes of the New Sleep Model networks with the Original Idle Energy Model. The New Sleep Optimised grids network shows 157 hours of life for the cluster head node of grid 2 as compared to 95.8 hrs of lifetime for the Original Idle sleep model. This is approximately an increase of 63% in network lifetime.

One more point being noted is that by comparing grids 1 and 2 of the New Sleep Equal grids network with that of the New Sleep Optimised grids network, they both have nearly the same cluster head lifetime. This is due to the fact that an increase in cluster head lives for the New Sleep Equal grids network is due to the poor performance that is shown in forwarding packets from the previous grid. This can be seen by a sharp drop in packet delivery in Figure 5.13 after cluster head node 3. This also answers the question to why there is 32.3 % less throughput delivered by this network as compared to the rival New Sleep Optimised grids network.

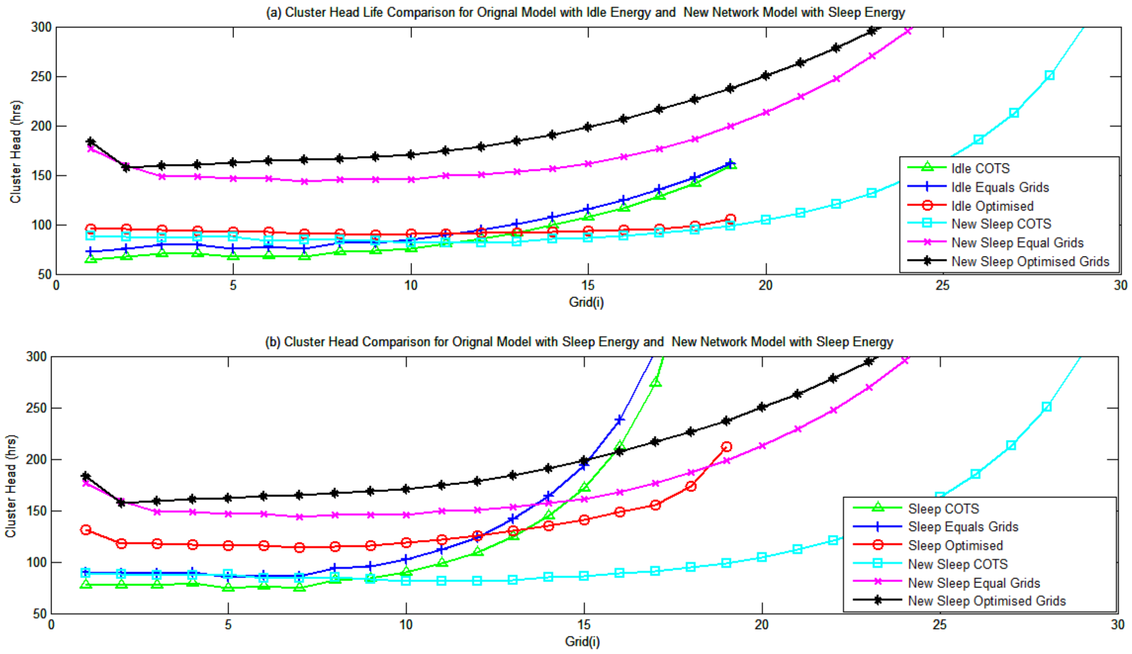

Figure 5.16 100% Traffic cluster head lifetime comparison among New Sleep Model, Original model with and without Sleep Mode

Figure 5.16(b) compares the cluster head lifetime for the New Sleep Model with the Original Model with sleep mode described in section 5.1. Cluster head node 7 of the Sleep Optimised grids network has the least lifetime of 114 hrs, as compared to157 hours for the cluster head node 2 of the New Sleep Optimised Model. This shows there has been 37% improvement in cluster head lives for the New Sleep Optimised grids model.

The next area to look into is the increase in network lifetime of the New Sleep Optimised grids network as compared with Original Model with idle energy and the Original model with Sleep Mode. Figure 5.17(a) shows that grid 2 of New Sleep Optimised grids network was a minimum lifetime of 373 hours as compared to 301 hours of lifetime for grid 1 of Idle Optimised network. Hence an increase has come, but to no surprise as this advantage has been brought by the using the saved idle energy. The real challenge is to see if it has any advantage over the Original Optimised grids Model with Sleep Mode. Figure 5.17b compares both the New Sleep Model with the Original Model with Sleep Mode. It can be seen that the grid lifetimes of Original Optimised grids model is about 9% higher as compared with New Sleep Optimised grids model.

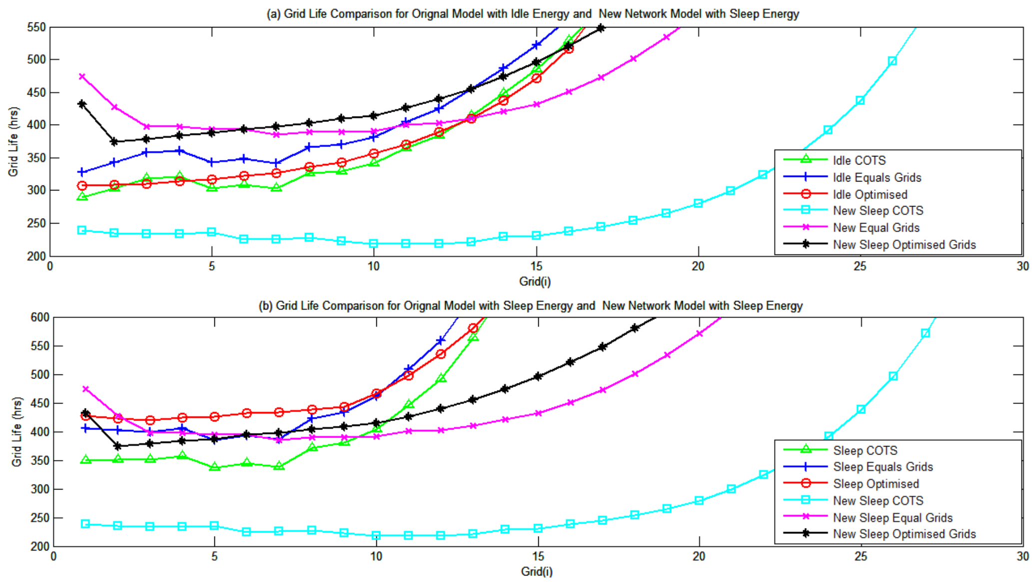

Figure 5.17 100% Traffic network lifetime comparison among New Sleep Model, Original model with and without Sleep Mode

The answer is quite simple. At the moment both the models use the saved energy, so the only benefit comes from the ratio of grid size to transmission range. At cluster head level the New Sleep Optimised grids model has an advantage with an average increase of 37% cluster head lifetime. At network level, the Sleep Optimised grids network has the advantage with 9% extra lifetime due to the larger grid size and therefore more nodes are present in the grid to rotate with plenty of energy. One way to confirm this is to complete a theoretical calculation for both models, where the conditions are ideal, that is 100% packet delivery, with no latency, jitter, collisions or packet loss. Figure 5.18 shows the theoretically calculated cluster head 1 lifetime of the New Sleep Optimised grids network is 160 hrs as compared to only 115 hrs for the Original Sleep Optimised network, an improvement of 39%. In the simulation the improvement was 37% from Figure 5.16(b) showing good agreement between the theoretical and simulated results.

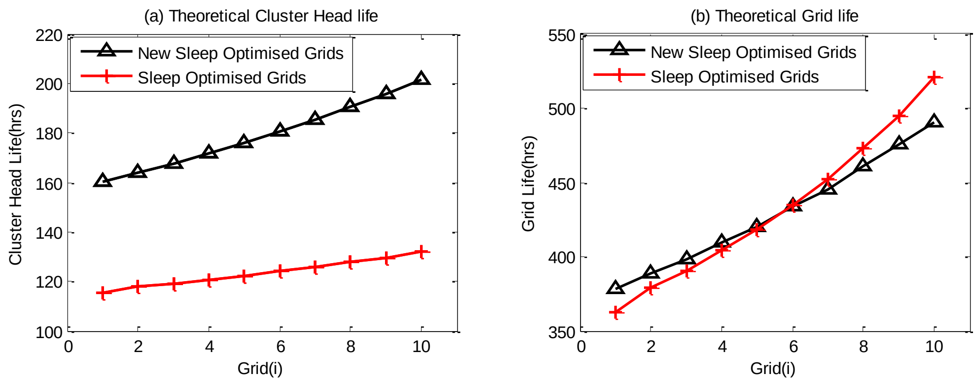

Figure 5.18 Theoretical cluster head and grid lifetime comparison for New and Original Model

The first grid of the New Sleep Optimised grids network has 5% more life compared to Sleep Optimised grids model. During simulation, both the networks do not have 100% packet delivery due collisions, retransmissions, and dropping packets due to long wait times, this causes the cluster head and grid lifetimes to deviate slightly from the theoretical values.

5.4.3 Reducing Network Traffic to 50% & 10% with the New Sleep Model

As network traffic is reduced to 50%, the data generated from each node is reduced from 0.003 Erlang to 0.0015 Erlang. At lower data rates the throughputs and packet delivery for all the networks are 100%. As Figure 5.19(a) shows that cluster head 2 of the New Sleep Optimised grids cluster head has around 55 hours more lifetime as compared to the Original Sleep Optimised grids network.

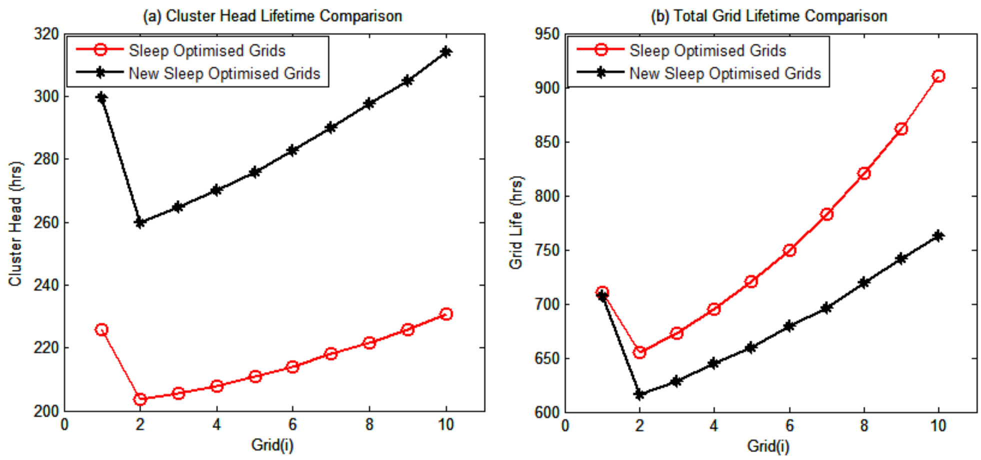

Figure 5.19 Comparison of cluster head lifetime of New Sleep Optimised grids with Sleep Optimised grids Network with 50% Traffic

However Figure 5.19(b) shows that grid 2 of Original Sleep Optimised grids network has around 40 hours more lifetime as compared with New Sleep Optimised grids. Again that advantage gained by the cluster head is lost, as the Original Sleep Optimised grids network has more nodes to rotate in the grid due to larger size.

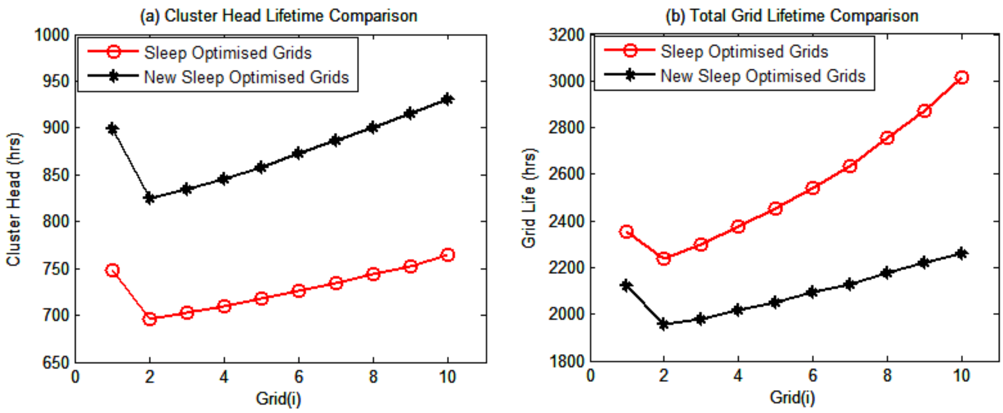

Figure 5.20 Comparison of cluster head lifetime of New Sleep Optimised grids with Sleep Optimised grids Network with 10% Traffic

In the last part of this section the network traffic produced by each node in the network is reduced from 0.003 Erlang to 0.0003 Erlang. The New Sleep Optimised grids networks again show a much higher cluster head lifetime for node as shown in Figure 5.20(a) but the Original Sleep Optimised grids network has higher grid lifetime (Figure 5.20(b)) as more node are present in individual grids.

5.5 Dynamic New Sleep Model with Lower Traffic

As the traffic is increased or lowered in the network, it has been concluded in Chapter 4.0 section 4.5 that by re-optimising the existing network, an increase in cluster head and grid life can be achieved. In this section the algorithm developed in section 5.4 is used again to see if re-optimisation brings any further benefits to the network. Two scenarios, when the traffic is reduced to 50% and 10% have been developed and the results are compared with all the simulations that have been carried out with lower traffic networks.

5.5.1 Dynamic New Sleep Optimised grids Network with 50% Network Traffic

When the network traffic is reduced from 100% to 50%, the total amount of data reaching the base station is halved to 128700 bits/s. Using equation 5.5, the new Dynamic grid sizes are calculated for the entire three networks. Table 5-3 shows the recalculation of grid sizes. It can be seen that for the New Sleep Optimised grids network, the number of grids have decreased from 32 to 28. The New Sleep COTS and New Sleep Equal grids network were also set up using 28 Equal grids. The traffic produced from each cluster head node along with the CBR setting is also shown in Table 5-3.

The simulations were run for 1010 seconds. The CBRs were started after 10 seconds and stopped at 1010 seconds. The energy consumption is calculated for 990 seconds.

Table 5-3 Packets transmitted from each cluster head for the Dynamic networks with 50% Traffic

	Optimised Grids CBR Timings					COTS & Equal Grids CBR Timings		
Grid	Grid Size	Traffic	CBR Time		Grid	Grid Size	Traffic	CBR Time
(i)	(m)	Packets/s	(s)		(i)	(m)	Packets/s	(s)
1	17.9	0.4799	2.08		1	21.42	0.5743	1.74
2	18	0.4826	2.07		2	21.42	0.5743	1.74
3	18.1	0.4853	2.06		3	21.42	0.5743	1.74
4	18.2	0.4880	2.05		4	21.42	0.5743	1.74
5	18.3	0.4907	2.04		5	21.42	0.5743	1.74
6	18.4	0.4934	2.03		6	21.42	0.5743	1.74
7	18.5	0.4960	2.02		7	21.42	0.5743	1.74
8	18.7	0.5014	1.99		8	21.42	0.5743	1.74
9	18.8	0.5041	1.98		9	21.42	0.5743	1.74
10	18.9	0.5068	1.97		10	21.42	0.5743	1.74
11	19.1	0.5121	1.95		11	21.42	0.5743	1.74
12	19.3	0.5175	1.93		12	21.42	0.5743	1.74
13	19.5	0.5228	1.91		13	21.42	0.5743	1.74
14	19.7	0.5282	1.89		14	21.42	0.5743	1.74
15	19.9	0.5336	1.87		15	21.42	0.5743	1.74
16	20.2	0.5416	1.85		16	21.42	0.5743	1.74
17	20.5	0.5497	1.82		17	21.42	0.5743	1.74
18	20.9	0.5604	1.78		18	21.42	0.5743	1.74
19	21.3	0.5711	1.75		19	21.42	0.5743	1.74
20	21.7	0.5818	1.72		20	21.42	0.5743	1.74
21	22.3	0.5979	1.67		21	21.42	0.5743	1.74
22	23	0.6167	1.62		22	21.42	0.5743	1.74
23	23.9	0.6408	1.56		23	21.42	0.5743	1.74
24	25	0.6703	1.49		24	21.42	0.5743	1.74
25	26.7	0.7159	1.40		25	21.42	0.5743	1.74
26	29.2	0.7829	1.28		26	21.42	0.5743	1.74
27	33.7	0.9036	1.11		27	21.42	0.5743	1.74
28	30	0.8124	1.23		28	21.42	0.5808	1.72
	599.7	16.0875				599.76	16.0875	

Figure 5.21(a) compares the cluster head life between the New Sleep and the New Dynamic sleep for all the three networks. It can be seen that by re-optimisation, the cluster head life has decreased for the New Dynamic Sleep Equal grids network. The reason is that the grid sizes have become larger; therefore more energy is consumed in transmitting messages over a longer distance.

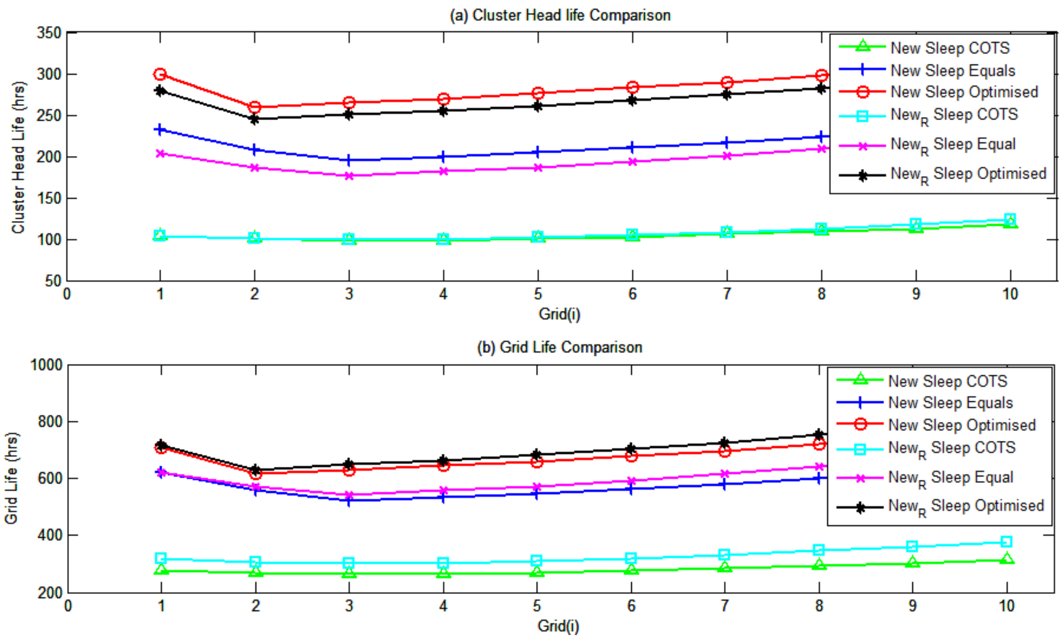

Figure 5.21 50% Traffic cluster head & network lifetime comparison between the New sleep and New Dynamic Sleep Networks

So what has been the benefit of re-optimisation? Well it can be seen in Figure 5.21(b), the Re-Optimisation has led to larger grid sizes, even though the cluster head life has decreased, the total grid lifetime for the New Dynamic Sleep Optimised grids has in fact increased by 25 hours for grid 2 compared with New Sleep Optimised grids model. Also it can be noticed comparing with New Dynamic Equal grids network and New Dynamic COTS network, the lifetime has increased by over 13% and 200% respectively.

At this point it is clear that the Optimised grids networks using the Sleep Mode or the New Sleep Model has increased cluster head and grid lifetime advantage over Equal grids and COTS network including the Sleep Mode as well as New Sleep Model. The next step is to compare all the models together and see which has the most advantage. Figure 5.22 with 5 graphs compares the cluster head lifetimes for all the models studied for the Optimised grids network with 50% traffic. Figure 5.22 (a,b,c,d) shows that the New Dynamic Sleep Optimised grids cluster heads have much higher lifetimes compared to four other models that include the a) Optimised grids model with Idle energy, b) Dynamic Optimised grids model with idle energy, c) Optimised grids model with Sleep Mode and d) Dynamic grids model with sleep mode.

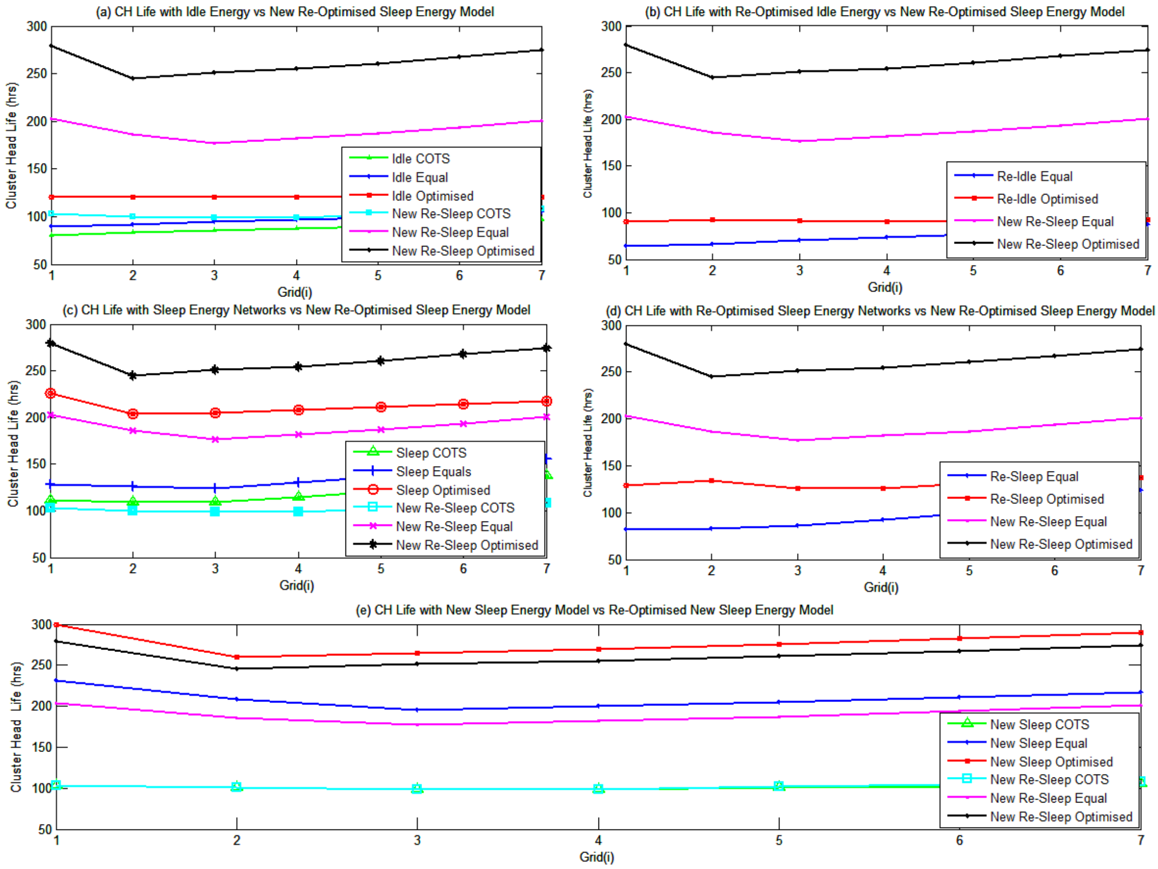

Figure 5.22 50% Traffic: Cluster head lifetime comparison between 5 different models

Figure 5.22(e) shows that only the New Sleep Optimised Network model has around 20hrs of more lifetime compared with the New Dynamic Sleep Optimised grids and that is because the grid size has increased. This also concludes that the New Sleep Model provides the longest cluster head lifetime at lower traffics.

But higher cluster head lifetime does not necessarily means a higher grid life, as the size of the grid varies with traffic fluctuation, it becomes necessary to compare the grid lifetimes for all the different networks.

Figure 5.23 compares the network lifetimes for all the models. Again it can be seen that the grid lifetime for the New Dynamic Sleep Optimised grids is higher as compared with Figure 5.23(a) Optimised grids model with Idle energy, 5.23(b) Dynamic Optimised grids model with idle energy, 5.23 (d) Dynamic grids model with sleep mode and 5.23e) New Sleep model (Please note this model has the highest cluster head lifetime).

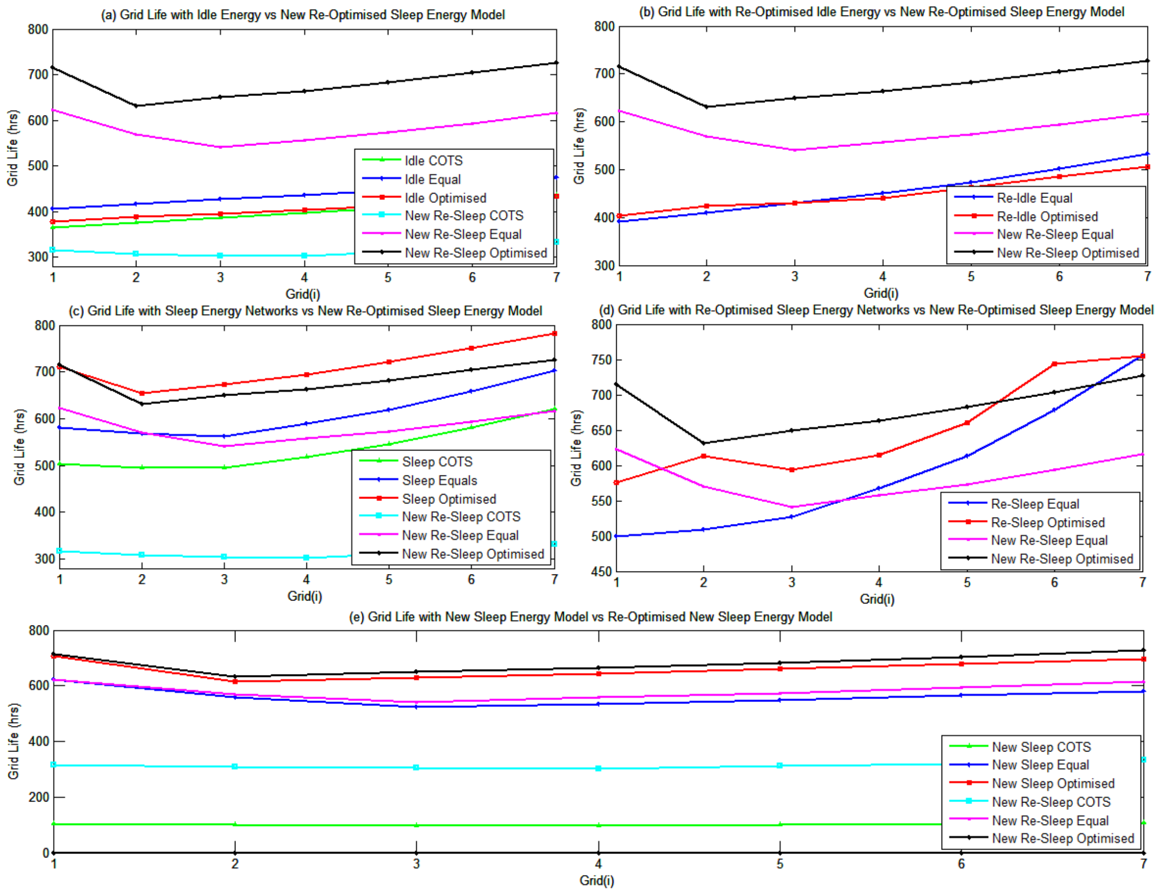

Figure 5.23 50% Traffic: Cluster head lifetime comparison between 5 different models

Figure 5.23(c) shows that the Sleep Optimised grids model has highest grid lifetime as compared to New Dynamic Sleep Optimised grids. The grid lifetime difference is around 16 hours before the first grid runs out of energy. The key question to answer is to find out if there is still any advantage at even lower loads.

5.5.2 Dynamic New Sleep Optimised grids Network with 10% Network Traffic

The final results section of this chapter deals with the situation when the traffic drops from 100% to 10% of the normal traffic load. A quick reminder, at 100% traffic 0.2574 Mbits/s of data is being forwarded by the cluster head node nearest to the base station. At 10% traffic, this load is reduced to 0.02574 Mbits/s. The New Sleep Optimised grids network was Dynamic with lower traffic. The number of grids has reduced from 32 to 17 only. The grid size for the first grid has increased by 61.8% from 16.5m to 26.7m. Table 5-4 displays the new grids sizes with traffic transmitted by each cluster head and also the CBR timings.

Table 5-4 Packets transmitted from each cluster head for the Dynamic networks with 10% Traffic

	Optimised Grids CBR Timings					COTS & Equal Grids CBR Timings		
Grid	Grid Size	Traffic	CBR Time		Grid	Grid Size	Traffic	CBR Time
(i)	(m)	Packets/s	(s)		(i)	(m)	Packets/s	(s)
1	26.7	0.1432	0.143		1	35.3	0.1893	5.283
2	27.1	0.1453	0.145		2	35.3	0.1893	5.283
3	27.5	0.1475	0.147		3	35.3	0.1893	5.283
4	28	0.1502	0.150		4	35.3	0.1893	5.283
5	28.6	0.1534	0.153		5	35.3	0.1893	5.283
6	29.3	0.1571	0.157		6	35.3	0.1893	5.283
7	30	0.1609	0.161		7	35.3	0.1893	5.283
8	30.8	0.1652	0.165		8	35.3	0.1893	5.283
9	31.8	0.1705	0.171		9	35.3	0.1893	5.283
10	32.9	0.1764	0.176		10	35.3	0.1893	5.283
11	34.2	0.1834	0.183		11	35.3	0.1893	5.283
12	35.9	0.1925	0.193		12	35.3	0.1893	5.283
13	38.1	0.2043	0.204		13	35.3	0.1893	5.283
14	41.1	0.2204	0.220		14	35.3	0.1893	5.283
15	45.5	0.2440	0.244		15	35.3	0.1893	5.283
16	53.1	0.2847	0.285		16	35.3	0.1893	5.283
17	59.5	0.3185	0.319		17	35.3	0.1888	5.298
	600.1	3.2175				600.1	3.2175	

The simulation was carried out for 1010 seconds with CBR start time at 10 seconds and stop time of 1010 seconds during the simulation. Figure 5.25 compares the cluster head lifetimes of the of all all three New Dynamic Sleep COTS, Equal and Optimised grids networks with New Sleep COTS, Equal and Optimised grids networks. It can be seen from Figure 5.24(a) by re-optimisation, the cluster head lifetime of the New Dynamic Sleep Optimised grids cluster head lifetime has fallen below the New Sleep Optimised and Equal grids network considerably. As the grid size has increased by re-optimsation the transmisison energy has increased. But on the other hand the number of nodes has also increased. So despite decrease in cluster head lifetime is there any increase in grid life?

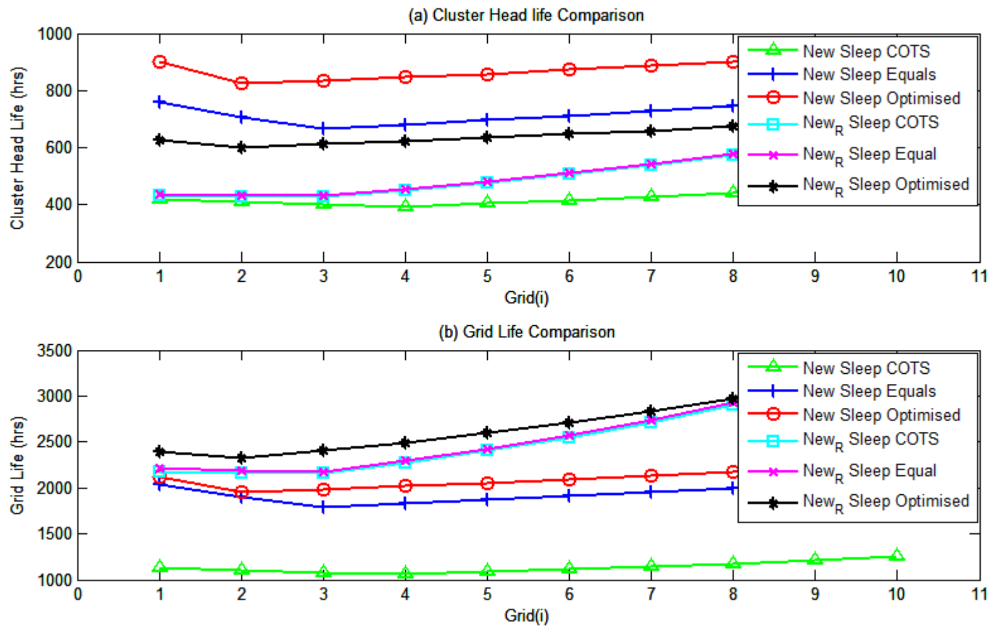

Figure 5.24 10% Traffic cluster head & network lifetime comparison between the New sleep and New Dynamic Sleep Networks

Figure 5.24(b) indicated that re-optimisation has actually benefited the New Dynamic Sleep Optimised grids (black line) network as it has a higher grid lifetime as compared to New Sleep Optimised grids and Equal grids network. In fact it also has over 200% more network lifetime as compared New Sleep COTS network. This means that if the traffic becomes much lower, then advantage can be taken by re-optimsation of New Sleep Model.

Further comparisons of cluster head and network lifetime models were carried out as shown by Figure 5.24. Quite obviously at 10% traffic with new Dynamic sleep model, the New Dynamic Sleep Optimised grids network has much higher cluster head lifetime as compared with Figure 5.25(a) Optimised grids model with Idle energy, 5.25(b) Dynamic Optimised grids model with idle energy, 5.23 (d) Dynamic grids model with sleep mode. But compared with 5.23(c) Optimised grids model with sleep mode and 5.23(e) New Sleep model (Please note this model has the highest cluster head lifetime), it has lower cluster head lifetime. When the network traffic is very low, advantage can be gained with more number of cluster heads to rotate in the grid by having larger grids. This is because at low traffic it can be seen from Figure 5.10(e) that one cluster head node can have a lifetime of up to 900 hours. The next step is to compare the grid life for all the models with 10% traffic.

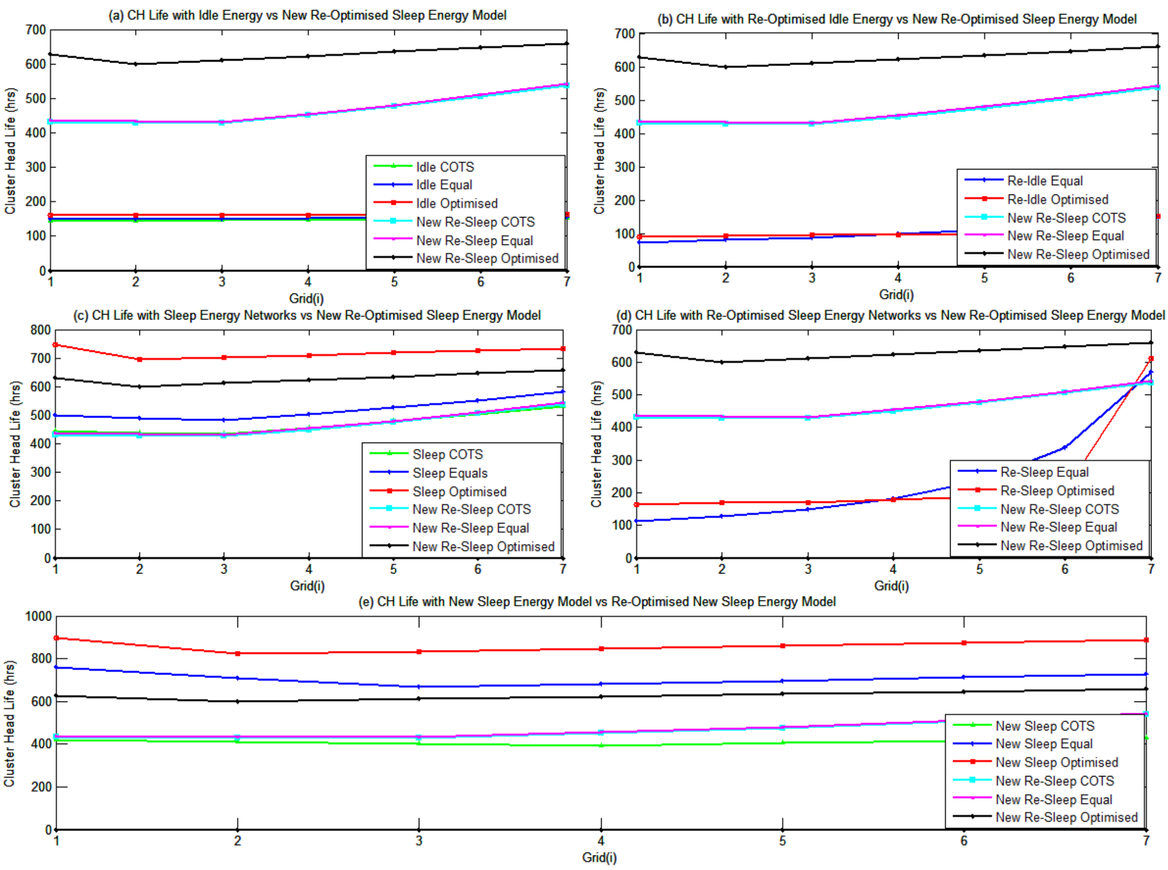

Figure 5.25 10% Traffic: Cluster head lifetime comparison between 5 different models

Figure 5.26 shows that at 10% traffic, the New Dynamic Sleep Optimised grids network has much higher lifetime compared to all the other 5 models. It has a much higher grid lifetime (90 hours and 300 hrs) as compared to its 2 biggest rivals, the Optimised grids network with Sleep Mode (Figure 5.26c) and New Sleep Optimised grids model (Figure 5.26e). So at lower traffic, The New Dynamic Sleep Optimised grids network can be used to increase grid lifetime as it carefully balances the grid size with lower traffic.

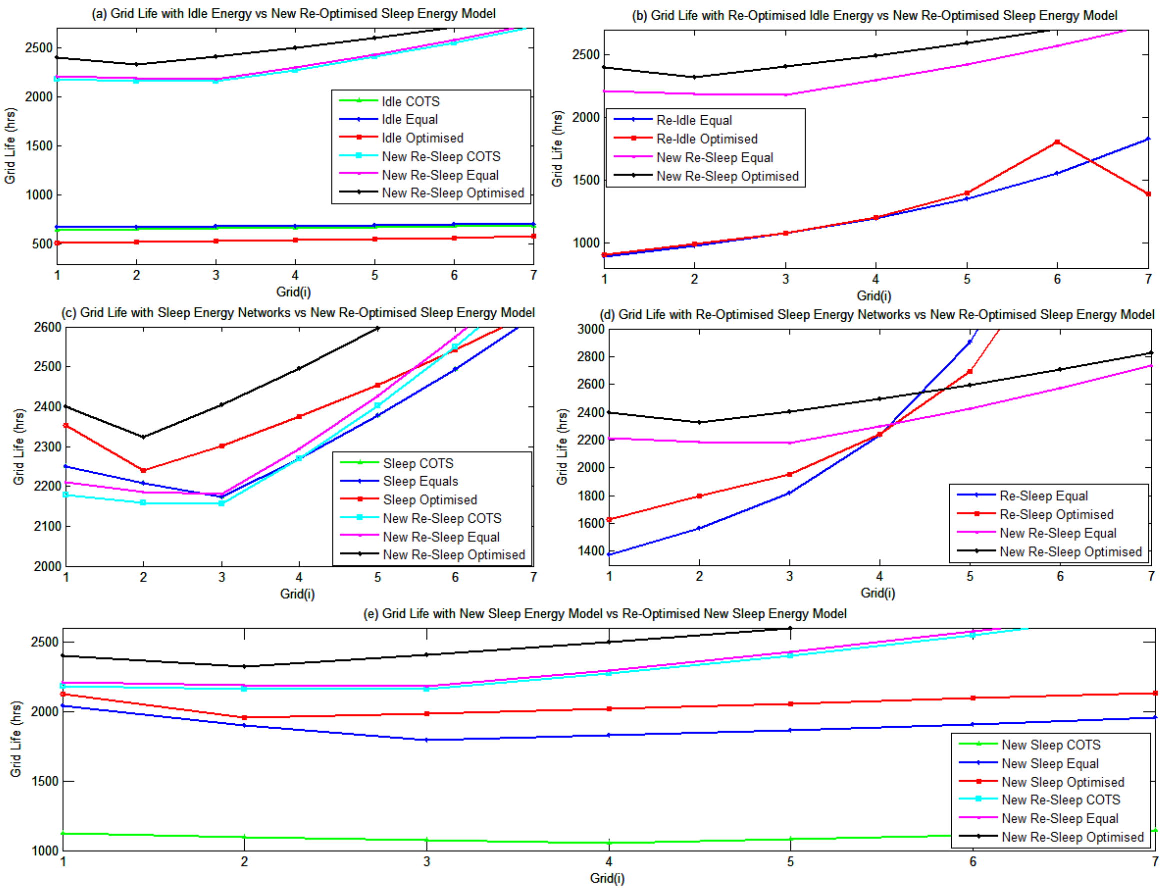

Figure 5.26 10% Traffic: Grid lifetime comparison between 5 different models

5.6 Conclusion

In this chapter, the sleep energy was introduced in the Optimised grids, Equal grids and COTS networks. Four different models were prepared that included

i) Sleep Mode: where the sleep energy was introduced to the existing model.

ii) Dynamic Sleep Mode: this required re-optimising the three networks with the Sleep Mode model during higher or lower traffic.

iii) New Sleep Model: this involved in modifying the original model by adding duty cycles for Idle and Sleep time.

iv) New Dynamic Sleep Model: Again re-optimising the three networks created using the New Sleep Model (iii) during higher and lower traffic.

At 100 % traffic it was noticed that by introducing Sleep Mode to the Original Model, the cluster head lifetime and grid lifetime for the Sleep Optimised grids network increased by 26% and 39% for the first five cluster heads, while that for Equal grids and COTS network the cluster head life increased only by 13.3 and 18.4%.

During the 10% traffic load, the Sleep Optimised grids network's total lifetime increased from 530 hours to 2300 hours. The node energy saved during the sleep state was very efficiently utilised. The Sleep Optimised grids network also had a higher network lifetime compared to Sleep Equal and Sleep COTS network.

At higher traffic loads of 200%, the Sleep Optimised grids lifetime was 32% higher as compared to Sleep Equal grids network.

At lower traffic, Dynamic Sleep Model decreases the network lifetime for the Optimised grids network as the grids becomes larger in size and use higher transmission energy.

By adding the idle and sleep duty cycles to the Original Model, a New Sleep Model was introduced. It is shown by simulation that at 100% traffic, the cluster head lifetime of New Sleep Optimised grids network increased by at least 37% compared to the Sleep Optimised grids network. Even at lower traffic rates of 50% and 10%, the New Sleep Model delivered much higher cluster head lifetime for all the three networks, with New Sleep Optimised grids network having the highest cluster head lifetimes.

As the New Sleep Model decrease the grid sizes, the total number of nodes rotating as cluster head decreases, and hence the total grid life of New Sleep Optimised grids network was slightly less compared to the Sleep Optimised grids network.

However by re-optimising the New Sleep model at lower traffic e.g. 10% load, showed that the New Dynamic Sleep Optimised grids network had the highest network lifetime compared to all the other models.

Keeping in mind that the wireless sensor networks are usually in the idle state for long periods of time until an event occurs. In the state of inactivity, they would have much lesser traffic than normal. The Dynamic New Sleep model can increase the network lifetime by up to 480% as compared with the network that consumes idle energy with similar lower traffic.

Chapter 6

Two Dimensional Networks with Wireless Sensor Data

The original model developed in Chapter 4.0 consists of a one dimensional linear network in which the cluster heads were required to forward the data to the base station. This led into an in-depth study of the network QoS parameters and also the cluster head and grid lifetimes for one dimensional networks. In this, chapter, wireless sensor nodes were added to the existing original one dimensional (1-D) network. Each wireless sensor node communicates directly with its cluster head. The cluster head was then responsible to forward all the data to the base station. This included the cluster head’s own sensor data as well as the data received from all the other wireless sensor nodes in that grid. The cluster head also had to forward data received from the cluster head from the previous grid.

A two dimensional (2-D) Optimised grids linear network was setup with all the wireless sensor nodes corresponding with their own cluster head node. Each cluster head node now not only had to communicate with its neighbouring cluster head node but also had to receive data from all the nodes within its cluster. This meant that now the cluster head node will have less time to receive and forward data from its neighbouring cluster head nodes and will result in more congestion on the network. The QoS parameters, cluster head and grid lifetimes were re-examined to study the effect of extra wireless network traffic interference caused by the new wireless sensor nodes. The 2-D models were modified by changing the network parameters, e.g. traffic fluctuation, RTS/CTS handshakes and introducing Sleep Mode.

6.1 Introducing Wireless Sensor Nodes into the Existing Model

The simulation models developed in this section are based on the Optimisation theory developed in Chapter 4.0 section 4.1. The length of the 2-D linear network was set to be 600m. The data transmitted by each node was set to 0.003 Erlang. The node density was set to 0.143 nodes/m. The total traffic approaching the base station was calculated by using equation (4.16) from Chapter 4.0. Therefore the total traffic reaching the base station was (600)*0.143*0.003 = 0.2574 Erlang. This amount of data is referred as 100% traffic.

Using equation (4.15) from Chapter 4.0, the Optimised grids sizes and the number of nodes in each grid were calculated as defined in Table 6-1 for the 2-D Optimised grids network. The transmit energy is the amount of energy consumed in transmitting the message for one second for the cluster head and for the wireless sensor nodes in that grid.

Table 6-1 2-D Optimised grids Sizes and Sensor Nodes Data for 600m Network

Grid (i)	R (i) (m)	Number of nodes in each grid	Transmit energy consumption for r(i) at 1Mbit/s (j/s)
Base (0)	0	0.0	0.0000
1	22	3.1	0.2420
2	22.5	3.2	0.2480
3	22.9	3.3	0.2561
4	23.4	3.3	0.2644
5	23.9	3.4	0.2737
6	24.5	3.5	0.2843
7	25.1	3.6	0.2960
8	25.9	3.7	0.3101
9	26.7	3.8	0.3267
10	27.6	3.9	0.3448
11	28.6	4.1	0.3658
12	29.9	4.3	0.3922
13	31.3	4.5	0.4245
14	33.1	4.7	0.4647
15	35.4	5.1	0.5192
16	38.4	5.5	0.5946
17	42.8	6.1	0.7093
18	50.1	7.2	0.9130
19	65.9	9.4	1.3956

The energy consumed in receiving a message is a fixed amount and is also same as the idle energy consumption that is 0.05j/s for all the cluster heads and wireless sensor nodes throughout the network. Table 6-1 also indicates that by moving away from the base station, the Optimised grids start to increase in size as the traffic becomes less. The numbers of wireless sensor nodes also increase within that grid based on the node density of 0.143 nodes/m. The total number of un-equal Optimised grids calculated for the 2-D Optimised grids network is 19. Noah was used as the routing protocol that defines a pre-set multi-hop network, which only allows nodes to transmit to their neighbouring nodes, or wireless sensor nodes to communicate only to their cluster head respectively.

Table 6-2 defines the number of grids for the 2-D Equal grids and 2-D COTS networks. The grid sizes are of equal distance and the number of nodes is also equal in all these grids. The 2-D COTS network has higher fixed transmission energy consumption as compared with the 2-D Equal grids network.

Table 6-2 Equal grids and COTS Networks Grid size and Number of Nodes for 600m 2-D Network.

Grid (i)	R (i) Equal Grids & COTS (m)	Number of nodes in each grid	Transmit energy consumption for r(i) at 1Mbit/s (j/s)	Transmit energy consumption for r(i) at 1Mbit/s (j/s)
Base (0)	0	0.0	Equal Grids	COTS
1	31.57	4.5	0.45	0.54
2	31.57	4.5	0.45	0.54
3	31.57	4.5	0.45	0.54
4	31.57	4.5	0.45	0.54
5	31.57	4.5	0.45	0.54
6	31.57	4.5	0.45	0.54
7	31.57	4.5	0.45	0.54
8	31.57	4.5	0.45	0.54
9	31.57	4.5	0.45	0.54
10	31.57	4.5	0.45	0.54
11	31.57	4.5	0.45	0.54
12	31.57	4.5	0.45	0.54
13	31.57	4.5	0.45	0.54
14	31.57	4.5	0.45	0.54
15	31.57	4.5	0.45	0.54
16	31.57	4.5	0.45	0.54
17	31.57	4.5	0.45	0.54
18	31.57	4.5	0.45	0.54
19	31.57	4.5	0.45	0.54

The data rates and the basic rates for all the three networks were set to 1Mbit/s. Each packet was set to 1000 bytes which included the preamble of 72 bytes, RTS: 44 bytes, CTS: 38 bytes and acknowledgment 38 bytes. Each wireless sensor node generates 0.003 Erlang of data per second; this is equal to 0.375 bytes/s. Therefore each wireless sensor node transmits a data packet of 1 kByte with an interval of 2.66 seconds. For all the three

2-D networks, all the wireless sensor nodes transmit a one Kbyte packet at a constant rate of 2.66 seconds to their respective cluster heads.

The total number of nodes in each of the 2-D network is 86 including 19 cluster head nodes and the base station.

Figure 6.1 shows the 2-D Optimised grids network in the enhanced NS2 simulation setup. Node 0 is always set as the base station. Nodes 1 to 19 with dark circles depict the cluster heads for each grid. The rest of the nodes from 20 to 85 are wireless sensor nodes. The number of nodes in each grid is given by Table 6-1. With the Optimised grids network, the grids become larger as the distance between the base station increases. It can be seen grid 19 has much higher number of nodes compared with grids 1 and 2.

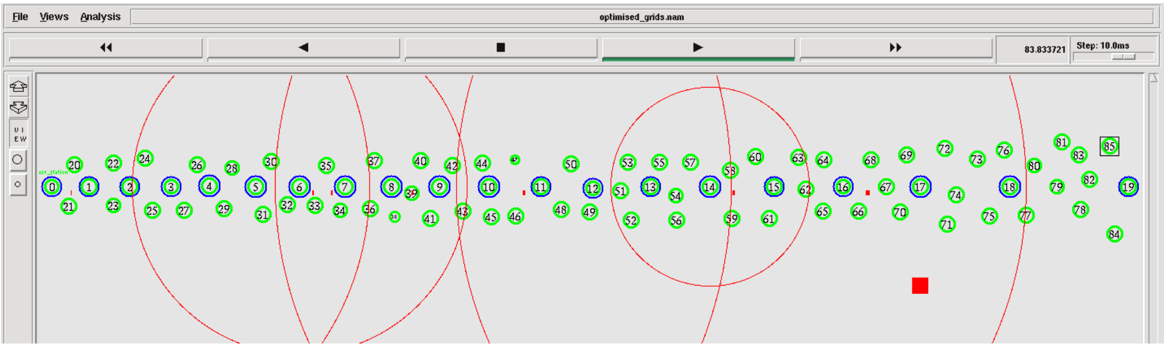

Figure 6.1 2-D Optimised grids network with wireless sensor nodes.

The 2-D Equal grids and 2-D COTS network were setup as shown in Figure 6.2. The distance between all the grids is equal, hence all the grids have equal number of wireless sensor nodes. Again node 0 is set as the base station. Cluster heads are represented by nodes 1 to 19 and have darker outer circles. Nodes from 20 to 85 are wireless sensor nodes.

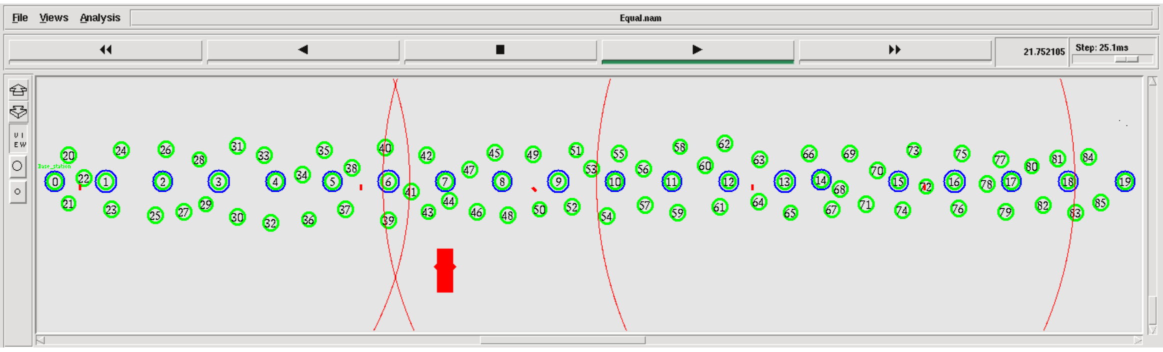

Figure 6.2 2-D Equal grids and COTS network with wireless sensor nodes.

Once the 2-D Optimised grids, 2-D Equal grids and 2-D COTS network were configured, the NS simulation was run for 2000 seconds. The results achieved after running the simulations were analysed and the results are discussed in the next section.

6.1.1 Performance Evaluation of 2-D Optimised grids vs 2-D Equal grids and 2-D COTS Networks.

One of the key differences between the linear 1-D and 2-D network is that all the wireless sensor nodes are included in the simulation. These wireless sensor nodes add extra burden on the network near the base station as the cluster heads not only have to receive and forward all the data from the previous cluster heads, but also have to communicate with its local wireless sensor nodes. This extra traffic and interference caused by the local wireless sensor nodes can have detrimental effects on the total throughput as they will be trying to communicate with the cluster head, and decreasing its performance in receiving packets from previous cluster head and forwarding them to the next cluster head.

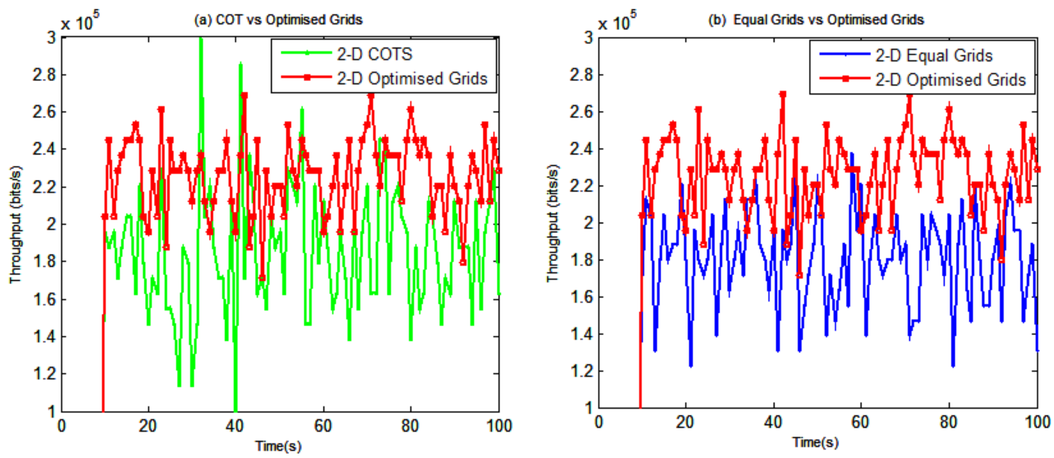

Figure 6.3 2-D 100% Traffic Throughput comparison between all the three 2-D networks

Figure 6.3 compares the throughput achieved by the all the three 2-D linear sensor networks. The 2-D Optimised grids network has a much higher throughput of 225789 bits/s as compared to 180596 bits/s and 185707 bits/s compared with 2-D Equal grids and 2-D COTS network. This proves that the 2-D Optimised grids network has much better spatial reuse where cluster head nodes do not receive message from grid ($i+2$) due to Optimised grid's asymmetric spacing hence reducing network congestions and collision while improving throughput. When compared with 1-D networks, all the three 2-D networks suffered a drop in throughput by approximately 7.5%. With respect to 2-D COTS and 2-D Equal grids network, the 2-D Optimised grids network showed an increased throughput between 21% and 25% respectively.

As the throughput is affected due to the addition of wireless sensor traffic in the network, Figure 6.4 (abc) compares the packet delivery, average latency and jitter for the three 2-D networks. The 2-D Optimised grids network exhibits a higher percentage of packet delivery (over 77%) for all the cluster heads in the network as well as nearly over 98% for the first three grids nearest to the base station. The 2-D Equal grids and 2-D COTS network show great performance for the first 3 grids, but then comes a sharp drop in packet delivery up and until grid 12 and onwards, where an average just below 55% is maintained for the rest of the grids. Due to inefficient Equal grids spacing, the network suffers from large number of collisions, retransmissions and elongated waiting times. The conclusions are justified by Figure 6.4(b) that shows the 2-D Optimised grids network having around 9 times less latency compared with the other two networks.

For the 2-D Equal grids and 2-D COTS network, the trouble starts, when cluster heads, 1,2 and 3 are forwarding all their sensor data, and queues start to build up on cluster heads 4 and onward till the end of the two networks.

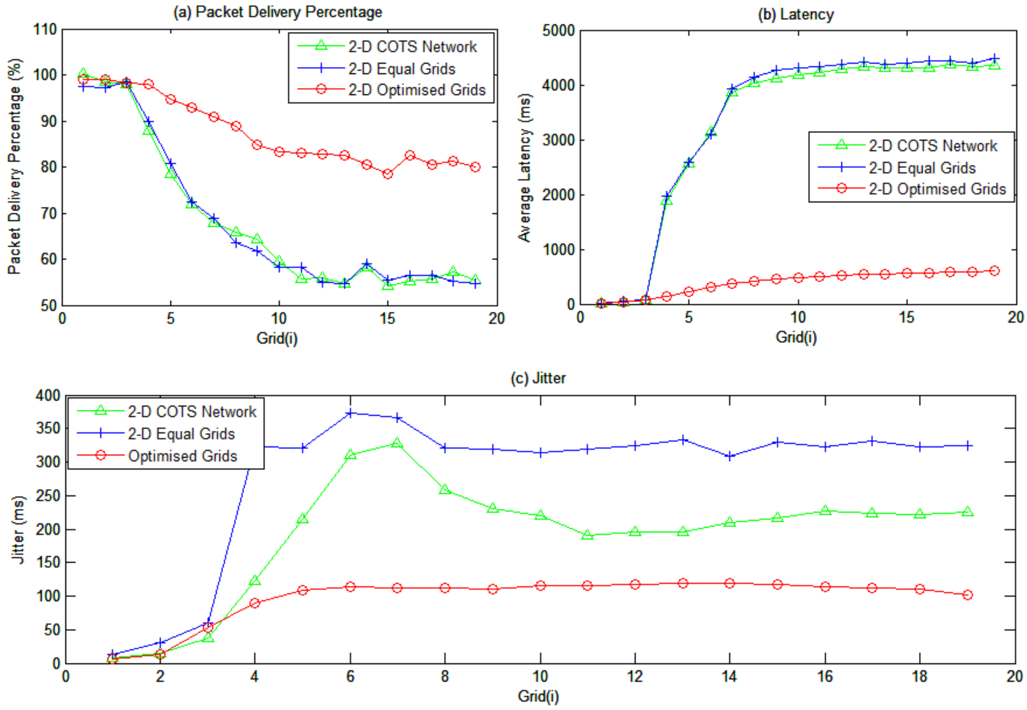

Figure 6.4 Packet Delivery, Latency and Jitter comparison for 2-D networks with 100% traffic.

The jitter for the 2-D Optimised grids network is also around 1/3 compared to 2-D Equal grids ½ compared to 2-D COTS network. A key point to remember is that while comparing these results with 1-D linear networks, all the three networks suffered a reduction in packet delivery and an increased average latency and jitter.

Moving away from cluster heads, Figure 6.5 compares the network QoS parameters for all the wireless sensor nodes in each of the 2-D network. Please note, that nodes 1to 19 are cluster head nodes, that are not included in Figure 6.5, due to their higher traffic capacity. As all the three networks have 85 nodes, nodes from 20 to 85 are sensor nodes. All these nodes produce the same amount of data irrespective of their grid size or location in the network. Each node has to transmit 0.003 Erlang data which is equivalent to generating a 1000 byte packet every 2.67 second. Depending on grid size and number of nodes in each grid from Table 6-1, for the 2-D Optimised grids network, nodes 20 and 21 will be in grid 1, nodes 22 and 23 will be in grid 2. Hence for all the three networks, nodes from 20 and 30 lie between the first 4 grids nearest to the base station. Another thing to note is that these wireless sensor nodes only report to their respective cluster heads. They have no contact with the base station nor do they transmit any data directly to other wireless sensor node (this does not exclude that other nodes within their transmission range will not hear them). Some peaks can be seen where sensor nodes are transmiting over 100%, as the packet delivery percentage is measured as the No of packets received over total expected packets, per second at the cluster head node. The wireless sensor nodes transmission rate is set as random. E.g from above a sensor node has to send a packet every 2.67 second. However when set to random, it can send that packet any time between 0 and 2.67 second. And again in the next cycle period it has to send one packet within that time period. Hence in some cases, the packets can reach very close to each other when the packets are sent back to back as shown as a peak in the graphs.

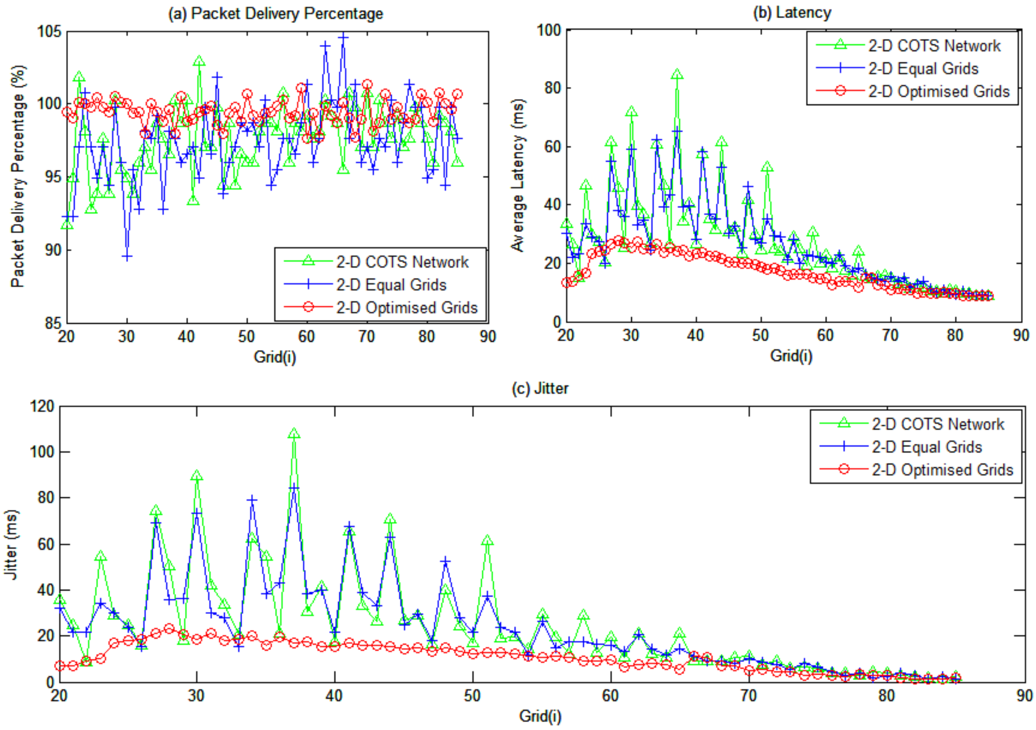

Figure 6.5 Wireless sensor nodes QoS parameters in 2-D networks.

The 2-D Optimised grids's wireless sensor nodes have nearly 99% packet delivery, while the other 2 network have slightly less. The latency and jitter between wireless Sensor nodes 30 to 40 are relatively high for 2-D Equal grids and 2-D COTS network. This where these networks, start to become inefficient, and cluster head nodes start dropping majority of the packets. From Figure 6.5 (b,c) the latency and jitter decreases for all the three 2-D networks towards the furthest end away from the base station due to less traffic.

6.1.2 Sensor Nodes, Cluster head and Network Lifetimes for 2-D Networks with 100% Traffic

In 1-D linear networks, the energy consumption was only concerned with cluster heads, and the network lifetime was based on the rotation of cluster heads in each grid. This section looks into a lot more detail with the energy consumptions of single wireless sensor node, total wireless sensor nodes, cluster head and total grid consumption for the three 2-D networks with full idle energy and also Sleep Mode. In Sleep Mode, the idle energy consumption for all the nodes is reduced to 10% of the original value. This means that the nodes are only awake for 10% of the idle time.

Figure 6.6 (a,b,c) gives a complete breakdown of energy consumptions for all the three 2-D networks with full idle energy consumption. Figure 6.6 (a) represents the 2-D

Optimised grids network, while Figure 6.6 (b&c) represents the 2-D Equal grids and 2-D COTS networks, respectively.

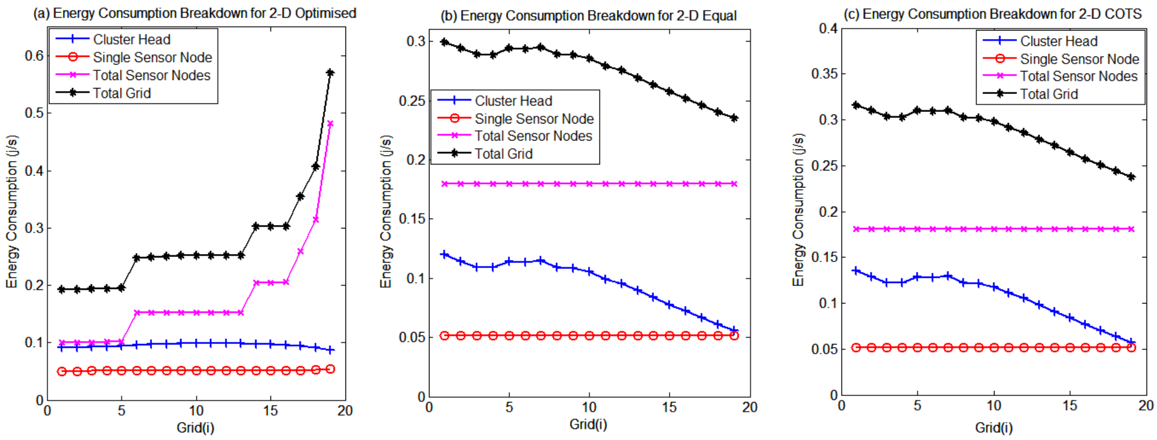

Figure 6.6 Sensor node, cluster head and grid energy consumption for 2-D networks with 100% idle Energy.

The individual wireless sensor node energy consumption per second for the 2-D Optimised grids network is 2% & 3 % lower as compared with the other two networks. This might not seem as a big value, but over a couple of days and the number of nodes, these values can produce significant savings in energy costs and hence an increase the network lifetime. Also realising that these wireless sensor nodes transmit very little data and normally remain idle for long periods of time. e.g. one message every 2.67 seconds. The most important factor is the total cluster head energy consumption. The 2-D Optimised grids network uses 30% and 47% less energy compared with the 2-D Equal and 2-D COTS network. The blue line of Figure 6.6(a) indicates how the network energy consumption is balanced throughout all the cluster head nodes in the 2-D Optimised grids network. The total grid energy consumption (black line) includes the total consumption for all the sensor nodes and the cluster head for the three 2-D networks. The 2-D Optimised grids network has 55% and 63% less energy consumption as compared with 2-D Equal grids and 2-D COTS network. Near to the base station, the 2-D Equal grids and 2-D COTS network have bigger grid size compared to the 2-D Optimised grids network. This bigger size worked out in their advantage in the 1-D linear networks where they had more nodes to rotate to become cluster heads and hence have a longer network lifetime.

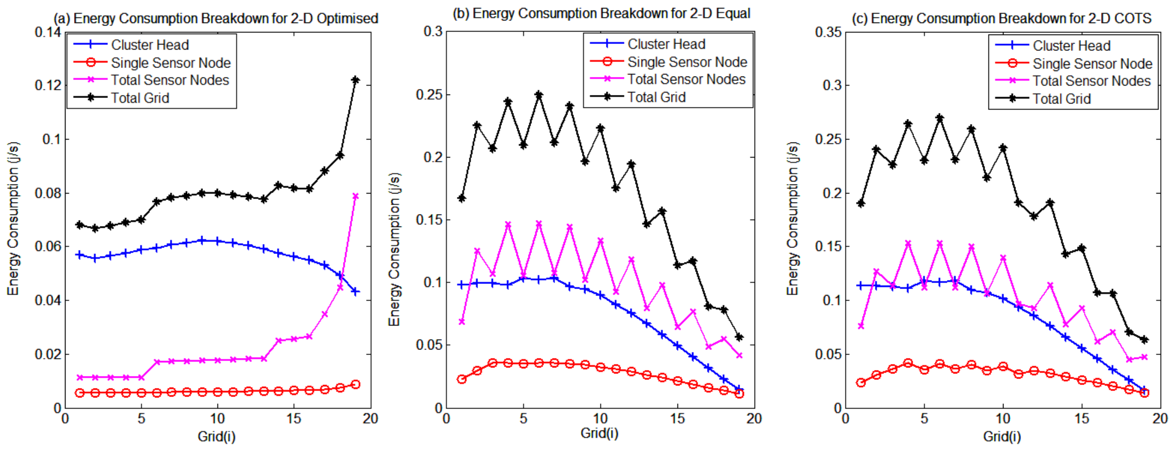

Figure 6.7 Sensor node, cluster head and grid energy consumption with 10% idle energy.

It has been learnt from Chapter 4.0 that idle energy becomes dominant when the traffic is low. This also means that apart from the cluster heads nearest to the base station, all the other wireless sensors nodes spend a lot of their time in idle state and therefore consume large amounts of idle energy. The next stage involved in adding the Sleep mode to the three 2-D networks. The Sleep mode is explained in Chapter 5.0 section 5.1. In Sleep mode the nodes only stay awake for 10% of the total idle time. For 90% of the time it is assumed that the node goes to sleep and does not consume any energy at all.

Figure 6.7 (a,b,c) reflects the energy consumptions for the wireless sensor nodes, cluster heads, and total grid for the three 2-D networks with the Sleep Mode. By introducing the Sleep mode, the total grid consumption for the first grid of the 2-D Optimised grids networks is 40% and 59% lower as compared with the 2-D Equal grids & COTS network.

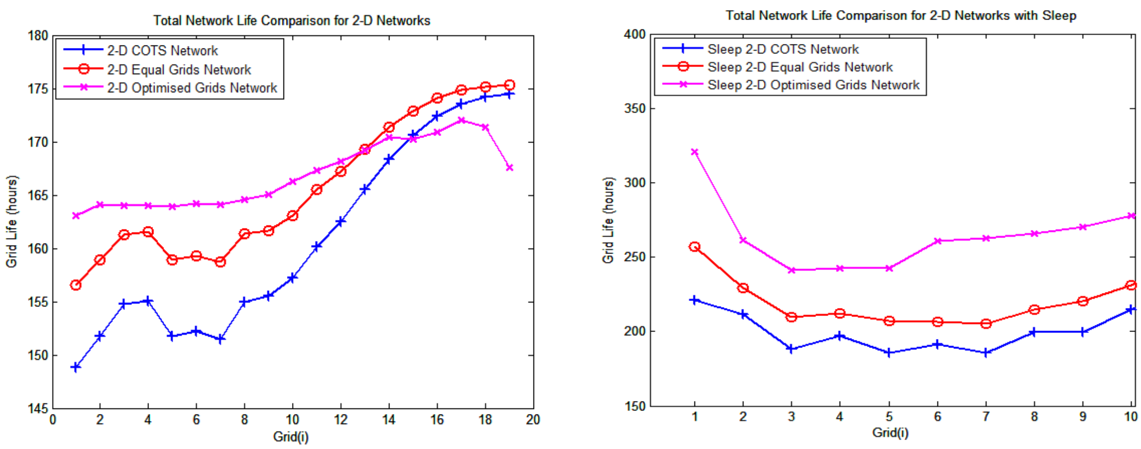

Figure 6.8 Total grid lifetimes for 2-D sensor networks with 100% idle and Sleep mode.

The total network lifetime for the three 2-D networks was compared with the Idle and Sleep Mode as shown in Figure 6.8 (a,b) In both the cases, the 2-D Optimised grids network showed much better network lifetime performance. Without the Sleep Mode

(Figure 6.8a) the 2-D Optimised grids network has 4.5% and 10.1% more network lifetime as compared with the 2-D Equal grids and 2-D COTS network. With the Sleep Mode (Figure 6.8b), grid (4) in the Sleep 2-D Optimised network has the lowest grid life of 242 hours. This still has 18% more lifetime compared with lowest grid (7) of Sleep 2-D Equal grids network and 31% more than lowest grid (5) of Sleep 2-D COTS network.

A key point is that the 2-D Optimised grids network has 25% higher throughput and much lower latency and jitter. It is using more energy to forward these extra packets to the base station to achieve a 25% higher throughput and still has higher network lifetime.

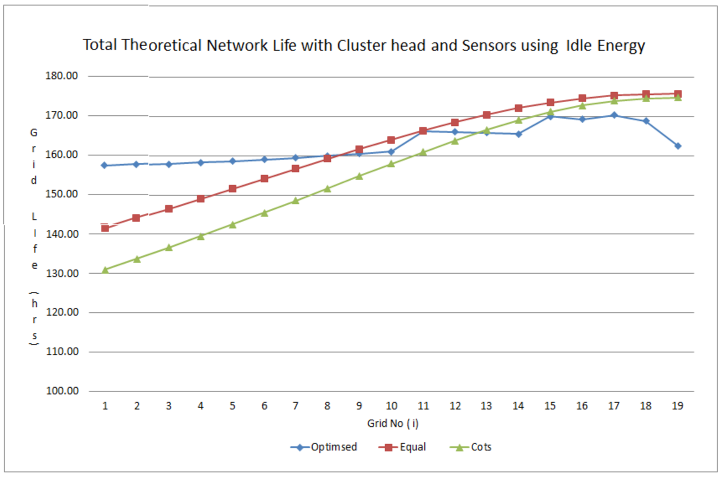

Figure 6.9 Theoretical Network lifetime expectancy for 2-D networks.

A theoretical calculation for the grid lifetimes were carried out to see if the simulated models had any correlation with theoretical values. Figure 6.9 shows that in an ideal network where there are no delays, collisions or any other overhead, the 2-D Optimised grids network has 12 % and 20% more lifetime compared to the other two 2-D networks. Another key point is to compare the theoretical values of Figure 6.9 with simulated values of Figure 6.8(a) from grid 13 to 19. The theoretical and simulated values for all the three networks are very close. This is due to the reason that at the lower end of these networks, the traffic is very low and the three networks behave ideally. But from grids 1 to 12, the 2-D Optimised grids deviates a lot less compared to the other two 2-D networks.

6.2 Disabling the RTS-CTS Handshake

In a network, when the traffic load is not high and if there is no hidden node problem then it is useful to switch off the RTS-CTS handshake as it creates unwanted network traffic and energy consumption for all the wireless sensor nodes. In this simulated network, the maximum traffic is less than 25% of the network bandwidth, and that is most likely present at the grid near to the base station. Hence the grids that are furthest away hardly have much traffic, and the system does not need the RTS-CTS protocol at all. In all the previous simulations, the Request to Send - Clear to Send (RTS-CTS) handshake feature of the 802.11 protocol had been enabled. When RTS-CTS feature is enabled, all the nodes in the network have to acquire access to the transmission medium before they can transmit their data packets. The node that wants to transmit a packet initiates the process by sending a RTS frame to the receiving node. The receiving node will then reply with a CTS frame to the requesting node. Only after receiving this CTS frame, the requesting node can send its data packet. This process allows for other nodes to hold off from accessing the medium until the transmission from the requesting node has completed. The key advantage of CTS-RTS is to remove the hidden node problem. A typical scenario is when nodes A and node C cannot hear each other due to their transmission range but both can communicate with node B. If node A now sends a RTS message to node node B, node B will send reply back with a CTS message. Because both node A and node C are within range of node B, both will receive the CTS message. Now node C will refrain from sending the message to node B until the transaction between node A and Node B is completed. If the CTS-RTS handshake was not present, then while node A was transmitting its packet to node B, node C might also start transmitting. This will cause a collision of packets between node A and node C at node B. As a result, both node A and node C will have to re-transmit their messages, which results in higher overhead and decreased throughput.

6.2.1 Analysis of QoS Parameters without RTS-CTS handshake

During this part of simulation the RTS-CTS feature was disabled for all the three 2-D networks. The simulation was ran for 1010 seconds. All the network parameters were kept similar to previous section 6.1.

Figure 6.10 (a,b) shows the throughput for the 2-D Optimised grids, 2-D Equal grids and 2-D COTS network. One of the most striking outcomes is that by removing the CTS-RTS handshake protocol, the throughput of the 2-D Optimised grids network has improved from 225789 bit/s to 256839 bits/s. The maximum throughput that can be attained is 257400 bits/s. This proves that 2-D Optimised grids spacing is highly effective as 99.8% throughput is achieved.

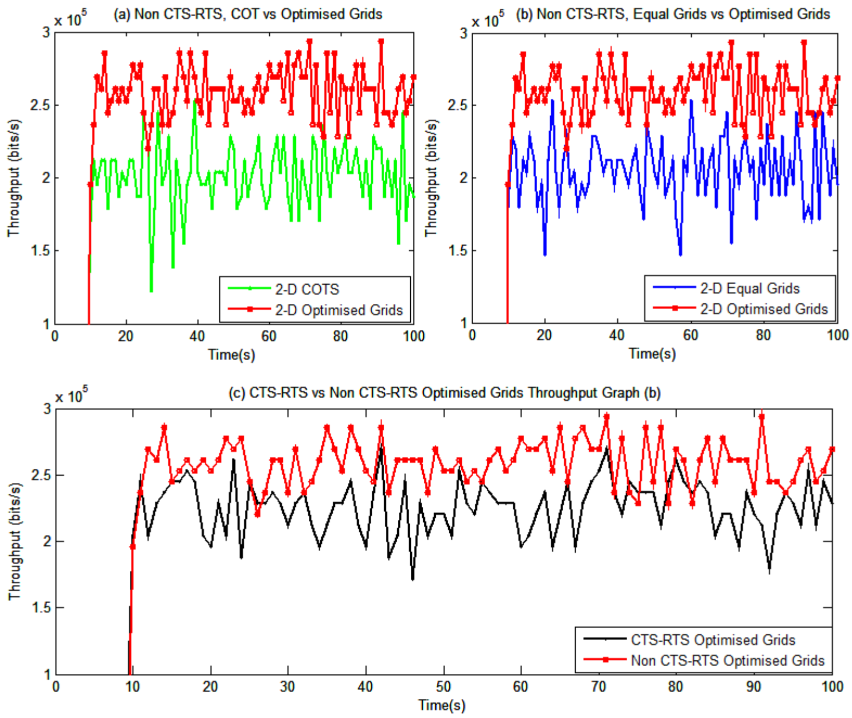

Figure 6.10 100% Traffic without CTS-RTS activation for 2-D networks.

The 2-D Optimised grids network also shows a 25% higher throughput compared with the 2-D Equal grids and 2-D COTS network (Figure 6.10 a,b).

While CTS-RTS improves performance by reducing retransmissions, but in case of the 2-D Optimised grids network, the hidden node problem is a lot less. A slight hidden node problem introduces degradation in throughput when CTS-RTS is introduced. The additional RTS-CTS frames cost more in overhead then the gain achieved by reducing retransmissions.

Figure 6.11(a) confirms that the packet delivery from all the cluster heads is nearly 100% for the 2-D Optimised grids network, while it falls sharply for the 2-D Equal grids and 2-D COTS network. The hidden node problem is becoming a dominant feature causing, collisions, and retransmissions and also resulting in much higher latency and jitter for the 2-D Equal grids and 2-D COTS network as shown by Figure 6.11 (b,c).

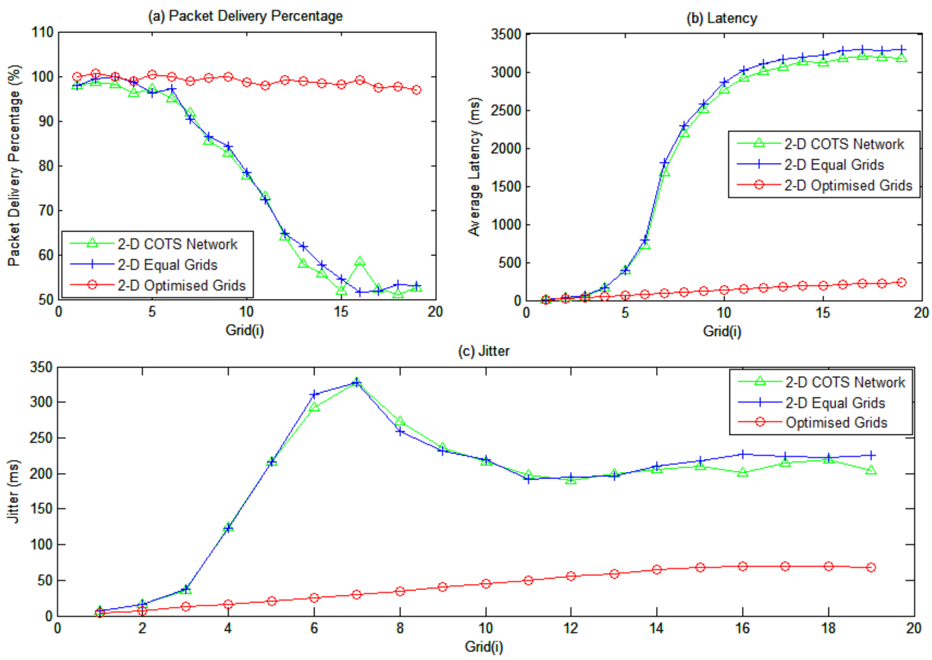

Figure 6.11 Packet delivery, latency and jitter comparison for 2-D networks without RTS-CTS.

Figure 6.12(a) shows a direct comparison of QoS parameters for the cluster head nodes of the 2-D Optimised grids networks with and without CTS-RTS. The packet delivery is near 100% for non CTS-RTS network for all the grids throughout network. For the 2-D Optimised grids network with CTS-RTS enabled, after grid 3, the packet delivery starts to falls steadily until it reaches below 80%. The CTS-RTS hand shaking protocol, not only creates an overhead in the network, but also increase the latency and jitter (Figure 6.12 b,c). The nodes now have to wait longer to transmit their messages. A key point to remember is that once the waiting period is over, the node that wants to transmit a message still has to send the RTS message to the receiving node (in this case the cluster head), and wait for a CTS message before it can actually start it transmission.

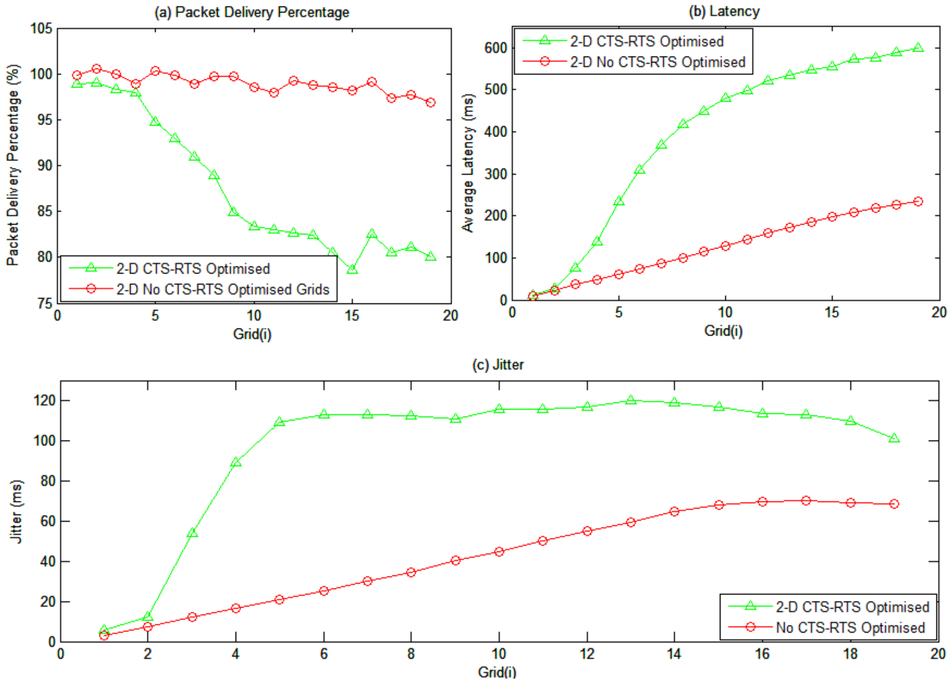

Figure 6.12 Comparison of 2-D Optimised grids network with and without CTS-RTS activation.

The wireless sensor nodes for the 2-D Optimised grids networks have over 99% throughput between their respective cluster heads (Figure 6.13a).

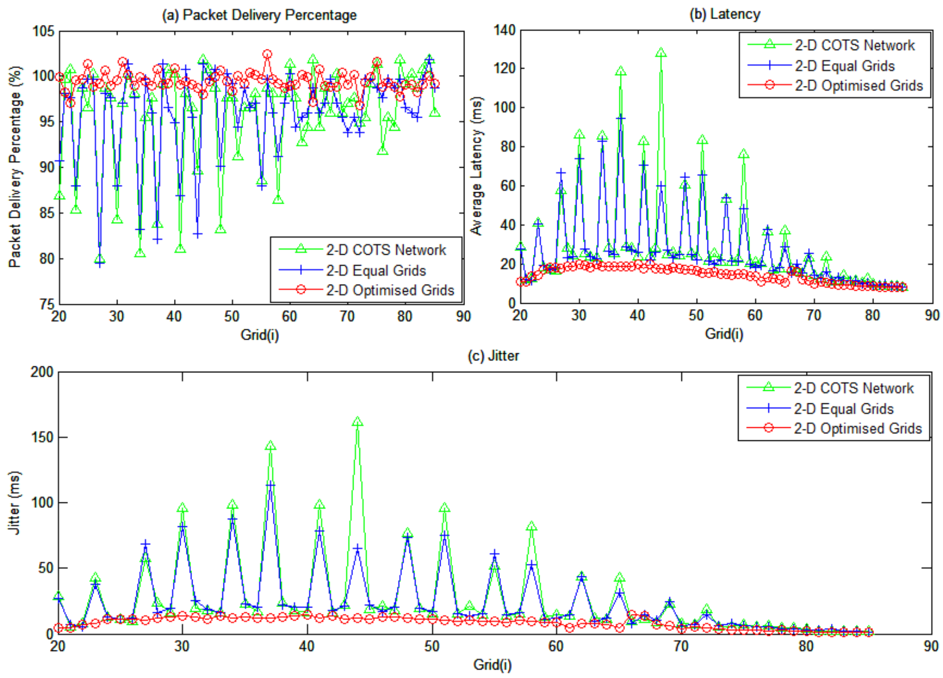

Figure 6.13 Wireless sensor nodes QoS parameters without CTS-RTS enabled.

The wireless sensor nodes for the 2-D Equal grids and 2-D COTS networks that belong to the grids that are nearer to the base station, suffer a considerable loss of packet delivery. Due to an increased volume of traffic, passing through the cluster head nodes near the base station, a large number of collisions are taking place between the wireless sensor nodes packets and the cluster head packets received from previous grids. This is causing packet loss not only of the wireless sensor nodes data, but also the data that had been forwarded from the previous grids that are furthest away from the base station and hence making that data irrecoverable. The wireless sensor nodes of the 2-D Optimised grids network exhibit much lower latency and jitter and appears to be operating in much more steady state conditions compared to the other two networks as shown by Figure 6.13(b,c).

Between grid 60 and 70 in Figure 6.13 (b,c), anomalies can be seen, which are caused as the cluster head in that grid is busy in receiving packets from the previous grid cluster head and forwarding these packets to the next grid cluster head. The sensor nodes in this grid have to wait much longer before their cluster head is ready to receive packets from them as compared to sensor nodes in the neighbouring grids. Collisions of packets are also taking place between sensor grids as all the sensor nodes share the same common transmission medium. For the Optimised grids Network, the grid size becomes larger as the distance increases from the base station. The grids furthest away from the base station have more sensor nodes that are sending messages to their cluster head. This causes congestion on the network for the cluster head in next or previous grid and results in packet transmission to be delayed for the sensor nodes in neighbouring grids to their cluster head, as the transmission medium is busy. Hence this causes an increase in latency and jitter as seen for these sensor nodes.

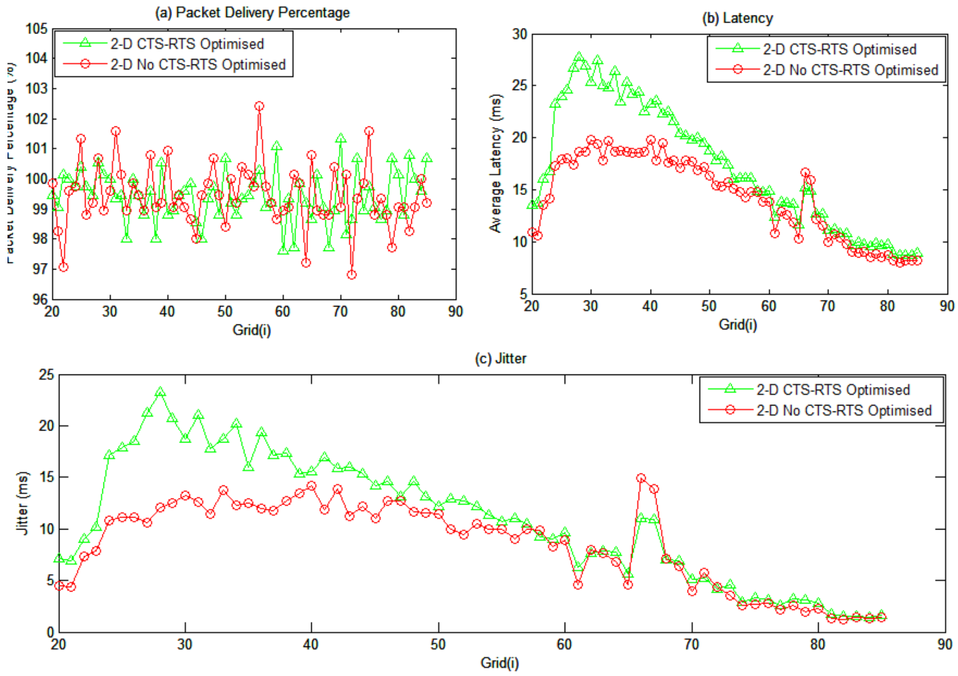

Figure 6.14 Wireless sensor node QoS comparison of 2-D Optimised networks with and without CTS-RTS.

While the 2-D Optimised grids wireless sensor nodes have significant QoS improvement over the 2-D Equal grids and 2-D COTS network, Figure 6.14 (abc) compares the QoS parameters between the two 2-D Optimised network with and without the CTS-RTS being enabled. The reduction of unnecessary overhead and delay caused by CTS-RTS has shown an improvement in the latency and jitter. The wireless sensor nodes in the grids near to the base station, show a significant drop and also a smoother slope in latency and jitter as compared with the 2-D Optimised grids network with CTS-RTS enabled. In the case of CTS-RTS enabled 2-D Optimised grids network, the small jagged edges in the graphs proves that some wireless sensor nodes are spending more time in waiting while their neighbours always get to transmit their messages.

6.2.2 Network Liftimes for 2-D Networks with 100% Traffic and Without the CTS-RTS Handshaking

As the RTS-CTS has been de-activated, this should bring some energy savings for all the three networks. It has to be kept in mind that for each data packet to be transmitted, one RTS and one CTS packet is required. But on the other hand, more retransmission due to collissions can also cost in an increased energy consumption.

The cluster head nodes nearest to the base station of the 2-D Optimised grids network achieves 35% and 48.8% less energy consumption (keeping in mind the 25% greater throughput as well) as compared with the 2-D Equal grids and 2-D COTS network as shown by Figure 6.15(abc). Figure 6.15(b) shows the peak and troughs for the cluster head node total grid energy consumtion (blackline) for the 2-D Equal grids network. When RTS-CTS is not enabled, the alternating cluster nodes go in transmit and receive states. Hence cluster heads that are always transmitting are using more energy, and are causing the peaks in the graph, while those cluster heads that are always receiving, consume less energy and are causig the troughs. The total grid energy consumption of the 2-D Optimised grids network is also 58% and 65% lower as compared with the 2-D Equal and 2-D COTS network

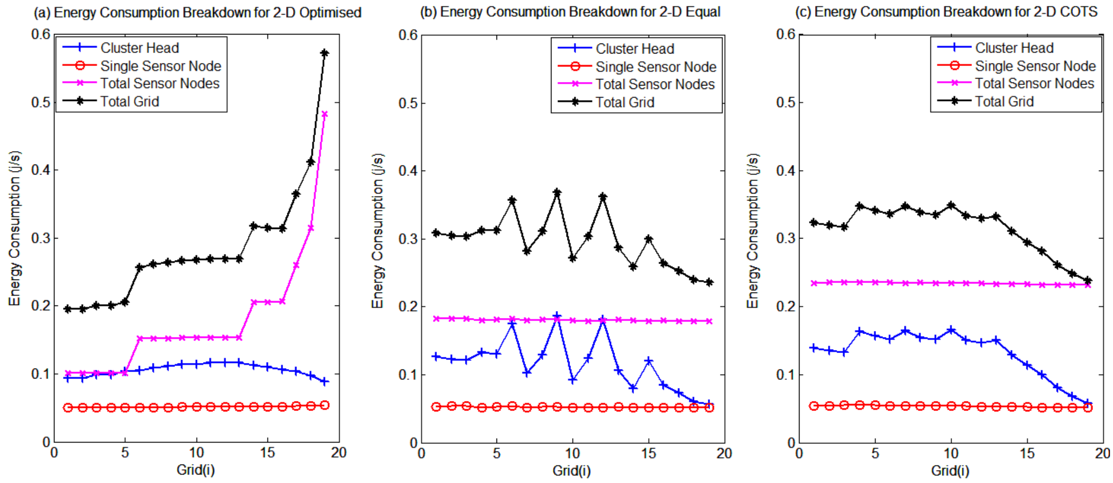

Figure 6.15 Sensor, cluster head and grid energy consumption for 2-D networks with 100% idle energy.

Another point to note is that an individual wireless sensor node, consumes as much as half the amount of the energy consumed by the cluster head node e.g. in the case of 2D Optimised grids network, while only transmitting about 1/85 amount of data as compared with the cluster head nearest to the base station. The reason is that too much idle energy is being consumed. To overcome this problem, the Sleep mode is introduced in all the three networks where the node is only stay awake for 10% of the idle time. Figure 6.16 shows that by introducing the Sleep mode in the 2-D Optimised grids network, a reduction in energy consumption of upto 45%, and 38 % can be achieved by the wireless sensor nodes and cluster heads. The total grid consumption for this network also decreases by 58%. The Sleep 2-D Equal grids and Sleep 2-D COTS network still consume between 67% and 79 % more total grid energy as compared the Sleep 2-D COTS network.

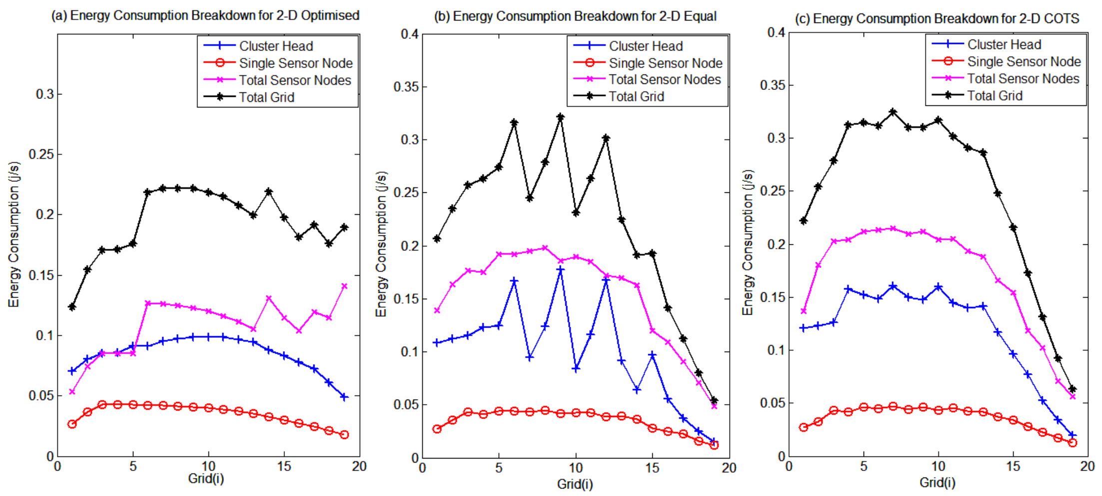

Figure 6.16 Sleep Mode implementation in 2-D Networks without CTS-RTS.

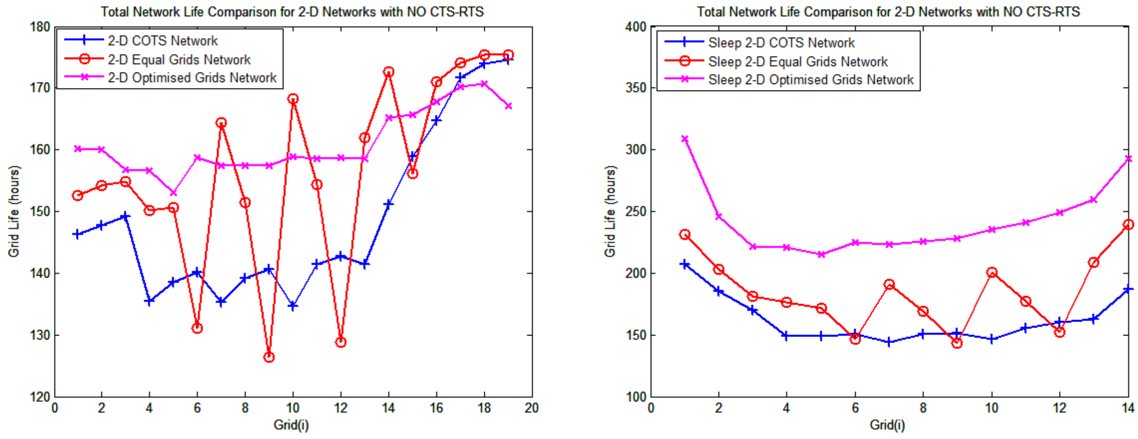

Figure 6.17 Comparison of 2-D network lifetime with idle energy and Sleep Mode and without CTS-RTS.

During Idle energy consumption the 2-D Optimised grids network (grid 4) has 21% and 13.3% more grid life as compared with 2-D Equal grids (grid 9) and 2-D COTS (grid7) networks as shown by Figure 6.17(a). By introducing the Sleep mode (Figure 6.17 b), the Sleep 2-D Optimised grids network has an increased lifetime of 54% and 53% as compared with Sleep 2-D Equal grids (grid 9) and Sleep 2-D COTS (grid 7) networks.

Clearly by disabling of the CTS-RTS, The Sleep 2-D Optimised grids network has the most advantage as the throughput has increased to 99.8%, but the network lifetime when the first grid dies has decreased from 242 hours to 221 hours (approx. 10% decrease). In the case of Sleep 2-D Equal grids and Sleep 2-D COTS network, their throughputs did not increase beyond 77%. However for the Sleep 2-D Equal grids network the minimum grid lifetime fell from 205 hours to 143 hours (43% decrease) and for Sleep COTS network, the minimum grid lifetime decreased from 184 to 144 hours (approx. 27% less). So clearly the highly efficient Optimised grids spacing proved to deliver much better performance in terms of network QoS parameters as well as increasing network lifetime.

6.3 Traffic Fluctuations in 2-D Networks

In this section a study is carried to see the effects of traffic fluctuation on 2-D networks with sensor data. In the prevoius section the total traffic approaching the base station was set to 0.2574 Erlang (0.2574 Mbits/s) which is refered to as 100% traffic . Initially the traffic is increased to 200%, i.e 0.5148 Mbits/s and the simulations are ran with the CTS-RTS feature enabled. The CTS-RTS feature is then disabled and the simulations are ran again to compare the overal QoS parameters and network lifetime. The traffic is then reduced to 50% and 10% of the 100% load i.e. 0.1287 Mbits/s and 0.02574 Mbits/s and study is carried out to see the effect on network QoS parameters and netowrk lifetimes.

6.3.1 Increasing the Network traffic to 200% with the CTS-RTS Feature Enabled.

In this setup the total traffic generated from each node was increased from 0.003 Erlang to 0.006 Erlang. This required each wireless sensor node in the netowrk to send a 1 kbytes packet after every 1.33 second. A important difference between the 1-D linear and 2-D linear networks is that in the 1-D networks, it was assumed that the cluster head nodes had already received data from the wireless sensor nodess in their grid, and only had to forward their own data as well as the data received from the previous cluster head to the next cluster head toward the base station. The only traffic on the network was created by intra-cluster head communcations. In 2-D networks, along with the intra-cluster head communications, the cluster heads also have to deal with data received from their own grid's wireless sensor nodes. In the case of 20% traffic the cluster heads not only will receive and will have to forward twice as much traffic from the prevoius grid's cluster head but will also have to deal with twice the amount of traffic generated by its own grid's wireless sensor nodes.

With 200% traffic load, the simulation was ran for 1010seconds. Figure 6.18 shows that the throughtput obtained by the 2-D Optimised grids network was 230837 bits/s where as for the , 2-D Equal grids and 2-D COTS network, the throughput was 218436 bits/s and 207945 bits/s.

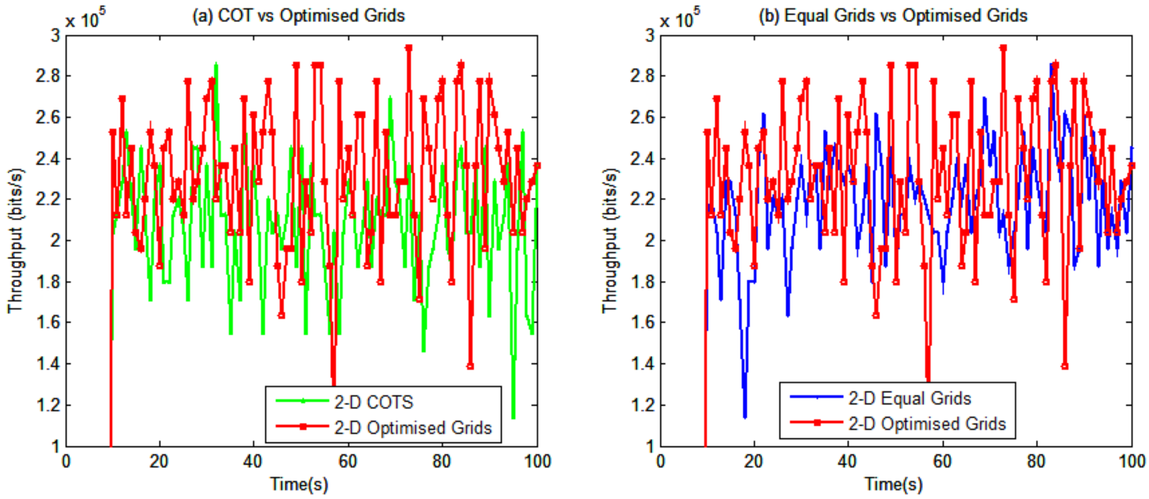

Figure 6.18 Throughput graphs with 200% traffic for 2-D wireless network.

The total theoretical throughput is calculated to be 514800 bit/s. None of the networks manages to achieve even the half of the value of the theoretical throughput with the RTS-CTS feature enabled. The 2-D Optimised grids network still manages to achieve 5.6% and 11.1% more throughput with respect to 2-D Equal grids and 2-D COTS networks. This increase in throughput is further investigated by looking into the packet delivery, average latency and jitter plots as shown by Figure 6.19 (a,b,c). All the three networks suffer from packet delivery loss after grid 3. This is where the intra-cluster head communication is at its maximum with all the cluster head nodes in these grids. These cluster heads not only have to receive data from the previous cluster head nodes but also have to forward the received data, as well as their own grid data. In general the total network bandwidth is 1Mbit/s. The cluster heads nearest to the base station for all three 2-D networks have to transmit 514800 bit/s data to the base station. This data alone is just over half the total network bandwidth. Cluster head of grid 1 has to transmit for at least 50% of the time and receive 50% of the time if it is to maintain a throughput anywhere near the ideal value. But when cluster head of grid 1 nearest to the base station sends a RTS packet to the base station by using the RTS-CTS feature, then if cluster heads of grid 2 and grid 3 overhear the CTS command sent by the base station. They are obliged not to have any communication with either between themselves or their neighbouring nodes. This causes extended delays and packet drops by these cluster heads. Despite the less than ideal throughput for all the three networks, the 2-D Optimised grids network has much lower average latency and jitter and higher overall packet delivery compared with the other two 2-D networks.

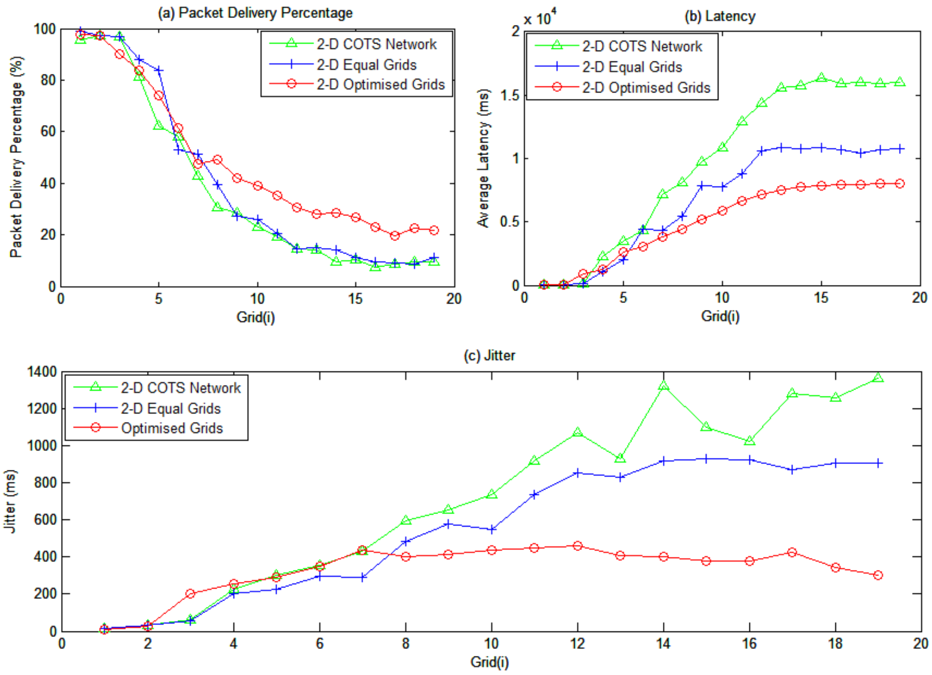

Figure 6.19 QoS parameters comparison for two 2-D networks with CTS-RTS enabled.

Looking at the behaviour of the wireless sensor nodes in all the three 2-D networks, it shows from Figure 6.20 (a) that all the three 2-D networks managed to transmit over 87% of the packets, despite the huge amounts of congestions near grids 1-3. The 2-D Optimised grids network obtains a minimum packet delivery of 93%. However the average latency and jitter from Figure 6.20 (b,c) reveal that for the 2-D Equal grids and 2-D COTS networks, between grids 3-15 (wireless sensor nodes 30 to 70), had a considerably high latency and jitter compared with 2-D Optimised grids network. Some of the wireless sensor nodes had to wait a lot longer compared to their neighbouring nodes in the same grid, causing the spikes in graphs of Figure 6.2 (b ,c).

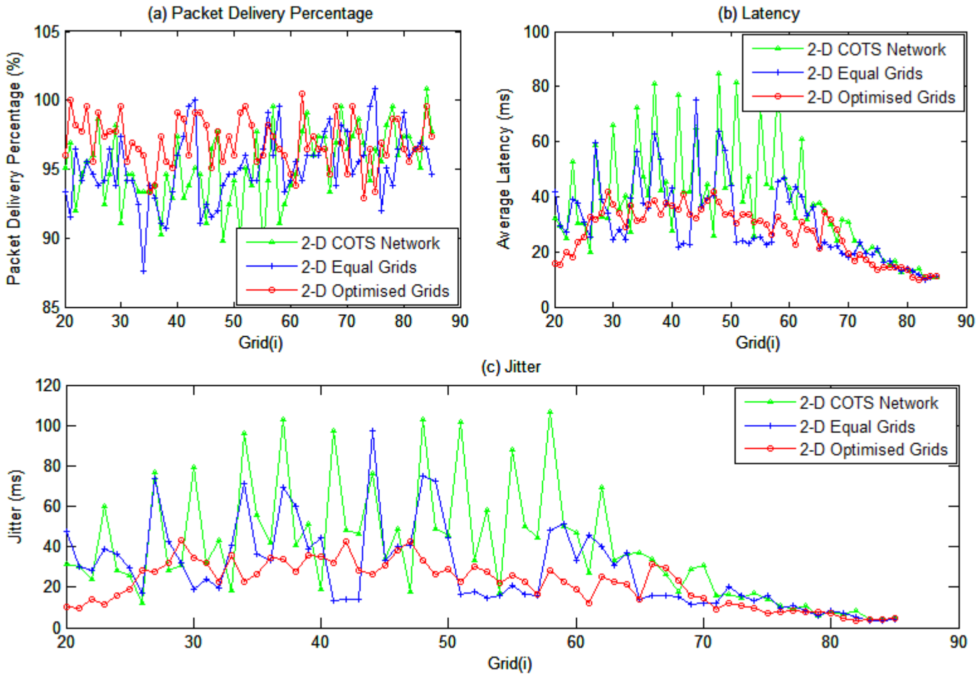

Figure 6.20 Comparison of wireless sensor nodes QoS parameters in 2-D networks with 200% traffic.

6.3.2 Network Liftimes for 2-D Networks with 200% Traffic including the CTS-RTS Feature

This section compares the total energy consumption of the three networks when the traffic is increased to 200%, The sensor nodes, cluster heads, grid consumptions and total grid lifetimes are compared with 100 % idle energy and also by introducing the Sleep mode.

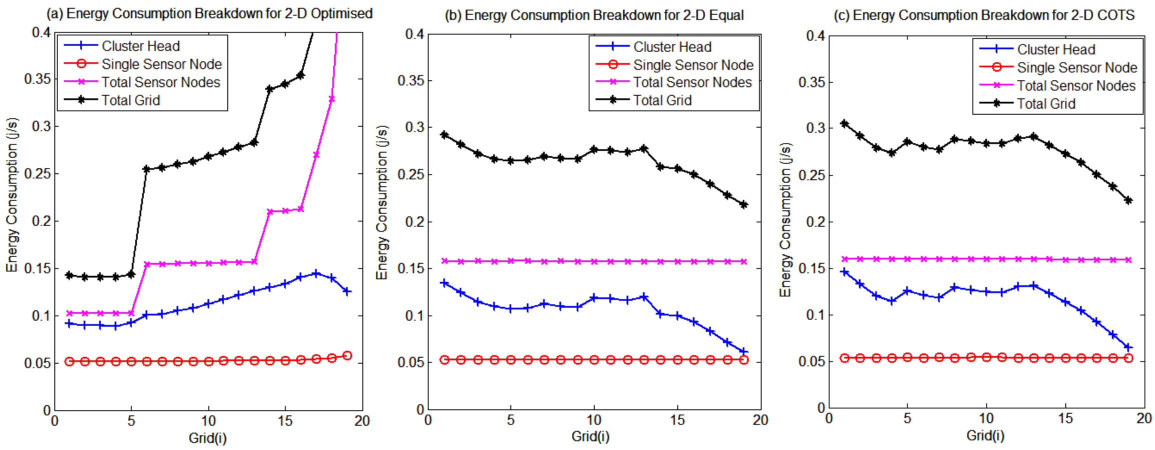

Figure 6.21 Cluster head and node energy consumption breakdown of 200% traffic 2-D networks.

The 2-D Optimised grids network (Figure 2.16 a) has 46% and 58% less cluster head energy consumption compared with the 2-D Equal grids (Figure 6.21b) and 2-D COTS network (Figure 6.21c). The individual wireless sensor node energy consumption is also between 3% and 5% less for the 2-D Optimised grids network compared with the other two. Keeping in mind that advantage in energy gain is only obtained when the nodes are transmitting, as the 2-D Optimised grids as efficient grid spacing. In idle or reception state, all the nodes in the three networks are consuming the same amount of energy. This also explains why the 2-D Optimised grids cluster heads are highly efficient as most of their time is spent in transmission.

By introducing the Sleep mode (Figure 6.22 abc) the cluster head energy consumption of 2-D Optimised grids network has decreased by 74% and 78% compared with other two 2-D networks. The total grid consumption is also decreased by 77% and 91% compared with 2-D Equal grids and 2-D COTS network.

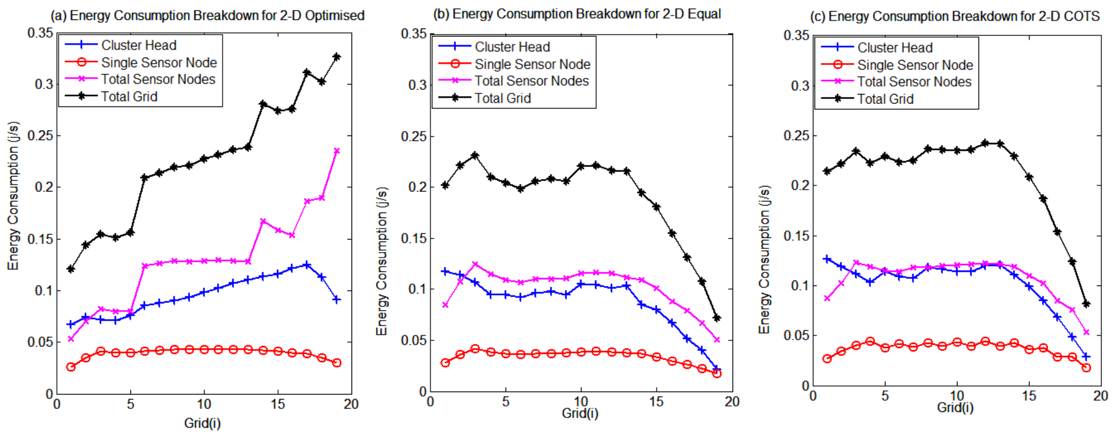

Figure 6.22 200% Traffic with Sleep mode and CTS-RTS feature enabled.

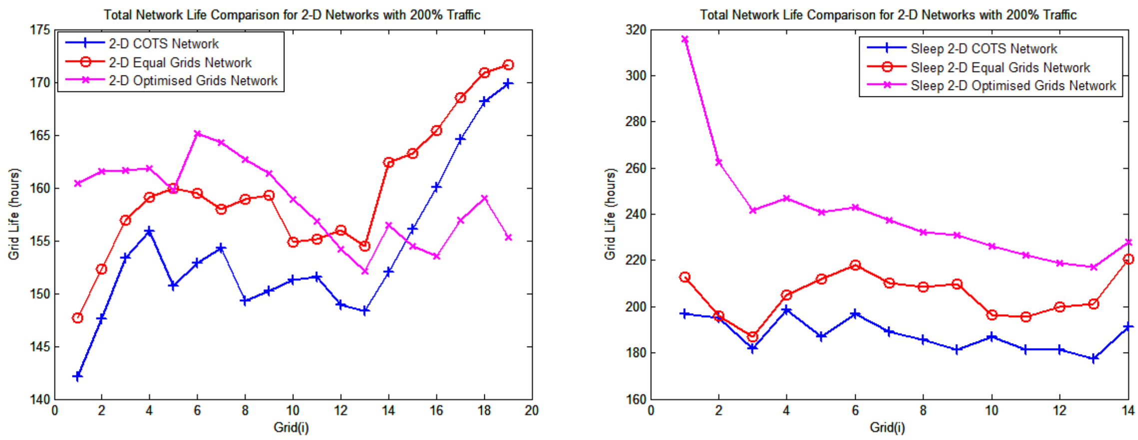

Figure 6.23 Comparison of total network lifetime with and without Sleep Mode with RTS-CTS enabled.

With 100% idle energy (Figure 6.23a), comparing the three networks with the least grid lifetime, the 2-D Optimised grids network has between 7% and 8% more lifetime. After introducing the Sleep mode (Figure 6.23 b), the network lifetime for all the three networks improved considerably, with the Sleep 2-D Optimised grids network having 11.2 % and 20% more network lifetime compared with Sleep 2-D Equal grids and Sleep 2-D COTS network. With respect to 2-D Optimised grids network with idle energy, the lifetime of the Sleep 2-D Optimised grids network increased by 52%. The novel idea of unequal grids not only enhances the throughput but also increase the network lifetime considerably.

6.3.3 Network Liftimes for 2-D Networks with 200% Traffic without the CTS-RTS Feature.

In section 6.2 it was shown that by disabling the RTS-CTS feature, the throughput of the 2-D Optimised grids network increased to 99.8%. Keeping in mind that in this case the network traffic has increased to 200% of the original value, this would have increased the hidden node problem quite considerably for the entire three networks.

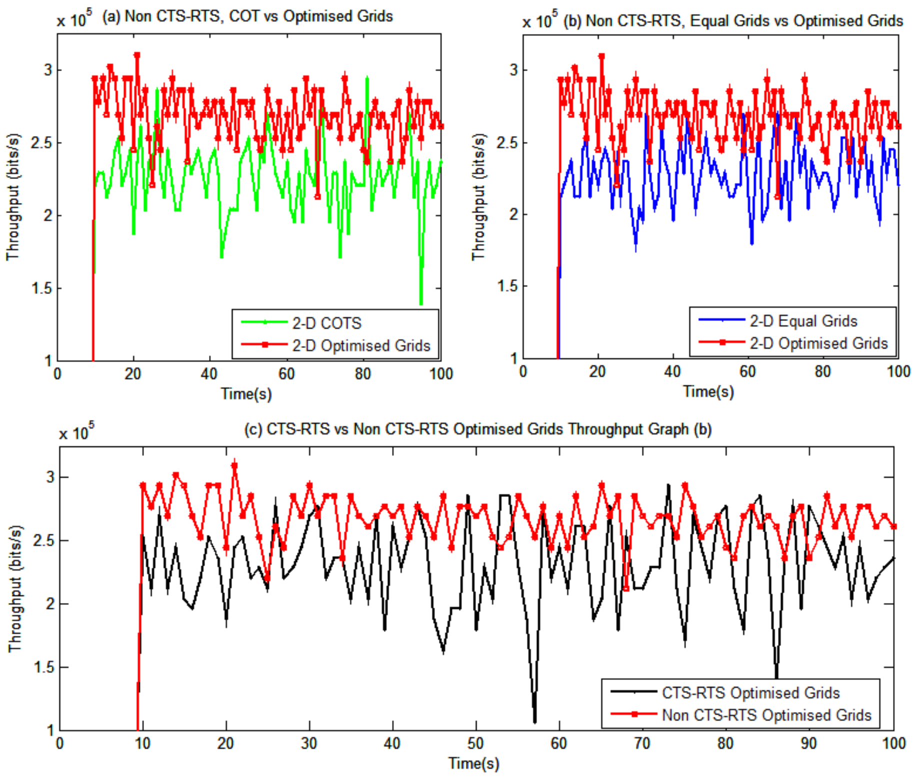

Figure 6.24 Comparison of throughput between all the 2-D networks with RTS-CTS disabled.

After disabling the RTS-CTS feature for the three networks, the simulation was run for 1010 seconds. Figure 6.24 (a,b) shows that 2- D Optimised grids network (red line) has throughput of 267217 bits/s as compared to 227941 bits/s for 2-D Equal grids and 226238 bits/s for 2-D COTS network. An increase in throughput of 17% compared to both the networks. Compared with CTS-RTS enabled, all the three networks have an increase in throughput. Even though the gain is not very high as compared to the required theoretical throughput of 514800 bit/s, but the 2-D optimised network has still managed to attain more than half of that throughput value. The other two networks have lower throughput.
Figure 6.24 (c) compares the throughput for the 2-D Optimised grids networks with and without the CTS-RTS. There has been an increase in average throughput from 230837 bits/s to 267217 bit/s, an average increase of 15.7%.

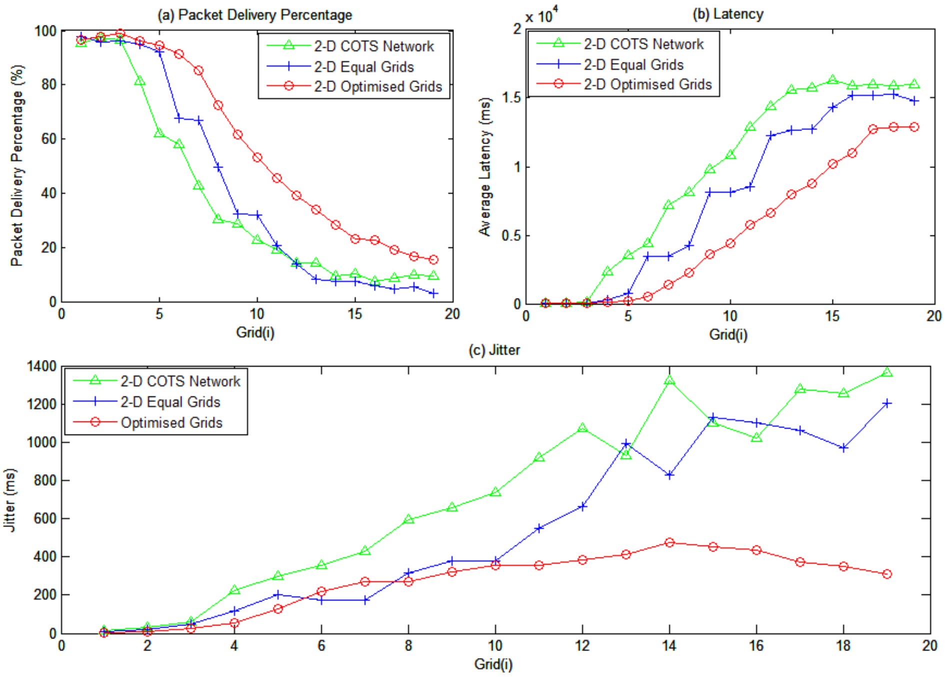

Figure 6.25 Comparison of QoS parameters with the CTS-RTS feature disabled.

Without the RTS-CTS feature, the packet delivery for all the three networks has slightly improved from grid 3 to grid 13, mainly because now the nodes are constantly transmitting the packets without waiting to receive the CTS message from the receiving node. However this has increased the collisions and retransmission. This is confirmed by the increase in latency for all the three networks. The average latency has increased for all the three networks from grid 11 to 19 as compared with Figure 6.19b where the CTS-RTS was enabled. The jitter has decreased throughout the 2-D Optimised grids and the 2-D

Equal grids network but only for the first 8 grids of the 2-D COTS network as compared with CTS-RTS enabled networks of section 6.3.2.

The benefits achieved by disabling the RTS-CTS feature can clearly be seen by directly comparing the QoS parameters for both the 2-D Optimised grids network as shown by Figure 6.26(a) shows as the network overhead has been reduced by the lack of CTS-RTS packets, this allows more packets from the cluster heads to occupy the medium, and therefore improving the throughput. The average latency Figure 6.26(b) is also considerably less for the first 12 grids as mentioned earlier that there is no waiting time, but it climbs steadily from grid 5 onwards as the collisions on the medium are causing re-transmission. The jitter is lower but steadily climbs due to the retransmissions and caused by the variance in latency.

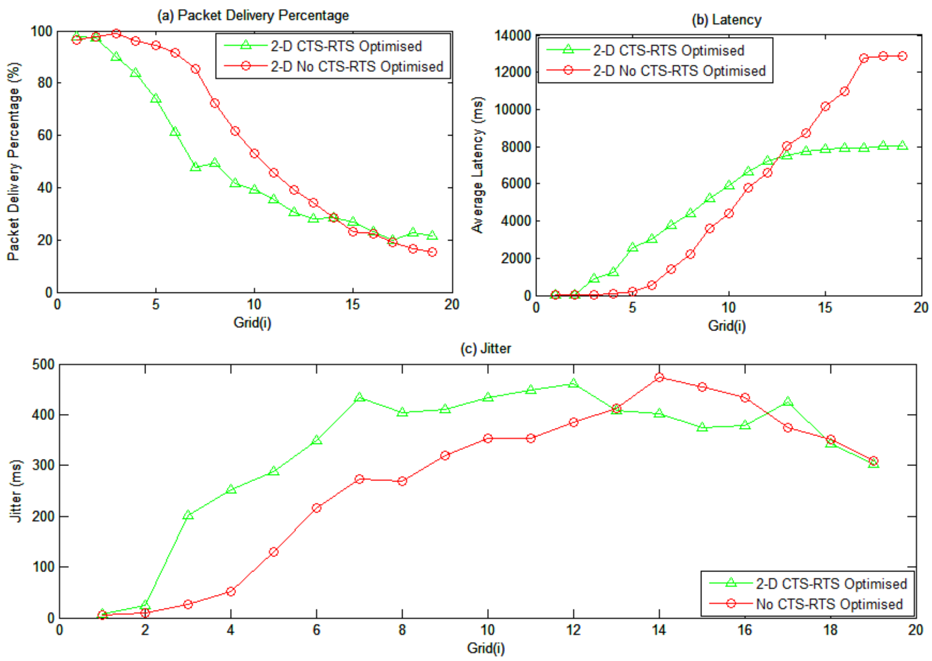

Figure 6.26 Comparing the 2-D Optimised grids network with and without the RTS-CTS feature.

The 2-D Optimised wireless sensors nodes have packet delivery above 95%. Whereas for the 2-D COTS the packet delivery falls as low as 79% and 72% for the 2-D Equal grids network (Figure 6.27a). The efficient grid spacing provided by the 2-D Optimised grids networks ensure that all the wireless sensor nodes are able to access the network and transmit the packets efficiently as compared with the 2-D COTS and 2-D Equal grids network where some wireless nodes are only able to transmit and have better packet delivery compared to other that do not have much luck in transmitting, either in waiting for their turns or their packets colliding with other packets on the receiving nodes.

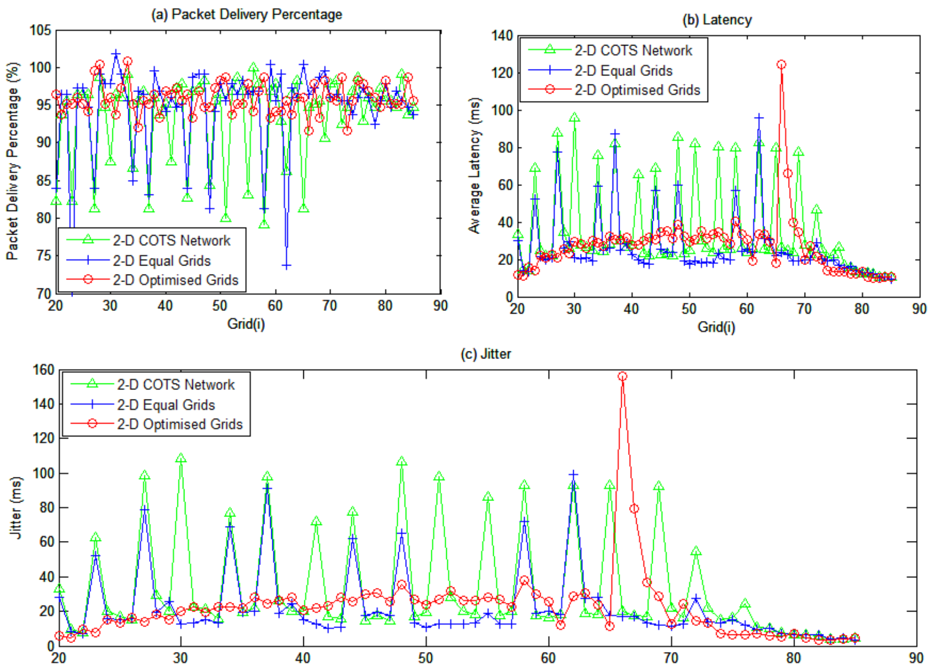

Figure 6.27 QoS parameters for 2-D networks with 200% traffic and CTS-RTS disabled

This is also reflected by the peak and trough in the latency and jitter Figures of the 2-D Equal grids networks as shown by Figure 6.27(b,c). The anomalies are seen again between sensor node 60 and 70, caused by an increase in wait time for the sensor nodes as the cluster head node for that grid is busy forwarding packets received from previous grids.

By comparing the two 2-D Optimised grids with and without CTS-RTS feature, it can be seen that the throughput for wireless sensor nodes has slightly dropped as shown by Figure 6.28(a). The main reason is that the network traffic is too high, and despite no control packets on the medium, the collision are ending with re-transmissions. The key point to remember is that despite a slightly lower packet delivery rate between sensor nodes to cluster head without the CTS-RTS functionality, there is a higher packet delivery from cluster head to base station as shown by Figure 6.26(a). Thus for the data packets reaching to the cluster head, higher proportion of these data packets reach the base station and are not being dropped by the cluster heads.

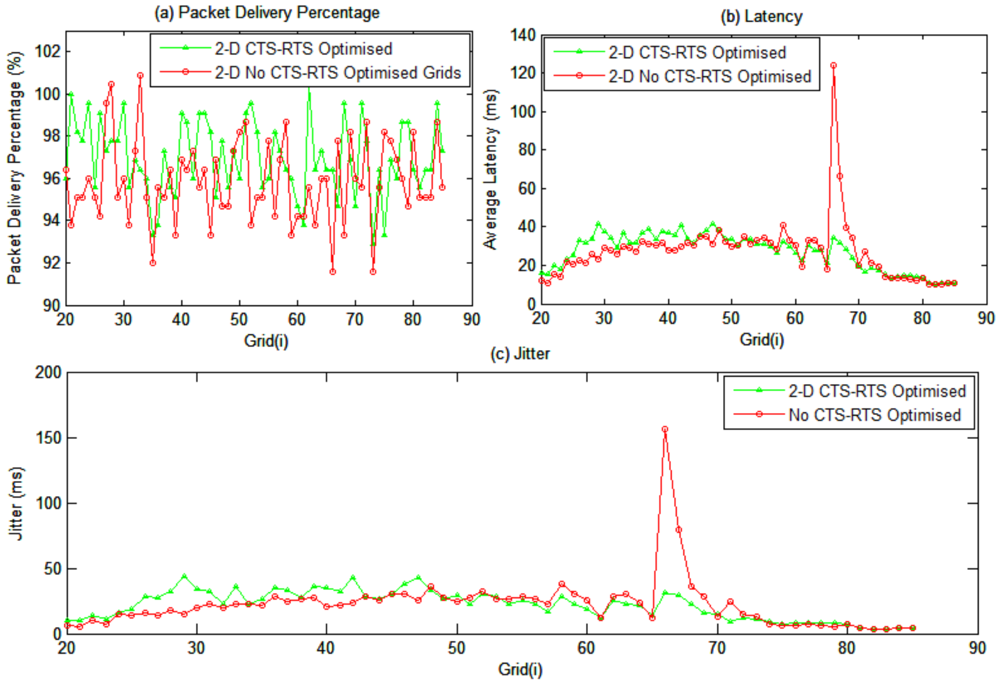

Figure6.28 Comparison of QoS parameters for the 2-D Optimised grids network with and without RTS-CTS.

6.3.4 Decreasing the Network Traffic to 50 %

As the network traffic is lowered to 50%, each node now only transmits 0.0015 Erlang of data. Each wireless sensor node transmits a one kByte data packet after every 5.33 seconds to its cluster head. When the network traffic was low, all the cluster heads have 100% throughput and nearly equal latency and jitter. The only key difference now lies between

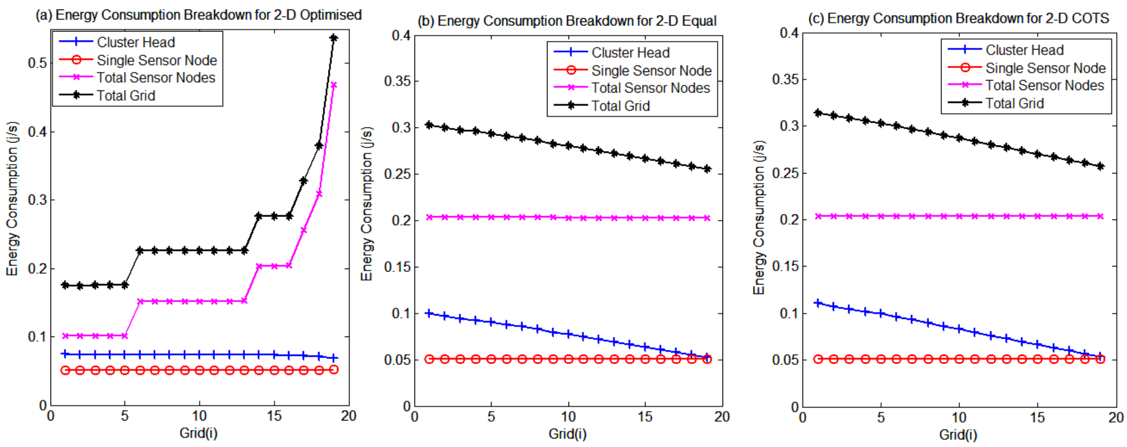

Figure 6.29 Breakdown of energy consumption for the 2-D networks with 50% traffic and full idle energy.

the cluster head nodes energy consumption and the grid lifetimes. For the 2-D Optimised grids networks, majority of the energy saving is provided by efficient transmission distance. At lower traffic rates, idle energy becomes dominant and all the nodes in the network consume an equal amount of idle energy. Figure 6.29 compares the energy consumptions of wireless sensor nodes, cluster head nodes and total grid consumption for all the three networks without the Sleep mode. The cluster head node energy consumption of the 2-D Optimised grids network is 34% and 56% less as compared with the other two 2-D networks. The total grid energy consumption is also 72 % and 79.3% less with respect to the 2D Equal grids and the 2-D COTS network. However a lot of this energy consumption is being wasted as the node spend majority of their time in idle state.

When the Sleep mode is applied as shown by Figure 6.30, the 2-D Optimised grids energy consumption per second for the cluster head reduces by 83% and the total grid consumption for the first grid also reduces by 235%. This is a significant amount of energy saving. By comparing with the Sleep Equal grids and Sleep COTS networks, Figure 6.30 (abc). The Sleep Optimised grids network consumes 75.6 % and 102% less energy for the cluster heads and 66% and 87% less energy for the total grid consumption.

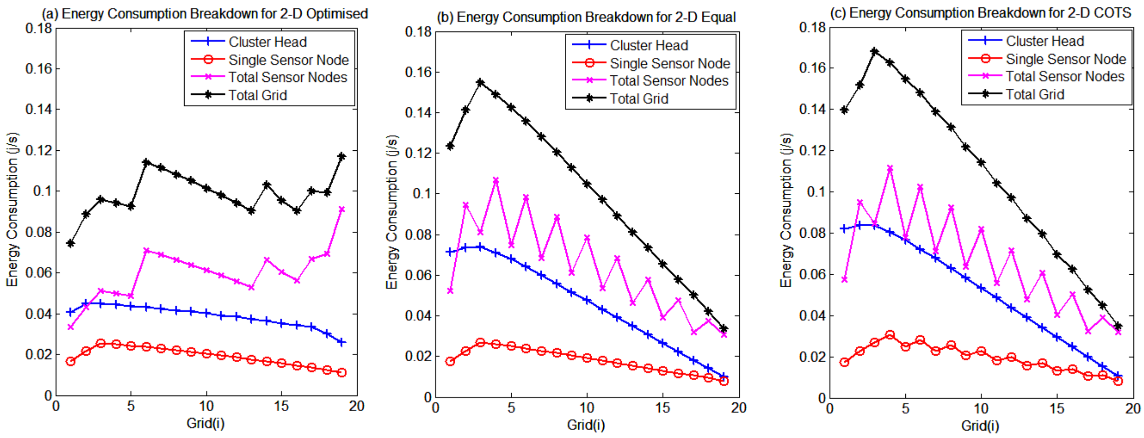

Figure 6.30 Breakdown of energy consumptions for the 2-D networks with 50% traffic with Sleep mode.

The total grid lifetimes can be found from Figure 6.31. total network lifetime before the first grid dies when full idle energy is utilised is 174, 166 and 161 hours for the 2-D Optimised grids, 2-D Equal grids and the 2-D COTS network. Even though when the traffic is half, as compared to 100 % traffic there has only been a little increase in network lifetimes for all the three network. However when the Sleep mode is applied, i.e. all the nodes only stay awake for 10% of the idle time. The total network lifetime for the Sleep Optimised grids network when the first grid (grid3) runs out of energy is 372 hours as compared with 289 hours (grid 3) for Sleep Equal grids and 261 hours (grid 3) for the

Sleep COTS network. Again comparing 2-D Optimised grids with the Sleep 2-D Optimised grids, the network lifetime has increased by 113%

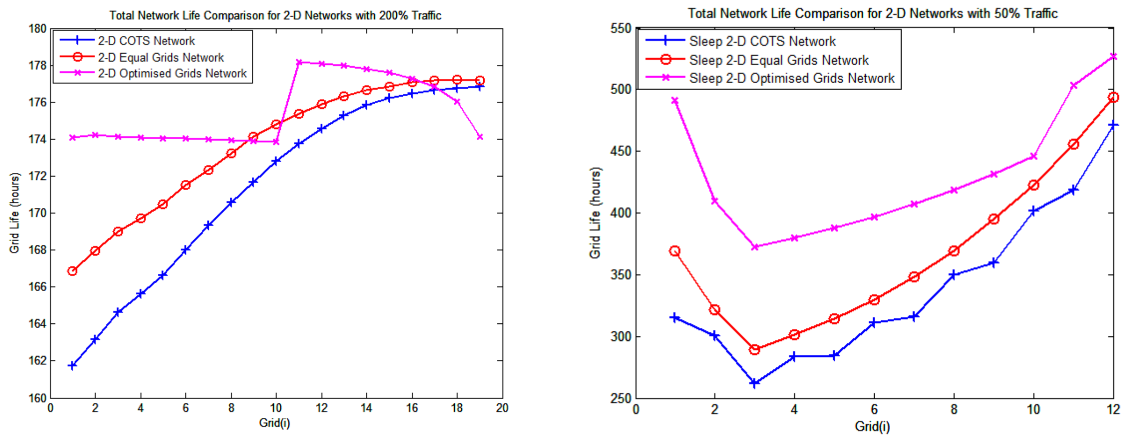

Figure 6.31 Comparison of grid lifetimes with and without the Sleep mode and 50 % network traffic.

6.3.4 Decreasing the Network Traffic to 10 %

In this case the network traffic is reduced to only 10% of the total traffic. Each wireless sensor node will now only transmit 0.0003 Erlang data. This is equivalent to sending one kByte data packet every 26.6 seconds in the network. Therefore the rest of the time the node will remain idle and will consume idle energy. It is already understood that when wireless sensor node is in idle state it consume a minimum energy of 0.05 Joules/s. In

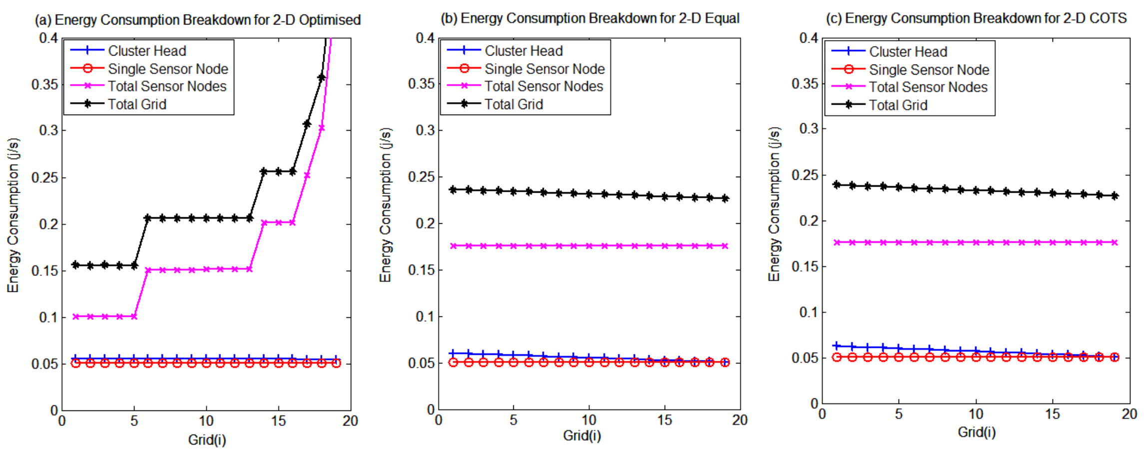

Figure 6.32 Breakdown of energy consumption for the 2-D networks with 10% traffic and full idle energy.

Figure 6.32 (abc), the red line represents the wireless node energy consumption and the blue line represent the cluster head energy consumption. It can be seen that the red and blue line nearly overlap each other for the 2-D Optimised grids network (Figure 6.32a). The reason is that the traffic to forward is so low that the difference in energy consumption of the cluster head is nearly equivalent to any other wireless sensor node in the grid. For the 2-D Equal grids (Figure 6.32b) and 2-D COTS network (Figure 6.32c) the blue line starts to separate as the traffic approaches the base station. This is because their transmission energy is higher due to un-Optimised grids sizes. The total grid energy consumption (black line) for the 2-D Equal grids and 2D COTS is higher compared with 2-D Optimised grids network; this is because these two networks have more nodes in their grids due to larger grid sizes.

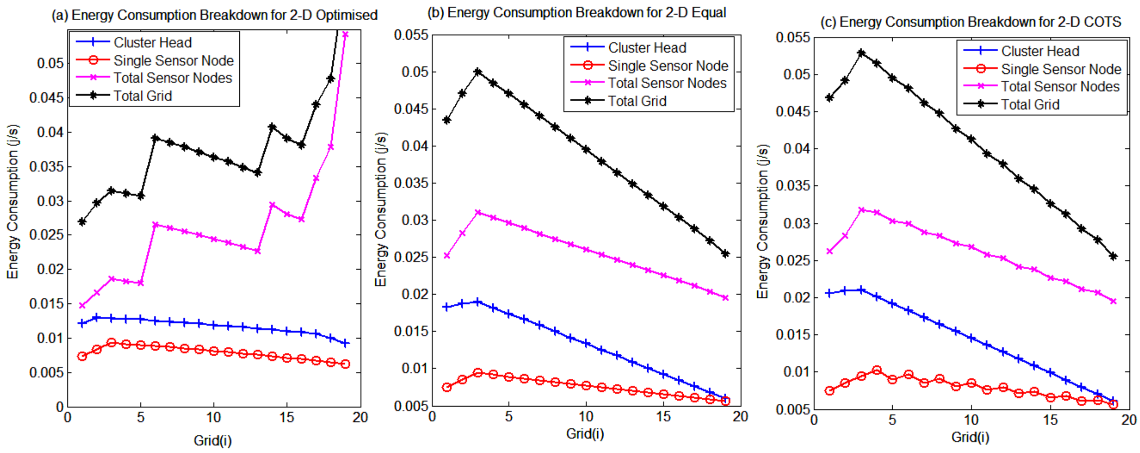

Figure 6.33 Breakdown of energy consumption for the 2-D networks with 10% traffic and Sleep mode.

By introducing the Sleep mode as shown in in Figure 6.33 with 10% network traffic, The cluster head energy consumption (blue lines) can clearly be differentiated from the wireless sensor node energy consumption (red lines) for all the three network. It can be seen clearly that 2-D Optimised grids network has much lower cluster head energy consumption as compared to the other two 2-D networks.

The network lifetime for the three 2-D networks with very low traffic is dictated by the idle energy consumptions. It can be seen from Figure 6.34 (a) that when traffic is very low and idle energy is dominant, the network lifetimes for all the three networks is nearly equal and approaches the maximum network lifetimes of 180 hours. When the Sleep mode was introduced, the total network lifetimes dramatically changed for all the three networks as shown by Figure 6.34 (b). The Sleep 2D Optimised grids network now has a minimum life of 1040 hours compared with 894 hours for Sleep 2-D Equal grids and 824 hours respectively. The Sleep 2-D Optimised grids network also has 570% more longer life compared with 2-D Optimised grids network.

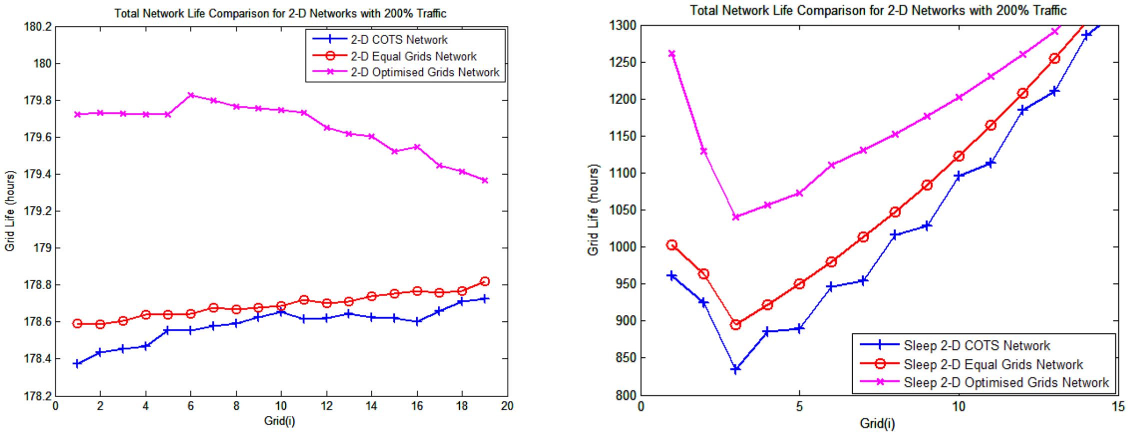

Figure 6.34 Comparison of grid lifetimes with and without the Sleep mode with 10 % network traffic.

Clearly Optimisation with Sleep greatly enhances network lifetimes at lower traffic.

6.4 Conclusion

This chapter has explained the development of Two Dimensional (2-D) wireless sensor networks in which sensor nodes were introduced in the existing networks to measure and compare the overall network QoS parameters and lifetimes. This chapter has demonstrated that by applying the novel Optimisation algorithm to model the new 2-D Optimised grids network and by simulating this newly developed model in the enhanced NS2 simulator huge benefits can be gained in network QoS parameters as well as network lifetimes.

In 2-D networks, the wireless sensor nodes gather and forward the sensory data repeatedly, adding extra burden on the cluster heads that are near to the base station. These cluster heads are very busy in forwarding the data received from previous grids. This extra wireless sensor traffic causes an increased interference on the transmission channel, and can have detrimental effects on the total throughput of the network.

The initial study involved in developing three wireless sensor network models with CTS-RTS handshaking protocol enabled. Wireless sensory data was also added to these three models. Two of the models that were based on the existing Equal grids and COTS network algorithm, were compared with the third model based on the novel Optimised grids algorithm. The results achieved concluded that despite the added sensory data, the new 2-D Optimised grids network had a much higher throughput of 87% as compared to 70% and 72.0% obtained by 2-D Equal grids and 2-D COTS network. The new Optimised grids algorithm provided much better spatial reusability by using unequal grids sizes and reducing collisions. Despite having much higher throughput, the new 2-D Optimised grids network also showed higher network lifetimes.

After modifying the model by eliminating RTS-CTS functionality, the new 2-D Optimised grids network, delivered a staggering 99.8% throughput while the other two networks only delivered between 76% and 77%. This showed the new Optimised grids algorithm greatly reduced the hidden node problem present in wireless networks hence reducing collisions. The latency and jitter for the new 2-D Optimised grids network were nearly ten times less, proving to be very useful for time critical applications that use sensors with actuators.

Further research showed that despite increasing the network traffic from 100% to 200%, when congestion in the network became extremely high as the network was working on its maximum capacity, the new results showed that the new 2-D Optimised grids network managed to deliver more than half of the throughput while the other two 2-D delivered less than half of the total throughput required.

In all the simulation cases, the node energy, the cluster head and total grid energy consumption of the 2-D Optimised grids network was much lower in the range between 30% and 70% that in result boosted the total network lifetimes.

In the case when the network traffic was reduced to 50% and then lowered to 10%, all the three 2-D networks achieved 100% throughput and the latency and jitter became inherent to the system.

At lower traffic, the idle energy becomes dominant. By introducing the Sleep modes the nodes go to sleep if they are awake for more than 10% of the idle time. In the best case scenario, when the network traffic is only 10%, the network lifetime for the new 2-D Optimised grids network increased from 179 hours to 1040 hours until the first grid completely ran out of energy.

The use of the novel Optimised grids algorithm proved that during higher traffic loads, it helps by improving QoS parameters as increasing the throughput upto 26% while reducing the latency and jitter by a factor of ten. At the same time it also increases the network lifetimes.

At lower traffics loads in best case scenario it increases the network lifetime by over 500%. The new Optimised grids algorithm can also be used with existing network protocols like GAF, LEACH, SPAN and SMAC to further increase their performance.

Chapter 7

Conclusions and Future Research

In this research a new energy efficient Sleep Optimised grids model was developed, implemented and examined which included the sleep algorithm to extend the network lifetime and QoS parameters for wireless sensor networks. The implementation of the new Sleep Optimised grids algorithm dramatically improved not only on the network lifetime and energy/bit consumption costs, but also delivered superior performance in terms of QoS parameters for the wireless sensor networks. Detailed packet level simulation models were developed using the enhanced NS2 simulation tool to conduct cost and performance trade-off analysis between the new Sleep Optimised grids network with similar existing protocols. This chapter summarises the work carried out during this research and addresses the main contributions of the current research.

7.1 Summary of Research

Ad hoc wireless sensor networks (WSNs) are formed from self-organising configurations of distributed, energy constrained, autonomous sensor nodes. The service lifetime of wireless sensor nodes depends on the energy consumption of the communication subsystem. One of the key challenges in unlocking the potential of such data gathering sensor networks is conserving energy so as to maximize their post deployment active lifetime. The primary goal of this research was to increase the wireless sensor network lifetime while improving network performance, under full load conditions. The new Sleep Optimised grids model proved to be most effective solution in providing energy costs saving as well as improving network QoS parameters throughout this research. Based on the wireless sensor node transmission range and traffic relationship, the new Sleep Optimised grids model provides a robust traffic dependent energy efficient grid size that minimises the cluster head energy consumption in each grid and balances the energy use throughout the network. All the wireless sensor nodes that are in idle state go to sleep, thus providing huge energy savings with the new Sleep Optimised grids model. The most important advantage of this new Sleep Optimised grids model is that it can be applied to all one and two dimensional traffic scenarios where the traffic loads may fluctuate due to sensor activities. During traffic fluctuations the new Sleep Optimised grids model can be used to re-optimise (new Dynamic Sleep Model) the wireless sensor network to bring further benefits in energy reduction and QoS parameters. As the idle energy becomes dominant at lower traffic loads, the new Sleep Optimised grids model incorporates the sleep energy and idle energy duty cycles which can be implemented to achieve further network lifetime gains in all wireless sensor network models.

7.2 Significant Contributions to the Field of Wireless Sensor Networks

Initial study was carried out to learn the key challenges facing wireless sensor networks. The need for research into energy efficient transmission techniques that could enhance the network lifetimes and improve on the QoS parameters was identified and provided a basis for this research. Many of the performance metrics required by wireless sensor network were highlighted, which included energy efficiency, latency, accuracy, fault tolerance, scalability, transport capacity and throughput. Battery lifetimes and energy harvesting techniques were investigated. Many existing wireless sensor network energy efficient MAC, Routing and Topology management protocols were examined while exposing their advantages and limitations in terms of energy efficiency (idle/sleep/single-hop /multi-hop), clustering techniques (cluster head rotation) and network throughput (packet delivery/latency/litter).

A selection criterion was established for a wireless sensor network simulator. Many different simulation tools were compared including OPNET, QualNet, GloMoSim and NS2. NS2 was chosen to be the most appropriate simulation tool based on its flexibility as well as being easy to modify. It is also regarded as the most credible network simulator among the research community. Initial part of the research involved in setting up simple two node networks to verify the accuracy of all the protocols that were going to be used in this research. One of the issues found with the NS2 energy model was that it did not update the idle energy consumption of the wireless node when using 802.11 MAC with different routing protocols. The Energy model in NS2 was only provided for SMAC, and was not completely updated for use with other NS2 MACs and routing protocols.

The contributions from this research with the most significant first are as follows.

1 A new Sleep Optimised grids model has been derived and developed which allows the user to achieve new optimised grid sizes based not only on the network traffic, but also with variable sleep duty and idle duty times. The new Sleep model puts the redundant nodes to sleep, hence conserving energy that increases the network lifetime.

This new Sleep Optimised grids model was fully implemented in NS2 along with the Equal grids model and COTS model. Packet level simulation was carried and network lifetimes and QoS parameters were recorded for all the three models

The benefits of the new Sleep Optimised grids models can be realised at all levels of traffic load, either low or high. Even when the Equal grids and COTS networks had the Sleep model included, the new Sleep Optimised grids model showed an increase of 63% for cluster head lifetime and 19% for network lifetime. The new Sleep Optimised grids network also had 33.3% more throughput and much lower latency and jitter compared to the Equal grids and COTS network with Sleep model.

For the new Sleep Optimised grids model, which involves the idle and sleeps duty cycles, the cluster head lifetime was 37% higher as compared with the original Optimised grids model developed by (Gao, Blow et al. 2006) with sleep mode. Simulation results have concluded that at lower traffic the new Sleep Model increases the network lifetime by 77%.

2 A new Dynamic Sleep Model was fully developed and implemented in NS2. The new Dynamic Sleep model recalculates the optimised grid size during varying traffic loads. If the network traffic increase or decrease, the transmission range is recalculated to achieve optimum transmission range for that particular grid. Idle duty and sleep duty can also be varied. The key benefit of the Dynamic Sleep model is that the transmission range is always

kept optimised based on the network traffic. The new Dynamic Sleep model will always re-optimise the network to keep the transmission energy as low as possible. The throughput of the network also increases significantly due to much better spatial re-usability, by reducing collisions and improving on packet delivery.

Packet level simulation has proven that at low traffic loads, the new Dynamic Sleep model can increase the network lifetime by 480% compared to Equal grids and COTS networks that do not have dynamic optimisation.

At higher traffic loads in case where the traffic is doubled, the new dynamic Sleep Optimised grids network delivers a higher throughput. Packet level simulation in NS2 has revealed that the new dynamic Sleep Optimised grids network achieves a staggering 31.3% and 40% higher throughput and much lower latency and jitter compared to the Equal grids and COTS networks with identical traffic load. The results highlight that new Dynamic Sleep model brings significant contribution to the field of wireless sensor networks.

3 Research was carried out on the network lifetime and QoS parameters for 2-D wireless sensor networks that included sensory data. A complete 2-D wireless sensor network field was developed and implemented in NS2. Three 2-D wireless sensor network models were developed including the original Optimised grids network, the Equal grids network and the COTS network.

Results concluded that by using the RTS-CTS feature enabled, the original Optimised grids algorithm attained 87% higher throughput as compared to the 70% and 72% attained by the Equal grids and COTS networks with much lower latency and jitter and higher network lifetime. Using the enhanced NS2 tool, new packet level simulation results showed that by disabling the RTS-CTS feature the new 2-D Optimised grids network attained 98.8% throughput, but the Equal grids and COTS networks attained much lower throughput around 77%. At lower traffics and using the new Dynamic Sleep model, the network lifetime of 2-D new Dynamic Sleep Optimised grids network increased by 600%.

4 The original Optimised grids algorithm developed by (Gao, Blow et al. 2006) was implemented in NS2. A complete packet level simulation was carried out measuring the key QoS parameters including throughput, latency and jitter. The cluster head and network lifetimes were studied and compared with Equal grids and COTS networks.

The benefits of the original Optimised grids algorithm were evident through packet level simulation. The original optimised grids network showed an increase of 30% and 50% cluster head lifetime as compared with the Equal grids network and COT network. The original Optimised grids network also demonstrated a much higher network throughput increased by 24%, The QoS parameter showed a significant rise as packet delivery was improved on average by 30%, latency reduced by tenfold and jitter reduced by 55%.

5 NS2 does not implement idle energy update procedure in all the ad hoc routing protocols. The NS2 simulation tool was modified to give correct energy values for idle, sleep transmit and receive states. Further enhancements were made by adding transmit, receive, sleep and idle times in the NS2 trace files.

6 Another contribution in this research was to modify the channel properties of wireless node in NS2 which allows each node to have its unique transmission range. A problem in NS2 was that it did not allow the nodes to have an individual range. Thus all nodes had to have equal range which would have been a limitation in this research. The enhanced NS2 tool now provided a complete energy consumption breakdown with correct energy consumptions and times in each state as well as unique transmission range for each wireless node.

From this research it can be concluded that the new Sleep Optimised grids Model and the new Dynamic Sleep Model based on original Optimised grids algorithm are successful in further improving the network lifetime and QoS parameters for 1-D and 2-D wireless sensor network. The key advantage of these models is that they can be implemented in conjunction with other energy saving protocols similar to SMAC and TMAC as it does not interfere with the actual protocol, but only creates an overlay to optimise the grids sizes and transmission range of wireless sensor nodes.

The results from this thesis have been published in

Iqbal, Q. R., D. J. Holding, et al. (2007). "Energy efficient radio range allocation in ad hoc wireless sensor networks." Proceedings of the 2007 spring simulaiton multiconference-Volume 1: 58-65.

Iqbal, Q. R., D. J. Holding, et al. (2007). “Radio Range Adjustment for Optimising Energy Consumption in Wireless Sensor Networks” 4th Wireless Sensing Interest Group (WiSiG) Conference. Aston University 13th September 2007

7.3 Future Research Directions

This research presents with topology management solutions to increase the wireless sensor network lifetime and QoS parameters. The traffic source in this simulation has been based on UDP, and further work can be carried out by implementing higher layer protocols, like TCP. In this case there would be some interplay between network lifetime and QoS since higher throughput means fewer retransmissions.

Significant research can be carried out by implementing this model in an existing wireless sensor MAC protocol and transferring it into hardware to study the robustness of this algorithm. Another key benefit could be to add an energy efficient clustering algorithm, which can detect or calculate the number of nodes in the Optimised grids and can then efficiently calculate the cluster head rotation sequence so all nodes can use their energy in a balanced manner.

End Of Chapters

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