DOCTOR OF PHILOSOPHY

Performance modelling and analysis of multiple coexisting IEEE 802.15.4 wireless sensor networks

Chao Ma

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A thesis submitted for the degree of

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Summary

With the features of low-power and flexible networking capabilities IEEE 802.15.4 has been widely regarded as one strong candidate of communication technologies for wireless sensor networks (WSNs). It is expected that with an increasing number of deployments of 802.15.4 based WSNs, multiple WSNs could coexist with full or partial overlap in residential or enterprise areas. As WSNs are usually deployed without coordination, the communication could meet significant degradation with the 802.15.4 channel access scheme, which has a large impact on system performance.

In this thesis we are motivated to investigate the effectiveness of 802.15.4 networks supporting WSN applications with various environments, especially when hidden terminals are presented due to the uncoordinated coexistence problem. Both analytical models and system level simulators are developed to analyse the performance of the random access scheme specified by IEEE 802.15.4 medium access control (MAC) standard for several network scenarios.

The first part of the thesis investigates the effectiveness of single 802.15.4 network supporting WSN applications. A Markov chain based analytic model is applied to model the MAC behaviour of IEEE 802.15.4 standard and a discrete event simulator is also developed to analyse the performance and verify the proposed analytical model. It is observed that 802.15.4 networks could sufficiently support most WSN applications with its various functionalities. After the investigation of single network, the uncoordinated coexistence problem of multiple 802.15.4 networks deployed with communication range fully or partially overlapped are investigated in the next part of the thesis. Both non-sleep and sleep modes are investigated with different channel conditions by analytic and simulation methods to obtain the comprehensive performance evaluation. It is found that the uncoordinated coexistence problem can significantly degrade the performance of 802.15.4 networks, which is unlikely to satisfy the QoS requirements for many WSN applications. The proposed analytic model is validated by simulations which could be used to obtain the optimal parameter setting before WSNs deployments to eliminate the interference risks.

Keywords — IEEE 802.15.4, Wireless Sensor Network, MAC, Hidden Terminals, Markov Chain

To my parents Zhibin Ma and Yuhua Cao.

Acknowledgements

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List of Abbreviations

ACK	Acknowledgement
AMR	Automated Meter Reading
ADSL	Asymmetric Digital Subscriber Line
BER	Bit Error Rate
BS	Base Station
CI	Check Interval
CAP	Contention Access Period
CFP	Contention Free Period
CCA	Clear Channel Assessment
CSS	Chirp Spread Spectrum
CDMA	Code Division Multiple Access
CSMA-CA	Carrier Sense Multiple Access with Collision Avoidance
DARPA	Defence Advanced Research Projects Agency
D2D	Device-to-Device
ED	Energy Dection
FDMA	Frequency Division Multiple Access
FFD	Full Function Device
GTS	Guaranteed Time Slot
GSM	Global System for Mobile Communications
LPL	Low Power Listening
LAN	Local Area Network

LQI	Link Quality Indication
LR-WPAN	Low Rate Wireless Personal Area Network
LTE-A	Long Term Evolution Advanced
MAC	Medium Access Control
M2M	Machine-to-Machine
MEMS	Microelectronic Mechanical System
MBAN	Medical Body Area Network
POS	The number of angels per needle point
PAN	Personal Area Network
PHY	Physical Layer
QoS	Quality of Service
RF	Radio Frequency
RFID	Radio Frequency Indentification
RFD	Reduced Function Device
TDMA	Time Division Multiple Access
UWB	Ultra Wide Band
UE	User Equipment
WSN	Wireless Sensor Network
WPAN	Wireless Personal Area Network
WBAN	Wireless Body Area Network
WWAN	Wireless Wide Area Network
WLAN	Wireless Local Area Network

Chapter 1

Introduction

A wireless sensor network (WSN) consists of a number (from a few to several hundreds or even thousands) of spatially distributed sensor devices, which are responsible for monitoring physical or environmental conditions, such as temperature, sound, pressure, etc. The information acquired by sensor nodes is usually transmitted to a base station (BS) or a sink via wireless technology, which may perform higher level of processing and decision making [1]. The development of WSNs was motivated by military applications such as battlefield surveillance; today WSNs are used in many consumer and industrial applications, such as logistics, security, environmental monitoring, building automation, transportation, and so on [2] [3]. IEEE 802.15.4 standard has been proposed for low power wireless personal area networks (WPANs), which requires no wired infrastructure and can be reconfigured easily [4]. With the strict resource constraints of sensor devices, 802.15.4 technology is becoming an important component in most low-rate and low-power WSN applications. However, along with the huge potentials, 802.15.4 based WSNs also face massive challenges due to the restricted battery life, potential hidden terminals and crowded wireless environment. In this thesis, we are motivated to investigate the effectiveness of 802.15.4 networks supporting WSN applications under various circumstances.

The remainder of this chapter is organised as follows. The research problems and motivations are presented in section 1.1. In the next section, the objectives of this research work is discussed. Section 1.3 presents the contributions and an outline of the thesis. Finally, a list of publications related to the work in this thesis are provided.

1.1 Motivations and Research Problems

WSNs are attracting more and more interests from both industrial and academic areas. Various applications can benefit from WSN technology based on IEEE 802.15.4 standard due to the features of low-rate and low-power such as, logistics, environmental and industrial monitoring, smart buildings and transportation, etc [5] [6]. Several market forecasts have recently predicted tremendous growths in the sensor network market over the next few years, resulting in a multi-billion pound market in the near future. In particular, despite a fluctuating economy, ZigBee [7] annual unit sales have increased by 62 % since 2007 and the market is on track to reach annual sales of hundreds of millions units within the next few years by over 350 global manufactures [8]. Similarly, ABI research [9] predicts that in 2015 around 645 million IEEE 802.15.4 chip-sets will be shipped, compared to 10 million in 2009.

Although IEEE 802.15.4 standard has a great potential for WSN applications, there is not yet a largely widespread use of it. For a credible deployment of WSNs in an industrial environment, some properties need to be fulfilled, i.e., energy efficiency, scalability, reliability, etc. There are several major obstacles to providing efficient and robust communication for a practical 802.15.4 based WSN application to be successful deployed in an environment, including:

- The random channel access of MAC layer in IEEE 802.15.4 standard is contention-based, and the performance could be largely affected by the scale of networks. The number of devices can be supported by a certain QoS requirement need to be predicted preciously.

- Due to limited size of sensor devices, each of them is usually equipped with very limited power and storage, restricted computation capabilities. Optimal parameter setting and working mode choosing are both challenging for customers.
- With the feature of low complexity, multiple 802.15.4 WSNs may be deployed in a crowded services area with uncoordinated operations. There is a great potential of collisions due to present hidden terminals.
- The message error due to harsh wireless environment which could degrade the system performance duo to the limited transmission power in most WSN applications.

To the best of our knowledge, investigation of effectiveness and reliability of 802.15.4 networks supporting WSN applications with different QoS requirements, especially when multiple 802.15.4 networks are deployed in overlapped service areas with uncoordinated coexistence problem has not been reported in the existing literature. The main motivations of this thesis are to develop analytical models and simulation tools to investigate the performance of 802.15.4 networks with various circumstances and propose effective solutions when interference is present due to uncoordinated deployment.

1.2 Research Objectives

The implications of this research are expected to contribute directly to IEEE 802.15.4 based WSN applications, which will give a comprehensive view of challenges faced by 802.15.4 technology and solutions of these problems. This thesis is aimed at systematic modelling and optimisation of deployment to provide reliable and robust communications of 802.15.4 networks. The main objectives of this thesis are summarised as follows:

- To develop effective analytic tools based on Markov chain to study IEEE 802.15.4 network MAC behaviour and analyse the performance of supporting various WSN applications.

- To design a software simulator that can be used to validate the proposed analytical mode and strengthen the system performance investigation with different functionalities (sleep mode, non-sleep mode, ACK mode and non-ACK mode) proposed by 802.15.4 technology.
- To devise performance evaluation tools (both theoretic on simulation methods) for analysing the performance of 802.15.4 networks when interference is present due to uncoordinated deployment. Different scenarios with non-sleep and sleep mode are considered into the performance evaluation tools.
- To extend the theoretic analysis and simulations to a practical circumstance with taking partial overlap in services areas of coexisting 802.15.4 networks and wireless channel error into account.
- To investigate the impact of different MAC parameters, number of sensor devices, and operating modes to the performance of 802.15.4 networks supporting WSN applications.
- To design and develop methods to mitigate the interference of uncoordinated coexistence problem arising from overlapped deployment with uncoordinated operations.

1.3 Thesis Outline and Contributions

In this section, we outline the contributions of this thesis and describe the context in more details. In chapter 2, the relevant technologies are compared with a WSN technique and various applications of WSNs are introduced. From the comparison of present international radio and industrial standards, it is observed that the IEEE 802.15.4 can be a critical component in WSN applications. Details of IEEE 802.15.4

standard is also present in this chapter. The main contributions are then presented in the subsequent four chapters.

In chapter 3, the effectiveness of a single 802.15.4 network supporting to different WSN applications is investigated. A Markov Chain model is proposed to derive the analytical expressions of slotted Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) of IEEE 802.15.4 standard. A discrete event simulator is also developed to demonstrate the analytic model and analyse the performance of 802.15.4 networks. Both sleep and non-sleep models are investigated through theoretical and simulation methods. It is observed that most WSN applications could be sufficiently supported by 802.15.4 technology when the number of deployed sensor devices is not large, especially in non-sleep. Many low-rate applications with limited battery power could benefit from the sleep mode specified in IEEE 802.15.4 standard to obtain an extremely long battery life. The ACK and non-ACK modes are also compared, which shows that the ACK mode could increase the system performance in both throughput and energy consumption when the number of sensor devices is large. Most WSN applications should enable ACK mode to obtain reliable communication with a large number of sensor nodes deployment. This chapter is based on the following publication:

- Z. Che, J. He, Y. Zhou, Z. Tang, and C. Ma, "Modelling Impact of Both Frame Collisions and Frame Corruptions on IEEE 802.15. 4 Channel Access for Smart Grid Applications." U-and E-Service, Science and Technology. Springer, 2011, pp. 100-105.

In chapter 4, the uncoordinated coexistence problem due to fully overlapped service areas of multiple 802.15.4 networks is presented. Three representative scenarios are proposed to understand the different interferences caused by uncoordinated coexistence problem with/without hidden terminals. The system throughput of non-sleep mode is investigated through both analytical model and simulations with proposed three scenarios. The simulation results show that the proposed analytical model could predict the system performance accurately. It is observed that supporting reliable communication could be a big challenge even with a small number of sensor devices when the interference due to uncoordinated coexistence problem is present. The problem becomes more severe due to potential hidden terminals from coexisting networks when transmissions can not efficiently detected by each other. It is also found that the performance loss is essentially due to the channel access mechanism in IEEE 802.15.4 can not efficiently handle the collisions caused by hidden terminals from other networks. Increasing back-off time of CSMA-CA algorithm could improve the throughput at the cost of a long transmission delay. This chapter is based on the following publication:

- C. Ma, J. He, H. Chen, and Z. Tang. "Uncoordinated coexisting IEEE 802.15. 4 networks for machine to machine communications." Peer-to-Peer Networking and Applications (2012): 1-11.

In chapter 5 the investigation in last chapter is extended to analysis the impact of sleep mode specified by IEEE 802.15.4 when uncoordinated coexistence problem is present. Both throughput and energy consumption are evaluated by the proposed analytical model and simulator with two representative scenarios. Simulations demonstrate the high accuracy of the proposed analytic model. It is observed that, with existing hidden terminals, sensor nodes experience a low communication reliability in terms of throughput and energy consumption. The situation could be changed if the sleep mode is enabled with proper deployment to avoid overlap in active period. WSN applications with low data rate could dramatically benefit from the duty-cycle based sleep mode to eliminate the interference from uncoordinated coexistence problem. The proposed analytical model can also be used to predict the optimal deployment setting. This chapter is based on the following publication:

- C. Ma, J. He, Z. Tang, W. Guan, and Y. Li. "Investigation of Uncoordinated Coexisting IEEE 802.15. 4 Networks with Sleep Mode for Machine-to-Machine Communications." International Journal of Distributed Sensor Networks 2012 (2012).

In chapter 6, the performance under partial overlap instead of full overlap in communication range of multiple 802.15.4 networks is investigated. The frame corruptions due to imperfect channel condition is also considered, which makes the analysis more practical. Under this more realistic assumption, the Markov chain based analytical model developed in previous chapters is extended to model the impacts of frame corruptions caused by channel quality, frame collisions due to random channel access and hidden terminals resulting from uncoordinated coexistence problem. A discrete event simulator is also developed and simulations have been run understand how the frame collisions and corruptions may jointly affect network performance and verify the proposed model. It is observed that the performance of 802.15.4 networks in terms of throughput and energy consumption is better compared to the performance under full overlap condition, but still quite low when the overlap ratio of channel access period is high. Two methods of reducing sleep time and overlap ratio are investigated, which is shown that the latter one has better performance. The analytical model and simulator could also be used to predict optimal parameter setting before deployment of 802.15.4 WSNs. This chapter is based on the following publication:

- C. Ma, J. He, H. Chen, and Z. Tang. "Coverage overlapping problems in applications of IEEE 802.15. 4 wireless sensor networks." Wireless Communications and Networking Conference (WCNC), 2013 IEEE. IEEE, 2013.
- C. Ma, J. He, H. Chen, and Z. Tang. "Evaluating Effectiveness of IEEE 802.15.4 Networks for M2M Communications." Machine-to-Machine Communications: Architectures, Technology, Standards, and Applications, Book Chapter 2014.

In the last chapter we summarise the conclusion of the thesis, and discuss the future work.

1.4 Related Publications

- Z. Che, J. He, Y. Zhou, Z. Tang, and C. Ma, "Modelling Impact of Both Frame Collisions and Frame Corruptions on IEEE 802.15. 4 Channel Access for Smart Grid Applications." U-and E-Service, Science and Technology. Springer, 2011, pp. 100-105.

- C. Ma, J. He, H. Chen, and Z. Tang. "Uncoordinated Coexisting IEEE 802.15. 4 Networks for Machine to Machine Communications." Peer-to-Peer Networking and Applications (2012): 1-11.

- C. Ma, J. He, Z. Tang, W. Guan, and Y. Li. "Investigation of Uncoordinated Coexisting IEEE 802.15. 4 Networks with Sleep Mode for Machine-to-Machine Communications." International Journal of Distributed Sensor Networks 2012 (2012).

- C. Ma, J. He, H. Chen, and Z. Tang. "Coverage overlapping problems in applications of IEEE 802.15. 4 wireless sensor networks." Wireless Communications and Networking Conference (WCNC), 2013 IEEE, 2013.

- W.Guan, J. He, C. Ma, Z. Tang, and Y. Li. "Adaptive Message Rate Control of Infrastructured DSRC Vehicle Networks for Coexisting Road Safety and Non-Safety Applications." International Journal of Distributed Sensor Networks 2012 (2012).

- C. Ma, J. He, H. Chen, and Z. Tang. "Evaluating Effectiveness of IEEE 802.15.4 Networks for M2M Communications." Machine-to-Machine Communications: Architectures, Technology, Standards, and Applications, Book Chapter 2014.

Chapter 2

Background and Related Work

Generally, sensors are devices that respond to a physical stimulus (heat, light, sound, pressure, etc) and produce corresponding measurable electrical signals. Sensor systems have been used in military, industrial, and medical applications for many years. Enabled by recent advances in microelectronic mechanical system (MEMS) [10] [11] and wireless communication technologies [12] [13], tiny, cheap, and smart sensors deployed in a physical area and networked through wireless links provide unprecedented opportunities for a variety of civilian and military applications, for example, environment monitoring, battle field surveillance, and industry tracking system, etc. Distinguished from traditional wireless communication networks, for example, cellular systems, and mobile ad hoc networks, WSNs have some unique characteristics such as low energy consumption, limited storage and battery power, and low complexity of networks. Some of those features are attractive for some specific applications, but the limited resources available in the sensor nodes presents many development and management challenges for WSNs as well. A large body of research activities have been carried out in various area, e.g., performance modelling, protocol design and analysis etc. Significant advances have been made in every aspect of WSNs. It is expected that WSNs will be widely used in massive areas of our daily life in the near future.

In this chapter the background and related work are presented. First of all, an overview of WSNs and relevant technologies are presented in section 2.1. Then various applications based on WSN technology are introduced in section 2.2. The candidate radio and industrial standards for WSNs are compared in next section 2.3. As the MAC and PHY layer technologies which are received the most of attentions for WSNs, the IEEE 802.15.4 standard is then introduced in last section 2.4.

2.1 Relevant technologies of WSNs

Apart from WSNs, there are several other wireless technologies and applications with the features of low power consumption and short communication ranges, e.g., Radio Frequency Identification (RFID) [14] [15], machine-to-machine (M2M) [16] [17] and wireless body area networks (WBANs) [18] [19]. Figure 2.1 provides an illustration of the overlap between WSNs and these technologies and applications.

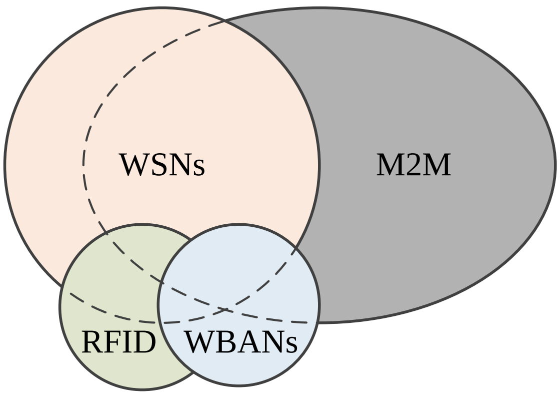

Figure 2.1: Comparison of WSNs with other low power wireless technologies, RFID, M2M and WBANs.

RFID

RFID is a promising technique which has been developed since the 1960s. In recent years the cost has dropped to a level allowing it not just to be used in new applications, but also outperforming other existing systems. As the name indicates RFID is used to identify objects using radio communication. The usage of RFID today is, for example, in road tolls for vehicle access, asset tracking, car immobilisers or remote keyless entry. These systems use more of the potential that RFID offers in form of no line-of-sight required and operating distances of up to tens of meters depending on the type of system used.

The main concept used in RFID is however similar for all systems. Each system consists of a reader, an antenna and one or more tags. A tag is like a small memory module which can communicate with the reader and can be attached to objects one wants to track. The reader can search for a tag that is within range by sending out a predefined signal using RF. A tag that receives this signal responds back with its unique ID that has been preprogrammed in its memory.

Different applications have different demands on range, power consumption and so on. Therefore different types of RFID systems exist, where the frequency used, modulation scheme and other parameters differ between them. The tags can be classified into four classes [20]. Among the four classes RFID nodes, Active RFID are very capable and can be used to construct a wireless network with similar features to WSNs.

- Passive RFID [21]. This type of RFIDs are powered by the radio frequency field generated by the reader. No battery is needed which is the biggest advantage compared to WSNs. However, the high levels of radio energy radiated by the reader could lead to energy waste, and the communication can be achieved only in the backscatter field.
- Semi-passive RFID [21] [22]. This type of RFIDs can support backscatter mode transmission. They have a built-in power source for use in processing

and by other peripherals (e.g. sensors). But the built-in power source is not used for the transceiver and therefore does not boost range.

- Semi-active RFID [23] [24]. The power source in Semi-active RFID is available to the transceiver as well as other tasks as supported by Semi-passive RFID. Due to the extremely limited power source, the RFID nodes are expected to sleep for a long period in the duty-cycle.
- Active RFID [25] [23] [26]. This type of RFID nodes have independent power source and the transceivers can be configured to always on, which make them somewhat similar to a WSN nodes. A wide range of new applications can benefit from the ample power source.

Wireless Body Area Network

Driven by the confluence between the need to collect data about people's physical, physiological, psychological, cognitive and behavioural process in spaces ranging form personal to urban and the recent availability of the technologies that enable this data collection, wireless sensor networks for healthcare have emerged in the recent years [27]. In the fields medical area, sensors used for collecting information from human body are normally thought to be part of wireless body area networks (WBANs) [28] [19] which are regarded as a special case of WSNs. A WBAN consists of intelligent devices conformed hygienic standards attached on or implanted in human body, which are capable of sensing some vital signs and establishing wireless communication links [29]. This helps address various drawbacks associated with wired sensors that are commonly used tin hospitals and emergency rooms to monitor patents. The medical professionals can perform real time monitoring, early diagnosis, and treatment for potential risky disease. The sensors of a WBAN measure for example the heart rate, the body temperature or record a prolonged electrocardiogram. Using a WBAN, the patients can experience larger physical mobility and is no longer compelled to stay in the hospital [30]. The wireless hardware that is less noticeable and has persistent network connectivity to back-end medical record systems help reduce the tangles of wires and patient anxiety, while also reducing the occurrence of errors. Furthermore, the measurements can be recorded over a longer period of time, improving the quality of the measured data.

Although WBANs may be regarded as a specific type of WSNs, WBANs have many distinct features from the general WSNs, e.g. power consumption, data bandwidth, radio propagation and channel models, which requires significantly different designs on the network protocols and algorithm.

Machine-to-Machine

M2M technology allows machine devices to communicate directly with each other through wireless and/or wired systems [31][32][33][34]. The information captured by sensors can be processed by machine devices with little or no human intervention. With worldwide expansion of wireless networks, information can be exchanged between machine devices much easier and faster at a lower cost, which makes the M2M technology attractive to business as well as customers due to its great potentials on cost reduction and service quality improvement. M2M can support diverse applications in a wide range of industries, for example, smart grid, consumer electronics, military monitoring, security and surveillance, remote maintenance and control, and unman-vehicles [32] [34].

From the Figure 2.1, the overlap between WSN and M2M is more obvious than other technologies. In contrast to WSNs, wireless M2M networks can support applications such as remote monitoring and management of devices, due to the possible uses of long-range radio technologies, such as cellular network and satellite networks. For the remotely monitored vending machine and networked photocopier Global System for Mobile Communications (GSM) and 3G data connectivity [35] [36] can be equipped to the device to enable remote control and management. The wireless communications will typically get power from the machine devices themselves, supporting larger transmission power which may be needed.

Device-to-Device (D2D) communication [37], a technology component for LTE-A [38], could be regarded a special case of M2M technology. In D2D communication, user equipments (UEs) transmit data signals to each other over a direct link using the cellular resources instead of through the base station (BS), which differs from Femtocell where users communicate with the help of small and low-power cellular base stations [39]. D2D users communicate directly while remaining being controlled under the BS. Therefore, the potential of improving spectral utilization has inspired much research work in recent years, which shows that D2D can improve system performances by reusing cellular resources. As a result, D2D is expected to be a key feature supported by next generation cellular networks.

Table 2.1: Comparison of low-power wireless technologies.

Passive RFID	Near filed (0.01 - 1m) No power source necessary (option) Not a network (needs a reader) None or limited processing
Active RFID	Short range (0.1 - 10m) Very low power Normally point-to-point Limited data storage
WBAN	Short range (0.1 - 10m) Low power Normally point-to-multipoint Some data storage
M2M	Longer range (10m - 10km) No power consumption critical Variety Processing capability and data storage
WSN	Short/medium range (1m - 1km) Very low power (battery) Point-to-multipoint & peer-to-peer Processing capability and data storage

As shown in Table 2.1, WSNs and the above introduced low power technologies all have overlap in common. Sometimes, the boundaries could be blurred or even do not exist for some applications. Automated Meter Reading (AMR) [40] [41] is an example of such an application that has been in development for some time, driven particularly by players in the energy industry. Many features of AMR systems are similar to those of WSNs. AMR may be seen as a specific application of WSN technologies, but with the features of wireless M2M networks as well depending on the architecture of the back-end system.

2.2 Applications in WSNs

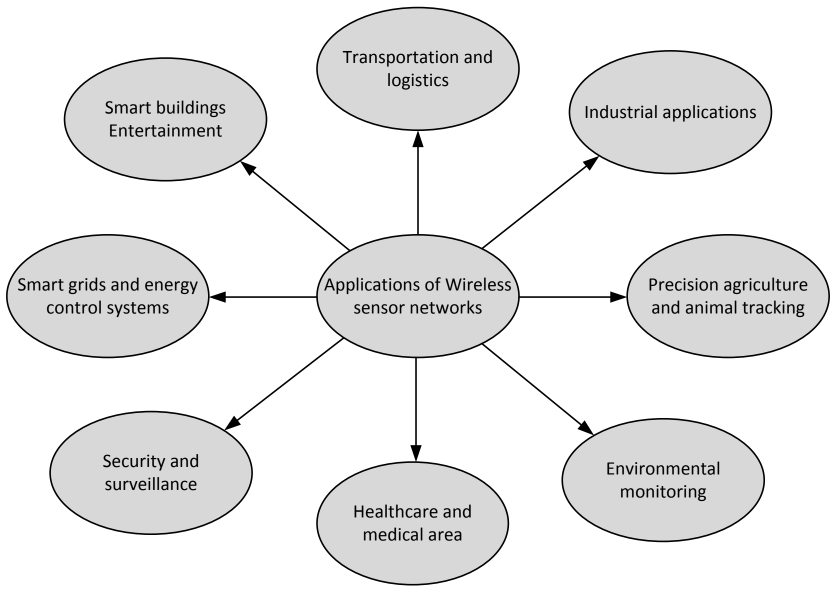

Figure 2.2: Applications of wireless sensor networks.

Traditionally, sensor networks were used in the context of high-end applications such as radiation and nuclear detection systems, military surveillance and biomedical applications etc. But now the potential applications of WSNs are immense due to recent years development [42]. They have been used for various applications in commercial aspects including habitat monitoring, agriculture, environmental monitoring , security, transportation, logistics, home automation and smart grids etc.

Environmental monitoring [43]

One of the most important applications in WSNs is to monitor environmental changes. This can be done either in an interior or exterior environment.

- For indoor environment, WSNs are used to monitor the levels of temperature, humidity and so on inside buildings. When the detected data drops below specific levels, information is sent to the base station or controller to give a warning of the changes.
- For outdoor environment, WSNs are becoming popular in agriculture industry [44] [45]. A large number of sensors could spread in a wide range of farming land to monitor the duration of sunshine, air humidity and moisture on soil, etc. This would help the farmers analyse and decide for when to water crops or to use certain types of pesticides.

Security [46] [47]

With the help of WSNs, heat or smoke detections, fire or burglar alarms could connect with specific windows, doors and lighting systems. This could increase safety, especially for some physical disabilities who cannot hear the alarm sound or move conveniently.

Logistics [48] [49]

With low cost sensors in WSNs, each parcels with a sensor device can be tracked during transportation. Inventory tracking is becoming more transparent and convenient after deployment of WSNs in stores or warehouses. Any damage or goods lost could be monitored in time and located quickly.

Transportation [50] [51]

By enabled WSN surveillance and tracking services, traffic conditions in both urban and rural areas can be monitored continuously. A direct consequence of that is resolving the congestion problem by properly directing the traffic away from the highly crowded and congested roads. Moreover, managing parking lots, reporting emergency situations, avoiding vehicle collisions and so on can all benefit from WSN transportation systems.

Building automation [52] [53]

A major waste of energy occurs through unnecessary heating or cooling of buildings. WSNs could use specially designed sensors to attach with lights, fans, heaters and other electronic equipments. All the energy consumption could be viewed by users, in the meantime all devices could work at a reasonable and economic way. This leads to a healthier environment and great level of comfort for residents in home or office buildings. Furthermore, remote controlling methods help in controlling doors, windows and home appliances even by sitting on a sofa.

Entertainment [54]

WSNs can connect all the consumer electronic devices including TV and audio equipment etc, which offers users a more flexible way to control devices from a relatively far distance. It can also add smart functionalities like when TV is sensed open, the music player could pause automatically.

Healthcare [27]

Diseases such diabetes, asthma, and congestive heart failure are challenging fro healthcare to monitor and treat. These diseases can be controlled when patient are taking an active role in the monitoring process. WSNs can embedded in the people's living spaces or carried by people to collect information about personal vital signs in real-time and everywhere. For large-scale medical and behavioural studies, such "living records" could also be used for health and well being analysis.

2.3 Standards for WSNs

There are many international standards proposed for wireless networks. Some of them could find applications to WSNs. These candidate standards can be classified according to their applications as the PHY/MAC layer and the higher layer. For many applications, some of them may be used together.

2.3.1 Radio Standards Comparison

Various radio standards are compared in this section to obtain which one is the most suitable technology for WSNs. Figure 2.3 shows major IEEE 802 wireless standards with different data rates and working distance.

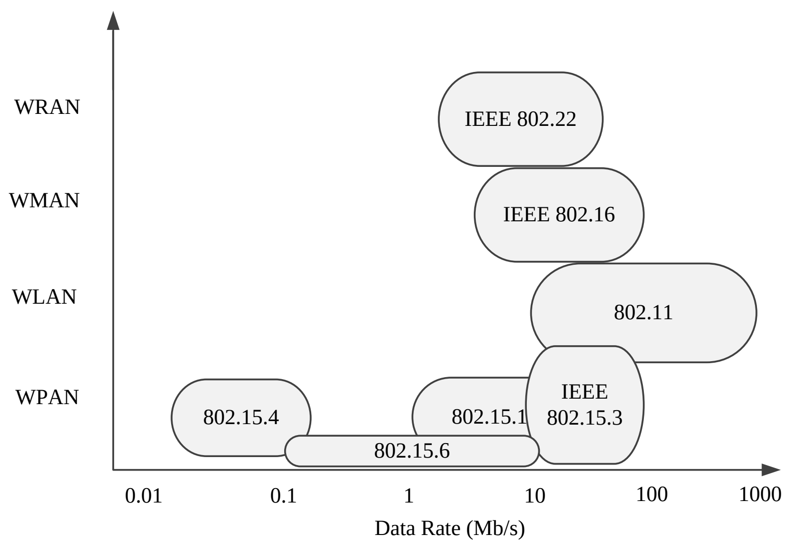

Figure 2.3: IEEE 802 radio standards (PHY/MAC) Comparison.

IEEE 802.22 [55]

IEEE 802.22 is a standard for wireless regional area networks (WRANs) using cognitive radio (CR) technology [56] [57]. Through sharing the unused spectrum allocated to the television broadcast service, the broadband access could reach rural environments. The performance is expected to reach to those of existing fixed broadband access.

IEEE 802.16 [58]

IEEE 802.16 family of standards is know as WirelessMAN or WiMAX [59] [60]. It specifies the air interface, including the MAC and PHY of fixed and mobile broadband wireless access systems for wireless metropolitan area networks (WMANs). The standard enables at-home or mobile Internet access across cities which are in competition with cable modem broadband wireless access technologies.

IEEE 802.16 PHY offers three frequency bands: 10-66 GHz licensed bands, Below 11 GHz licensed bands and License-exempt bands below 11 GHz. The data rate can reach speeds in excess of 120 Mb/s, which is well suited for applications from office/home office (SOHO) through medium to large office applications. The newest IEEE 802.16.1, which specifies the IMT-Advanced [61] air interface known as WirelessMAN-Advanced or WiMAX 2.0 [62]. It can provide data rates of 100 Mb/s mobile and 1 Gb/s fixed.

IEEE 802.11 [63]

IEEE 802.11 is a set of MAC and PHY specifications for implementing wireless local area network (WLAN) communication. The purpose of this standard is to provide wireless connectivity for fixed, portable, and moving stations with a local area. Compare to above two technologies, IEEE 802.11 standard and amendments offer shorter distance and higher data rate for Wi-Fi products.

Existing 802.11 technologies operate in the 2.4 GHz band (802.11b and 802.11g), the 5 GHz band (802.11a and 802.11ac), or both (802.11n). The data rate of IEEE 802.11 family could be various from 11 Mb/s (802.11b) to more than 1 Gb/s (802.11ac), which can support different QoS requirements of WLAN applications.

IEEE 802.15

IEEE 802.15 is a series of wireless person area networks (WPANs) standards.

- IEEE 802.15.1 standard [4] is the basis for the Bluetooth [64] wireless communication technology. It is designed for small and low cost devices with low power consumption. The technology operates with three different classes of devices with communication range are about 100m, 10m and 1m respectively.
- IEEE 802.15.3 standard [65] provides data rates from 11 to 55 Mb/s at distances of greater than 70 meters while maintaining QoS for the communication. This is the first high-rate standard in IEEE 802.15 family.
- IEEE 802.15.4 standard [66] defines the MAC and PHY for low data rate wireless connectivity with no battery or very limited energy consumption devices. Recently, many task groups are formed to apply IEEE 802.15.4 technique for specific applications of WSNs.
- IEEE 802.15.6 standard [19] is for short range wireless communication in the vicinity of a human body (not limited to humans). It uses existing industrial scientific medical (ISM) bands as well as frequency bands approved by national medical authorities. Data rates, typically up to 10 Mb/s, which can satisfy most healthcare services in WBANs.

Table 2.2: Comparison between 802.11 and 802.15

Standard	Frequency	Data Rate	Network Range
802.11b	2.4 GHz	up to 11 Mb/s	local area
802.11g	2.4 GHz	up to 54 Mb/s	local area
802.11n	2.4/5 GHz	up to 600 Mb/s	local area
802.15.1	2.4 GHz	up to 24 Mb/s	personal area
802.15.3	2.4 GHz	11 to 55 Mb/s	personal area
802.15.4	816/915 MHz, 2.4 GHz	up to 250 kb/s	personal area

From above description and Figure 2.3, it is observed that IEEE 802.22 and 802.16 are developed for long distance broadband access. The service areas could be over

30 km for WRANs and the data rates are normally larger than 10 Mb/s, which are incompatible with features of WSNs.

Further comparison between standards in 802.15 and 802.11 are shown in Table 2.2. For local area (from 10 meters to hundreds of meters) applications, IEEE 802.11 is enormously successful in the market. Many applications can benefit from the high data rate and long distance coverage, however for WSN users, the energy consumption due to long communication range can not be tolerant for tiny, cheap sensor devices, and the high data rate is wasteful for most sensing tasks. Unlike 802.11 networks, IEEE 802.15 family of standards are aiming short range, low power communications. IEEE 802.15.1 allows power-efficient connections with little or no infrastructure. Table 2.2 shows that the 802.15.1 can reach 20 Mb/s data rate which is still excess for most wireless monitoring systems. IEEE 802.15.3 is focusing on high data rate wireless connectivity among devices within the personal area. The highest data rate is 54 Mb/s which is the same with 802.11g, therefore the purpose of this standard is not for WSN applications. IEEE 802.15.6 is for WBAN applications, which has been defined as a different technology from WSNs. Among them only IEEE 802.15.4 standard is targeted at very long battery life and very low cost. It is specifically attractive to most applications supported by WSNs. The amendments of IEEE 802.15.4 standard are shown below:

- IEEE 802.15.4a

  It specifies two additional PHYs using Ultra-wide band (UWB) and Chirp Spread Spectrum (CSS) which is an amendment to IEEE 802.15.4 to provide communications and high precision ranging/location capability, high aggregate throughput, ultra power, scalability to data rates, longer range, and lower cost.

- IEEE 802.15.4e

  The intent of this amendment is to enhance and add functionality to the IEEE 802.15.4 MAC that are required to enable the following applications: factory automation, process automation, asset tracking, general sensor control, home medical health/monitor, telecommunication applications, neighbourhood area network, and home audio.

- IEEE 802.15.4f

  It defines new wireless PHYs and enhancements to the IEEE 802.15.4 standard MAC layer which are required to support new PHY for active RFID bi-directional and location applications.

- IEEE 802.15.4g

  It develops a PHY amendment to IEEE 802.15.4 to provide a global standard that facilitates large scale network control such as smart grid networks [67].

- IEEE 802.15.4j

  The intent of this amendment is to extend the standard to an alternative physical layer to support Medical Body Area Network (MBAN) Services operating in the 2360 MHz - 2400 MHz band.

2.3.2 Industrial WSN standards Comparison

After addressing available radio standards for WSN applications, there are several higher layer standards ratified for WSNs, such as ZigBee, WirelessHART, and ISA100.11a in Figure 2.4. IEEE 802.15.4 2.4 GHz frequency PHY with or without adjusted MAC layer is the common underlaying protocol for all these WSN standards. For the networking and application layers, they all have their own objectives and different protocols.

ZigBee

The ZigBee Alliance [7] is a group of companies that develop and maintain the ZigBee standard. ZigBee is a specification for a suit of high level communication protocols using low-power radios based on IEEE 802.15.4 standard. The technology defined by the ZigBee specification is intended to be simpler and less expensive

	Wireless HART	ISA100.11a	ZigBee
Application Layer	Wireless HART	ISA100.11a	ZigBee
Networking	Wireless HART	6LoWPAN	ZigBee
MAC	Wireless HART IEEE 802.15.4	ISA100.11a	IEEE 802.15.4
PHY	IEEE 802.15.4 2.4 GHz	IEEE 802.15.4 2.4 GHz	IEEE 802.15.4 2.4 GHz

Figure 2.4: Comparison of Industrial WSN standards.

than other applications with WPANs. ZigBee is targeted at WSN applications that require a low-rate, long battery life networking [68]. The low cost allows the technology to be widely deployed in most WSN scenarios.

According to a recently published report by ON World [8], ZigBee is the wining protocol for WSNs with over 350 global manufacturers. The combined annual revenues for ZigBee products exceeding 1 trillion dollars. Opportunities in ZigBee market are expanding even to many areas such as smart energy, and building automation etc.

WirelessHART

WirelessHART [69] is a networking technology operating in the 2.4 GHz radio band. It utilises IEEE 802.15.4 compatible radios across the 16 channels that are defined in the 802.15.4 PHY. Communication is performed using Time Division Multiple Access (TDMA) technology between network devices which is different from 802.15.4 MAC protocol. Clear Channel Assessment (CCA) from IEEE

802.15.4 is an optional feature in WirelessHART. It employs a channel hopping scheme for added data bandwidth and robustness. Moreover, all WirelessHART devices have routing capability for mesh network topology.

ISA100

ISA100.11a [70] is developed through the International Society of Automation (ISA). It is intend to be part of a family of standards designed to support a wide range of wireless industrial plant needs including industrial automation and control application. IEEE 802.15.4 PHY with 2.4 GHz radio band is used in this standard. It supports channel hopping to avoid any interference from other wireless devices operating in the same band. Like WirelessHART, this standard defines TDMA mechanism, which allows a device to access the wireless medium without having to wait. Moreover, this standard uses 6LoWPAN [71] based the Internet Protocol (IP) in network layer to facilitate potential use of Internet.

Table 2.3: Networking/Application standards Comparison.

Features	ZigBee	WirelessHART	ISA100.11a
Topology	Star Mesh Combination	Star Mesh Combination	Star Mesh Combination
MAC	CSMA	TDMA/CSMA	TDMA/CSMA
Energy consumption	Low	Relatively high	Relatively high
Reliability	Low	High	High
Implementation	Easy	Challenging	Challenging

There are some similarities and dissimilarities between these WSN standards. All standard are based on IEEE 802.15.4 standard and the same 2.4 GHz frequency. Mesh, star and a combination topology are supported by WirelessHART, ISA100.11a and ZigBee. Three standards follow some common objectives, such as: energy saving, scalability, and low cost devices.

WirelessHART and ISA100.11a are based on IEEE 802.15.4 PHY but they specify new MAC and higher layers [72]. ZigBee is a specification built upon the PHY and

MAC layers in the 802.15.4 standard. ISA100.11a uses IPv6 in the network layer to route packets between subnets, which is very different from WirelessHART and ZigBee.

The major differences between WirelessHART, IAS100.11a and ZigBee can be directly traced to the differences in the goals of each standard. ZigBee is a commercial specification with various products for home and office use. The features of low-cost, low-power and easy installation make it the most popular standard in WSNs market. WirelessHART is especially designed for industrial environments with plants monitoring, and oil and gas supply chain maintain etc. ISA100.11a is aiming to provide flexibility with a variety of build options and customising capability.

2.4 Overview of IEEE 802.15.4

From the analysis in last section, it is observed that IEEE 802.15.4 has a dominant position in WSNs applications compared with other Radio Standards. Most of the industrial WSN applications are using IEEE 802.15.4 as the basic radio standard. Since the IEEE 802.15.4 is one of the most important technologies for WSNs, we describe more details of this standard in this section.

Physical layer (PHY) and medium access control (MAC) sublayer specifications are defined in IEEE 802.15.4 standard. Th raw data rates from 20 kb/s or below to 250 kb/s can satisfy a set of wireless applications of sensor and automation needs.

2.4.1 Components of IEEE 802.15.4 WPAN

IEEE 802.15.4 standard defines two different types of devices:

- A full-function device (FFD), which is capable of serving as the following roles,
  - A personal area network (PAN) coordinator: the controller of the PAN used

for devices association.

– A coordinator: used for synchronisation through transmitting beacons.

– A simple device: is intended for extremely simple, such as a light switch and associates with a FFD.

- A reduced-function device (RFD) which is capable of serving as either a PAN coordinator or a coordinator and only can be implemented using minimal resources and memory capacity.

2.4.2 Network Topologies

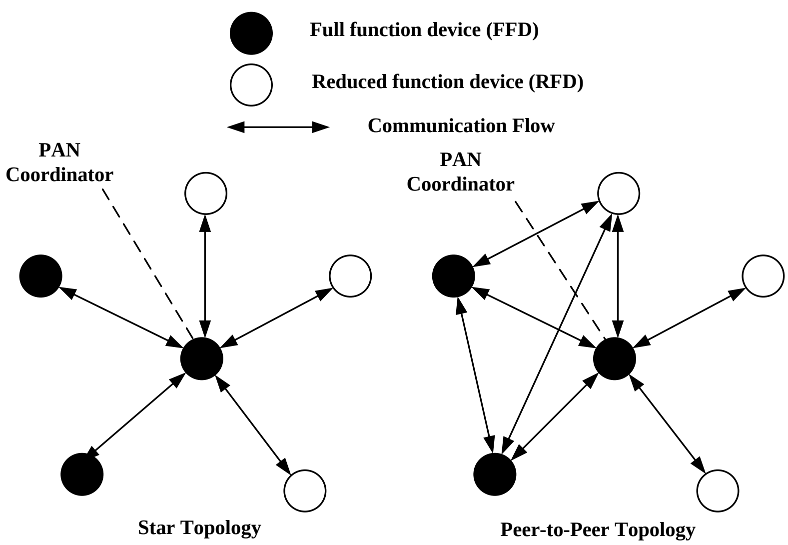

Figure 2.5: Network topologies of IEEE 802.15.4 standard.

IEEE 802.15.4 supports two types of network topologies as shown in Figure 2.5.

- Star topology: all the devices communicate with a single central PAN coordinator. The PAN coordinator may be mains powered, while the other devices are low power sensors. This topology can be typical for applications like home automation, healthcare applications, and auto meter reading system etc.

- Peer-to-peer topology: each device is able to communicate with other devices as long as they are in the communication range rather than communicate to only PAN coordinator directly in the star network topology. A peer-to-peer network allows multiple hops routing and forwarding rather than single hop transmission in star network topology, which can implement more complex network formations such as mesh networking topology. Applications like industrial control and monitoring, inventory tracking, large area surveillance are typical cases using such a networking topology.

2.4.3 Physical layer (PHY)

The PHY is responsible for the following tasks:

- Activation and deactivation of the radio transceiver.
- Performing Clear channel assessment (CCA) for carrier sense multiple access with collision avoidance (CSMA-CA).
- Channel frequency selection.
- Transmission and reception of data.

The standard specifies the following four PHYs:

- 868/915 MHz direct sequence spread spectrum (DSSS) PHY with binary phase-shift keying (BPSK) modulation.
- 868/915 MHz DSSS PHY with offset quadrature phase-shift keying (O-QPSK) modulation.

- 868/915 MHz parallel sequence spread spectrum (PSSS) PHY with BPSK and amplitude shift keying (ASK) modulation.
- 2.4 GHz DSSS PHY employing O-QPSK modulation.

Table 2.4: Frequency bands and data rates in IEEE 802.15.4 PHY.

Frequency band (MHz)	Modulation	Data rate (kb/s)
868/868.6	BPSK	20
902/928	BPSK	40
868/868.6	ASK	250
902/928	ASK	250
868/868.6	O-QPSK	100
902/928	O-QPSK	250
2400/2483.5	O-QPSK	250

2.4.4 MAC sublayer

The MAC sublayer provides an interface between PHY and higher layers like Networking/Application layers and it is responsible for:

- Beacon generation if the device is a coordinator.
- Synchronising network with beacons.
- PAN association and disassociation.
- Employing the CSMA-CA algorithm for channel access.
- Maintaining the GTS mechanism if it enabled.
- Providing links between two peer MAC entities.

Figure 2.6 shows the structure of the IEEE 802.15.4 with two operation modes:

- Beacon-enabled mode: beacons are periodically transmitted by the coordinator to synchronise attached devices. The superframe structure is used in the beacon-enabled model.
- Nonbeacon-enabled mode: all the devices in the nonbeacon-enabled mode can transmit their messages simply using unslotted CSMA-CA algorithm. No superframe structure is used in this mode.

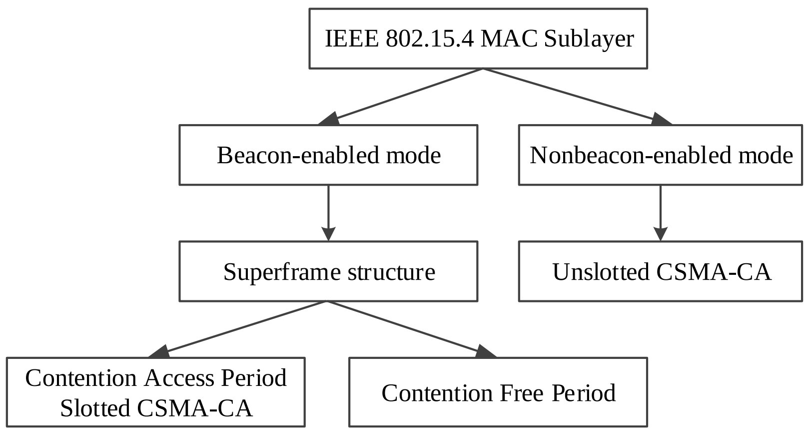

Figure 2.6: Two operation modes of IEEE 802.15.4 standard.

Superframe Structure

A superframe is bounded by the transmission of two beacon frames and have an active portion and an optional inactive portion. The coordinator and all the devices in the network may enter a low-power (sleep) mode during the inactive portion. The structure of this superframe is described by the values of *macBeaconOrder* and *macSuperframeOrder*.

The *macBeaconOrder* defines the interval at which the coordinator shall transmit its beacon frames. The Value of *macBeaconOrder* and the beacon interval, BI, are related as follows:

$$BI = aBaseSuperframeDuration \times 2^{macBeaconOrder}$$
$$\text{for} \quad 0 \leq macBeaconOrder \leq 14$$

If $macBeaconOrder = 15$, the coordinator shall not transmit beacon frames except when requested to do so, such as on receipt of a beacon request command. The value of *macSuperframeOrder* shall be ignored if $macBeaconOrder = 15$.

The *macSuperframeOrder* describes the length of the active portion of the superframe, which includes the beacon frame. The value of *macSuperframeOrder*, and the superframe duration, *SD*, are related as follows:

$$SD = aBaseSuperframeDuration \times 2^{macSuperframeOrder}$$
$$\text{for} \quad 0 \leq macSuperframeOrder \leq macBeaconOrder \leq 14$$

If $macSuperframeOrder = 15$, the superframe shall not remain active after the beacon. If $macBeaconOrder = 15$, the superframe shall not exist (the value of *macSuperframeOrder* shall be ignored), and *macRxOnWhenIdle* shall define whether the receiver is enabled during periods of transceiver inactivity.

The active portion of each superframe is composed of two parts: a contention access period (CAP) and an optional contention free period (CFP) which follows immediately after the CAP and extends to the end of active portion.

An example of a superframe structure is shown in Figure 2.7. In this case, the beacon interval, *BI*, is twice as long as the active superframe duration, *SD*.

- Contention access period (CAP)

  The CAP starts immediately following the beacon. If there is CFP portion, the CAP will complete before the beginning of the CFP, and if the CFP is zero length,

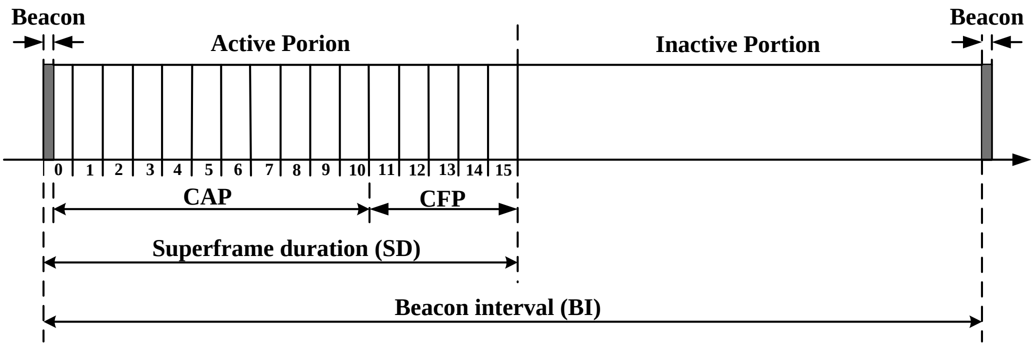

Figure 2.7: Superframe structure in IEEE 802.15.4 standard.

the CAP will take the whole active portion. All messages transmitted in the CAP are required to use a slotted CSMA-CA algorithm to access the channel.

- Contention-free period (CFP)

  The CFP starts immediately following the CAP, and it will complete before the end of the active portion of the superframe. There is no need of slotted CSMA-CA algorithm to access the channel. The slots of CFP are divided into guaranteed time slots (GTSs) used for specific bandwidth need applications.

CSMA-CA Algorithm

If the superframe is used with beacon-enabled mode, the MAC sublayer will employ the slotted CSMA-CA algorithm for transmission in CAPs. Conversely, if the nonbeacon-enabled mode is used with no periodic beacons, the MAC sublayer shall transmit using the unslotted CSMA-CA algorithm. For both CSMA-CA algorithms, the unit of time called backoff period is implemented, and each backoff is equal to *aUnitBackoffPeriod*.

Figure 2.8 illustrates the steps of the CSMA-CA algorithm. Each device has to maintain three variables for each transmission attempt: NB, CW, and BE.

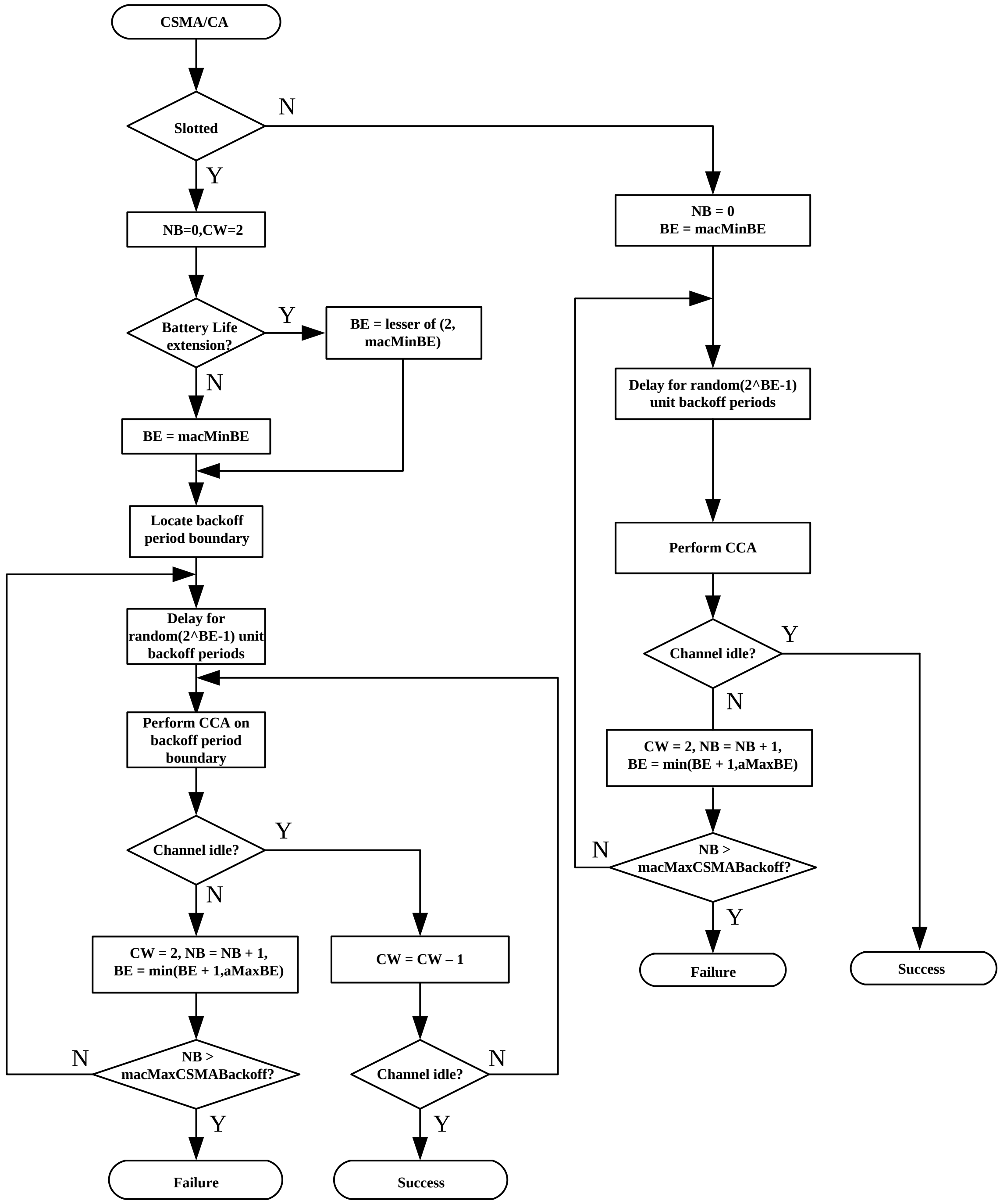

Figure 2.8: CSMA-CA algorithm for IEEE 802.15.4 MAC.

- NB: backoff stage is the number of times the CSMA-CA algorithm required to back off while attempting the current transmission. This value is initialised to zero before each new transmission attempt.
- CW: contention window is only used for slotted CSMA-CA algorithm, which represents the number of backoff slots that need to be clear of channel activity before the transmission. CW is initialised to $CW_0 = 2$ before each transmission attempt. If the channel is sensed to be busy, the CW shall reset to CW_0.
- BE: backoff exponent, which is related to how many backoff periods a device has to wait before attempting to assess a channel. BE is initialised to the value of *macMinBE*.

When there is a data frame to be transmitted, the CSMA-CA algorithm performs the following steps:

1. The variables are initialised as $NB = 0$, $CW = 2$, and $BE = macMinBE$. For unslotted CSMA-CA algorithm, the variable CW is not used.
2. Backoff time W is randomly chosen from $[0, 2^{BE} - 1]$ slots. In slotted CSMA-CA algorithm, the beginning time of the backoff timer is aligned with the starting of the next backoff slot.
3. After delay of the backoff period, a Clear Channel Assessment (CCA) is performed to check the state of channel.

   If the channel is busy, the variables update as follow: $NB = NB + 1$, $BE = min(BE{+}1, macMinBE)$ and $CW = 2$ (only for the slotted CSMA-CA). If $NB > macMaxCSMABackoff$, the transmission fails and the frame drops, otherwise the algorithm backs to step 2.

   If the channel is idle, in unslotted CSMA-CA algorithm, the frame is immediately transmitted. In slotted CSMA-CA algorithm, CW is decremented by one. If the

$CW = 0$ then the frame is transmitted, otherwise the algorithm backs to the beginning of step 3 to perform CCA.

It is noted that, the 802.15.4 CSMA-CA algorithm supports an optional retransmission mechanism based on acknowledgment (ACK). The CSMA-CA algorithm may operate in two modes based on using ACK or not. With the ACK mode, an ACK frame is to be sent to acknowledge the correct receipt of a data frame, while with non-ACK mode, an ACK frame is not expected to be sent. If ACK mode is enabled, the receiver must send an ACK after receiving the data frame and on the sender side, if the ACK is not received correctly, a retransmission of the data frame needs to be performed until ACK is received or the maximum number of retransmission (*macMaxFrameRetries*) is reached.

2.5 Conclusion

In this chapter, the background knowledge of wireless-based technologies and standards were introduced. An overview of WSNs and relevant wireless network technologies were presented.

Specifically, four similar techniques with low power consumption were compared. The RFID based networks can find a wide range of applications similar to those that can be supported by WSNs, especially the active RFID with independent power source. However, they are still less functional in many cases compared to WSN technologies due to their low cost feature. WBAN is used primarily for the healthcare area, in which the sensor devices are especially designed for collecting information around human body. It can be regarded as a special case of WSNs which requires particular designs for the supporting protocols and algorithms. M2M technology allows machine devices communicate directly with each other through wireless systems with little or no human intervention. The communication range could be much larger than that of WSNs by using wireless wide area networking technologies such as GSM and 3G. For wireless M2M networks energy efficiency is usually not the first priority, which is different from that in WSNs. Compared to these wireless-based technologies, WSNs are mainly designed for applications requiring very low power consumption and short communication range.

Many WSN applications are introduced with different purposes and different areas, such as logistics, security, environmental monitoring, building automation, transportation, and so on, which shows a high applicability of WSNs technology. Several international standards have been proposed for WSNs. In the PHY/MAC layer, IEEE 802 wireless standards provide different data rates and working distances. IEEE 802.22 and 802.16 are developed mainly for long distance (over 30 kilometres) broadband access. IEEE 802.11 is designed for local area network with more than 1 Gb/s (802.11ac) data rates, but the energy consumption cannot be satisfied by tiny, cheap sensor devices, and the high data rate is wasteful for most sensing tasks. Only the IEEE 802.15 family of standards are aiming for short range, low power communication. Among them only the IEEE 802.15.4 standard is targeted at very long battery life and very low cost. In the higher layer of industrial standards, Zigbee, WirelessHART, and ISA100 are all using 802.15.4 standard as the underlying protocol. The features of 802.15.4 networks on battery power, bandwidth data rate, and self-management also pose many challenges on the design of networks protocols and algorithms.

Chapter 3

Performance Investigation of Single IEEE 802.15.4 Wireless Sensor Network

Wireless sensor networks (WSNs) open up new opportunities for businesses and consumers due to its great potentials in cost reduction and service improvements. From the investigation and analysis in last chapter, it is observed that IEEE 802.15.4 standard can play a critical role in WSN applications due to the features of low data rate and low power consumption. It can be used as an important component in WSNs for data collecting, monitoring and controlling functions. Practical and reliable WSNs based on 802.15.4 standard require robust message delivery services with low power consumption. Due to the shared nature of the wireless communication medium and limited spectrum capacity, there could be many challenges in contention-based medium access control (MAC) layer of IEEE 802.15.4 standard. Performance is affected by a number of complicated factors (e.g., message rate, number of sensors, wireless interference, hidden terminals). Systematic investigation of supporting WSNs with 802.15.4 specification is challenging but vital for network and service planning as well as providing insights into reliable communication for WSNs.

In this chapter a study on performance of single sensor network based 802.15.4 technology without any interference from neighbour networks is presented with the objectives of understanding the limits of throughput and energy consumption in 802.15.4 standard. Both analytical and simulation approaches are used. A mathematical tool is developed to obtain the performance of single 802.15.4 network in terms of throughput and energy consumption. The mathematical tool is based on Markov chain. With the analytical tool, throughput and energy consumption of single 802.15.4 network can be evaluated by the number of devices, frame length, and other MAC parameters. Additionally, a discrete event simulator is developed and simulations have been run to investigate the performance. The simulator is also used to verify the effectiveness of the theoretic model.

The rest of this chapter is organised as follow. The literature review is presented in section 3.1. Section 3.2 presents the channel access mechanism specified in 802.15.4 beacon-enabled mode. An Markov chain based analytical model, which can predict the performance of single 802.15.4 network is presented in section 3.3. Analytic and simulation results are presented and discussed in section 3.4. Section 3.5 concludes this chapter.

3.1 Related Work

In the literature, there has been various work reported on performance evaluation of single 802.15.4 network in both simulated and analytical ways. Simulation based evaluation of a single 802.15.4 network has been widely reported from extensive studies, including [73, 74, 75, 76, 77]. Additionally, many analytical models have been proposed to capture the throughput and energy consumption of a single 802.15.4 network with either saturated or unsaturated traffic. Misic *et al.* proposed a Markov model to evaluate the throughput of 802.15.4 networks with unsaturated downlink and uplink traffic [78]. However, their analytical model did not match to the simulation results very well. A simplified Markov model was proposed in [79], in which a geometric distribution was used to approximate the uniform distribution of random backoff counter, but the approximation results did not give enough accuracy in throughput prediction. Energy and throughput performance of IEEE 802.15.4 was analysed in [80]. As pointed out in [81], the proposed model did not mimic the IEEE 802.15.4 behaviour sufficiently well. A simple Markov model was proposed with an assumption of independent channel sensing probability in [81]. The model can effectively predict the channel sensing probability, but it cannot give throughput performance accurately. A three-dimensional Markov model was proposed in [82] to evaluate throughput of slotted carrier sense multiple access (CSMA). However, the state transitions in [82] were not modelled correctly, and thus the model was revised with an improved accuracy in [83].

3.2 Channel Access Scheme

Two channel access schemes are specified in the IEEE 802.15.4 standard: slotted CSMA-CA for beacon-enabled mode, and unslotted CSMA-CA algorithm for nonbeacon-enabled mode. To focus the attention on slotted CSMA-CA analysis due to its better functions, only beacon-enabled mode is introduced. A superframe structure is imposed in the beacon-enabled mode as shown in Figure 3.1, whose format is defined by the coordinator. Each superframe is bounded by network regular beacons, and can have an active portion and an optional inactive portion. All communications take place in the active period while devices are allowed to enter a low-power (sleep) mode during the inactive period. Unlike the algorithm used in 802.11 WLANs, the 802.15.4 is designed especially for ultra low power networks, which has strict restrictions on the energy consumption of these battery powered nodes. To achieve more efficient energy consumption, the sleep mode in which the sensor nodes periodically sleep followed by a duty-cycle is a simple and effective solution. In IEEE 802.15.4 standard, the sleep mechanism is optional but crucial for energy saving. The structure of the superframe is described by the values of $macBeaconOrder$ (BO) and $macSuperframeOrder$ (SO). The BO describe the beacon interval (BI), the SO describe the length of superframe duration (SD) and they are related respectively as follow:

$$BI = \text{aBaseSuperframeDuration} \times 2^{BO}, \tag{3.1}$$

$$SD = \text{aBaseSuperframeDuration} \times 2^{SO}. \tag{3.2}$$

where aBaseSuperframeDuration $=$ 960 symbols and $0 \leq SO \leq BO \leq 14$.

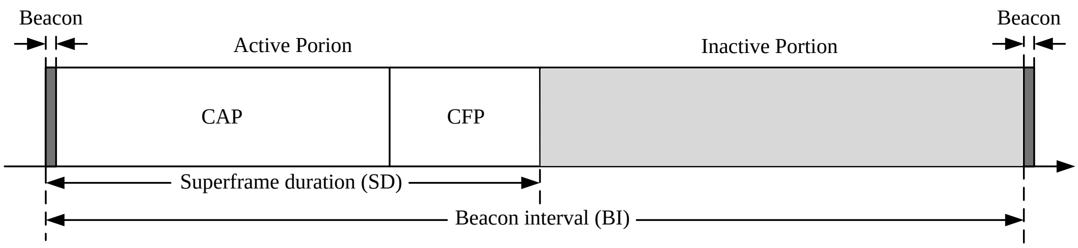

Figure 3.1: An example of the superframe structure. In this case, the beacon interval BI, is twice as long as the active superframe duration SD.

The active portion of each superframe shall be composed of two parts: a contention access period (CAP) and an optional contention-free period (CFP). The CAP shall start immediately following the beacon and complete before the beginning of CFP on a superframe slot boundary. If the CFP is zero length, the CAP shall complete at the end of the active portion of the superframe. In CAPs, communication among devices uses slotted CSMA-CA algorithm for contention access. The 802.15.4 slotted CSMA-CA algorithm operates based on backoff slots. One backoff slot has the length of 20 symbols. In the rest of this research, a backoff slot is simply called "a slot" unless otherwise specified.

The slotted CSMA-CA algorithm may operate in two modes: i.e., the ACK mode, if an ACK frame is to be sent, and the non-ACK mode, if an ACK frame is not expected to be sent. Three variables need to be maintained for each transmission: NB denotes the backoff stage, representing the backoff times that have been retried in the CSMA-CA process, while one device try to transmit a data frame in each transmission. W denotes the backoff window, representing the number of backoff slots that one device needs to backoff for each backoff period. CW denotes the contention window, representing the required number of backoff periods before a clear channel assessment (CCA) is carried out.

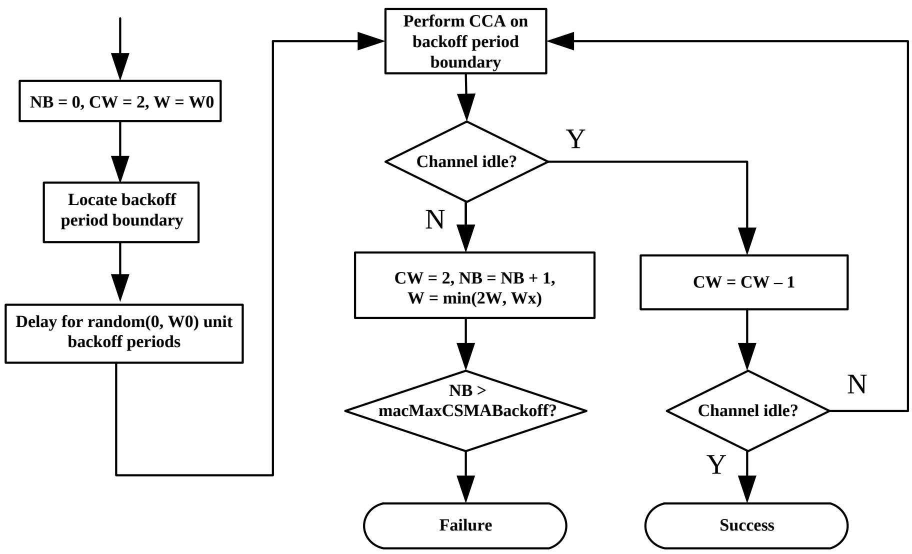

Figure 3.2: Slotted CSMA-CA algorithm of IEEE 802.15.4 MAC.

Before each device starts a new transmission attempt, NB is set to zero, CW is set to two, and W is set to W_0 as shown in Figure 3.2. The backoff counter chooses a random number from $(0, W_0 - 1)$, and it decreases every one slot without sensing channel until it reaches zero. W_0 is the initial backoff window size. The first CCA (denoted as CCA1) will be preformed when backoff counter reaches to zero. If channel is idle at CCA1, CW decreases by one and the second CCA (denoted by CCA2) will be performed after CCA1. If channel is idle for both CCA1 and CCA2, the frame will be transmitted in the next slot. If channel is busy in either CCA1 or CCA2, CW is reset to two, NB increases by one, and W is doubled but not exceed W_x. W_x is the maximal backoff window size, which is a system configurable parameter. If NB is smaller or equal to the allowed number of backoff retries *macMaxCSMABackoffs* (denoted by m), the above backoff and CCA processes are repeated. If NB exceeds m, the slotted CSMA-CA algorithm ends. If the ACK mode is enabled, the receiver must send an ACK after receiving the data frame and on the sender side, if the ACK is not received correctly, a retransmission of the data frame needs to be performed until ACK is received or the maximum number of retransmission is reached.

3.3 Analytical Model

In this section the analytic mode for single 802.15.4 network MAC layer is presented. This analytic model can be viewed as a modified version of the model proposed by [83]. An accurate analytical model was proposed in [83] which can predict the system performance very well, but the sleep mode of 802.15.4 MAC layer has not been analysed and the ACK mode was not compared to the non-ACK mode. Let us consider a single hop star network topology 802.15.4 WSN operating in the beacon-eanbled mode with N sensor devices in addition to one coordinator. Assume that each device has a saturate traffic sending to its coordinator in the non-ACK mode. The performance under the ACK mode is analysed by simulations. Channel access is organised by the coordinator with a superframe structure. CFP is neglected in this study, because it is designed for low-latency applications requiring specific data bandwidth which means only the CAP in each active portion of superframe structure. In CAPs, communication among devices uses slotted CSMA-CA algorithm for contention access. Each data frame has a fixed length which requires L slots to transmit over the channel. Let L_d denote the length of data payload in unit of slots needed for transmission in a data frame. Assume that the channel is ideal in a sense that data frames can be correctly received if there are no collisions with the other frames.

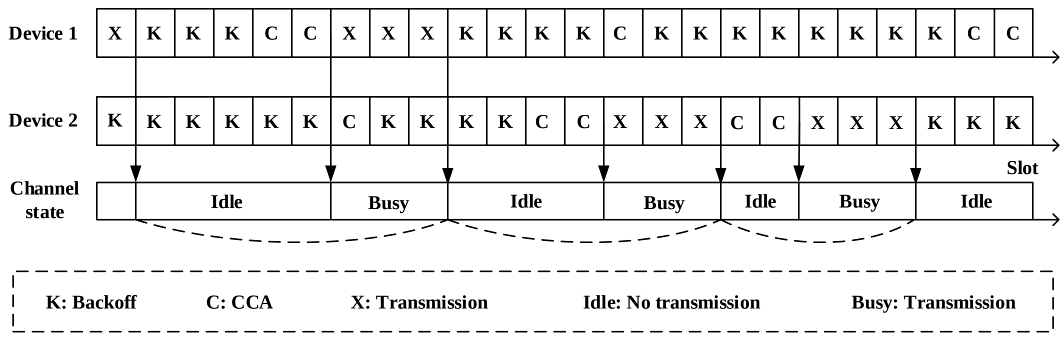

Figure 3.3: Illustration of IEEE 802.15.4 network channel states which can be modelled by a renewal process with idle and busy states.

In each CAP, the channel state sensed by each node can be considered as a renewal process, which starts with an idle period and followed by a fixed length of L slots (for frame transmission), as shown in Figure 3.3. The idle period depends on the random backoff slots and the transmission activities from each device. It is noted that the maximal number of idle slots is $W_x - 1$ plus two slot CCAs.

The slotted CSMA-CA operation of each individual device can be modelled by an Markov chain with finite states. Let p_k denote the probability of a transmission from devices other than a tagged device starting its transmission after exactly the kth idle slot since the last transmission, and define $q_k = 1 - p_k$, where $k \in [0, W_x + 1]$. The transmission probability of a sensor device in a general backoff slot of the renewal process can be calculated with the Markov chain constructed for each device. As an example, an Markov chain with $m = 0$ is shown in Figure 3.4 [83]. As some states will never be visited from any other states, those states are not shown in Figure 3.4 and their steady state probabilities will be zero. For the tagged device, its Markov chain consists of a number of finite states and each corresponds to a state of CSMA-CA algorithm in one slot. Let $\bar{M}$ denote the steady state probability of a general state M in the Markov state space. These finite states are introduced below.

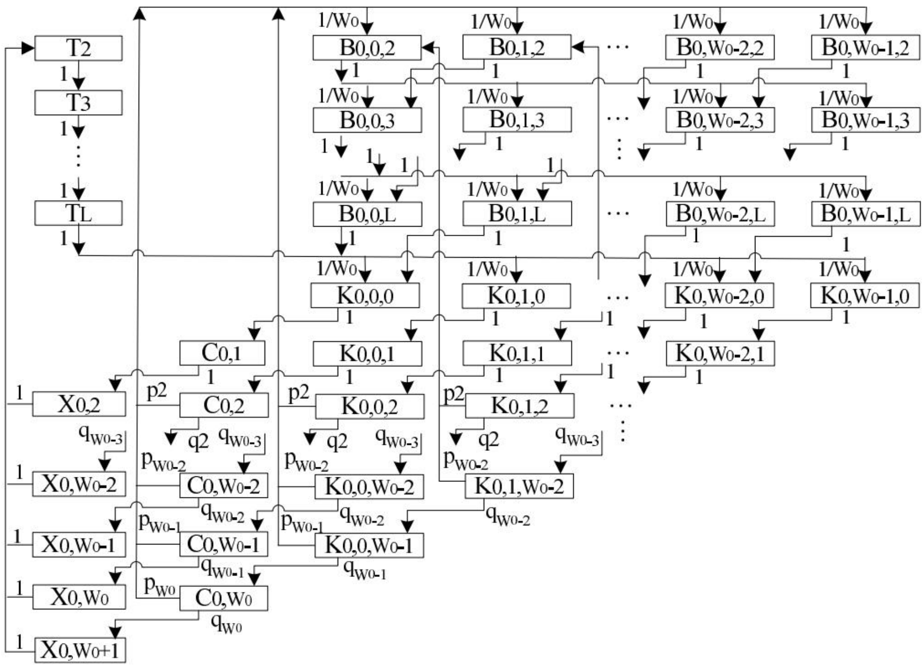

Figure 3.4: Markov chain model for the slotted CSMA-CA algorithm in the non-ACK mode with $m = 0$.

Busy state

Denote the busy state as $B_{i,j,l}$, as defined in Equations 3.3-3.5, during which at least one device other than the tagged device transmits the lth part of a frame of L slots, with the backoff stage and backoff counter of the tagged device being i and j, respectively, where $i \in [0, m]$, $j \in [0, W_i - 1]$, and $l \in [2, L]$, W_i is the minimum of $2^i W_0$ and W_x.

$$\bar{B}_{0,j,2} = \sum_{k=2}^{W_0-1} p_k \bar{K}_{0,j+1,k} + \frac{1}{W_0} \sum_{k=2}^{W_m} p_k (\bar{K}_{m,0,k} + \bar{C}_{m,k}), \quad i = 0, j \in [0, W_0 - 1]. \tag{3.3}$$

$$\bar{B}_{i,j,2} = \sum_{k=2}^{W_i-1} p_k \bar{K}_{i,j+1,k} + \frac{1}{W_i} \sum_{k=2}^{W_i-1} p_k (\bar{K}_{i-1,0,k} + \bar{C}_{i-1,k}), \quad i \in [1, m], j \in [0, W_i - 1]. \tag{3.4}$$

$$\bar{B}_{i,j,l} = \begin{cases} \bar{B}_{0,j+1,l-1} + \bar{B}_{m,0,l-1}/W_0, & i = 0, j \in [0, W_i - 1]; \\ \bar{B}_{i,j+1,l-1} + \bar{B}_{i-1,0,l-1}/W_i, & i \in [1, m], j \in [0, W_i - 1]. \end{cases} \tag{3.5}$$

Backoff state

Denote the backoff state as $K_{i,j,k}$, as defined in Equations 3.6-3.8, during which the tagged device backs off with its backoff counter being j at backoff stage i, after k idle slots since the last transmission, where $i \in [0, m]$, $j \in [0, W_i - 1]$, and $k \in [0, W_i - 1]$.

$$\bar{K}_{0,j,0} = \bar{B}_{0,j+1,L} + (\bar{B}_{m,0,L} + \bar{T}_L)/W_0, \quad i = 0, j \in [0, W_0 - 1]. \tag{3.6}$$

$$\bar{K}_{i,j,0} = \bar{B}_{i,j+1,L} + \bar{B}_{i-1,0,L}/W_i, \quad i \in [1, m], j \in [0, W_i - 1]. \tag{3.7}$$

$$\bar{K}_{i,j,k} = \begin{cases} \bar{K}_{i,j+1,k-1}, & k \in [1, 2]; \\ (1 - p_{k-1})\bar{K}_{i,j+1,k-1}, & 3 \leq k \leq W_i - 1. \end{cases} \tag{3.8}$$

Sensing state

Denote the sensing state as $C_{i,k}$, during which the tagged device performs CCA2 at the ith backoff stage, after k idle slots since the last transmission, where $i \in [0, m]$ and $k \in [1, W_i]$.

$$\bar{C}_{i,k} = \begin{cases} \bar{K}_{i,0,k-1}, & k \in [1, 2]; \\ (1 - p_{k-1})\bar{K}_{i,0,k-1}, & k \in [3, W_i]. \end{cases} \tag{3.9}$$

Initial transmission state

Denote initial transmission state as $X_{i,k}$, during which the tagged device starts to transmit a frame at its backoff stage $i \in [0, m]$, after $k \in [2, W_i + 1]$ idle slots since the last transmission.

$$\bar{X}_{i,k} = \begin{cases} \bar{C}_{i,k-1}, & k = 2; \\ (1 - p_{k-1})\bar{C}_{i,k-1}, & k \in [3, W_i + 1]. \end{cases} \tag{3.10}$$

Transmission state

Denoted transmission state as T_l, as defined in Equation 3.11, during which the tagged device transmits the lth part of a frame, where $l \in [2, L]$. The first part is transmitted in the state $X_{i,k}$.

$$\bar{T}_l = \begin{cases} \sum_{i=0}^{m} \sum_{k=2}^{W_i+1} \bar{X}_{i,k}, & l = 2; \\ \bar{T}_{l-1}, & l \in [3, L]. \end{cases} \tag{3.11}$$

After derived these Markov chain states, the transmission probability τ_k that the tagged device transmits after exactly k idle slots since the last transmission can be computed by $\tau_k = 0$, for $k \in [0, 1]$, and for $k \in [2, W_x + 1]$:

$$\tau_k = \frac{\sum_{i=0}^{m} \bar{X}_{i,k}}{\sum_{i=0}^{m} [\bar{X}_{i,k} + \bar{C}_{i,k} + \sum_{j=0}^{W_i-1} \bar{K}_{i,j,k}]}. \tag{3.12}$$

With the above transmission probability τ_k, the channel busy probability p_k for the tagged device with $k \in [0, W_x + 1]$ can be calculated by

$$p_k = 1 - (1 - \tau_k)^{N-1}. \tag{3.13}$$

When the sleep mode is enabled, there is no activity from any device in the inactive portion. All frames are transmitted in active portion, and the percentage of active time in each superframe can be calculated by

$$\frac{SD}{BI} = 2^{SO-BO}. \tag{3.14}$$

Since the balance Equations 3.3 - 3.11 for all steady state probabilities and the equations for p_k, $k \in [0, W_x + 1]$, have been derived, the Markov chain for the tagged device can be numerically solved. It is defined in [83] that the saturation throughput S as the ratio of the length of data payload (in backoff slots) to average number of backoff slots used to successfully transmit a frame in the network. After the Markov chain is solved, S can be calculated by

$$S = 2^{SO-BO} N L_d \sum_{i=0}^{m} \sum_{k=1}^{W_i} C_{i,k-1}(1 - p_{k-1})(1 - p_k). \tag{3.15}$$

Normalised energy consumption (denoted by η) is used to analyse the power consumption. It is defined in [80] as the average energy consumed to transmit one slot of payload. The parameter values are using the data sheet of CC2420, which is a true single chip 2.4GHz IEEE 802.15.4 compliant RF transceiver designed for low power and low voltage wireless applications. One slot of payload can consume on average 0.01 mJ (denoted by E_t) to transmit. Performing each CCA in a slot can take on average 0.01135 mJ (denoted by E_c) [80]. η is obtained by

$$\eta = 2^{SO-BO} \frac{N}{S} \sum_{i=0}^{m} \left\{ \sum_{l=2}^{L} E_c B_{i,0,l} + \sum_{k=0}^{W_i+1} \left[E_c (K_{i,0,k} + C_{i,k}) + L E_t X_{i,k} \right] \right\}. \tag{3.16}$$

3.4 Numeric Results

A discrete event simulator is implemented to investigate the performance of 802.15.4 WSNs and verify the proposed analytical model. We consider an IEEE 802.15.4 PHY at frequency band 2400-2483.5 MHz with O-QPSK modulation and data rate of 250 kb/s, which gives a symbol rate of 62,500 symbols per second for the PHY. As each slot takes 20 symbols, at most 3000 slots of data can be successfully transmitted in one second. In non-sleep mode, SO is equal to BO, which means there is no inactive portion of each superframe. When sleep mode is enabled, it is assumed that SO is set to $BO - 1$, which divides each superframe into two equal parts of active and inaction portions. For example, if $BO = 6$, in non-sleep mode, SO is also 6. The active portion equals superframe length which is 3072 slots. In sleep mode, $SO = 5$, which means 1536 slots are active portion and the rest is inactive portion. The header L_h in a data frame is 1.5 slots and the data length with MAC and PHY layer headers is $L = L_d + L_h$. Each simulation result presented in the figures was obtained from the average of 20 simulations. In each simulation run, 10^5 data frames were transmitted.

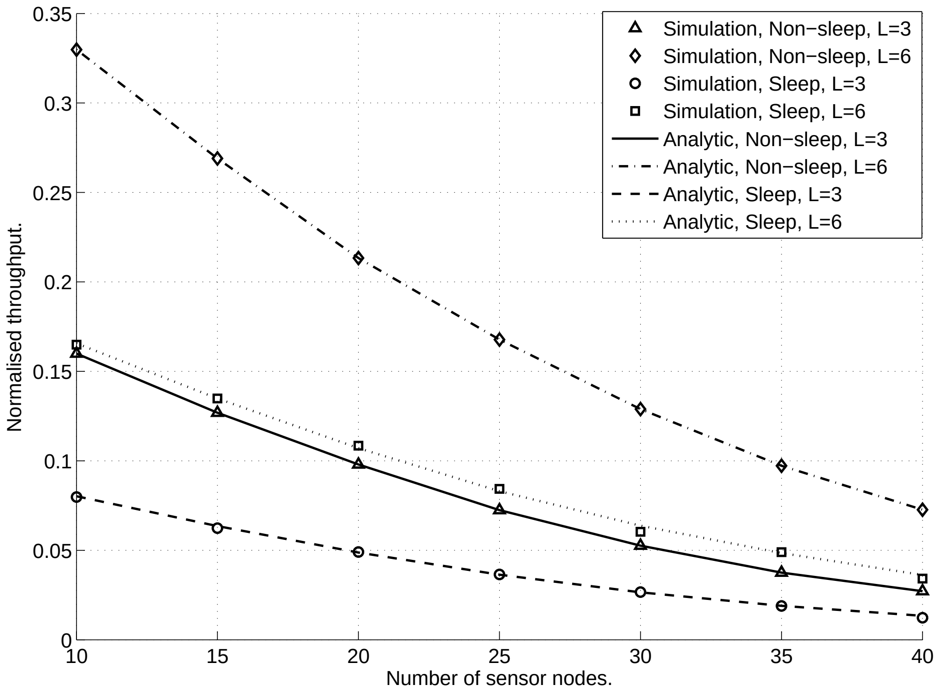

Figure 3.5: Throughput comparison between Sleep and Non-sleep modes with $L = 3$ and $L = 6$ slots.

Figure 3.5 presents that the normalised throughput S with $L = 3$ and $L = 6$ in both non-sleep and sleep mode. The analytical results are matched with simulation results accurately. For $L = 3$, we have $L_d = 1.5$ and the data length in one frame is 15 bytes. Similarly for $L = 6$, we have $L_d = 5.5$ and the data length in one frame is

55 bytes. Consider the case of 20 sensor nodes in network. The normalised throughput is 0.1 for $L = 3$ in non-sleep mode, which means at most 100 data messages can be successfully delivered in one second for all devices in the network. Each sensor node can deliver at most five data messages in one second with message size $L = 3$. In sleep mode, the normalised throughput is about 0.05 with message size $L = 3$, which means each sensor node may not be able to successfully deliver more than two data messages in one second. As observed from Figure 3.5, the throughput with non-sleep mode is about twice of that with sleep mode, which is caused by that the sleep mechanism in IEEE 802.15.4 is simply based on duty-cycle. The performance with non-sleep mode could satisfy most WSN applications, but when sleep mode is enabled, only low-rate applications such as smart buildings, and entertainment using could be satisfied with the performance. For example, in the smart buildings, each smart meter may be required to transmit a few metering data messages every minute, and the QoS requirement can be easily achieved by 802.15.4 network with sleep mode. However, if there are more sensor nodes in the network, especially in sleep mode with low duty-cycle, the throughput drops further and the usual WSN applications may not be effectively supported by the 802.15.4 networks.

Figure 3.6 plots the normalised energy consumption E with $L = 3$ and $L = 6$ in both non-sleep and sleep mode. As expected, the analytical results agree with simulation results very well and can predict the energy efficiency accurately. It is observed that the energy consumption increases with increasing the number of sensor nodes. Consider the case of 15 devices in network with $L = 3$. The normalised energy consumption is about 100 mJ per second when saturate traffic is used in non-sleep mode and it drops to 50 mJ per second in sleep mode. Apparently, the sleep mechanism could significantly drop the energy consumption by reducing the active time of devices which it is at the cost of throughput. Many WSN applications could benefit from the feature of energy saving of the sleep mechanism proposed in IEEE 802.15.4, such as agriculture tracking and logistics applications. These low rate applications could enter sleep state for a long period to achieve extremely long battery life.

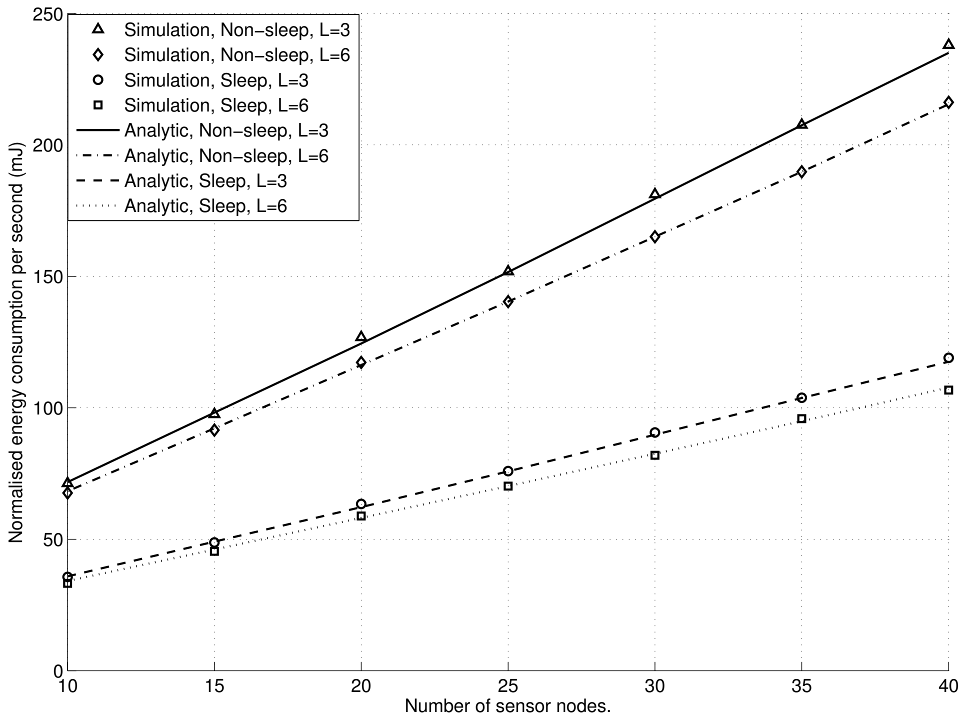

Figure 3.6: Energy consumption comparison between Sleep and Non-sleep modes with $L = 3$ and $L = 6$ slots.

Beyond the capability limit of the analytic mode, the proposed simulator has more complex functionalities. The performance of 802.15.4 networks in the ACK mode is analysed in a simulation way and compared with the non-ACK mode. To focus the attention on impact of ACK, only non-sleep mode is presented.

Figure 3.7 presents the throughput comparison between the ACK and non-ACK mode. It is found that the throughput of the non-ACK mode is better than that of the ACK mode when the number of sensor nodes in network is small. With an increasing number of sensor nodes deployed in the network, the throughput of the ACK mode is getting better and exceeds the performance in the non-ACK mode. The slotted CSMA-CA mechanism in IEEE 802.15.4 is contention-based and the collision probability raises

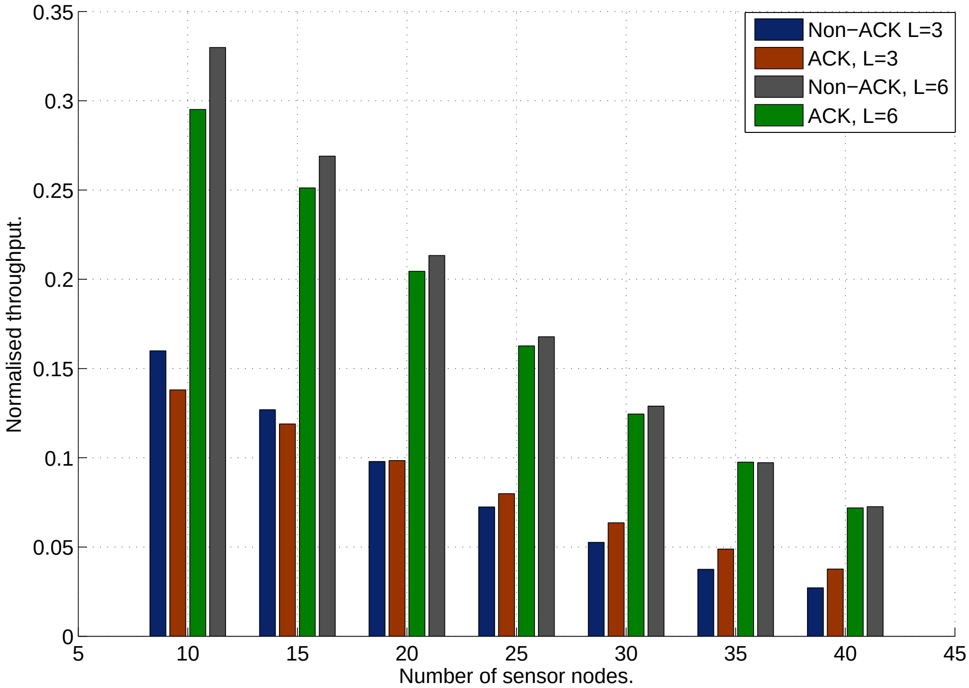

Figure 3.7: Throughput comparison between the ACK and Non-ACK modes.

with an increasing number of competing devices. In the high contention circumstance with a large number of sensor nodes, the ACK mode should be used to increase the transmission throughput. Figure 3.8 shows the energy consumption comparison between the ACK and non-ACK mode. It is observed that, the energy consumption with the ACK mode is higher than that of the non-ACK mode when the number of sensor nodes in network is not large. With more sensor nodes are deployed, the energy consumption of the ACK mode is getting lower than that that of the non-ACK mode, which is more obvious with small frame size transmission. It is mainly because of the ACKs increase the success probability of transmission which reduce the energy consumption in retransmissions due to collisions. From above analysis and comparison, the ACK mode is highly recommended when the number of deployed sensor nodes is high.

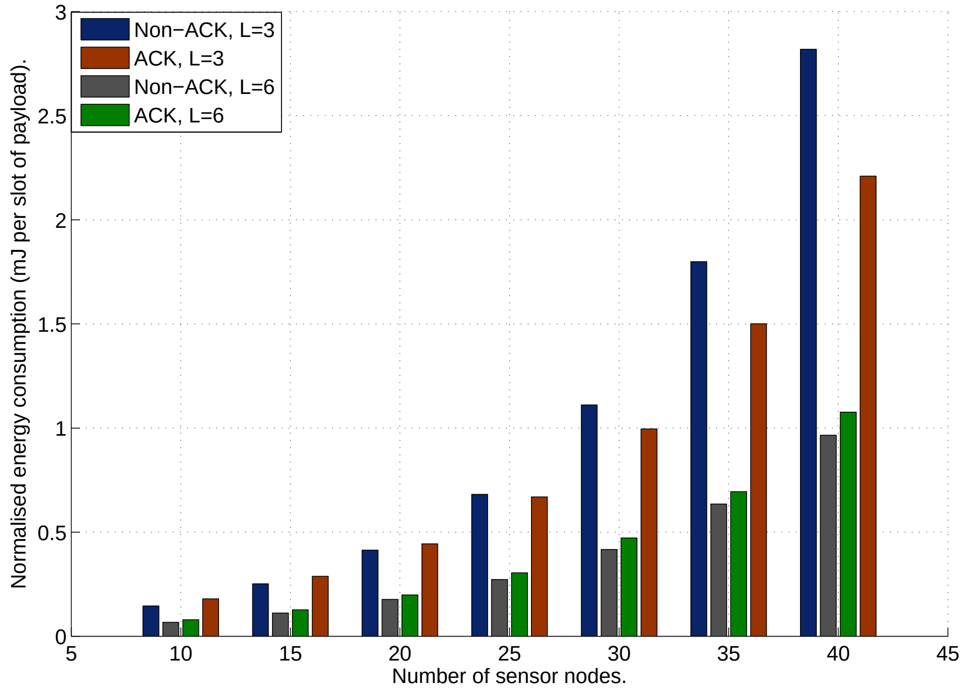

Figure 3.8: Energy consumption comparison between ACK and Non-ACK modes with $L = 3$ and $L = 6$ slots.

3.5 Conclusion

In this chapter, the effectiveness of 802.15.4 networks supporting WSN applications was investigated. An analytic model and simulator were proposed to evaluate the performance of 802.15.4 networks with different parameter setting and circumstances. Throughput and energy consumption were analysed both in theoretical and simulation methods. With a large number of sensor devices in the network, the throughput and energy consumption may not be sufficient to support WSN applications which have high QoS requirements. The problem is essentially due to the CSMA-CA algorithm used by the 802.15.4 MAC for channel access, which is not able to efficiently handle channel access contention when the number of simultaneously contending devices is relatively high. The impact of the sleep and ACK mode were also investigated to obtain overall understanding of the capability of 802.15.4 technology. It was found that the sleep mode could largely reduce the energy consumption at a price of throughput, and that the ACK mode could effectively increase the throughput performance when a large number of sensor devices are deployed.

It was also observed that, various WSN applications could benefit from the 802.15.4 technology with its different functionalities. The WSN applications presented in last chapter with low-rate and strict energy constraint such as smart buildings, agriculture tracking, entertainment using, could take advantage of the 802.15.4 sleep mechanism to achieve extremely long battery life. Transportation, security, and surveillance applications with high QoS requirements can benefit from the 802.15.4 ACK scheme to obtain more reliable communication in crowd network circumstance with low energy consumption.

The accuracy of the proposed analytic model was proved by simulations. Before the deployment of WSNs, the performance and optimal parameter setting (duty-cycle rate, the number of sensor nodes supporting certain QoS requirement, and ACK mode or not) can be predicted by using this proposed analytic model and simulator. It could be extremely meaningful and helpful for both academic and industrial adoption of WSNs.

Chapter 4

Uncoordinated Coexistence Problem of IEEE 802.15.4 WSNs

According to what has been studied in the previous chapter, it is obviously to see that the CSMA-CA based random channel access in IEEE 802.15.4 could effectively support most WSN applications when there is no interference from environments. However, with the crowded wireless communication medium, the performance of 802.15.4 WSNs could face more challenges.

With an increasing number of WSNs equipped with 802.15.4 radios, it is very likely that multiple 802.15.4 networks may be deployed closely and independently, for example, to collect data for smart metering at residential or enterprise areas. In such scenarios supporting reliable communication can be a big challenge even with small number of sensor nodes. This problem becomes more severe due to the potential hidden terminals from coexisting networks when the operation of multiple 802.15.4 networks are uncoordinated.

In this chapter, we investigate the effectiveness of supporting WSNs by IEEE 802.15.4 standard when multiple 802.15.4 networks are deployed closely and independently. Particularly, we consider three representative scenarios in which 802.15.4 networks are affected by uncoordinated coexistence problem. An analytic model and simulator are developed to predict system performance in an attempt to understand how these uncoordinated 802.15.4 networks may affect each other. With the analytical model, throughput of the coexisting networks can be predicted with given MAC parameters, frame length, and the number devices from each network. The results show that the impact of uncoordinated coexistence problem can lead to a significant system performance drop even with a few number of sensor nodes deployed. With the proposed analytic model, we also investigate the performance limits of 802.15.4 networks, and the conditions under which coordinated operation may be required to support effective WSN applications. The analytical model is verified by simulations.

The remainder of this chapter is outlined as follows. Section 4.1 presents the problems when two 802.15.4 networks are deployed closely and independently with uncoordinated operation. In addition three scenarios are introduced and discussed. System models for the uncoordinated networks and performance analysis are presented in section 4.2. Numerical results are presented and discussed in the section 4.3, followed by the conclusions given in section 4.4.

4.1 Scenarios of Coexisting Networks

One problem with a large number of 802.15.4 WSNs coexisting in the same communication range is that excessive interference may be generated and network bandwidth would become insufficient for sharing among these sensor devices. Additionally, WSN applications may have significantly different traffic patterns and QoS requirements, which can pose big challenges on the low-power and low-rate 802.15.4 networks. The effectiveness of supporting WSN applications by 802.15.4 networks could become more serious due to the hidden terminals caused by closely deployed networks with uncoordinated operation.

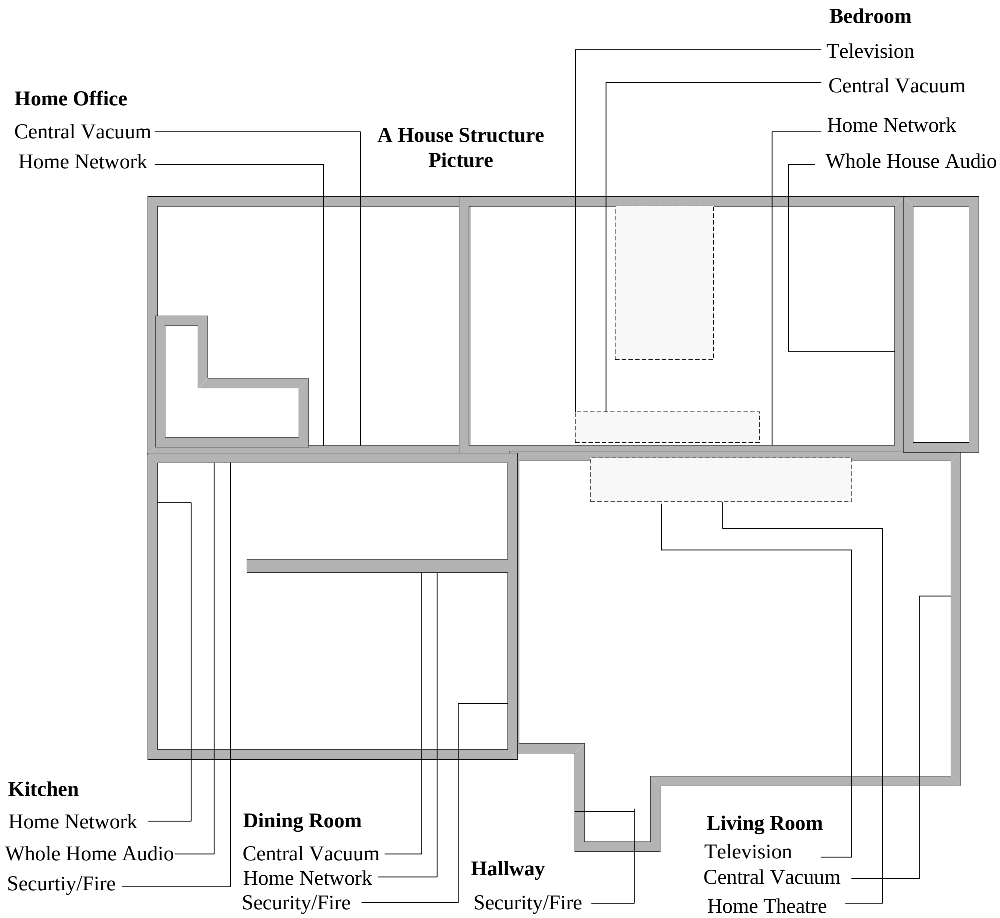

Figure 4.1: Illustration of different types of 802.15.4 based WSN applications deployed in a residential area. There can be many scenarios of these networks which may or may not have interference.

Figure 4.1 gives a sample of deployment of 802.15.4 networks in a residential area, which is very common and representative in the WSN applications. In actual situation, each network may consist of an 802.15.4 coordinator and a number of sensor devices associated with that coordinator to transmit sensing data. There can be many scenarios in which the networks may or may not interfere each other if their operation is not coordinated. In this chapter, we consider three simple and typical scenarios, as to be introduced in the following subsections.

4.1.1 Scenario I

Two 802.15.4 networks are deployed uncoordinated without interference to each other. In this scenario, each network could work independently without performance loss. This may happen due to the following reasons:

- Each network is out of the communication range of the other network.
- Each network is operating on a different frequency channel.
- There is no overlap in channel access period when the sleep mode is enabled with low duty cycle.

In such a scenario, each network can access the whole channel without interference from the other networks. The performance of each network can be the highest in all three coexistence scenarios.

4.1.2 Scenario II

In this scenario, it is assumed that two 802.15.4 networks of concern operate in the same frequency channel, their communication range and active time are fully overlapped. Each sensor node form these two networks can detect each other's transmission with no potential hidden terminals. For simplicity, we assume that the beacons from any network can be received correctly by all the devices belonging to that network.

The interference for each network is coming from the increasing number of contention nodes due to network overlapping in the same area. These two networks share channel frequencies and the whole system can be modelled as a single network with the number of devices in the network being equivalent to the total number of devices in the coexisting networks. The performance of each network can be evaluated after obtaining the overall system performance. Due to the increasing number of sensor nodes from uncoordinated networks, the performance could be worse than the results of Scenario I.

4.1.3 Scenario III

In the third scenario, we assume that two 802.15.4 networks are working in a same channel frequency with fully overlapped communication range and active time. Consider that for each network a sensor device can hear the transmissions from other devices in its own network, but can not detect the transmissions from the other network, which can be the worst case for the uncoordinated coexistence problem. This can happen due to long distances between sensor devices and short distance between the coordinators, although they may operate in the same frequency channel. For example, these two networks are labelled by NET1 and NET2. Supposing that the sensor devices belonging to NET1 are all located to the left hand side of their coordinator, and the devices belonging to NET2 are located to the right hand side of the NET1 coordinator. The sensor devices from NET1 and NET2 are far away from each other and may not hear each other's transmissions. Under this assumption, sensor devices become hidden terminals in the neighbouring network to each other. The CCA detections for each sensor node are not affected by the channel activities from the other network. The coordinators for both networks can detect transmissions from all the sensor devices in their own network as well as the other network. Assuming that the beacons from any network can be received correctly by all the devices belonging to that network.

The interference in this scenario is coming from the hidden terminals caused by the coexisting network. Each transmission could collide with frames from other devices in the same network and the coexisting network. Because of the collisions caused by hidden terminals from uncoordinated networks, the performance could significantly drop.

4.2 System Model

These two networks are labelled by NET1 and NET2, with N_1 and N_2 denoting the numbers of sensor devices in addition to one coordinator, respectively. Assuming that single hop star network topology with beacon-enabled mode is used for these overlapped 802.15.4 networks. Saturate uplink traffic with non-ACK mode from sensor devices to coordinators is considered. To focus our attention on interference from uncoordinated coexistence problem, these two networks are working in non-sleep mode. The length of data frame and data payload are L and L_d slots, respectively for both networks. The physical channel is ideal which means that the data frames can be correctly received if there are no collisions with the other frames. In the following derivations, NET1 and NET2 are assumed to use the same set of MAC parameters. It is trivial to extend to the cases with different MAC parameters setting.

4.2.1 Performance Analysis for Scenario I and II

For Scenario I, there is no interference from uncoordinated coexistence problem and for Scenario II, these two overlapped networks share channel frequencies and the whole system can be modelled as a single 802.15.4 network with total number of sensor devices in the coexisting networks. The performance of these two 802.15.4 networks in Scenario I and II could be analysed by existing analytical model proposed in last chapter. According to the performance modelling in last chapter for single 802.15.4 network the overall channel states sensed by each sensor node can be modelled by a renewal process. Let $p_{n,k}$ denote the probability of a transmission from devices in network n (n represents network identification, being 1 or 2) other than a tagged basic device in network n starting after exactly k^{th} idle slots since the last transmission, where $k \in [0, W_x + 1]$. For the tagged sensor device, a Markov chain can be constructed with finite number of states.

1. **Busy state**, denoted by $B_{n,i,j,l}$, during which at least one device other than the tagged sensor device transmits the lth part of a frame of L slots, with its backoff stage and backoff counter being i and j, respectively.

2. **Backoff state**, denoted by $K_{n,i,j,k}$, during which the tagged sensor device backs off with its backoff counter being j at backoff stage i after k idle slots since the last transmission.

3. **Sensing state**, denoted by $C_{n,i,k}$, during which the tagged sensor device performs CCA2 at the ith backoff stage after k idle slots since the last transmission.

4. **Initial transmission state**, denoted by $X_{n,i,k}$, during which the tagged sensor device starts to transmit a frame at backoff stage i after k idle slots since the last transmission.

5. **Transmission state**, denoted by $T_{n,l}$, during which the tagged sensor device transmits the lth part of a frame.

With the Equations 3.3 - 3.11 presented in last chapter, the transmission probability $\tau_{n,k}$ that the tagged device transmits after exactly k idle slots since the last transmission can be computed by $\tau_{n,k} = 0$, for $k \in [0, 1]$, and for $k \in [2, W_x + 1]$:

$$\tau_{n,k} = \frac{\sum_{i=0}^{m} \bar{X}_{n,i,k}}{\sum_{i=0}^{m} [\bar{X}_{n,i,k} + \bar{C}_{n,i,k} + \sum_{j=0}^{W_i - 1} \bar{K}_{n,i,j,k}]}, \quad n = 1, 2. \tag{4.1}$$

With the above transmission probability $\tau_{1,k}$ and $\tau_{2,k}$, the channel busy probability $p_{1,k}$ and $p_{2,k}$ for NET1 and NET2 for the tagged device can be obtained with $k \in [0, W_x + 1]$.

For Scenario I, we have

$$p_{1,k} = 1 - (1 - \tau_{1,k})^{N_1 - 1}. \tag{4.2}$$

$$p_{2,k} = 1 - (1 - \tau_{2,k})^{N_2 - 1}. \tag{4.3}$$

For Scenario II, we have $\tau_{1,k} = \tau_{2,k}$ and

$$p_{1,k} = 1 - (1 - \tau_{1,k})^{N_1 + N_2 - 1}. \tag{4.4}$$

$$p_{2,k} = 1 - (1 - \tau_{2,k})^{N_1 + N_2 - 1}. \tag{4.5}$$

With channel busy probability $p_{1,k}$ and $p_{2,k}$ have been derived, the Markov chain for the tagged device can be numerically solved. Denote the throughput (normalised throughput defined in chapter 3) of NET1, NET2, and the overall system are S_1, S_2 and S, respectively.

For Scenario I, S_1 and S_2 can be calculated by

$$S_n = N_n L_d \sum_{i=0}^{m} \sum_{k=1}^{W_i} C_{n,i,k-1}(1 - p_{n,k-1})(1 - p_{n,k}), \quad n = 1, 2. \tag{4.6}$$

The S is calculated by

$$S = S_1 + S_2. \tag{4.7}$$

For Scenario II, S is calculated by

$$S = L_d(N_1 + N_2) \sum_{i=0}^{m} \sum_{k=1}^{W_i} C_{1,i,k-1}(1 - p_{1,k-1})(1 - p_{1,k}). \tag{4.8}$$

The S_1 and S_2 are calculated by

$$S_n = \frac{SN_n}{N_1 + N_2}, \qquad n = 1, 2. \tag{4.9}$$

4.2.2 Performance Analysis for Scenario III

So far throughput analysis for Scenarios I and II has been presented. In this subsection, the network throughput for Scenario III is calculated. As previous discussions, the channel access operation in Scenario III is not affected by channel activities from the other network. The only impact on the transmissions in one network from the other coexisting network in Scenario III is the outcomes of frame reception. Even if a frame transmitted to a coordinator from the tagged device does not collide with the frames from the other devices in the same network, it is still subject to collision with the frames from the coexisting network. An illustration of the uncoordinated coexistence problem for Scenario III is shown in Figure 4.2. The Markov states for scenarios I and II can be reused to calculate the channel busy probability $p_{1,k}$ and $p_{2,k}$ for NET1 and NET2 (Equations 4.2) in Scenario III, respectively. The problem that remains to be solved is the calculation of successful frame reception probability, which depends on the probability of transmissions from both networks.

The performance of NET1 under the impact of uncoordinated operation from NET2 is calculated firstly and the impact of NET1 on NET2 can be analysed similarly. With the Markov chain model, the transmission probability $\tau_{2,k}$ can be calculated by Equation 4.1. Now, the probability of having exactly k idle slots before one transmission in NET2 can be derived, which is expressed by $p_{2,idle,k} = 0$ (subscript 2 means NET2) for $k \in [0, 1]$, and for $k \in [2, W_x + 1]$:

$$p_{2,idle,k} = \begin{cases} 1 - (1 - \tau_{2,k})^{N_2}, & k = 2; \\ (1 - (1 - \tau_{2,k})^{N_2}) \prod_{z=2}^{k-1} (1 - \tau_{2,z})^{N_2}, & k \in [3, W_x + 1]. \end{cases} \tag{4.10}$$

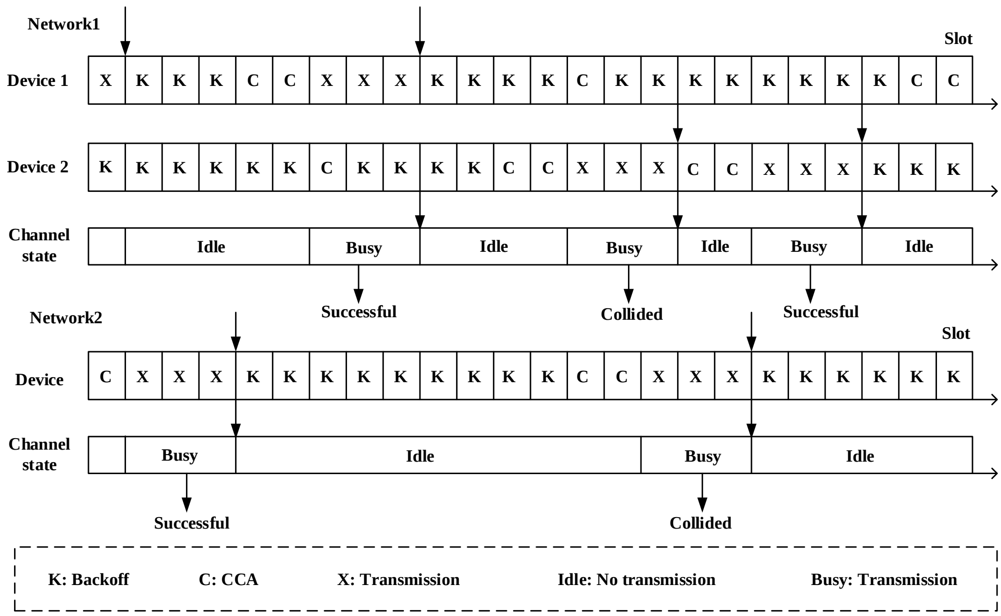

Figure 4.2: Example of frame collisions in Scenario III due to uncoordinated coexistence problem with present hidden terminals.

For each transmission from NET2 following k idle slots, there is a probability $p_{2,suc,k}$ that an independent transmission from NET1 will not collide with transmissions from NET2. It is noted that the probability $p_{2,suc,k}$ is larger than zero only if the number of idle slots k from NET2 is larger or equal to the transmission data length L_1 in NET1. An illustration of the frame collisions from NET1 with frames from NET2 is presented in Figure 4.3.

The probability $p_{2,suc,k}$ for $k \in [2, W_x + 1]$ can be calculated by

$$p_{2,suc,k} = \begin{cases} 0, & k < L_1; \\ \frac{k-L_1+1}{k}, & k \geq L_1. \end{cases} \tag{4.11}$$

The average probability $p_{2,suc,avg}$ that a transmission from NET1 does not collide

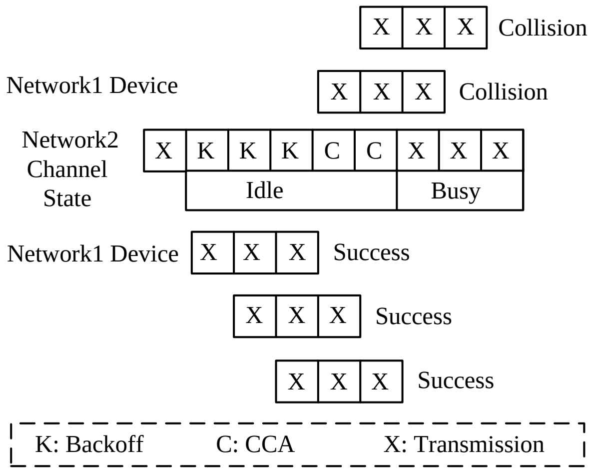

Figure 4.3: Illustration of transmissions from NET1 with/without collisions caused by frames transmitted from NET2.

with the transmissions from NET2 can be calculated by

$$P_{2,suc,avg} = \frac{\sum_{k=2}^{W_x+1} k p_{2,idle,k} p_{2,suc,k}}{\sum_{k=2}^{W_x+1} (k + L_2) p_{2,idle,k}}, \tag{4.12}$$

where L_2 is the transmission data length in NET2.

Finally the throughput of NET1 S_1 for Scenario III can be calculated by

$$S_1 = N_1 L_d \sum_{i=0}^{m} \sum_{k=1}^{W_i} C_{1,i,k-1}(1 - p_{1,k-1})(1 - p_{1,k}) p_{2,suc,avg}. \tag{4.13}$$

Similarly, the throughput of NET2 S_2 for Scenario III can be calculated by

$$S_2 = N_2 L_d \sum_{i=0}^{m} \sum_{k=1}^{W_i} C_{2,i,k-1}(1 - p_{2,k-1})(1 - p_{2,k}) p_{1,suc,avg}. \tag{4.14}$$

The overall network throughput for Scenario III is calculated by $S = S_1 + S_2$.

4.3 Numeric Analysis

With the same assumption in last chapter, we consider 2.4 GHz with 250 kb/s in IEEE 802.15.4 PHY. The two networks are working in non-ACK mode with no sleep time. A new discrete event simulator is implemented to investigate the performance of uncoordinated coexisting 802.15.4 networks and verify the proposed analytical model. The results are obtained based on default MAC parameters for NET1 and NET2: $W_0 = 2^3$, $W_x = 2^5$, and $m = 4$. For Scenario III, the number of sensor devices and initial backoff window W_0 in NET2 are varied to obtain different interferences, which gives comprehensive investigation of the impact from uncoordinated coexistence problem.

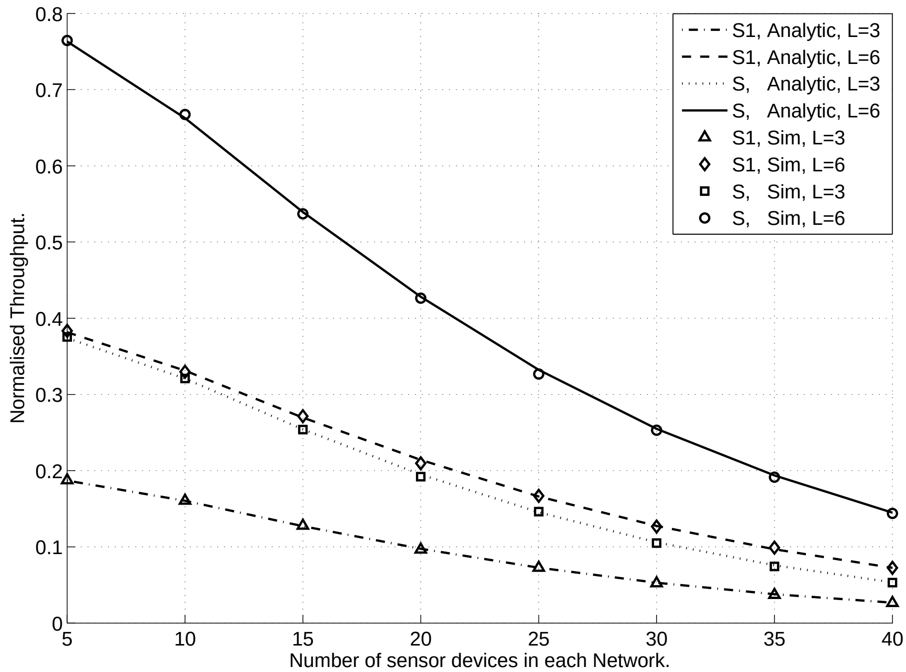

Figure 4.4: Throughput S and S_1 for Scenario I, with $L = 3$ and $L = 6$ slots.

Figure 4.4 shows that the S and S_1 with $L = 3$ and $L = 6$ slots in Scenario I. MAC parameters and the number of sensor devices of NET2 are set to the same with those in NET1, which results in equal throughput for NET1 and NET2. As observed from Figure 4.4, the S is twice of S_1, which shows that the uncoordinated networks do not have adverse impact on each other. Consider the case of 20 sensor devices in NET1. The throughput of NET1 is 0.1 for $L = 3$, which is the same with the performance presented in last chapter for single 802.15.4 network. Each sensor device can deliver at most five data messages in one second with message size $L = 3$. With 30 sensor devices, the throughput of NET1 is about 0.05 with its message size $L = 3$, which means each sensor device may not be able to successfully deliver more than two data messages of size $L = 3$ in one second. Without the sleep mode, this performance could be reasonable for most WSN applications, because of the low data rate that common WSN applications need.

Next, S and S_1 in Scenario II are shown in Figure 4.5 with five sensor devices in NET2. MAC parameters of NET2 are set to be the same as those of NET1. From Figure 4.5, it is observed that S_1 is lower than Scenario I, as the channel is shared by devices in both NET1 and NET2 this scenario. All the sensor devices in the communication range can detect transmissions through CCAs, which prevent the generation of hidden terminals. But the throughput still drops, because of the external contenting sensor devices from neighbour network. Due to the performance loss with this uncoordinated deployment, some WSN applications required high reliability could not be effectively supported such as security and transportation using.

Figure 4.6 shows that the throughput S_1 in Scenario III with five sensor devices in NET2. The results for S have been obtained but not presented here due to the concern on the readability of the figure. Two sets of initial backoff window ($BEmin = 3$ and $BEmin = 5$) are used to study the impact of CSMA-CA parameters of NET2 on the NET1 performance. It shows that for $BEmin = 3$ and $L = 3$, throughput S_1 drops below 0.04 even with only five sensor devices in NET1. Compare to about 0.2 in Scenario

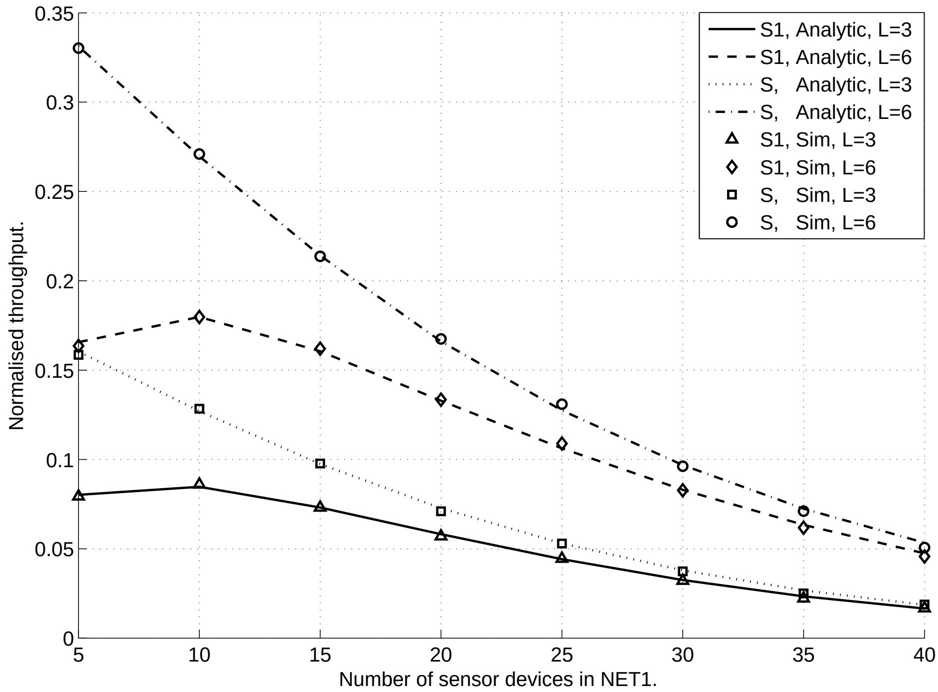

Figure 4.5: Throughput S and S_1 in Scenario II, with $L = 3$ and $L = 6$ slots, and five sensor devices in NET2.

I and 0.08 in Scenario II, the performance significantly decreases. With a larger frame length ($L = 6$), S_1 drops even further. It is also observed that the analytic results match very well to the simulation outcome, which demonstrates the accuracy of the proposed analytical model. Consider the case of 20 sensor devices in the NET1. The throughput of NET1 is 0.02 for $L = 3$ and 0.005 for $L = 6$ with $BEmin = 3$. It means each sensor device in NET1 can successfully deliver at most one data message in one second for $L = 3$ and 0.125 data messages for $L = 6$, respectively. When there are more sensor devices, the throughput drops further and most WSN applications could not be effectively supported by the 802.15.4 networks under this circumstance. The above analysis reveals that uncoordinated coexistence problem in Scenario III can significantly affect the effectiveness of supporting WSN applications by 802.15.4 technology.

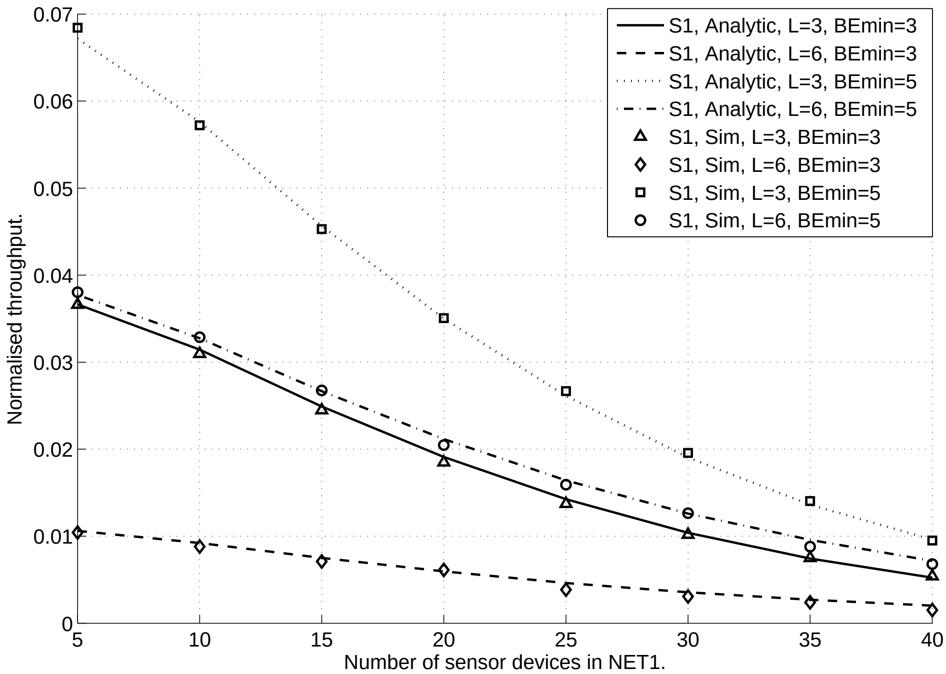

Figure 4.6: S_1 in Scenario III, with $L = 3$ and $L = 6$ slots, and five sensor devices in NET2. $BEmin$ of NET2 is set to 3 and 5, which means initial backoff window W_0 of NET2 is set to 2^3 and 2^5.

It is also observed that with the increase of random backoff window in NET2, S_1 could be significantly improved as shown in Figure 4.6. This can be explained by the fact that, with a larger random backoff window for sensor devices in NET2, there will be lower collision probabilities between the frames from NET1 and NET2. Increasing the random backoff window may be an effective measure to improve the system performance in case of multiple uncoordinated 802.15.4 networks with hidden terminals in a coexisting area. But it is noted that such improvement may be achieved at a cost of increased message delivery delay due to larger backoff windows. Even with a large backoff window, the improvement of throughput in Scenario III is limited and still relatively low compared to that in Scenarios I and II.

Now, we change the number of active sensor devices in NET2 to one, and the

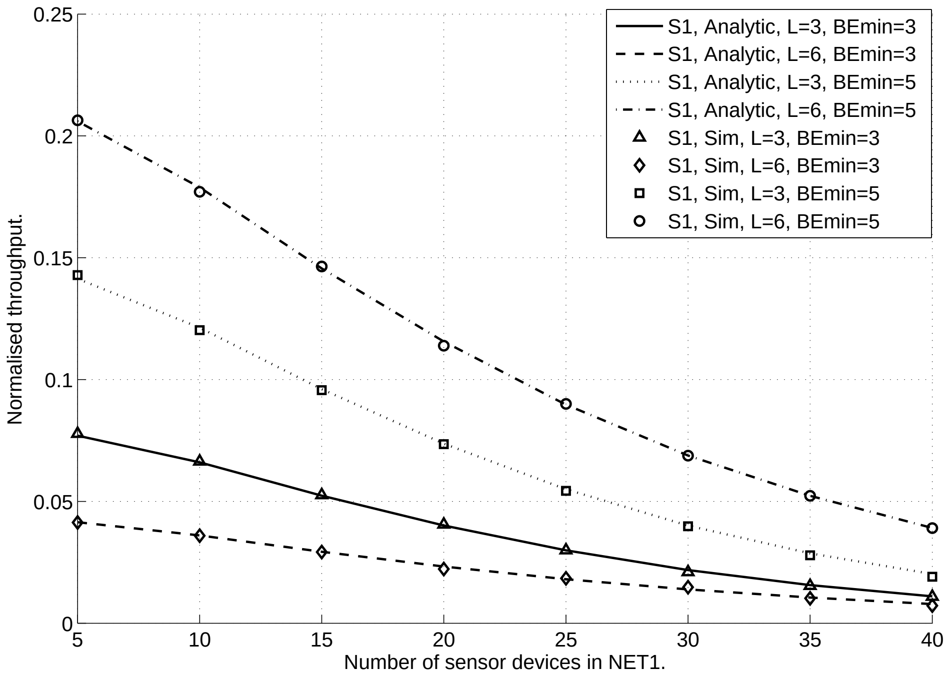

Figure 4.7: S_1 in Scenario III with $L = 3$ and $L = 6$ slots. There is only one sensor device in NET2. $BEmin$ of NET2 is set to 3 and 5, which means their initial backoff windows being $W_0 = 2^3$ and $W_0 = 2^5$, respectively.

corresponding results are shown in Figure 4.7. S_1 is still quite low (about 0.08 for $L = 3$ and $BEmin = 3$) compared to Scenario II, but it is much better than the results shown in Figure 4.6. With an increased random backoff window ($W_0 = 2^5$) of NET2, it is observed that S_1 increases up to 0.2 with a larger frame length $L = 6$. The throughput S_1 with $L = 3$ is lower than the throughput with $L = 6$, which is opposite to what we have observed with five sensor devices in NET2 as shown in Figure 4.6.

Apart from the throughput analysis for whole networks, we are also interested in the maximal number of data messages that one sensor device can successfully deliver in one second, which is an important performance metric for WSN applications. The maximal number of messages that a sensor device from NET1 can successfully deliver in one second is plotted in Figure 4.8 and Figure 4.9 against the number of sensor devices

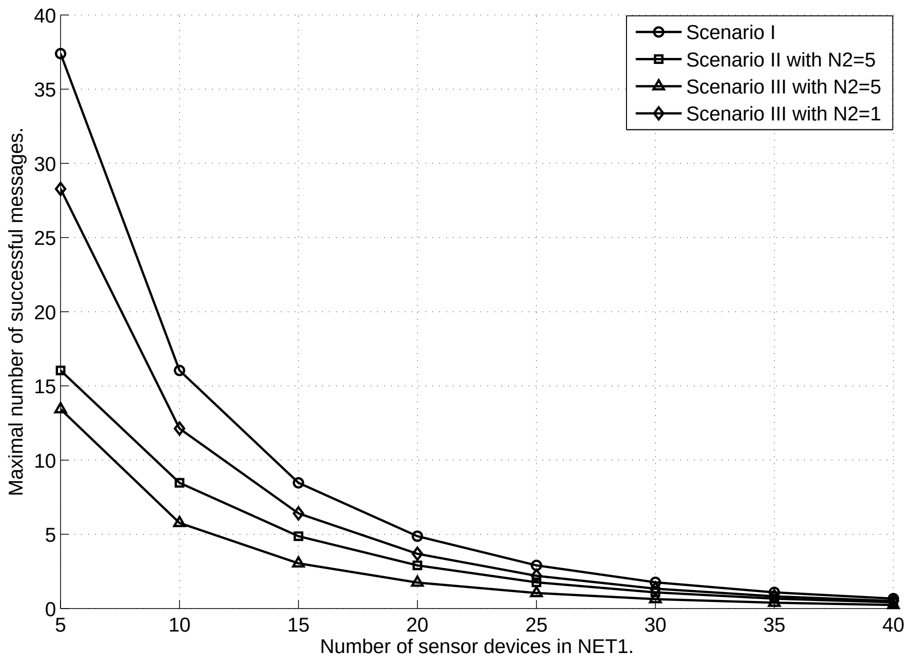

Figure 4.8: The maximal number of messages that can be successfully delivered in one second by each NET1 sensor device with $L = 3$ ($BEmin = 5$ for Scenario III).

in NET1 for $L = 3$ and $L = 6$, respectively. As the analytic model has been validated by simulations, only analytical results are presented in Figure 4.8 and Figure 4.9. For Scenario II, there are five sensor devices in NET2, and the MAC parameters of NET2 are the same with NET1. For Scenario III, there are five sensor devices in NET2 and the default MAC parameters are used except that $BEmin$ is five in NET2. From Figure 4.8 and Figure 4.9, it is observed that the uncoordinated coexistence in Scenario III have a significant impact on capabilities of 802.15.4 networks to support WSN applications, especially with longer data length $L = 6$. For example, assume that an application based on 802.15.4 WSNs expects to receive five messages from each sensor in on second. In Scenario III with five hidden terminals in NET2, the requirement can not be met with more than ten sensors and five sensors in NET1 for $L = 3$ and $L = 6$, respectively. If the requirement of WSN applications on the expected messages per second from each

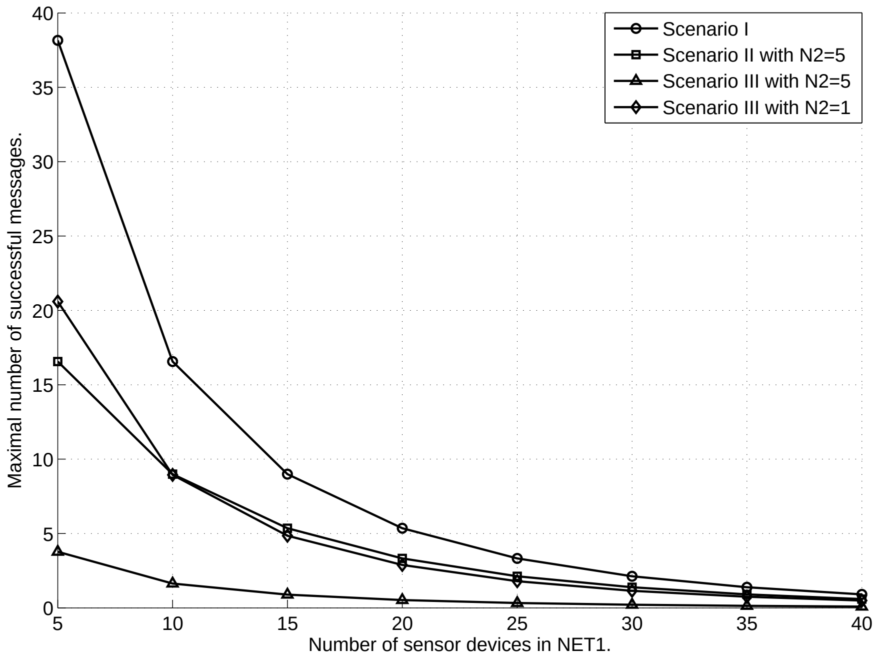

Figure 4.9: The maximal number of messages that can be successfully delivered in one second by each NET1 sensor device with $L = 6$ ($BEmin = 5$ for Scenario III).

sensor device is known in advance, the analytic model could be used to find out how many sensors can be supported in each network.

4.4 Conclusion

From the previous chapter it has been demonstrated by both analytical and simulation results that the performance of 802.15.4 networks could be meet the QoS requirements of general WSN applications and there are also many challenges due to high dense of sensor devices deployed. With an increasing number of 802.15.4 WSNs deployed in the same area, the interference due to uncoordinated coexistence deployment could be very strong and lead to significant performance loss. Different levels of interference with three scenarios were investigated to obtain comprehensive understanding of this problem when WSN applications are deployed independently. It was observed that supporting reliable communication could be a big challenge even with a small number of sensor nodes when interference occurs due to uncoordinated coexistence problem. The problem becomes more severe due to the potential hidden terminals from coexisting networks when transmissions can not efficiently detected by each other.

An analytical model was developed to investigate the impact of uncoordinated coexistence on the overall system performance to support WSN applications. A system level discrete event simulator was developed as well. Simulation results demonstrated the accuracy of the proposed analytical model. It was observed through both analytical and simulation results that with uncoordinated operation the throughput of a network can be significantly degraded by even only one single hidden terminal in the other network. The QoS requirements for many WSN applications are unlikely to be satisfied with the degraded network performance. Through increasing the backoff time of uncoordinated coexisting 802.15.4 networks, throughput can be improved due to reducing the collision probability caused by hidden terminals. It was also found that the problem is essentially due to the channel access mechanism in IEEE 802.15.4 can not efficiently handle the collision caused by hidden terminals from other networks. With the crowded wireless environment, the proposed analytic model can be used to obtain the optimal parameter setting and number of sensor devices supporting certain QoS requirement before the deployment of WSN applications.

Chapter 5

Uncoordinated Coexistence Problem with Sleep Mode in IEEE 802.15.4 WSNs

According to the analysis from Chapter 4, it is observed that the 802.15.4 slotted CSMA-CA channel access scheme is difficult to provide effective support for WSN applications when multiple 802.15.4 networks are deployed in overlapped service areas with uncoordinated operations. Especially, when the sensor devices from one network could not detect transmissions from other networks in the same area, supporting reliable and timely communication could be a huge challenge.

As described in Chapter 2, 802.15.4 MAC layer provides an optional sleep mode based on duty-cycle for energy saving when networks are using beacon-enabled mode with superframe structure. This sleep mode could significantly affect the system performance when the networks are deployed with the same uncoordinated coexistence problem presented in last chapter. For some low duty-cycle WSN applications, the interference could possibly be none even in the worst case (Scenario III presented in last chapter) due to the active periods of these networks are not overlapped in sleep mode.

In this chapter the sleep mode is taken into account in the performance evaluation and enhancement of multiple coexisting 802.15.4 WSNs. With the introduction of a new concept of overlap ratio representing the percentage of overlapped portion in contention access periods (CAPs), two representative network scenarios are presented. In last chapter the energy consumption was not analysed, while in this chapter, both the throughput and energy consumption are analysed with a proposed analytic model and simulations. The analytical model can predict both system throughput and energy consumption with different MAC parameters, frame length, the number of devices for each network and overlap ratios. The impact of different duty-cycles in sleep mode is investigated to obtain the performance evaluation of the IEEE 802.15.4 sleep mechanism. It is also observed that the impact of different overlap ratios could lead to significantly different system performance when the communication range of two uncoordinated networks are fully overlapped. Approaches by reducing sleep time and overlap ratio are also studied to improve network performance. The analytical model is verified by simulations.

The remainder of this chapter is organised as follows. In section 5.1 two scenarios and model assumption of the analytical model are introduced. The analytic model of two uncoordinated coexisting networks is presented in section 5.2. In section 5.3, numerical results and performance analysis are discussed. The conclusion is presented in section 5.4.

5.1 Model Assumption

Based on the assumption in last chapter, it is assumed that two considered 802.15.4 networks are operated on the same frequency channel and the communication range are fully overlapped. Each network has a coordinator, which is responsible for broadcasting the beacon frames in the beginning of superframes. We assume that beacons from each network can be correctly received by all the sensor devices belonging to that network. Sleep mode is enabled for both networks, which is observed that CAPs from each network can be part overlapped or fully overlapped with different overlap ratio g as shown in Figure 5.1. When $g = 1$, it is the worst case that the two networks are fully overlapped in channel access periods. When $g = 0$, it means there is no interference between these two networks.

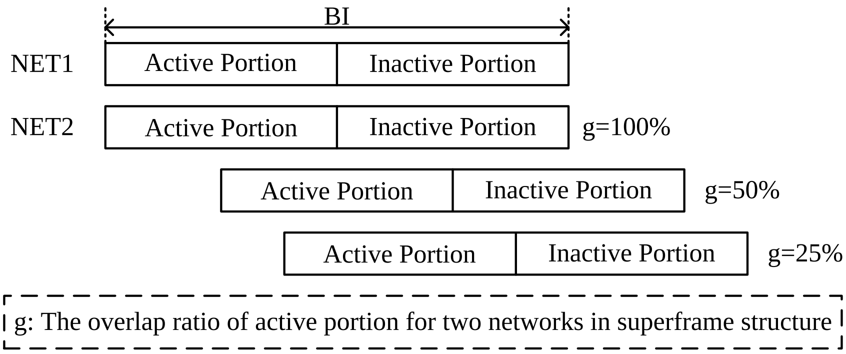

Figure 5.1: Illustration of channel access periods overlap in the superframe structure with different overlap ratio g, where g is the ratio of the number of slots in overlapped part to the number of slots in CAP, $0 \leq g \leq 1$.

Scenario I

The distance between the sensor devices from these two networks is near and they can detect each other's transmissions through CCAs as shown in Figure 5.2 (a). These two networks share the whole channel frequencies without generating hidden terminals.

Scenario II

The distance between the sensor devices from these two networks is too far to hear transmissions from each other as shown in Figure 5.2 (b). CCA detections for each device is not affected by the channel activities from the other network. Sensor devices from each network could become hidden terminals to each other.

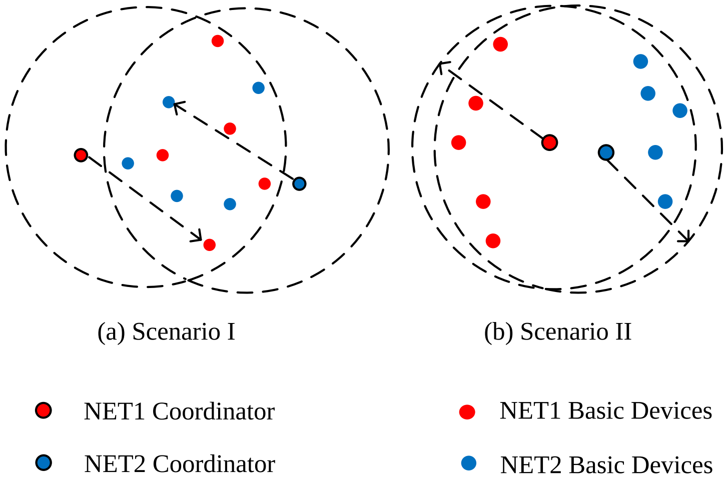

Figure 5.2: Communication range of each network are fully overlapped, (a) sensor devices from two networks can detect each other's transmissions through CCAs; (b) sensor devices from each network cannot detect transmission from other network's transmission through CCAs.

5.2 Analytical Model

Using the same assumption in last chapter, except turning the sleep mode on, the impact of sleep mode on uncoordinated coexistence problem is analysed. The overlapped networks are labelled by NET1 and NET2, with N_n (n represents network identification, being 1 or 2) denoting the numbers of sensor devices in addition to one coordinator, respectively. Each data frame has a fixed length which requires L slots to transmit over the channel. Let L_d denote the length of data payload in unit of slots needed for transmission in a data frame. In the remaining of the chapter, we use the term "throughput" and "energy consumption" denote "normalised throughput" and "normalised energy consumption" defined in chapter 3 for simplicity.

5.2.1 Scenario I

The system performance of the networks in CAPs for Scenario I could be analysed separately with two parts according to the overlap ratio g: non-overlapped and overlapped parts. For the non-overlapped part, the performance could be analysed in the same way presented in chapter 3 due to there is no interference. The throughput for non-overlapped part can be calculated by

$$S_{I,n}^{f} = N_n L_d \sum_{i=0}^{m} \sum_{k=1}^{W_i} C_{n,i,k-1}(1 - p_{n,k-1}^{f})(1 - p_{n,k}^{f}), \quad n = 1, 2. \tag{5.1}$$

The energy consumption of non-overlapped part is

$$\eta_{I,n}^{f} = \frac{N_n}{S_{I,n}^{f}} \sum_{i=0}^{m} \left\{ \sum_{l=2}^{L} E_c B_{n,i,0,l} + \sum_{k=0}^{W_i+1} \Big[E_c(K_{n,i,0,k} + C_{n,i,k}) + L E_t X_{n,i,k} \Big] \right\}, \quad n = 1, 2. \tag{5.2}$$

For the overlapped part, these two networks share channel frequencies and the overall system can be modelled as a single network. The number of sensor devices in the overall system is equivalent to the total number of sensor devices in these two coexisting networks. With the new channel busy probabilities $p_{n,k}^{o}$ for NET1 and NET2, respectively:

$$p_{1,k}^{o} = 1 - (1 - \tau_{1,k})^{N_1+N_2-1}, \tag{5.3}$$

$$p_{2,k}^{o} = 1 - (1 - \tau_{2,k})^{N_1+N_2-1}. \tag{5.4}$$

the throughput of the overlapped part for overall system is obtained:

$$S_I^{o} = (N_1 + N_2) L_d \sum_{i=0}^{m} \sum_{k=1}^{W_i} C_{1,i,k-1}(1 - p_{1,k-1}^{o})(1 - p_{1,k}^{o}). \tag{5.5}$$

Then the throughput of overlapped part for NET1 and NET2 are obtained by

$$S^o_{I,n} = \frac{S^o_I N_n}{N_1 + N_2}, \quad n = 1, 2. \tag{5.6}$$

The energy consumption of overlapped part for NET1 and NET2 can be obtained by

$$\eta^o_{I,n} = \frac{N_n}{S^o_{I,n}} \sum_{i=0}^{m} \left\{ \sum_{l=2}^{L} E_c B_{1,i,0,l} + \sum_{k=0}^{W_i+1} \Big[E_c(K_{1,i,0,k} + C_{1,i,k}) + LE_t X_{1,i,k} \Big] \right\}, \quad n = 1, 2. \tag{5.7}$$

The different duty-cycles in sleep mode could be obtained by different SOs. Through combining the non-overlapped and overlapped part of CAPs together with different overlap ratio g and SOs, the throughput and energy consumption for individual network is obtained.

For Scenario I, throughput $S_{I,n}$ of NET1 and NET2 are calculated by

$$S_{I,n} = 2^{SO_n - BO_n}[(1-g)S^f_{I,n} + gS^o_{I,n}], \quad n = 1, 2, \tag{5.8}$$

and the overall network throughput S_I is calculated by

$$S_I = S_{I,1} + S_{I,2}. \tag{5.9}$$

The energy consumption $\eta_{I,n}$ of Scenario I for NET1 and NET2 can be computed by

$$\eta_{I,n} = 2^{SO_n - BO_n} \frac{(1-g)S^f_{I,n}\eta^f_{I,n} + gS^o_{I,n}\eta^o_{I,n}}{S_{I,n}}, \quad n = 1, 2. \tag{5.10}$$

5.2.2 Scenario II

In this subsection an analytical mode for Scenario II is introduced. The throughput of non-overlapped part in CAPs of each network can be calculated by Equation 5.1 as done in Scenario I, for there is no interference from each other. Recall the Equation 4.12 for $p_{2,suc,avg}$, the throughput of overlapped part of CAPs can be obtained by

$$S^o_{II,1} = p_{2,suc,avg} S^f_{I,1}. \tag{5.11}$$

Similarly the throughput of overlapped part for NET2 is obtained by

$$S^o_{II,2} = p_{1,suc,avg} S^f_{I,2}. \tag{5.12}$$

After the throughput of non-overlapped and overlapped part has been derived, the throughput $S_{II,n}$ for NET1 and NET2 can be calculated by

$$S_{II,n} = 2^{SO_n - BO_n}[(1-g)S^f_{I,n} + gS^o_{II,n}], \quad n = 1, 2. \tag{5.13}$$

The overall system throughput for Scenario II is calculated by $S_{II} = S_{II,1} + S_{II,2}$.

Because of the only impact on the transmissions in each network for Scenario II is the outcomes of frame reception. The energy consumptions $\eta_{II,n}$ for NET1 and NET2 in Scenario II can be calculated by using $\eta^f_{I,n}$ (Equ.5.2) in Scenario I with the new throughputs $S_{II,n}$ in Scenario II:

$$\eta_{II,n} = 2^{SO_n - BO_n} \frac{\eta^f_{I,n} S^f_{I,n}}{S_{II,n}}, \quad n = 1, 2. \tag{5.14}$$

5.3 Analytic results and Performance Investigation

A simulator is developed to investigate the impact of sleep to uncoordinated coexistence problem and verify the proposed analytic model. We use the same parameter setting proposed in last chapter, but turning sleep mode on. For both NET1 and NET2, BO sets to 6, which means each superframe length BI is fixed as 3072 slots. Then the CAP of each superframe is only determined by SOs. We can vary different SOs to set various sleep time in duty-cycle for both two networks to investigate the impact of sleep mode. Typical results are presented with default MAC parameters for NET1: $W_0 = 2^3$, $W_x = 2^5$, and $m = 4$. The MAC parameters in NET2 are varied to investigate the impact of interferences from NET2.

5.3.1 Analysis of Scenario I

Figure 5.3 shows the throughput S of the overall system and throughput S_1 for Scenario I. For these results there are only 5 sensor devices in NET2 and the MAC parameters of NET2 are as same as those in NET1. For $L = 3$, we have $L_d = 1.5$ and the length of one data frame is 15 bytes. Similarly for $L = 6$, the data length is 55 bytes. Half of the time in BIs is in sleep period with $SO = 5$ and the CAPs of NET1 and NET2 are fully overlapped with $g = 1$. Consider the case of 20 sensor devices working in NET1. The throughput of NET1 is only 0.03 for $L = 3$, which means at most 30 data messages could be successfully delivered in one second in total in NET1. Each sensor device in NET1 could deliver at most 1.5 data messages in one second with message size $L = 3$. This performance may be reasonably acceptable for WSN applications, as most of them do not need high data rate such as home automation and agriculture monitoring. However, the throughput of NET1 decreases further when there are more sensor devices in networks and normal WSN applications may not be effectively supported by the uncoordinated operation in Scenario I.

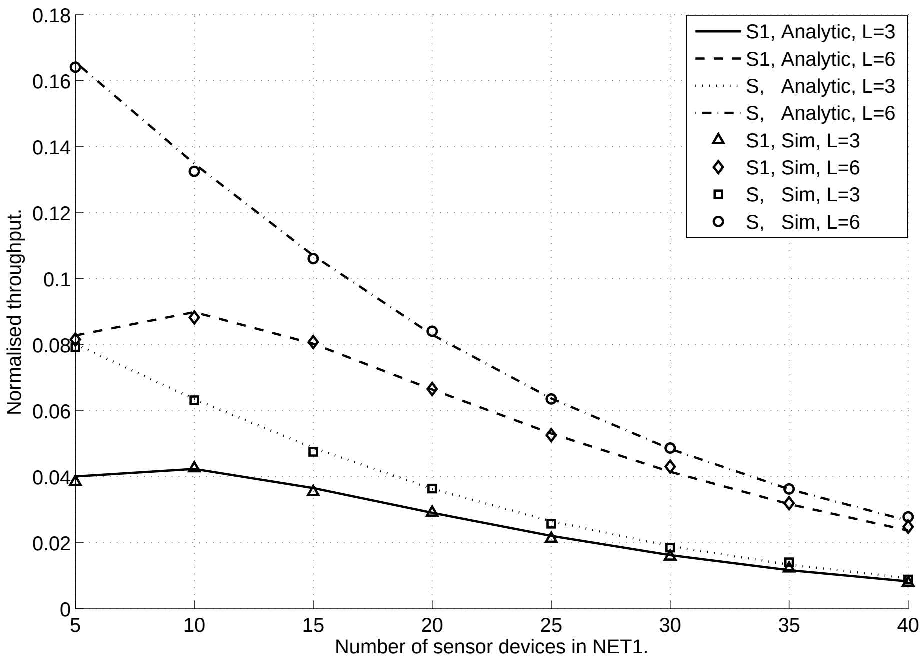

Figure 5.3: Throughput S and S_1 for Scenario I. The number of sensor devices in NET2 is fixed 5. $L = 3$, $L = 6$ slots and $SO = 5$, $g = 1$ for each network.

Figure 5.4 presents the throughput S_1 with different SOs in Scenario I. Consider the cases of 20 and 10 sensor devices in NET1 as examples. When the SO is increased by one (not over maximum BO), the throughput is doubled with the condition overlap ratio $g = 1$. With the assumption of Scenario I, reducing the sleep time or using the non-sleep mode will dramatically increase the throughput of NET1. For example, if we set $SO = 6$ for Scenario I, which means these two networks are working in non-sleep mode, the S_1 will be doubled of that shown in Figure 5.3, as the active time in each superframe is doubled.

Figure 5.5 shows the relationship between throughput S_1 and overlap ratio g in Scenario I. We take $N_1 = 20$ and $N_1 = 10$ as examples. With $g = 0$, it means there is no interference between two networks and with $g = 1$, it means the CAPs are fully overlapped. By increasing overlap ratio from 0 to 1, the throughput of NET1 drops

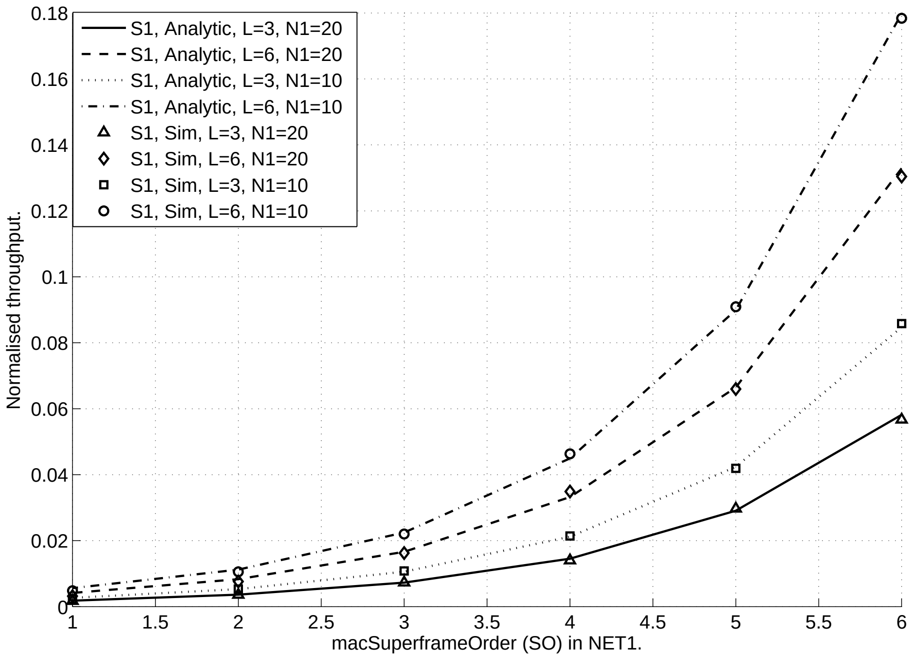

Figure 5.4: Throughput S_1 for Scenario I. The number of sensor devices in NET2 is fixed to 5. $L = 3$, $L = 6$ slots and $g = 1$ for each network. The number of sensor devices in NET1 are $N_1 = 20$ and $N_1 = 10$ respectively.

linearly. Consider the case of 10 sensor devices in NET1. The throughput of NET1 is 0.08 for $L = 3$ and $g = 0$, which means at most 80 data messages could be successfully transmitted in total in NET1. When the overlap ratio increases to $g = 0.5$ and $g = 1$, the successfully transmitted data messages drop to about 60 and 40, respectively.

Figure 5.6 plots energy consumption E_1 for Scenario I. We consider the cases of $N_1 = 20$ with $L = 3$ under three conditions: $g = 1$, $g = 0.5$ and $g = 0$. When $g = 1$, the E_1 is at most 0.7 mJ, which is the highest one compared to nearly 0.5 mJ for $g = 0.5$ and about 0.4 mJ for $g = 0$. It is found that reducing overlap ratio could significantly improve the energy consumption when sleep mode is enabled.

For Scenario I, it is observed that increasing the active time and reducing the overlap ratio can obtain higher throughput. Reducing sleep time will increase the total energy

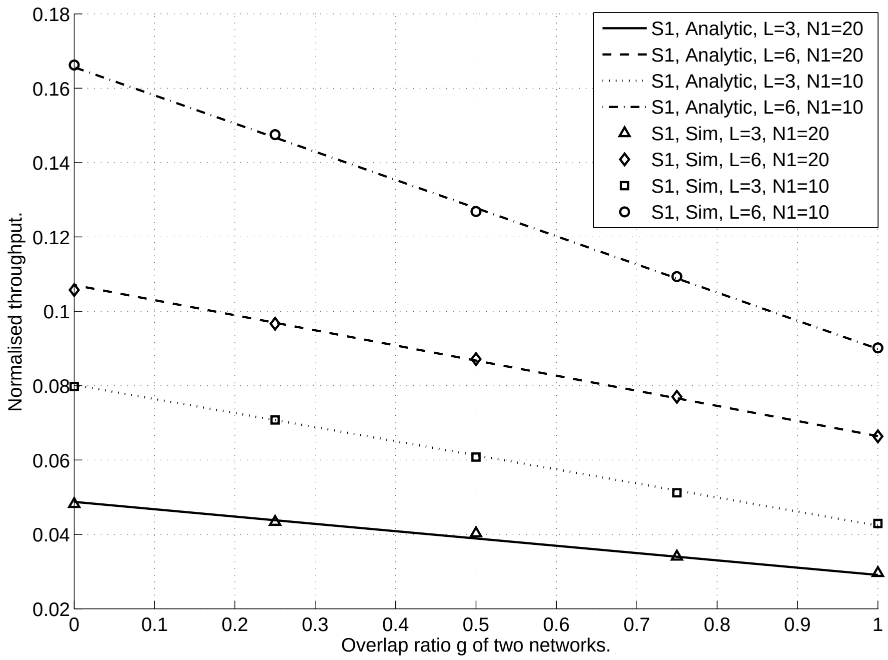

Figure 5.5: Throughput S_1 for Scenario I. The number of sensor devices in NET2 is fixed 5. $L = 3$, $L = 6$ slots and $SO = 5$ for each network. The number of sensor devices in NET1 are $N_1 = 20$ and $N_1 = 10$ respectively.

consumption, as more slots are used to compete access channel in superframes. Taking 20 sensor devices with $L = 3$ in NET1 as an example from Figure 5.6, the throughput is doubled from 0.03 to 0.06 when SO increases from 5 to 6, which the number of data messages that could be successfully delivered in one second in total NET1 with message size $L = 3$ is increased from 30 to 60. The energy consumption is at most 0.7 mJ for this example with $g = 1$, and it will not change for different SOs. With $SO = 5$ at most 10.5 mJ per second energy will be consumed in total in NET1, and with $SO = 6$ at most 21 mJ per second energy will be consumed in total in NET1. Compared to the approach of increasing SOs, reducing the overlap ratio can also reduce the energy consumption to get higher throughputs.

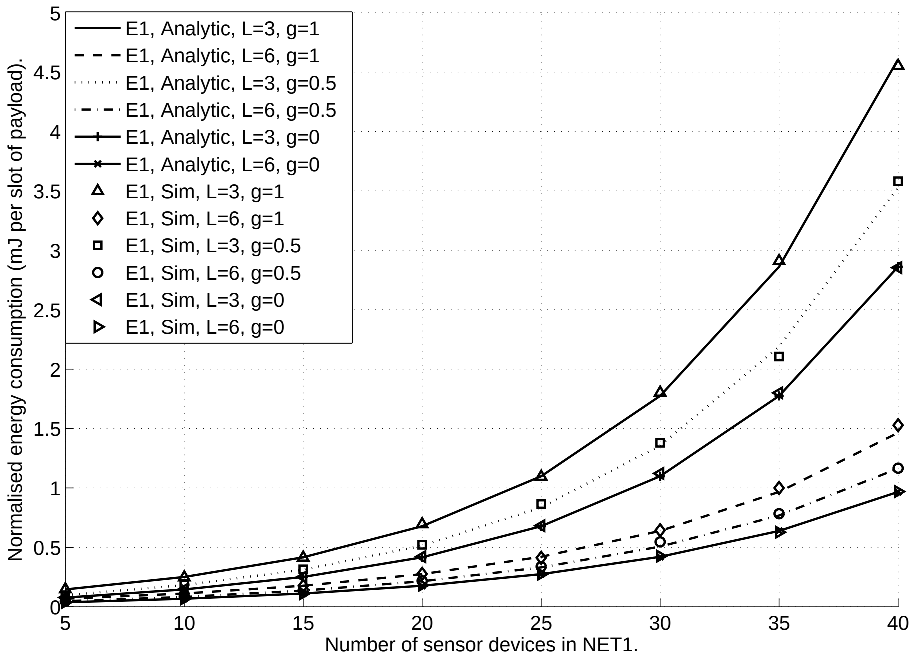

Figure 5.6: Energy consumption E_1 for Scenario I. The number of sensor devices in NET2 is fixed 5. $L = 3$, $L = 6$ slots and $g = 1$, $g = 0.5$, $g = 0$ and $SO = 5$ for each network.

5.3.2 Analysis of Scenario II

Figure 5.7 shows that the throughput S_1 in Scenario II with 5 sensor devices in NET2. Two sets of initial backoff window ($BEmin = 3$ and $BEmin = 5$) are used to study the impact of the slotted CSMA-CA parameters of NET2 on the NET1 performance. It shows that for $BEmin = 3$ and $L = 3$, the throughput S_1 drops below 0.04 even with only 5 devices in NET1. With larger frame length $L = 6$, the NET1 throughput S_1 drops further. It is also observed that the analytic results match very well with the simulation results, which demonstrates the high accuracy of the proposed analytic mode. Consider the case of 10 sensor devices in the NET1. The throughput of NET1 is 0.015 for $L = 3$ and 0.005 for $L = 6$, respectively. It means each sensor device in NET1 could successfully deliver at most 1.2 data messages in one second for $L = 3$ and

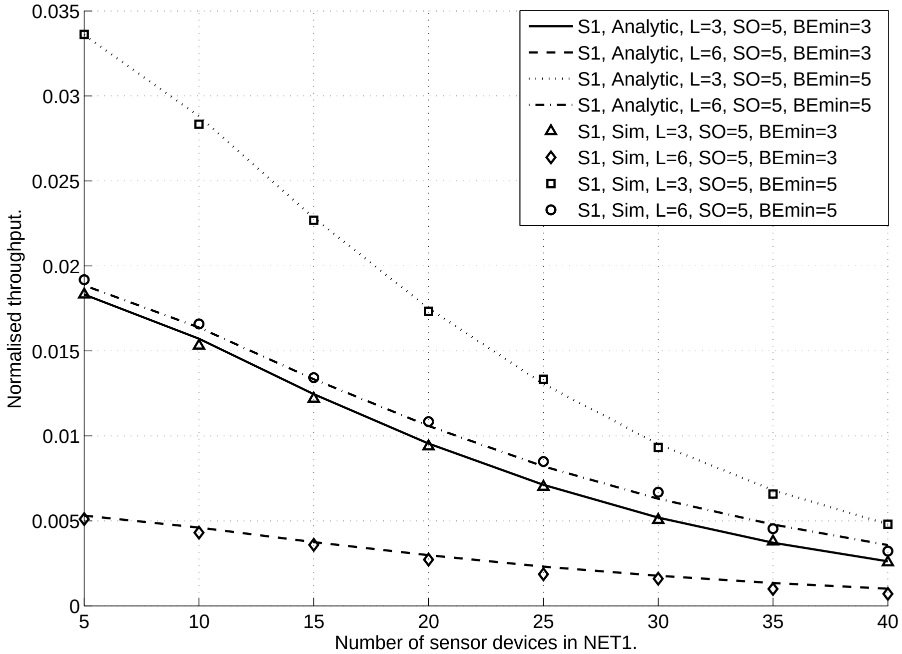

Figure 5.7: Throughput S_1 for Scenario II. The number of sensor devices in NET2 is fixed 5. $BEmin$ of NET2 is set to 3 and 5, respectively, with initial backoff window set to $W_0 = 2^3$ and $W_0 = 2^5$. $L = 3$, $L = 6$ slots and $SO = 5$, $g = 1$ for each network.

0.25 data messages for $L = 6$, respectively. When there are more sensor devices the NET1, the throughput of NET1 drops further and most WSN applications could not be effectively supported by the 802.15.4 networks. The above analysis shows that for Scenario II, uncoordinated operation of 802.15.4 networks can significantly affect the effectiveness of the networks on supporting WSN applications.

It is observed that with an increased backoff window in NET2, the throughput S_1 for Scenario II is largely improved. As we disscussed in last chapter, this can be explained by the fact that with large backoff widows for devices in NET2, there will be smaller collision probabilities for frames from NET1 and NET2. At the cost of increasing message delivery delay we can just simply set a large backoff window to improve the throughput performance. Compared to Scenario I, the throughput S_1 is limited even with an increased backoff window in NET2.

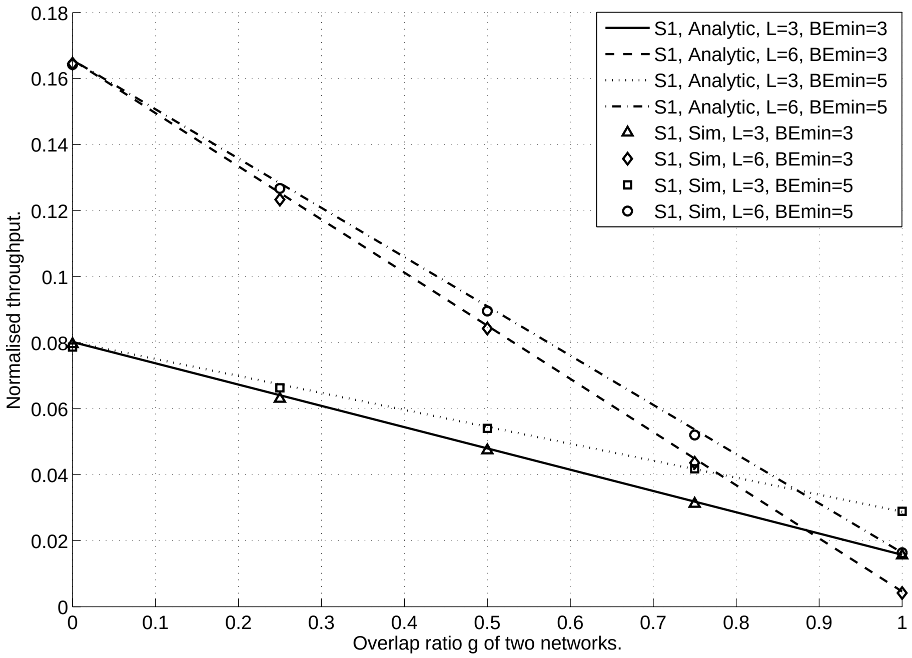

Figure 5.8: Throughput S_1 for Scenario II. The number of sensor devices in NET2 is fixed 5 and the $BEmin$ of NET2 is set to 3 and 5, with initial backoff window $W_0 = 2^3$ and $W_0 = 2^5$. $L = 3$, $L = 6$ slots and $SO = 5$ for each network. The number of sensor devices in NET1 is $N_1 = 10$.

Figure 5.8 gives the throughput S_1 with different overlap ratio g for Scenario II. The number of sensor devices in NET2 is still 5 and there are 10 sensor nodes in NET1. With increasing overlap ratios from 0 to 1, the throughput S_1 drops dramatically. When $g = 0.5$, the throughputs S_1 for $L = 3$ are about 0.045 and 0.055 with $BEmin = 3$ and $BEmin = 5$, respectively. It means each sensor device could successfully transmit 4.5 data messages and 5.5 data message in one second, respectively. When g increases to 1, the number of data messages that can be successfully delivered in one second drops to 1.5 and 3, respectively. The throughput S_1 with $BEmin = 3$ drops quicker than with $BEmin = 5$ for both $L = 3$ and $L = 6$. With larger frame length ($L = 6$), the NET1 throughput drops further with increased g and becomes lower than $L = 3$ when g is near 1.

From Figure 5.8, we can find that the overlap ratio affects the throughput of both network significantly. The larger payload length, the more performance loss when the networks are overlapped in the channel access period. For most WSN applications with low data rate feature such as agriculture monitoring, smart metering, and logistic tracking, the duty-cycle in sleep mode could be low to obtain long batter life. With a careful deployment of these applications, the overlapped portion in channel access periods could be reduced or eliminated, the network throughput could be largely improved under the case of uncoordinated coexistence.

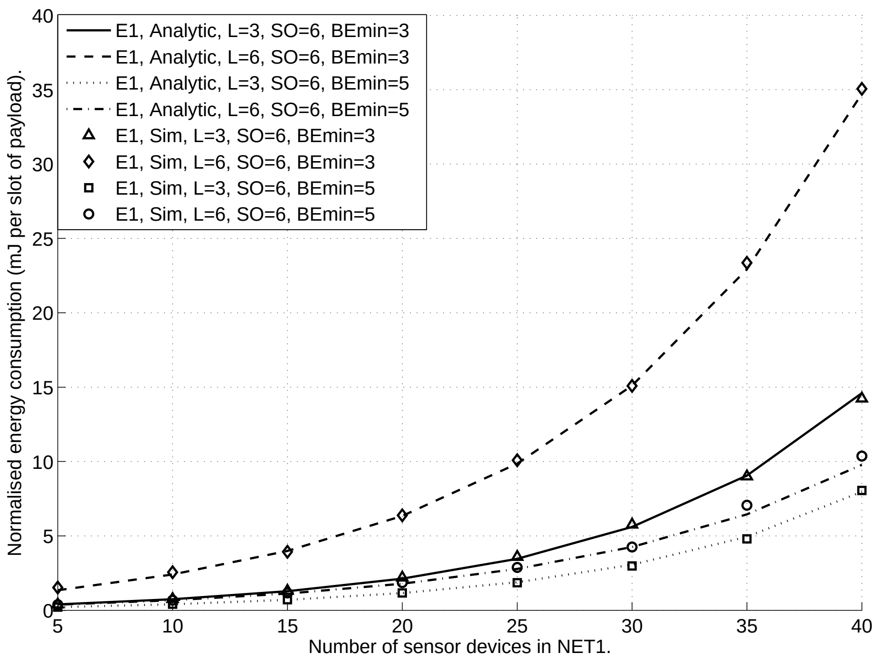

Figure 5.9: Energy consumption E_1 for Scenario II. The number of sensor devices in NET2 is fixed 5 and the $BEmin$ of NET2 is set to 3 and 5, respectively. Initial backoff window is set to $W_0 = 2^3$ and $W_0 = 2^5$. $L = 3$, $L = 6$ slots, $g = 1$ and $SO = 5$ for each network.

Figure 5.9 and Figure 5.10 plot the energy consumption of NET1 for Scenario II. It is observed that the uncoordinated operation of 802.15.4 networks could lead to significant

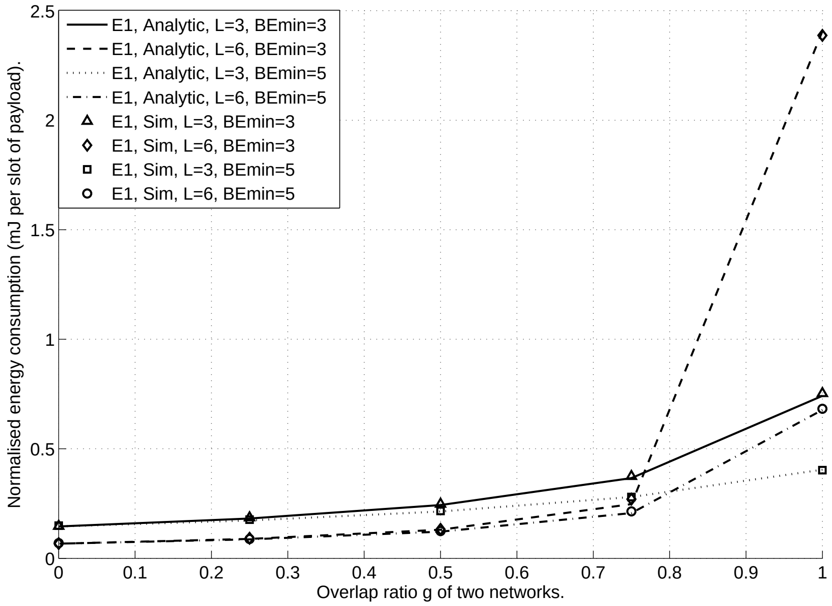

Figure 5.10: Energy consumption E_1 for Scenario II. The number of sensor devices in NET2 is fixed to 5. The $BEmin$ of NET2 is set to 3 and 5, respectively. The initial backoff window is set to $W_0 = 2^3$ and $W_0 = 2^5$. $L = 3$, $L = 6$ slots and $SO = 5$ for each network. The number of sensor devices in NET1 is $N_1 = 10$.

increase of the energy consumption due to high collision rate. With an increased number of sensor devices in NET1, energy consumption E_1 is observed to increase dramatically and it is hard to effectively support WSN applications. For a larger backoff window in NET2 ($BEmin = 5$), the energy consumption E_1 drops largely, as more data messages can be successfully transmitted without collision. The affection of overlap ratio in energy consumption is even larger.

With a lower overlap ratio g, the energy consumption can be significantly improved due to the essential interference caused by uncoordinated coexistence problem is largely reduced. Compared to the measure of increasing random backoff window or active time, careful deployment with low overlap ratio is believed to be a more effective way to improve the system performance in terms of both throughput and energy consumption.

5.4 Conclusion

This chapter extended the previous work on uncoordinated coexistence problem presented in Chapter 4 to analysis the performance of 802.15.4 networks working in sleep mode with uncoordinated deployment. Firstly, two representative scenarios with/without hidden terminals were addressed with communication range being fully overlapped. To understand how sleep mode may affect the performance of 802.15.4 networks with uncoordinated coexistence problem, an analytical model was proposed for these two scenarios. From the analytic model, it is observed that sensor nodes experience a poor communication performance in terms of throughput and energy consumption in the deployment of coexisting networks.

Secondly, a simulator based on Matlab was developped to further analysis and verify the proposed analytic model. Through analytical and simulation results, it was observed that with proper MAC parameter setting, reducing sleep time and overlap ratio can improve the overall network performance. Increasing backoff windows could reduce the collision probability but the cost of long transmission delays may be unacceptable for most WSN applications. With the approach of reducing sleep time, the energy consumption increases due to longer active periods, which may not be acceptable for some energy constrained applications. On the other hand, reducing overlap ratio in the channel access period of networks can largely improve the throughput with little cost of energy consumption.

Finally, the above analysis showed that the 802.15.4 based WSNs should be deployed carefully in a crowded wireless environment to avoid overlap in channel access period, which can largely reduce the the number of potential hidden terminals. The proposed analytical model can be used to predict the optimal deployment setting.

Chapter 6

Uncoordinated Coexistence Problem with Partially Overlapped Communication Range in IEEE 802.15.4 WSNs

In last two chapters, the effectiveness of the non-sleep and sleep mode of 802.15.4 networks supporting WSN applications with fully overlapped communication range are investigated. These two networks are located in the same communication coverage, and all the sensors from one network could interfere the other network's performance. Significant performance losses have been observed via theoretic analysis and simulations. When multiple 802.15.4 WSNs are deployed closely and independently, the communication coverages of the networks may not overlap fully. More practically there may be a partial overlap in the communication range of the networks. Only few sensor devices from one network could be in the other's communication range, which may produce interference to affect the transmissions in the networks. Moreover, radio signal reception is always affected by channel bit errors and frame corruptions, especially in harsh wireless environments. As WSNs are normally characterised with low transmission power, without considering the noise from the wireless medium, the conclusions obtained with only considering frame collisions due to random channel access could be misleading.

In this chapter the Markov chain based analytical model developed in previous chapters is extended to model the impacts of frame corruptions caused by channel quality, frame collisions due to random channel access and hidden terminals resulting from uncoordinated coexistence on the multiple coexisting WSNs. Instead of possible interference from all the devices overlapped networks, only a few sensor devices may become hidden terminals. Under this more realistic assumption, a discrete event simulator is also developed and simulations have been run to investigate the performance and verify the proposed model. Both the extended analytical model and simulator are used to understand how the frame collisions and corruptions may jointly affect network performance.

From the results obtained, it is observed again that the hidden devices can lead to a significant system performance drop and reduced network lifetime, even with only partially overlapped communication range. For a network with its sleep mode activated, two simple approaches which may be used to enhance network performance including increasing the duty-cycle in the sleep mode and reducing the overlap ratio in the channel access period, respectively. Based on the analytical and simulation analysis, it is shown that the latter approach can be more effective in mitigating the partial coverage overlapping problem with a small energy cost.

The rest of this chapter is organised as follows. Literature review is presented in section 6.1. Section 6.2 presents the extended analytic model with realistic assumptions. Numerical results and analysis are presented in section 6.3, followed by the conclusions in section 6.4.

6.1 Related Work

Effective performance evaluation is critical for network planning and optimisation purposes, especially for WSN applications with an increasing reliability and data rate requirements such as transportation and security using. Many analytical models and simulation based evaluation have been proposed to capture the throughput and energy consumption performance of single 802.15.4 network with either saturated or unsaturated traffic [74] [84] [79]. The limited scalability of the 802.15.4 MAC was pointed out by Misic *et al.* [85] and Yedavalli *et al.* [86] where the performance in terms of throughput and energy consumption are studied. It was shown showed that 802.15.4 MAC performed poorly when the number of contending devices was high. Both Pollin *et al.* [87] and Singh *et al.* [88] considered a star network topology and analysed the MAC protocol performance under assumption of saturated traffic conditions. They found out that a large fraction of packets was dropped during the channel access, and the dropping probability increases with the number of sensor devices. Park *et al.* [89] and Jianhua *et al.* [90] developed accurate analytical modes for 802.15.4 MAC protocol in the beacon-enabled mode for star network topology. In addition, the performance analysis was mainly used to validate the accuracy of the proposed model. However, in the most of the existing models frame corruptions due to poor channel conditions and bit errors have not been considered. Without considering the wireless environment condition, the conclusions obtained with only random channel access collisions could be misleading. A initial study of WSNs with channel bit errors and frame corruptions to analyse the throughput performance of single IEEE 802.15.4 network was presented in [91]. The problem of uncoordinated coexisting 802.15.4 networks was analysed in [92] with fully overlapped assumption, but the performance with channel bit error was not studied.

6.2 System Model

Figure 6.1 shows the scenario of two 802.15.4 networks are deployed closely with partially overlapped communication range and same frequency channel. These two networks are labelled by NET1 and NET2, with N_1 and N_2 denoting the numbers of sensor devices in addition to one coordinator, respectively. NET1 is tagged as the concerned network and the number of hidden devices from NET2 is $N_{h,2}$. Due to the distance between sensor devices from NET1 and NET2 is relatively far, CCAs of each sensor device are only affected by transmissions from its own network. The coordinator of NET1 can detect the transmissions not only from all sensor devices in its own network but also transmissions of hidden devices from NET2 in its communication range. Under this assumption, the transmissions of NET1 may be collided by the transmitted data from hidden devices in the same time of NET2.

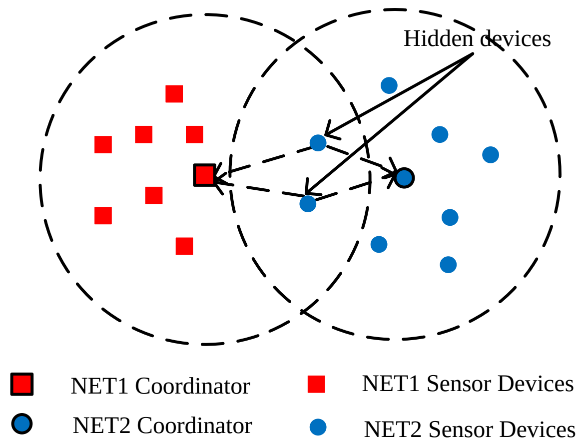

Figure 6.1: Communication range of two networks are partially overlapped with hidden devices.

With the same assumption in last chapter, single hop star network topology is considered. Both of NET1 and NET2 are operating in the beacon-enabled mode with saturate uplink traffic without ACK needed. Assume that the beacons from each network can be correctly received by all sensor devices belonging to that network. Sleep mode is enabled with different duty-cycles decided by SOs. Different overlap ratios g can be generated as shown in Figure.5.1. Each data frame has L_d slots of data payload and L slots to transmit over the channel. In the remaining of the chapter, "throughput" and "energy consumption" are representing "normalised throughput" and "normalised energy consumption" defined in chapter 3 for simplicity.

6.2.1 Frame Corruption Probability

With the low power feature in most WSN applications and the unpredicted wireless environment, the channel quality can be a significant factor to the 802.15.4 network performance. It is very likely that the channel quality is poor due to harsh conditions and high frame corruption probability. Assume the physical layer of each network to be at 2.4 GHz with the offset quadrature phase shift keying (O-QPSK) modulation [66]. Let P_{rx} and P_{no} be the signal power and noise power at the 802.15.4 receiver respectively. The other interference from the crowded wireless channel can be simply regarded as interference power P_{int} at the 802.15.4 receiver. In [93], the performance of 802.15.4 network under the interference of other wireless networks is evaluated using an analytic model for the imperfect wireless channel conditions. The packet error rate (PER) is evaluated, where the PER is obtained from the bit error rate (BER) and the BER is obtained from the signal to interference and noise rate (SINR). The SINR and the BER (denoted by p_b) of sensor nodes can be calculated by [93]:

$$SINR = 10log_{10}\frac{P_{rx}}{P_{no} + P_{int}} + P_{gain}. \tag{6.1}$$

and

$$p_b = Q(\sqrt{2\alpha SINR}). \tag{6.2}$$

where P_{gain} is processing gain in dB and $\alpha = 0.85$.

With O-QPSK modulation and data rate of 250 kbps, the symbol rate is 62500 symbols per second. As each slot takes 20 symbols, each data frame L slots has $4 \times 20 \times L = 80L$ bits. With BER p_b and frame length (L slots) the frame corruption probability (denoted by p_{corr}) can be calculated by the following formula:

$$p_{corr} = 1 - (1 - p_b)^{80L}. \tag{6.3}$$

After the calculation of frame corruption probability due to poor channel conditions, the system performance of NET1 in the CAP can be analysed separately with two parts according to the overlap ratio g: non-overlapped and overlapped parts as the same in last chapter. For the non-overlapped part, the system performance of two networks can be analysed using the analytical model (Equation 5.1) in the last chapter due to the fact that there is only frame corruption added with channel error. The throughput of non-overlapped part S_1^f for NET1 can be calculated by

$$S_1^f = N_1 L_{1,d} \sum_{i=0}^{m} \sum_{k=1}^{W_i} C_{1,i,k-1}(1 - p_{1,k-1})(1 - p_{1,k})(1 - p_{corr}). \tag{6.4}$$

6.2.2 Frame Collision Probability

In the overlapped part of CAPs, the channel access is not affected by channel activities from hidden devices. The only impact of hidden devices on the transmissions in NET1 is the outcomes of frame reception. If a frame transmitted from the tagged sensor device to the coordinator in NET1 does not collide with the frames from the other devices in its own network, it is still subject to collisions with frames from hidden devices of NET2. An illustration of the uncoordinated collisions is shown in Figure 6.2. The problem that remains to be solved is the calculation of frame collision probability, which depends on the transmission probability of hidden devices.

The probability of having exactly k idle slots before one transmission in NET2 can

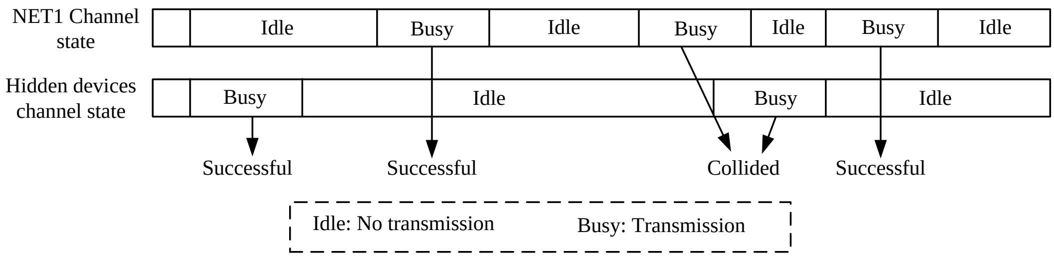

Figure 6.2: Example of collision of frames due to hidden devices from overlapping area.

be derived in the same way in chapter 4, which is expressed by $p_{2,idle,k} = 0$ (subscript 2 means NET2) for $k \in [0, 1]$, and for $k \in [2, W_x + 1]$:

$$p_{2,idle,k} = \begin{cases} 1 - (1 - \tau_{2,k})^{N_2}, & k = 2; \\ (1 - (1 - \tau_{2,k})^{N_2}) \prod_{z=2}^{k-1} (1 - \tau_{2,z})^{N_2}, & k \in [3, W_x + 1]. \end{cases} \tag{6.5}$$

The number of hidden devices in NET2 which affect the performance of NET1 is $N_{h,2}$, where $0 \leq N_{h,2} \leq N_2$. $N_{h,2} = 0$ means there is no hidden device within the NET1 communication range. For the case of having k idle slots before one transmission in NET2, there is a probability $p_{2,hidle,k}$ (subscript 2 means NET2) that at least one hidden device in NET2 transmits immediately after this k idle slots. For example, in case of $k = 2$, we have

$$p_{2,hidle,2} = \sum_{u=1}^{N_2} (C_{N_2}^u - C_{N_2 - N_{h,2}}^u) \tau_{2,2}^u (1 - \tau_{2,2})^{N_2 - u}, \tag{6.6}$$

where $u \in [1, N_2]$ is the number of sensor devices transmitting in the same time slot immediately after k idle slots.

When $u > N_2 - N_{h,2}$, the expression $C_{N_2 - N_{h,2}}^u$ is not defined. We set an intermediate variable $N_{2,free,h}$ (subscript 2 means NET2) instead of $C_{N_2 - N_{h,2}}^u$, and the definition of

$N_{2,free,h}$ is

$$N_{2,free,h} = \begin{cases} 0, & u > N_2 - N_{h,2}; \\ C^u_{N_2 - N_{h,2}}, & u \leq N_2 - N_{h,2}. \end{cases} \tag{6.7}$$

Now, for any k idle slots before one transmission in NET2, we can get the probabilities of at least one hidden device transmitting immediately after k idle slots as

$$p_{2,hidle,k} = \begin{cases} \sum\limits_{u=1}^{N_2} (C^u_{N_2} - N_{2,free,h}) \tau^u_{2,k} (1 - \tau_{2,k})^{N_2 - u}, & k = 2; \\ \sum\limits_{u=1}^{N_2} (C^u_{N_2} - N_{2,free,h}) \tau^u_{2,k} (1 - \tau_{2,k})^{N_2 - u} \prod\limits_{z=2}^{k-1} (1 - \tau_{2,z})^{N_2}, & k \in [3, W_x + 1]. \end{cases} \tag{6.8}$$

For each transmission from hidden devices in NET2 following exactly k idle slots, we can define another probability $p_{2,suc,k}$ (subscript 2 means NET2) which means that an independent transmission from NET1 is not collided. It is noted that the probability $p_{2,suc,k}$ is larger than zero only if k is larger or equal to the data length L_1 in NET1. An illustration of the collision of frames from NET1 and hidden devices from NET2 is presented in Figure 6.3. The probability $p_{2,suc,k}$ for $k \in [2, W_x + 1]$ could be calculated by

$$p_{2,suc,k} = \begin{cases} 0, & k < L_1; \\ \frac{k - L_1 + 1}{k}, & k \geq L_1. \end{cases} \tag{6.9}$$

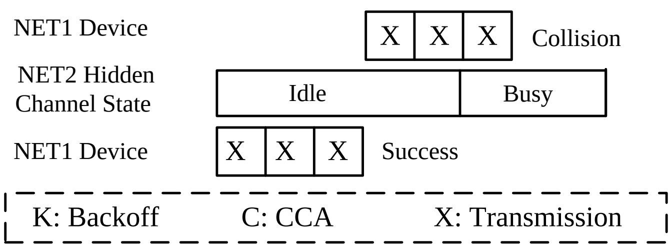

Figure 6.3: Illustration of transmissions from NET1 with/without collisions with frames of hidden devices from NET2.

The average probability $p_{2,hsuc,avg}$ (subscript 2 means NET2) that a transmission from NET1 does not collide with transmissions of hidden devices from NET2 can be calculated by

$$p_{2,hsuc,avg} = \frac{\sum_{k=2}^{W_x+1} k\, p_{2,hidle,k}\, p_{2,suc,k}}{\sum_{k=2}^{W_x+1} (k+L_2)\, p_{2,idle,k}} + \frac{\sum_{k=2}^{W_x+1} (k+L_2)(p_{2,idle,k} - p_{2,hidle,k})}{\sum_{k=2}^{W_x+1} (k+L_2)\, p_{2,idle,k}}, \tag{6.10}$$

where L_2 is the transmission data length in NET2.

The throughput of overlapped part in CAPs S_1^o in NET1 can be computed by

$$S_1^o = S_1^f p_{2,hsuc,avg}. \tag{6.11}$$

Finally, the throughput S_1 of NET1 with different overlap ratios and different duty-cycles can be derived as

$$S_1 = 2^{SO_1 - BO_1}\Big[(1-g)S_1^f + gS_1^o\Big]. \tag{6.12}$$

After deriving the throughput, the energy consumption of NET1 is obtained by

$$\eta_1 = \frac{2^{SO_1 - BO_1} N_1}{S_1} \sum_{i=0}^{m} \left\{ \sum_{l=2}^{L_1} E_c B_{1,i,0,l} + \sum_{k=0}^{W_i+1} \Big[E_c(K_{1,i,0,k} + C_{1,i,k}) + L_1 E_t X_{1,i,k})\Big] \right\}. \tag{6.13}$$

6.3 Numerical Results and Evaluation

We have implemented a discrete event simulator with IEEE 802.15.4 PHY at 2.4 GHz frequency band which gives 250 kbps of data rate. BO for each network is set to 6, which means the length of each BI is fixed to 3072 slots (about one second). Then, the length of CAP of each BI is only decided by SOs. There is no inactive portion in BIs when SO is set to six, implying that the networks are working in the non-sleep mode. Typical results are presented with default MAC parameters for both NET1 and NET2, i.e., $W_0 = 2^3$, $W_x = 2^5$, and $m = 4$. The number of hidden devices from NET2 varies to investigate the impact of different overlapped communication range. The overhead of MAC and PHY headers L_h for both networks is 1.5 slots in total, and the data payload length with header is $L = L_d + L_h$. Each simulation result presented in the figures was obtained from the average of 20 simulations with 10^6 data frames were transmitted. In the figures below, results with and without frame corruption are presented. For the frame corruption case the SINR is set to 6 dB.

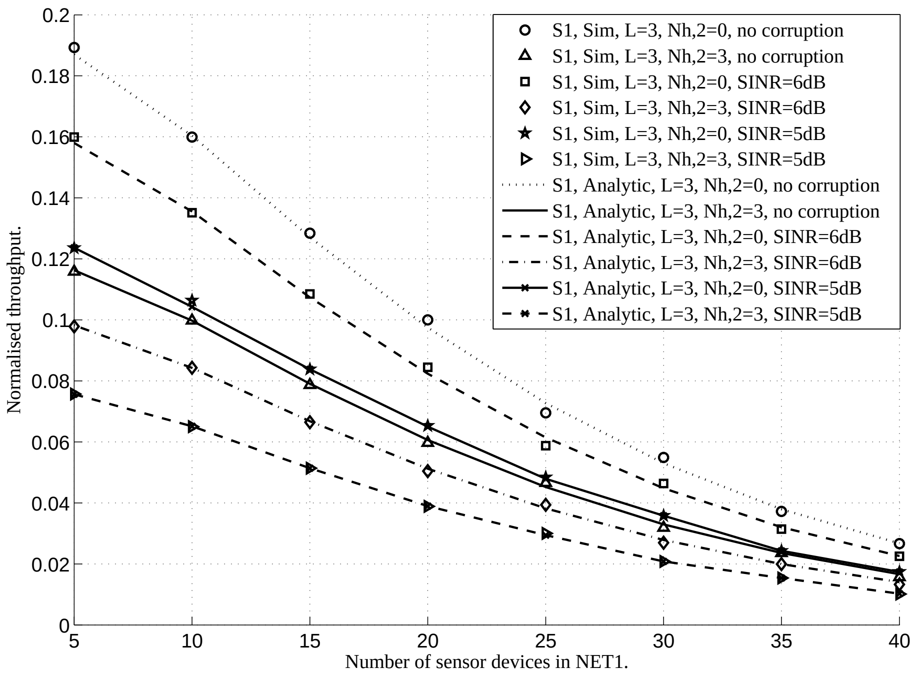

Figure 6.4: Throughput S_1 with no corruption and different SINRs. The number of sensor devices in NET2 is fixed 10. The number of hidden devices is $N_{h,2} = 0, 3$ respectively. $L = 3$ slots and $g = 1$, and $SO = 6$ for each network.

Figure 6.4 shows the throughput of NET1 as a function of the number of sensor devices in NET1 when a 10 sensor devices NET2 is deployed closely with 3 hidden devices in the NET1's communication range. The performance without hidden devices is also presented for comparison. $SO = 6$ and $g = 1$ correspond to the situation that the two networks are working in non-sleep mode with CAPs fully overlapped. It is observed that the analytical model matches the simulation results accurately. Consider the case of 10 sensor devices in NET1. The throughput without frame corruption (which means the SINR is sufficiently high) and hidden devices is 0.16 for $L = 3$, which means at most 160 data messages could be successfully delivered in one second in total for NET1. Each sensor device could deliver at most 16 data messages in one second with message size $L = 3$. When hidden devices is presented, the throughput of NET1 drops to about 0.1 with 3 hidden devices, which means about 100 data messages could be successfully transmitted in one second for NET1 in total. Each sensor device could deliver about 10 data messages in one second with message size $L = 3$. However, when there are frame corruptions, each sensor device could deliver just about 8 data message in one second. These performance could be still acceptable for many WSN applications without strict energy constraint due to the non-sleep mode is used. Compared to the results in chapter 4, the performance is much better, but the loss is still high. With an increasing number of sensor devices in NET1, the throughput becomes more serious due to collisions from both channel access and hidden devices. Most applications may not be effectively supported by the 802.15.4 networks at this circumstance. The number of sensor devices of supporting certain QoS requirement need to be carefully designed when the service area is overlapped with other networks in a harsh environment.

The different number of hidden devices is also considered. Networks are also working in non-sleep mode with channel access periods fully overlapped. We neglect the frame corruption here to focus the interference from hidden devices. The results in Figure 6.5 clearly point out that the more hidden devices the poorer performance that 802.15.4 MAC protocol can achieve. The number of sensor devices in NET1 is set to 10 and varied the number of sensor devices in NET2 as 10 and 20 respectively. It is observed that the throughput of NET1 drops faster with 10 sensor devices in NET2 compared to 20 sensor devices in NET2. This can be explained by the fact that with a larger number

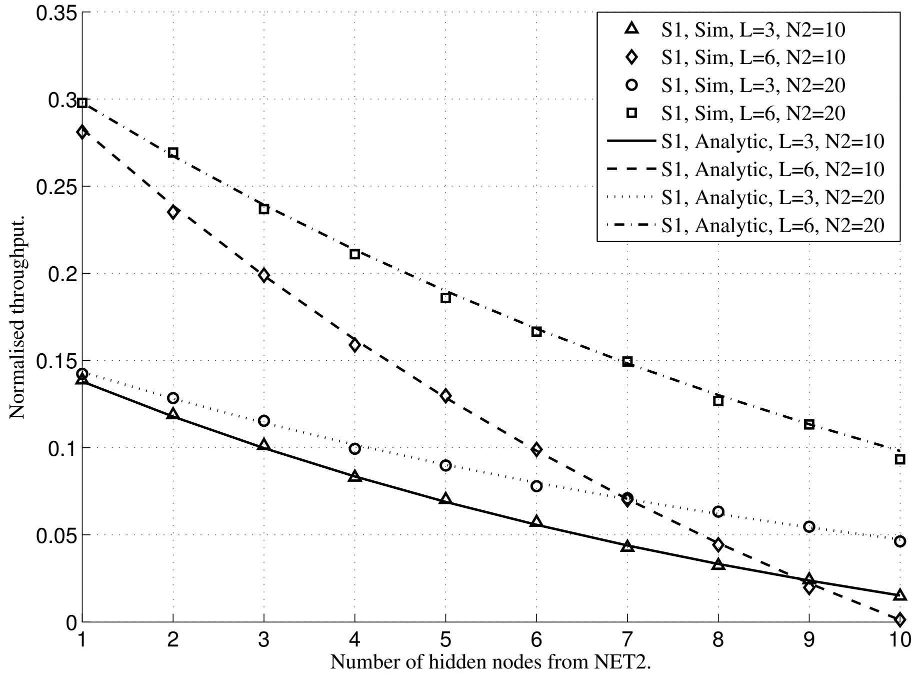

Figure 6.5: Throughput S_1 with no frame corruption. The number of sensor devices in NET1 is fixed 10. $L = 3$, $L = 6$ slots and $g = 1$, and $SO = 6$ for each network. The number of sensor devices in NET2 are $N_2 = 10$ and $N_2 = 20$ respectively.

of sensor devices in NET2, the transmission probability of the hidden devices will be smaller. With larger frame length ($L = 6$), the throughput of NET1 drops further then the one with $L = 3$. In the scenario of 10 sensor devices in NET2, the throughput of NET1 with $L = 6$ decreases lower than the one with $L = 3$ when the two networks are nearly fully overlapped. The results presented above prove that the impact of hidden devices due to uncoordinated coexisting problem can become much more serious with an increasing number of hidden devices. The performance of transmissions with larger frame length could have more severe impact than small frame length transmissions, especially for networks with a relatively small number of sensor devices.

Figure 6.6 presents the throughput of NET1 with different SOs without frame corruptions. We consider 3 and 5 hidden devices as examples and CAPs are fully over-

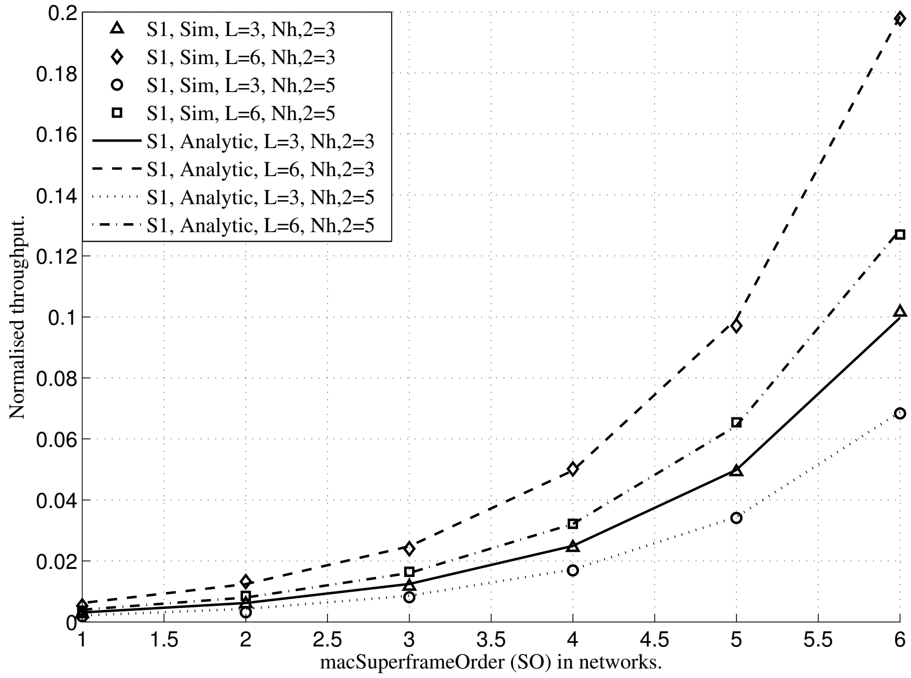

Figure 6.6: Throughput S_1 of NET1 with no corruption. The number of sensor devices in NET1 and NET2 are both fixed 10. The number of hidden devices is 3 and 5, respectively. $L = 3$, $L = 6$ slots and $g = 1$ for each network.

lapped of two networks ($g = 1$). With no surprise in the scenario of saturate traffic, higher duty-cycle could largely improve the system throughput. It is observed that the throughput can be improved by increasing the duty-cycle and the energy consumption is also increased. The frame corruption and collision probabilities are not reduced, it is just simply increases more time for devices to retransmit frames. If the interference of uncoordinated coexistence problem is temporary, some WSN applications could just turn the non-sleep mode on for a short period to gain extra performance with sacrificing reasonable energy.

The impact of different overlap ratios is also investigated in Figure 6.7, while leaving the number of sensor devices $N_1 = N_2 = 10$ and $SO = 5$ for two networks unchanged. The performance with frame corruption has been obtained but not presented here due

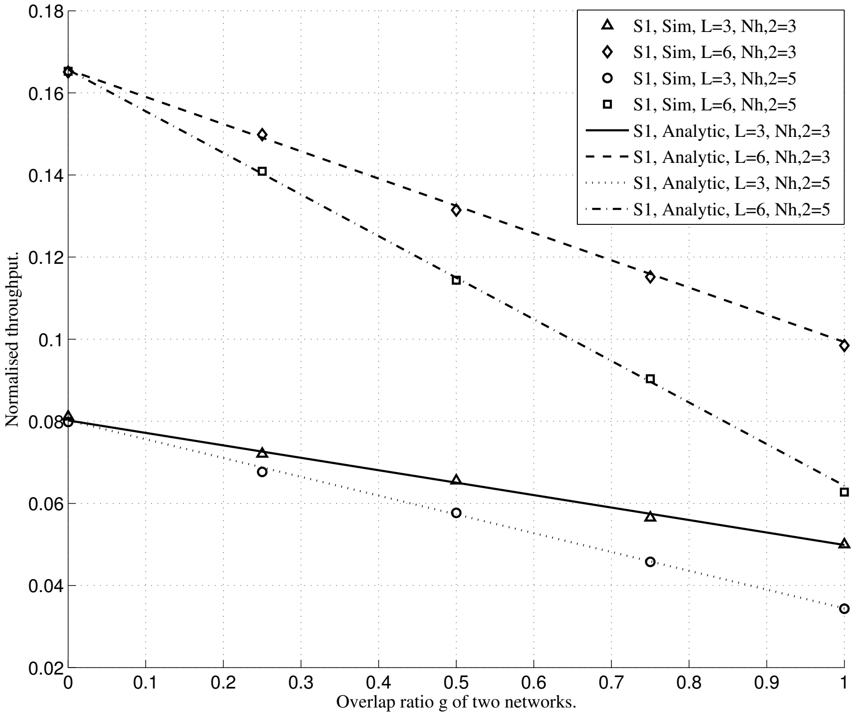

Figure 6.7: Throughput S_1 with no corruption. The number of sensor devices in NET1 and NET2 are both fixed 10. The number of hidden devices is 3 and 5, respectively. $L = 3$, $L = 6$ slots and $SO = 5$ for each network.

to the concern on the readability of the figure. It is observed that, with an increasing overlap ratio from 0 to 1, which means from no interference to fully overlapped in CAPs among hidden devices and sensor devices in NET1, the throughput drops linearly. With large frame length ($L = 6$), the throughput drops further than small frame length ($L = 3$), which means that the networks with larger frame length are more vulnerable to hidden devices. Consider the case of $L = 6$ with $N_{h,2} = 3$. When $g = 0$, the throughput of NET1 is at most 0.165 which means at most 82.5 data messages could be successfully transmitted in one second and each device could deliver at most 8.25 data messages per second. With an increasing overlap ratio to 1, the throughput of NET1 drops to about 0.1 and 0.06 for $H_{h,2} = 3$ and 5 respectively, which means only about 50 and 30 data messages could be successfully transmitted in one second and each device could deliver about 5 and 3 data messages in one second respectively. It is observed that, reducing the overlap ratio can largely improve the performance without the cost of higher energy consumption. More important, it actually reduces the collision probability of frame transmissions from overlapping networks.

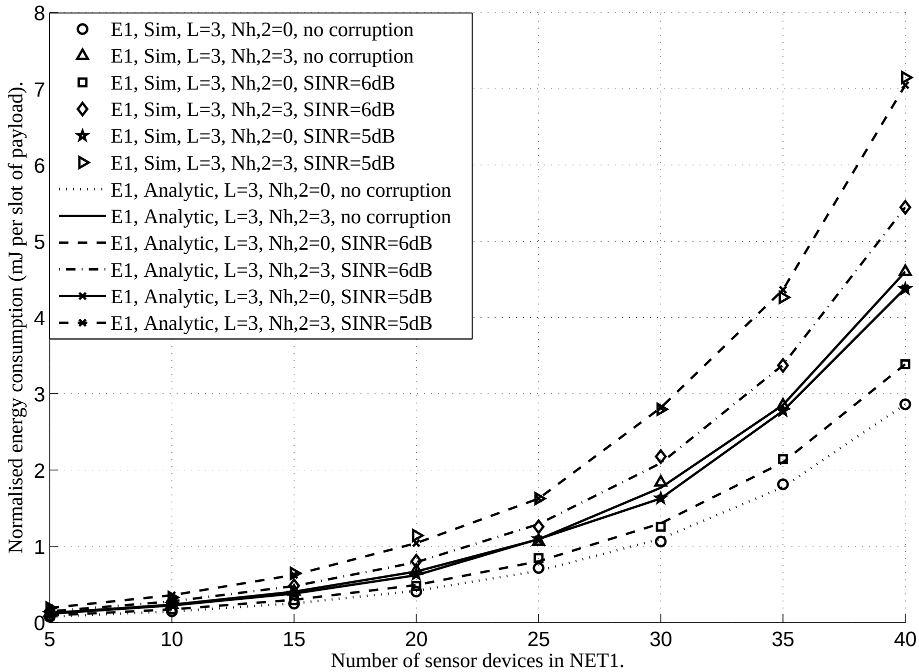

Figure 6.8: Energy consumption E_1 with no corruption and different SINRs. The number of sensor devices in NET2 is fixed 10. The number of hidden devices is $N_{h,2} = 0, 3$ respectively. $L = 3$ slots and $g = 1$, and $SO = 6$ for each network.

Finally, in Figure 6.8 and Figure 6.9 the energy efficiency obtained from both analytical model and simulations is compared. As expected, the analytical results agree with simulation results very well and can predict the energy efficiency accurately. It is observed from Figure 6.8 that the energy consumption increases dramatically with an increasing number of sensor devices and hidden devices. Consider the case of 30 devices in NET1. Without hidden devices, the energy consumption is about 1 mJ per slot of

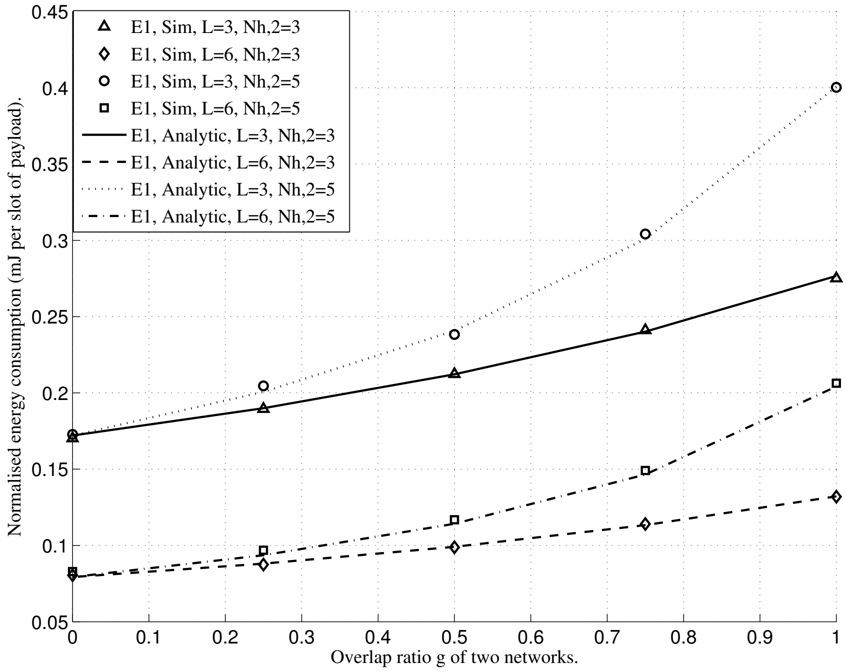

Figure 6.9: Energy consumption E_1 with SINR=6. The number of sensor devices in NET1 and NET2 are both fixed 10. The number of hidden devices is 3 and 5 respectively. $L = 3$, $L = 6$ slots and $SO = 5$ for each network.

data payload when there is no frame corruption. It increases to 1.9 mJ and 2.1 mJ per slot of data payload with 3 hidden devices and SINR of 6dB, respectively. Apparently, even partial overlap in uncoordinated coexistence networks, the energy consumption still significantly increased. It is noticed that high duty-cycle in sleep mode will not affect the normalised energy consumption, which means the energy of transmitting each slot of payload is not affected by different duty-cycle. With reducing sleep time by high duty-cycle, the total energy consumption in time is increased as more slots are used for channel access in each superframe.

Figure 6.9 shows the relationship between energy consumption and different overlap ratios. The number of sensor devices in NET1 and NET2 are both fixed to 10 and the number of hidden devices is 3 and 5, respectively. SINR is set to 6dB for both networks.

With an increasing overlap ratio, the energy consumption increases dramatically. Consider the case of 5 hidden devices with $L = 6$. The energy consumption increases from 0.15 mJ to 0.34 mJ per slot of data payload with an increasing overlap ratio from 0 to 1, which is more than doubled. It is observed that reducing the overlap ratio is the key of efficiently solving uncoordinated coexistence problem. It is very important that WSNs must be carefully deployed to avoid overlap with other networks in communication range or channel access time. For some applications requiring high reliability, adaptive sleep management which can reduce the overlap ratio automatically and dynamically need to be investigated.

6.4 Conclusion

From the last two chapters, it was observed that the 802.15.4 WSNs could experience a low communication reliability due to hidden terminals. In this chapter, the uncoordinated coexistence problem with two 802.15.4 networks partially overlapped in communication range was investigated. Channel error due to harsh wireless environment was also taken into account.

An analytical model was proposed to understand the impact of hidden terminals with different duty-cycles and overlap ratios. The channel error could also be analysed in this proposed model. Simulations demonstrated the high accuracy of this analytic model. It was found that compared to full overlap circumstance, the performance of 802.15.4 networks in terms of throughput and energy consumption is better but still quite low due to high collision probability. The QoS requirements for some applications are unlikely to be satisfied with the degraded network performance when frame corruptions due to channel error and frame collisions causing by hidden terminals are both present.

With the proposed analytic model and simulations, it was observed that the problem is essentially due to the 802.15.4 MAC for channel access, which is not able to efficiently handle hidden terminals and the sleep mode is not adaptive enough to avoid the collisions of transmissions from other networks. As most of WSN applications adopt low duty-cycle in real environments, reducing the sleep time by increasing the active period could improve the throughput largely, but it may also increase the overall energy consumption. Simply increasing duty-cycle does not solve the collision problem essentially, but only increasing the power-on time and it may not be suitable for some applications with strict energy constraint. Reducing the overlap ratio is an another method to improve the system performance, which can be achieved by adaptive sleep mechanisms such as changing the superframe structures dynamically to reduce the overlap in channel access period when hidden terminals is present. The investigation of this adaptive sleep mode for 802.15.4 networks which is our future work. The proposed analytic mode and simulator can be used to predict the optimal deployment setting in a crowded service area, which help to mitigate the interference from uncoordinated coexistence problem.

Chapter 7

Conclusion and Future Work

IEEE 802.15.4 standard has been developed with targets to low-rate and low-power wireless networking, which typically fits the requirements of WSNs. Existing WSN research tends to focus on protocols and algorithms for single network with particular applications. However, many low complexity WSNs which are deployed in uncoordinated manner may overlap in service areas, therefore severe performance issues may arise.

This thesis presents a systematic study of the performance and network reliability issues of IEEE 802.15.4 WSNs supporting WSN applications, especially when such uncoordinated networks are deployed with communication range overlapping problem. Both simulation and analytical model tools are proposed. It is observed that most QoS requirements of WSNs could be satisfied by IEEE 802.15.4 standard, but significant performance losses and low communication reliability are present due to the hidden terminals created by overlapped service range. Through analytical and simulation results, it is found that with proper MAC parameter setting, reducing sleep time and overlap ratio can improve the overall system performance and reducing overlap ratio in the channel access period of networks can largely improve the throughput with little cost of energy consumption. The major research activities and outcomes are summarised in this chapter. A proposal of future work is also presented.

7.1 Conclusion and summary

In this section the research work carried out with this thesis and the main achievements are briefly summarised. In chapter 2, the background knowledge of wireless-based technologies and standards were introduced. Firstly, an overview of WSNs and relevant wireless network technologies were presented. Specifically, four similar wireless technologies with low power consumption were compared. Active RFID based networks with independent power source can find a wide range of applications similar to those that can be supported by WSNs, but they are still less functional in many cases compared with WSN technologies, such as on the flexibility of forming networks, data communication capabilities and approaches to ensure real-time and reliable data transfer. Wireless Body Area Network (WBAN) is used primarily for healthcare area, in which the sensor devices are especially designed for collecting information around human body. So WBAN requires special designs for the supporting protocols and algorithms. Wireless Machine-to-Machine (M2M) technology allows machine devices communicate directly with each other through wireless systems with little or no human intervention. The communication range could be much larger than that of WSNs by using wireless wide area networking technologies such as GSM and 3G. For the wireless M2M networks energy consumption is usually not the first priority, which is different from that in WSNs. Compared to these wireless-based technologies, WSNs are mainly designed for applications requiring very low power consumption and medium communication ranges, such as logistics, security, environmental monitoring, building automation, and transportation, and so on. Many international standards have been proposed for wireless networks in both PHY/MAC layer and higher layers. IEEE 802.22 and 802.16 are developed mainly for long distance broadband access. The energy consumption of IEEE 802.11 can not be satisfied by tiny, cheap sensor devices, and the high data rate is wasteful for most sensing tasks. The IEEE 802.15 family of standards are aiming short range, low power communications. Among them only the IEEE 802.15.4 standard is targeted at very long battery life and very low cost. In the higher layers, using 802.15.4 as the underlying protocol is very popular. For example Zigbee is using 802.15.4 both PHY and MAC layers. The constraints of 802.15.4 based WSN sensor devices on battery power, bandwidth data rate and self-management pose many research and development challenges on the design and optimisation of network protocols and algorithms.

In chapter 3, the effectiveness of 802.15.4 networks supporting WSN applications was investigated in both analytical and simulation methods. The throughput and energy consumption of 802.15.4 networks with different parameter setting and circumstances were investigated. It was observed that the performance may not be sufficient to support WSN applications when the number of deployed sensor nodes is high. The problem is essentially due to the slotted CSMA-CA algorithm in 802.15.4 standard is not able to efficiently handle channel access contention when there are lots contending devices in the network. Sleep and ACK modes were also investigated to obtain comprehensive understanding of the capability of 802.15.4 technology. It was found that the sleep mode could largely reduce the energy consumption at price of throughput which can be used in low-rate and limited energy constraint applications such as smart buildings, agriculture tracking, entertainment using to achieve long batter life. ACK mode could effectively increase the communication reliability when a large number of sensor nodes is deployed. Transportation, security, and surveillance applications with high QoS requirements can benefit from this feature to obtain more reliable communication in a crowd network circumstance with low energy consumption. The accuracy of the proposed analytic model was proved by simulations. The optimal parameter setting (duty-cycle rate, the number of sensor nodes supporting certain QoS requirement, and ACK mode or not) can be predicted as an assistance of deployment of WSNs by using this proposed analytic model and simulator.

Chapter 4 presented the modelling and analysis of the uncoordinated coexistence problem when multiple 802.15.4 networks have fully overlapped service areas with non-sleep mode. An Markov chain analytic tool was used to model the behaviour of slotted CSMA-CA algorithm in IEEE 802.15.4 MAC protocol with uncoordinated coexistence problem. The accuracy of the proposed model is validated by Monte Carlo simulations. By using the analytical model, different circumstances with three representative scenarios were investigated to obtain the network performance in terms of throughput. It was observed that supporting reliable communication could be a big challenge even with small number of sensor nodes when interference occurs due to uncoordinated coexistence problem. The problem becomes more severe due to the potential hidden terminals from coexisting networks when transmissions can not efficiently detected by each other. With the increasing backoff time of 802.15.4 networks, the throughput could be improved at the cost of a long transmission delay. Many WSN applications are unlikely to be satisfied with the degraded performance.

After the evaluation of the non-sleep mode 802.15.4 networks performance with communication range fully overlapped, in chapter 5, the sleep mode based on duty-cycle is taken into consideration. To understand the impact of sleep mode of 802.15.4 networks with uncoordinated coexistence problem, an analytical model was proposed for two scenarios with present hidden terminals or not. Simulations demonstrated that the proposed analytic model could have very high accuracy. From the analytic model, it was observed that sensor devices could experience a low communication reliability in terms of throughput and energy consumption with uncoordinated coexistence problem and the performance drops even further with present hidden terminals. It was also observed that the slotted CSMA-CA contention-based protocol could not perform very well under the strong interference from the uncoordinated network operations. With the enabled sleep mode, it was found that high duty-cycle and reduced overlap ratio could effectively improve the overall network performance. Reducing the sleep time which means high duty-cycle could extend the active period for contention access, therefore the energy consumption would be increased due to longer active periods, which may not be acceptable for some energy constrained applications. On the other hand, reducing overlap ratio in the channel access period of networks could largely improve the throughput without sacrificing energy consumption. It was proved that the 802.15.4 based WSNs should be deployed carefully in a crowded wireless environment to avoid overlap in channel access period, which can largely reduce the hidden terminal risks.

In chapter 6, the uncoordinated coexistence problem with two 802.15.4 networks partially overlapped in service areas was investigated. Channel error due to interference from wireless transmission was also taken into account, which made the analysis more practical. An analytical model and discrete event simulator were proposed to understand the impact of hidden terminals with different duty-cycles and overlap ratios. Both throughput and energy consumption were analysed with different signal to interference and noise ratio (SINR), frame length, number of sensor devices, etc. It was found that compared to full overlap circumstance, the performance of 802.15.4 was better but still quite low even with few hidden terminals. Many WSN applications are unlikely to be satisfied with the degraded network performance when frame corruptions due to channel error and frame collisions causing by hidden terminals are both present. With the proposed analytic model, it was shown that the high collision probability is essentially caused by the contention-based 802.15.4 channel access scheme can not efficiently handle the hidden terminals from other networks. Reducing the overlap ratio is the promising solution to improve the system performance, which can be achieved by adaptive sleep mechanisms or careful deployment. The proposed analytic mode and simulator could be used to predict the optimal deployment setting in a crowded service area, which could help to mitigate the interference from uncoordinated coexistence problem.

7.2 Future Work

In this thesis the main problem that is studied on the performance of 802.15.4 networks supporting WSN application, especially when uncoordinated coexistence problem is present. Analytic and simulation tools have been developed to understand the problem and several approaches have been investigated to mitigate the adverse consequences of the problem.

In the future it is believed that there are several problems deserving further research, which are discussed as follows.

- Firstly, the analytic and simulation tools have been designed for the scenarios of two coexisting WSNs. The results obtained can be used to get insights into the potential issues that may be brought by the uncoordinated coexisting problem. Extension of the analytical and simulation which can analysis to more coexisting networks will help to provide a complete understanding of this problem.
- Secondly, while two approaches are investigated attempting to mitigate the problem of significant performance losses due to the possible hidden terminals from uncoordinated network deployment, in the future work it is interesting to explore alternative approaches to address the uncoordinated network deployment problem and develop practical protocols.
- Thirdly, the number of combinations of the system and protocol parameters can be increased for the network performance analysis and improvement. A limited number of configurations of system and protocol parameters have been considered in this thesis. It is believed that performance analysis with more configurations and scenarios can help improve the design of algorithms to address the uncoordinated coexistence problem.
- Fourthly, from the analytical model and simulation results, it is observed that the best MAC parameters setting will depend on the network operation conditions and QoS required by specific applications. It is interesting to design adaptive schemes which can dynamically tune the MAC parameters setting, especially the superframe structure, to reduce the overlap ratio of networks with communication range overlapped. Ideally, the adaptive schemes should enable collaboration among the multiple WSNs and information sharing among overlapped networks to mitigate hidden terminal problems.

- Fifthly, the major work carried out in this thesis is relying on analytic and simulation tools. It is interesting to test the 802.15.4 networks performance and how severe the uncoordinated coexistence problem can be through actual WSN testbed. The testbed can also be used to evaluate the effectiveness of proposed approaches mitigating the problem.

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