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On a Joint Physical Layer and Medium Access Control Sublayer Design for Efficient Wireless Sensor Networks and Applications

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by

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USE OF THESIS

Abstract

Wireless sensor networks (WSNs) are distributed networks comprising small sensing devices equipped with a processor, memory, power source, and often with the capability for short-range wireless communication. These networks are used in various applications, and have created interest in WSN research and commercial uses, including industrial, scientific, household, military, medical and environmental domains. These initiatives have also been stimulated by the finalisation of the IEEE 802.15.4 standard, which defines the medium access control (MAC) and physical layer (PHY) for low-rate wireless personal area networks (LR-WPAN).

Future applications may require large WSNs consisting of huge numbers of inexpensive wireless sensor nodes with limited resources (energy, bandwidth), operating in harsh environmental conditions. WSNs must perform reliably despite novel resource constraints including limited bandwidth, channel errors, and nodes that have limited operating energy. Improving resource utilisation and quality-of-service (QoS), in terms of reliable connectivity and energy efficiency, are major challenges in WSNs. Hence, the development of new WSN applications with severe resource constraints will require innovative solutions to overcome the above issues as well as improving the robustness of network components, and developing sustainable and cost effective implementation models.

The main purpose of this research is to investigate methods for improving the performance of WSNs to maintain reliable network connectivity, scalability and energy efficiency. The study focuses on the IEEE 802.15.4 MAC/PHY layers and the carrier sense multiple access with collision avoidance (CSMA/CA) based networks. First, transmission power control (TPC) is investigated in multi and single-hop WSNs using typical hardware platform parameters via simulation and numerical analysis. A novel approach to testing TPC at the physical layer is developed, and results show that contrary to what has been reported from previous studies, in multi-hop networks TPC does not save energy.

Next, the network initialization/self-configuration phase is addressed through investigation of the 802.15.4 MAC beacon interval setting and the number of associating nodes, in terms of association delay with the coordinator. The results raise doubt whether that the association energy consumption will outweigh the benefit of duty cycle power management for larger beacon intervals as the number of associating nodes increases.

The third main contribution of this thesis is a new cross layer (PHY-MAC) design to improve network energy efficiency, reliability and scalability by minimising packet collisions due to hidden nodes. This is undertaken in response to findings in this thesis on the IEEE 802.15.4 MAC performance in the presence of hidden nodes. Specifically, simulation results show that it is the random backoff exponent that is of paramount importance for resolving collisions and not the number of times the channel is sensed before transmitting. However, the random backoff is ineffective in the presence of hidden nodes. The proposed design uses a new algorithm to increase the sensing coverage area, and therefore greatly reduces the chance of packet collisions due to hidden nodes. Moreover, the design uses a new dynamic transmission power control (TPC) to further reduce energy consumption and interference. The above proposed changes can smoothly coexist with the legacy 802.15.4 CSMA/CA.

Finally, an improved two dimensional discrete time Markov chain model is proposed to capture the performance of the slotted 802.15.4 CSMA/CA. This model rectifies minor issues apparent in previous studies. The relationship derived for the successful transmission probability, throughput and average energy consumption, will provide better performance predictions. It will also offer greater insight into the strengths and weaknesses of the MAC operation, and possible enhancement opportunities.

Overall, the work presented in this thesis provides several significant insights into WSN performance improvements with both existing protocols and newly designed protocols. Finally, some of the numerous challenges for future research are described.

DECLARATION

I certify that this thesis does not, to the best of my knowledge and belief:

(i) incorporate without acknowledgement any material previously submitted for a degree or diploma in any institution of higher education;

(ii) contain any material previously published or written by another person except where due reference is made in the text; or

(iii) contain any defamatory material.

I also grant permission for the Library at Edith Cowan University to make duplicate copies of my thesis as required.

Signed ....

Dated ....

Dedication

All praises and complete gratitude are due to Allah for the blessings, guidance, wisdom and knowledge.

My late father, Professor Ramadhan Meghji

My mother, Hon Zakia Hamdani Meghji

To My partner, Raylene, my daughter, Ermina and my son Rayhaan.

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Publications by the Author Related to this Thesis

The following is the list of publications during the course of my candidature:

Conferences:

- **M. Meghji** and D. Habibi, "Transmission power control in multihop wireless sensor networks," in Proceedings of the third International Conference on Ubiquitous and Future Networks (ICUFN). IEEE, Dalian, China, 2011, pp. 25-30.
- **M. Meghji**, D. Habibi, C. Sacchi, B. Bellalta, A. Vinel, C. Schlegel, F. Granelli, and Y. Zhang, "Transmission Power Control in Single-Hop and Multi-hop Wireless Sensor Networks Multiple Access Communications," vol. 6886, Lecture Notes in Computer Science: Springer Berlin / Heidelberg, 2011, pp. 130-143.
- **M. Meghji**, D. Habibi and I. Ahmad, "Performance evaluation of 802.15.4 Medium Access Control during network association and synchronization for sensor networks," in Proceedings of the 4th International Conference on Ubiquitous and Future Networks (ICUFN). IEEE, Phuket, Thailand, 2012, pp. 27-33.
- **M. Meghji**, D. Habibi and I. Ahmad, “Practical Issues in Building an Embedded Sensor Network Application Using 802.15.4: Linking Hardware & MAC Protocol” in Proceedings of Australasian Telecommunication Networks and Applications Conference (ATNAC). IEEE, Brisbane, Australia, 2012

Journal paper to be published in Telecommunication Systems Journal:

- **M. Meghji** and D. Habibi, “Investigating transmission power control for wireless sensor networks based on 802.15.4 specifications,” Telecommunication Systems,

Journal and conference paper in progress:

- **M. Meghji** and D. Habibi "A Proposed Improvement and Performance Study of Slotted IEEE 802.15.4 MAC Clear Channel Assessment for Sensor Networks: Hidden & Non-hidden Nodes" to be submitted to the IEEE Transactions on Wireless Communications
- **M. Meghji** and D. Habibi "A New Simplified Analysis of Slotted CSMA/CA Using Markov Chain" to be submitted to the IEEE Conference Proceedings.

Contents

List of Tables

List of Figures

List of Algorithms

Chapter 1

Introduction

In the twentieth century and more recently, advances in electronics and telecommunication technologies such as wireless internet communication, Global Position Systems (GPS) and mobile communication played a significant role in human interaction. While wireless communication applications are widely used today, our work is motivated by an emerging field within wireless network technology known as the wireless sensor network (WSN).

Traditionally, sensor networks have been connected via wired networks that are considerably reliable. However, the establishment and maintenance costs for these networks comprise 33~70% of the entire system cost [1, 2, 3, 4]. For example, a wire fault in a wired sensor network may shut the whole network down and it may take time to identify and replace the faulty line. Furthermore, the nature of the application or sensing environment may make wired deployment and maintenance very difficult, if not impossible. In such cases wireless data transmission solves these practical problems, for example, monitoring a harsh environment, wildlife scene, or poisonous gases.

Wireless sensor networks (WSNs) are distributed networks of sensing devices used to cooperatively monitor physical conditions such as temperature, humidity, vibration, pollutants, and motion. A typical WSN device is composed of a sensing module, a radio communication module or transceiver, a data processing module, an analogy to digital converter (ADC) module and a power supply module (Figure 1.1). The sensing module would most likely have multiple sensors. The data processing module is a controller or microcontroller to process all relevant data and codes. Usually the memory is a component of the data processing module for storing programs and data. When an analogy sensor is used, the ADC module is used to convert sensor's analogy signal to a digital form for processing.

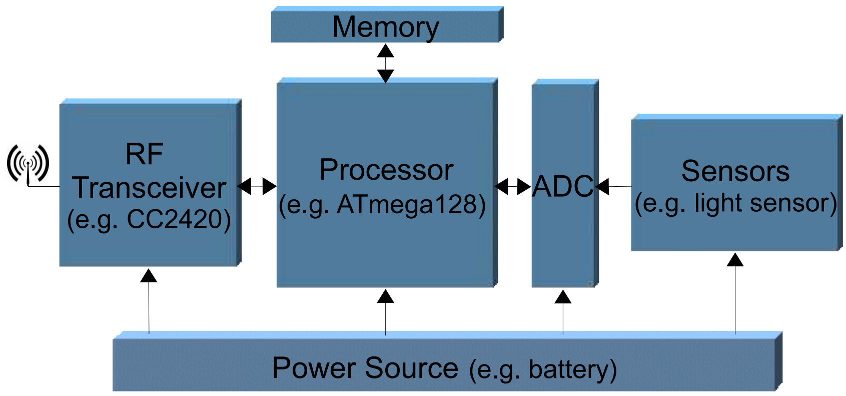


Figure 1.1: Sensor node hardware architecture

The power supply module may be a battery or power generator; however, often it will be quite limited.

WSNs have gained tremendous attention in research communities and commercial applications, partly due to ad-hoc wireless networks' ability to establish connectivity without the need for pre-existing infrastructure, and the fact that these networks are envisioned to support a wide range of embedded applications. The ability of networks to be established without pre-existing infrastructure provides a significant benefit in rapid sensor node deployment, and reduces the cost of establishing and maintaining networks.

1.1 System Architecture

WSN architecture consists of four main entities: sensor nodes, sink or sinks, monitored events, and users. The sensor nodes are capable of observing, measuring, and reacting to events and/or phenomena in a specified environment. The sink (base station or gateway) is the network node linking users to the monitored or sensed events, including via other other networks such as internet, satellite, and LAN. The monitored event or phenomenon that users collect or measure and analyse is detected by sensor nodes [5, 6]. Users, sink and sensor nodes may be stationary or mobile depending on the nature of the application and the network architecture. Figure 1.2 shows a typical WSN architecture. For example, in a simple sample and send application, sampled measurements are relayed to the base station or data sink; however, it is also possible for the in-networking processing operations such as aggregation, event detection, or actuation to be performed by individual sensor nodes in a network.

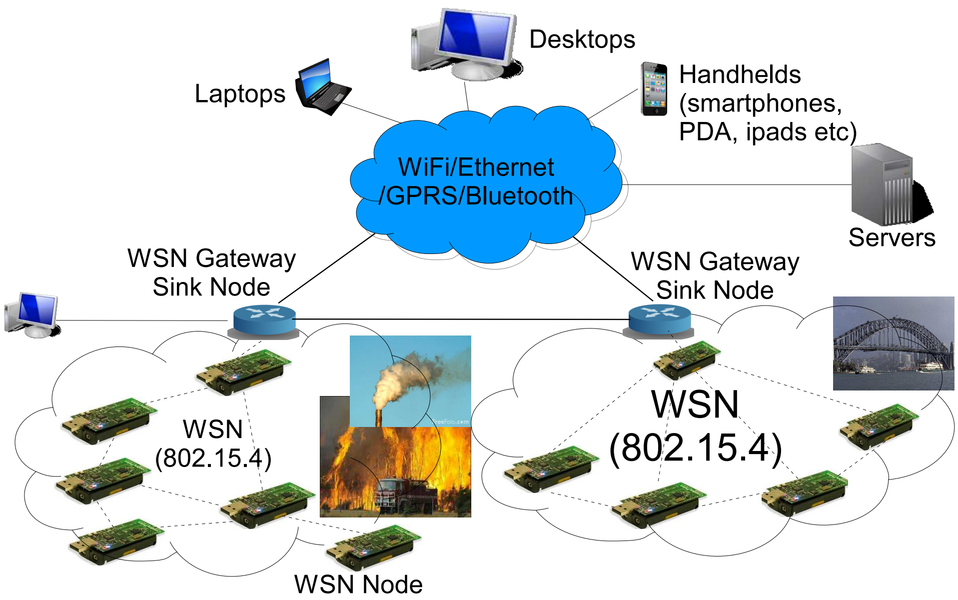


Figure 1.2: Typical WSN System Architecture

1.2 WPAN Architecture and Topology

The IEEE 802.15.4 standard describes the Physical layer (PHY) and medium access control (MAC) sublayer specifications for wireless communication particularly for low-rate, low-power consumption, wireless, personal area networks (LR-WPANs) [7]. The standard was designed with low complexity and cost wireless connectivity, making it a greatly valued technology for wireless sensor networks (WSNs). A personal area network (PAN) involves one coordinator which manages the whole network, but may involve one or more coordinators for a network's subset nodes.

In the IEEE 802.15.4 specifications, network devices can be classified as full-function (FFDs) or reduced function devices (RFDs), with the former having more processing ability and a full protocol stack with a complete set of MAC services. All PAN coordinators are FFDs that have the ability to communicate with other FFDs and RFDs. In contrast, a RFD is an end device operating with minimum implementation of the IEEE 802.15.4 protocol, i.e. contains only a subset of the protocol stack. A RFD cannot associate with more than one FFD concurrently.

Based on the IEEE 802.15.4 MAC sublayer protocol operational mode, wireless personal networks (WPANs) or wireless architecture in general can be classified into two distinct topologies, an infrastructure network topology, also known as a cellular network, and an ad-hoc network topology, also known as an infrastructure-less network. The former is a centralised network, which requires a coordinator to manage and police wireless nodes, while the latter is a decentralised network with no central management node. In the following subsection, the two wireless topologies are briefly outlined.

1.2.1 Infrastructure network

An infrastructure or cellular network topology consists of an area, surrounding a base station or access point (AP). The network is characterised by a star topology where wireless nodes do not exchange packets directly with each other, but through an access point or coordinator (Figure 1.3). The access point node will then forward the nodes' messages to the intended destination. In this case, a node (mobile or stationary) can only communicate in one hop with a base station or coordinator that is within its communication range. For a mobile node, communication is maintained with the base station while its moving, and if it goes out of base station range, it will try to connect with a new base station that is within its communication range and communicate through it. The process of moving from one base station to the other base station is referred to as handoff.

1.2.2 Infrastructure-less network

Infrastructure-less or ad-hoc networks are fully distributed wireless networks that do not use radios or communication in infrastructure mode. Instead, radios are used in a peer-to-peer mode, whereby a mobile node can directly send and receive packets from any other mobile node that is within its range. The peer-to-peer mode, forms a multi-hop wireless network in which a set of mobile nodes cooperatively maintains network connectivity. Each network node behaves as a router by taking part in discovery and maintenance of routes to other nodes in the network as shown in Figure 1.3. The 802.11 standard refers to nodes operating in this mode as an Independent Basic Service Set (IBSS)[8].

Since nodes are free to move arbitrarily, ad-hoc networks are characterised by a mesh multi-hop topology with typically no infrastructure support, unpredictability, randomness, and may consist of both bidirectional and unidirectional links.

Ad-hoc networks offer a very flexible and suitable environment for applications such as emergency search-and-rescue operations and data acquisition in inhospitable terrain, since

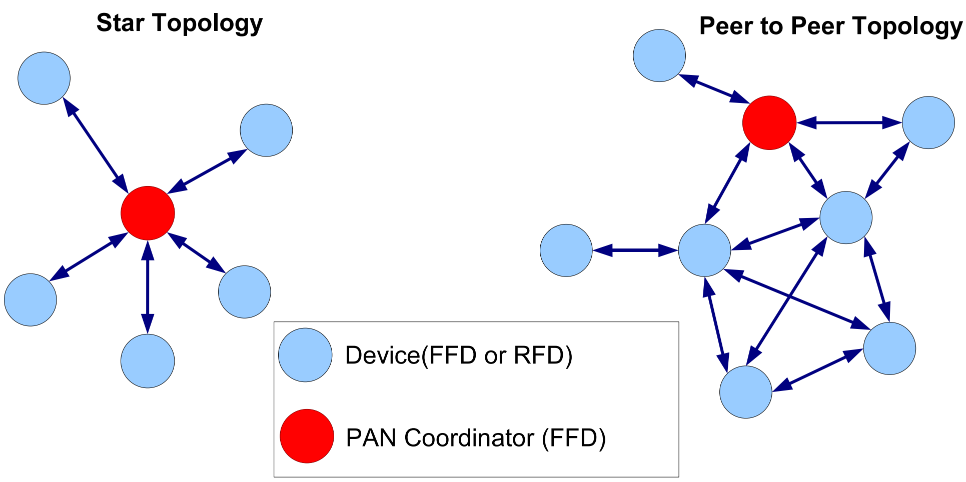


Figure 1.3: Basic network topologies

they allow the establishment of temporary communication without any pre-installed infrastructure. Although ad-hoc wireless networks offer significant benefits in terms of rapid deployment and low cost, the traditional flat multi-hop routing approach suffers from network scaling.

1.2.2.1 Wireless mesh topology

Wireless ad-hoc network (peer-to-peer) architecture is sometimes referred to as wireless mesh technology since a mesh network is a distributed network that generally allow transmission only to a node's nearest neighbour. Nodes in this kind of network are generally identical in terms of transmission capabilities and processing ability. Mesh networks are probably a suitable model for large-scale wireless sensor networks that are distributed over a given area. Since there are generally multiple paths between nodes, mesh networks tend to be robust to failure of individual nodes or links. Another advantage of mesh networks is that of a hybrid star and mesh topologies, where certain nodes can be designated as coordinators or "group leaders" that can take additional functions such as the ability to process and forward messages, and if a group leader is disabled, another node can take over the leader's duties.

1.2.3 System architecture design challenges

WSNs have various unique requirements and constraints to make them practical and operational. Apart from the resources constraints, WSN may be subjected to harsh environment conditions and dynamic network topology (wireless connectivity variation) that may even cause part of WSN to disconnect due to link failures.

The choice of communication architecture will strongly influence WSN performance and the efficacy of routing and MAC protocols. For example, the network topology will influence network performance parameters such as latency, energy consumption, capacity and robustness. In addition, the complexity of MAC and data routing processes depends on the network topology. Depending on the application under consideration (different design goals and constraints), the choice of network architecture can improve or degrade network performance [5, 9, 10]. No standard and design rules have been followed in designing sensor network architecture because of the broad range of applications, which have their own purpose and requirements in terms of sensor hardware and network capability [11, 3, 12]. For example, apart from very few setups that utilise mobile sensors, most sensor network architectures assume that sensor nodes are stationary. The dynamic nature of WSN will impact the choice of routing, MAC level protocols and physical hardware.

Mobility in WSN will cause further topology variation compared to static configurations. This will impose further complexity in protocol designs and may lead into further network performance degradation. However, supporting mobility of sink nodes or cluster-heads (gateways) is sometimes deemed necessary [13, 14, 15]. For example, [13], a case where a mobile WSN was more energy efficient than a static WSN, showed that in a static WSN, nodes closer to the gateway sink always lose their energy first, thus causing the overall network to expire. However, when the sink moves continuously, sensor node energy dissipation is more efficient. The sink movement can also decrease the number of hops and therefore reduce the probability of error. While supporting mobility in some of WSN applications can be advantageous, when connecting heterogeneous sensor network with internet protocol (IP) based wire or wireless links, the traditional architecture (static) is still more practical.

1.3 Communication Protocol Stack

Network devices, both wired and wireless, are commonly described by using the Open Systems Interconnection (OSI) seven-layer reference model [16]. This is the abstraction model that was developed by the International Standards Organization (ISO), starting in the 1980s, to describe communication related protocols and services (Figure 1.4). The model is generic and applies to all network types and all media types. However, not all networks, use the full model; in fact most do not, but the model is a useful reference for describing communication networks. Starting with Layer 1 closest to the media, the Physical Layer (PHY) describes the physical properties of the communications network which can include the electrical properties, signalling properties on the media (wireless or wired), connectors, data encoding, i.e., anything to do with the actual raw data transmission. Layer 2 or the Data Link Level, is divided into the Medium Access Control (MAC) sublayer and the Logical Link Control (LLC) sublayer. The MAC sublayer is closest to PHY, is serviced by the PHY and typically provides service to the LLC. In general, the MAC determines who is allowed access to the physical medium at a time. The IEEE 802.15.4 MAC protocol controls radio channel access using the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism [7]. The 802.15.4 MAC is also responsible for flow control via an acknowledgment of frame delivery; frame validation (as well as maintaining network synchronization); network association and dissociation; administration of device security, and the scheduling of the guaranteed time slot mechanism. Generically, the LLC sublayer sits above the MAC and provides multiplexing of protocols transmitted over the MAC, optional flow control, and any requested detection and retransmission of dropped packets. The five additional layers (from bottom to top) are:

- Network (Layer 3) - Path determination and IP (logical addressing).
- Transport (Layer 4) - End-to-end connections and reliability.
- Session (Layer 5) - Interhost communication.
- Presentation (Layer 6) - Data representation and encryption.
- Application (Layer 7) - User application running on top of the network

Relationship between the IEEE 802.15.4 standard and the OSI model is illustrated in Fig 1.4. The standard is limited to the PHY and MAC Layers targeting the following goals:

- 250 kbps over-the-air data rate
- Star or peer-to-peer operation
- Guaranteed time slots (GTSs) using communication scheduling
- Carrier Sense Multiple Access, Collision Avoidance (CSMA/CA) channel access

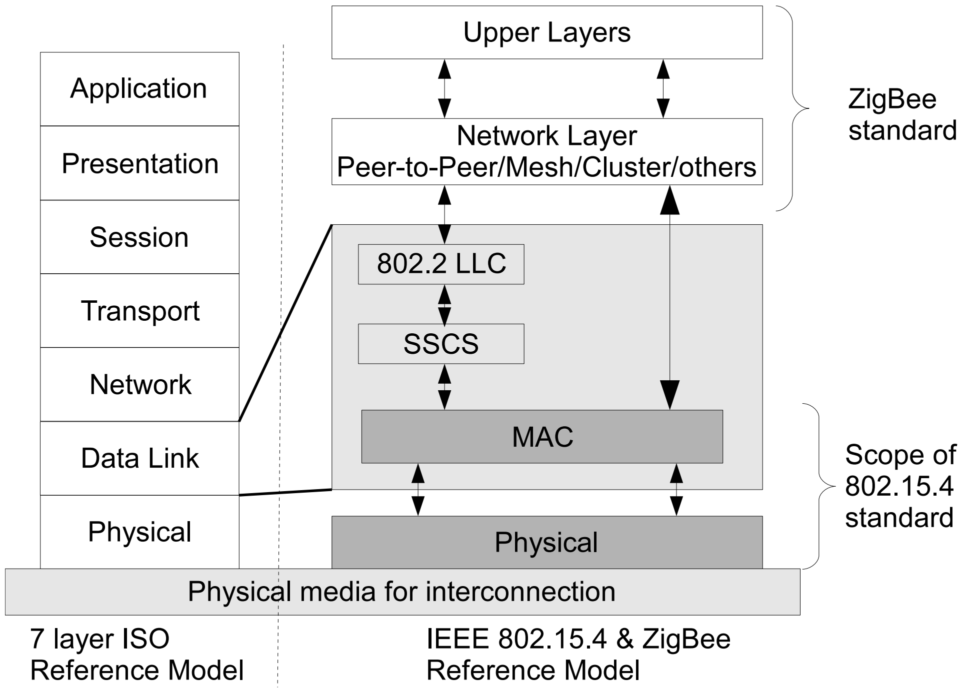


Figure 1.4: ISO reference model as adapted by 802.15.4 and ZigBee

- Acknowledged messaging for reliable data transfer
- Low power
- Short range operation
- Reasonable battery life
- Simple and flexible protocol

ZigBee network stack is built upon the IEEE 802.15.4 Standard and adds a communication layer at layer 3 (network layer) and upper layers services through an application interface (API). The standard provides all the advantages of a fully standardised communications stack including full compatibility across applications and vendors [13]. In WSN, it is essential for all protocols in a communication stack to be optimised with respect to resources. This thesis focuses on the two IEEE 802.15.4 standard layers for WSNs: PHY layer and MAC.

1.4 Wireless Sensor Network Applications

The concept of WSNs is based on a simple "equation":

Sensing + CPU + Radio + Efficient protocols = Many potential applications.

Developing an efficient, effective WSN application, requires an understanding of both the capabilities and limitations of the available hardware components and knowledge of modern networking and distributed technologies.

WSN applications can be categorised based on the application area such as health, home, environment and military applications; or by the way in which information is collected by sensor nodes in a network, such as periodically sending information to the data sink, event triggered and polling applications.

Currently, wireless sensor networking can offer a wide range of potential monitoring and control applications including [17, 18, 19];

- pollutant monitoring
- habitat monitoring
- environmental monitoring,
- areas such as security surveillance,
- rescue missions in inhospitable terrain,
- traffic surveillance,
- health care (patient care),
- robotic exploration,
- industrial and manufacturing automation,
- building and structure monitoring,
- inventory tracking,
- home appliances, and
- farming.

In industries, sensor networks may include sensing and detecting or diagnosing different parameters of interest, and industrial or appliance automation. Moreover, sensor networks can be used in infrastructure projects such as power grids, water distribution, waste disposal, security and even battlefields.

Sensor networks have been used for vehicular traffic monitoring and control. However, these networks and the communication network that connect them are costly, thus traffic control is usually limited to few critical points. Inexpensive reliable ad-hoc wireless networks will completely change the landscape of traffic control and monitoring.

Another more radical concept is having sensors attached to each vehicle and as vehicle pass each other, they can exchange information on the location of traffic jams and speed and density of traffic, the information might be generated by ground sensors.

Electric-power-system monitoring and diagnostic systems are typically realised through wired communications. However, such systems require expensive communication cables to be installed and regularly maintained, and thus, they are not widely implemented today because of their high cost. A more cost effective wireless monitoring and diagnostic system (WSN) will bring significant advantages over traditional communication technologies, including rapid deployment, low cost, flexibility and aggregate intelligence via parallel processing.

In the near future, sensor networks will be able to support new opportunities or applications for interaction between humans and their physical world and specifically WSNs are expected to contribute significantly to pervasive computing and space exploration. Deploying sensor nodes in an attended environment will provide tremendous possibilities for the exploration of new applications in the real world.

In many applications, such as forest fire monitoring or intruder detection, user intervention and battery replenishment is not possible. Since the battery lifetime is directly related to the amount of processing and communication involved in these nodes, optimal resources utilisation becomes a major issue.

1.5 Application Requirements and Design Goals

Most studies of wireless networks tackle some of the problems associated with them. Currently, a wide-range of research in wireless networks thrives on ways to improve the quality of service (QoS) of wireless networks for multimedia applications. WSN applications will usually have different quality-of-service (QoS) requirements and specifications such as reliability, latency, network throughput, and power efficiency. The primary performance objectives of wireless sensor networks in most cases are energy conservation, throughput improvement, scalability and self-configuration, whereas fairness and temporal delay are often secondary issues [20].

Since sensor nodes share a common wireless medium, an efficient medium access control (MAC) operation is required; however other issues which cannot be ignored include topology changes or mobility, multi-hop communication, self-configuration, unattended nature of wireless sensors (power), connectivity, and throughput improvement. In particular, a WSN application will require a high level of system integration, performance, and productivity.

To design good protocols for wireless sensor networks it is important to understand the parameters that are important to the sensor applications and in this thesis the following metrics are used.

1.5.1 System lifetime

A sensor network is expected to have a long operational life to further reduce the cost of maintenance and deployment. In WSNs, energy efficiency is often a critical issue due to a limited battery life [3]. Typical wireless sensor nodes are inherently resource constrained as are usually powered by batteries or harvested energy, and network lifetime usually depends on the reliance of sensor nodes. Power source replenishment is not possible in most of the application scenarios. Energy consumption in a WSN can be minimised by: efficient data aggregation, efficient routing, efficient MAC layer with power management, and topology management using transmission power control. The system's lifetime can also be extended through energy-efficient techniques at all system hierarchy or protocol stack levels.

Since sensor node main tasks include sensing or collecting events, processing data, and data transmission, power consumption can be categorised amoung these operations. Moreover, as sensor nodes become more compact, the challenges increase for processing, communication and storage capabilities.

1.5.2 Self-organisation and self-configuration

A wireless sensor network should self-organize and maintain connectivity efficiently and specifically the MAC protocol manages self configuration, i.e., ability to start a new PAN, associate or disassociate with an exiting network, and synchronize if required.

It is important that sensor networks can be easily deployed possibly in remote or dangerous environments where nodes have to communicate even without established network infrastructure. To function in such ad-hoc settings, sensor networks should be self-configuring (no global control to setup or maintain the network); thus such ad-hoc networks must be able to achieve neighbour discovery, topology organisation and topology reorganisation. During the neighbour discovery phase, every node in the network gathers information about its neighbors and maintains that information in appropriate data structures. This information is obtained periodically either by sending short packets named beacons, or by promiscuously snooping on the channel to detect the activities of neighbours. The communication among sensor nodes depend on topology organisation (section 1.2), and reorganisation in case of changes in a network, such as communication loss.

1.5.3 Reliability

Reliability or fault tolerance of a sensor node is the ability to maintain the sensor network functions without any interruption due to sensor node failure, for example, through lack of energy, physical damage or communication problems. Therefore the node power source, communication links and overlying protocols will contribute to system reliability.

1.5.4 Scalability

The vision of a mesh networking is based on the strength in numbers because unlike cell phone systems, service is not denied when too many devices are active in a small area. In a WSN, several sensors may be deployed to study a phenomenon of interest to users. The issue is: how well does the network perform, with an increasing number of nodes and node density, for coverage area, energy consumption, reliability and accuracy?

1.5.5 Latency

The time delay of sensor node information (latency) is another important performance variable because long delays due to processing or communication may be unacceptable depending on an application.

1.5.6 Packet Error Rate (PER)

Packet Error Rate (PER), is the percentage delivery ratio, which is defined as the number of data packets correctly received by the destination node over the total number of packets generated by source nodes. This reflects the degree of reliability achieved by the network for successful transmissions.

1.5.7 Throughput

The channel efficiency or throughput is defined as the fraction of time that the channel is used to successfully transmit payload bits or the fraction of data traffic correctly received by the node over a specified period.

1.5.8 Productivity

Another important factor for WSNs is the system productivity; this has two aspects, the most important being how well it assists the end user to do their task, i.e. to meet collaborators expectations. However, productivity is also about reducing the costs involved in a sensor network over its lifetime including planning, node hardware, deployment, troubleshooting and maintenance.

For any emerging technology, economic drivers and cost benefits are pivotal issues which could dramatic affect market growth and sensor networks face several relevant challenges. The field arguably emerged due to the commercialisation of cheap, low-power, single-chip microcontrollers and radios. These components emerged due to rapid growth of global electronics industries such as cell phones and wireless remotes. The biggest challenge in WSNs is developing effective communication systems that will run unattended for years in an increasingly energy efficient manner.

1.6 Research Motivation and Challenges

The emerging field of WSN research combines numerous disciplines and addresses a combination of the major challenges in sensor techniques, embedded techniques, distributed information processing, mobile computing and wireless communication [21, 22]. These networks differ from conventional wireless networks due to their hardware limitations of low cost and severe energy constraints for computation and communication, low data rates, potentially huge network size and a wide range of information flows [20, 22]. WSNs will have to cope with limited resources placed on individual devices, i.e. transceivers, embedded microprocessors will limited processing and memory capability, must implement and process complex networking protocols. A sensor node's, envisioned to shrink to cubic millimeter scale, poses stringent limitations on its processing, communication and storage capabilities. Despite continued advances in micro-electromechanical systems (MEMs), lower-power very large-scale integration (VLSI), and computing, aligning desired capabilities with compactness remains challenging [23].

Sensor networks, similar to Mobile Ad-hoc networks (MANET), are envisioned to have dynamic, sometimes rapid-changing, randomly distributed, multi-hop topologies that are composed of relatively limited wireless link bandwidth. WSN can be deployed with a large number of unattended nodes and therefore the underlying network architecture has also become one of the challenging areas in wireless sensor networks research [17, 24].

It is well established that the wireless medium is characterised with high bit error rates (BER) compared to wired mediums [25]. Errors in wireless mediums occur in bursts while in traditional wired networks errors occur randomly. Furthermore, it cannot be assumed that a fully connected topology exists between nodes in wireless networks, but rather a logical network topology that is constantly adapting to node or user movement. Therefore, wireless ad-hoc networks are characterised by unreliable links, burst errors and dynamically changing network topologies.

Running effective WSN communication systems, unattended for years from a limited energy resource, requires both energy-efficient, robust hardware and an efficient software management system. Emerging WSNs are likely to be more energy-efficient with reliable connectivity, despite the greater constraints on battery capacities and connectivity imposed by the compactness and increasing density of new wireless devices. To minimize the power loss in a node, system components must be optimized and be compatible with efficient algorithms or protocols without affecting the target application requirements [22, 26]. Furthermore, the design must be cost effective in terms of hardware costs, communication efficiency and other parts of the complete cost equation including development and product life cycle support costs. While technology is still emerging, progress has not been as rapid as predicted. Instead of smart dust sprinkles from aircraft, we have large nodes connected by myriad wires to transducers [4]. Researchers are still concerned with networking and maximizing the lifetime of networks powered by finite electrochemical primary cells.

While energy considerations have dominated most WSN research, the increasing interest in real-time applications involving imaging and video sensors poses additional challenges, including specific quality of service (QoS) requirements such as latency, throughput and jitter. Moreover, with the increasing need to connect IP network users to WSNs, a new wave of WSNs known as the Internet of Things (IoT) has engaged researchers in both academic and industrial communities [11, 27]. Sensor networks may incorporate many tiny, energy-constrained, distributed nodes that collect information via their sensors and relay it to a user or a general data sink for processing or reporting. Given the resources constraints (battery life, communication bandwidth, CPU capacity, and storage) inherent in WSN devices, protocol design and hardware component architecture selection or design are paramount.

Many WSN constraints are derived from the vision that sensor nodes will be deployed in vast quantities, unattended, compact and inexpensive. As Moore's law marches on, each device will get smaller but more powerful [28, 29, 30]. To achieve technological and marketplace success, the low power, inexpensive sensor networks need to achieve energy efficiency and reliable connectivity. Apart from the resources constrains, WSN may be subjected to harsh environment conditions and dynamic network topology that challenge its performance to the point at which a portion of a WSN is disconnected due to link failures.

Relevant factors for WSN design, include the robustness of network components, cost, energy efficiency, and sustainable implementation models. Enhancing communication networks to achieve reliable wireless connectivity, self-configuration, cost effectiveness and energy efficiency is the challenge for WSNs [26, 22]. Therefore the development of a particular WSN application will require a highly integrated solutions for both robust hardware and efficient protocols or software to achieve effective communication. So far there has been no clear guidelines or design rules that have been followed in designing sensor network architectures because of the wide range of sensor applications, with each application having its own unique purpose and performance requirements i.e, various hardware and network capabilities.

1.6.1 Application requirements and resources constraints

In general, the design and implementation of WSNs are constrained by four types of resources: energy, memory, communication and processing. The increasing interest in real-time applications along with introduction of imaging and video sensors has fostered applications that require certain end-to-end performance guarantees, this posing additional challenges in both QoS aware network protocols and energy efficiency. For example, many military and civil applications, such as disaster management, combat field surveillance, and security, will be required to detect moving targets.

It is essential to differentiate between an application's QoS objectives and constraints. Communication subjected to QoS requirements can be exceptionally challenging in a resource-constrained environment such as in sensor networks [5, 23]. The diversity of WSN applications will lead to different specifications and quality-of-service (QoS) requirements, including reliability, latency, network throughput, and power efficiency.

1.6.2 Integrating WSN with internet and Alternative Technologies

The adoption of WSNs will increase as they become more integrated with existing technologies such as internet, mobile and satellite communication. Currently, there are two main architectures for connecting WSN to the internet, a proxy based approach and internet protocol (IP) integration at the sensor node level (also referred to as IP stack).

The connection of a WSN to the internet through the former is achieved by using a proxy node that acts as a gateway to the internet for sensor nodes that communicate through separate WSN protocols. In this case, WSN and IP have different routing protocols , and therefore the proxy node acts as a protocol mapping device, converting IP to or from, to connect the WSN to the internet. The proxy node acts as a default sink for sensor nodes and stores the sensor readings. When a remote system requests information from sensor data, cached results (in a local database) are returned by the proxy node. Likewise, when requesting real-time information, a separate request will be sent from the proxy node to the sensor node and therefore regardless of the data retrieval method used, no direct connection between the querying system and the sensor node is established. Usually, the proxy is achieved at the application layer or may be applied at the network layer, where a sink or proxy node queries the network without the use of a local database. This approach allows an existing WSN to be connected to the internet with minimum changes. Currently, an application level proxy server is often used to separate the sensor network from the rest of the enterprise network. The application level proxy offer rich translation, caching, and support for reliable networking.

The IP based approach is achieved by using IP stack as the routing protocol inside the WSN itself and therefore there is no need to use proxy node. The use of IP on WSN provides significant advantages by providing more ubiquitous services. However such advantages come with a price including increased frame header overhead, addressing scheme, limited bandwidth, protocol complexity, memory and limited energy. For example, the maximum size allowed for 802.15.4 frame is 127 bytes, MAC header ranges 9-39 bytes, and an additional 20 (IPv4) to 40 (IPv6) bytes will be consumed by the IP header. To overcome this unacceptable overhead and allow IPv6 packet transportation over 802.15.4 frames, techniques such as those found in the 6LoWPAN standard must be used. Using a complete protocol stack, such as Zigbee protocol stack, which uses a proprietary layer 3 protocol on top of the IEEE 802.15.4 standard using IPv4 or IPv6 standards, would largely simplify the integration of these devices into a globally connected Internet of Things (IoT).

Another area of WSN integration is a suitable satellite remote sensing using system such as SPOT-5, 3G, 4G, 802.11 and 802.16. It is likely that a combination of current and future technologies will be used for future WSN deployment. Furthermore, the growing focus on using cognitive radios opens up new opportunities for current sensor networks to merge with other wireless services in order for systems to overcome some of the current limitations and to broaden WSN application areas.

1.7 Research Questions and Contributions

The main object of this thesis is to enhance the performance of WSN to maintain reliable network connectivity, improve scalability and save energy. The study focuses on the IEEE 802.15.4 MAC/PHY layers and the carrier sense multiple access with collision avoidance

(CSMA/CA) based networks. So the main research question is "how and what can be done to improve the performance of WSNs to maintain reliable network connectivity, scalability and energy efficiency in the IEEE 802.15.4 based networks?" To answer this question, this research consists of four semi-independent areas of study to which the following research questions are addressed:

1. How can we specifically test multi-hop TPC communication versus single-hop communication using typical wireless sensor node hardware parameters?
2. What is the performance advantage of using multi-hop TPC in energy constraint WSNs instead of a single-hop in terms of energy efficiency and other important performance parameters?
3. What is the impact of beacon interval (BI) and number of nodes during WSN association and synchronization stages in terms of energy and association or synchronization time?
4. How can we improve the performance of WSNs during association and synchronization stage (self-configuration)?
5. What is the impact of the number of times the clear channel assessment (CCA) is performed in the 802.15.4 MAC during frame transmission in terms of throughput, packet error rate, delay and energy consumption for both hidden and non-hidden nodes in a network ?
6. What can be done to improve the performance of the 802.15.4 MAC during frame transmission stage?
7. How can Markov chains be used to accurately model the IEEE 802.15.4 slotted CSMA/CA ?
8. What is the relationship between different performance variables and the MAC parameters derived from the Markov Chains?

The main research contributions of this thesis are:

- In chapter 4, a new detailed approach is presented for testing transmission power control (TPC) for multi-hop and single-hop WSNs at the physical layer using real hardware parameters. Following this approach, energy consumption performance results via simulation and a numerical model are presented. Both the radiation and electronic components of the energy consumption are characterized, and results indicate that sending packets using a short-range multi-hop path, instead of a single-hop, does not necessarily save energy as suggested by some researchers [31, 32, 33]. Moreover, transmitting in single-hop networks at lower transmission power levels, while still maintaining reliable connectivity, reduced energy consumption by up to 23%. Furthermore, the research shows that both packet collisions and delays affect the performance of WSNs that have an increased number of hops. Since the use of TPC in star topology or cellular networks transmission can save energy, we recommend cluster based (hybrid) or similar topology over completely multi-hop topology. The relationships among protocol layers are also revealed, possible improvement suggested, insights are provided into challenges associated with developing wireless sensor networks protocols and the significance of TPC is highlighted;

- In chapter 5, performance of the 802.15.4 MAC is evaluated during device association and synchronization with the PAN coordinator; this shows the impact of beacon interval and the number of associating nodes in terms of association time delay and energy consumption in stationary wireless sensor networks. Results illustrate that energy consumption and association time increase with increasing number of nodes associating with a coordinator. Moreover, short beacon intervals consume more energy due to the frequency of beacon frames that nodes have to keep track of to maintain synchronization. However, short beacon intervals reduce the time required for the nodes to associate, in contrast to longer beacon intervals that are undesirable for real time and mobile applications. Furthermore, for longer beacon intervals, BO= 12 to BO=14, there is an abrupt increase in energy consumption as the number of associating nodes increases, even for only four nodes. This appears to be the first investigation of the performance of the 802.15.4 MAC beacon interval setting and the number of associating nodes. To conserve energy in WSNs, we expect to use longer beacon interval (BI) and shorter active periods (SD) so that the nodes can go into inactive or sleep state during CAP to save energy. To date the longest beacon interval is 251.66s (about 4 minutes). Our results demonstrate that even with 7 nodes connected to the PAN coordinator, the association delay and energy consumption due to synchronization, increase. The question is whether the association energy consumption will outweigh the benefit of duty cycle power management for larger beacon intervals, as the number of associating nodes increases?

- In chapter 6, the impact of the number of times the CCA is performed in the 802.15.4 MAC during frame transmission is studied in terms of throughput, packet error rate, delay and energy consumption is presented. Both hidden and non-hidden nodes in a network system are considered. Results indicate a serious network performance degradation even with only a small number of hidden nodes in a network. Following these results a propose cross layer (PHY-MAC) mechanism to save energy, reduce interference, improve scalability and reliability, and reduce packet collisions due to hidden terminals is presented.

- Chapter 7 contains a proposed model to capture essential features of the IEEE 802.15.4 slotted CSMA/CA by using the Discrete Markov chain. The relationships for the successful transmission probability, throughput and average energy consumption are derived.

1.8 Thesis Structure

The remainder of the thesis is organised as follows. Chapter 2 provides the literature review on WSNs, including review on medium access control (MAC) and the IEEE 802.15.4 standard. The research questions and methodological framework layout for this research is presented in Chapter 3. Chapter 4 provides TPC investigation in multi-hop and single-hop WSNs, and a detailed description of a new approach to testing TPC in multi-hop networks at the physical layer. In Chapter 5, performance analysis of the 802.15.4 MAC during device association and synchronization with the PAN coordinator is presented. In Chapter 6, performance analysis of Slotted IEEE 802.15.4 MAC Clear Channel Assessment for both hidden and non-hidden nodes, and a proposed algorithm for improvement are presented. The developed Markov Chain analytical model is presented in Chapter 7. Finally, conclusions and a discussion on future work are given in Chapter 8.

Chapter 2

Literature Review

The aim of this chapter is to provide, through selective references to some of the literature, an overview of previous work on topics that provide the necessary background to this research. The literature review focuses on a range of WSN research, the IEEE 802.15.4 standard and key concepts, and theories relating to this research.

2.1 Introduction

Research on Sensor Networks and Mobile Ad-hoc Networks (MANET) is receiving increased interest within the research community [34, 24, 35, 5]. MANETs have been considered for a wide range of new applications since the early research efforts of the Defense Advanced Research Projects Agency (DARPA) research program on packet radio networks for military use [36]. Among these new applications include that of wireless sensor network (WSN). Research in wireless sensor networks have strong links to wireless ad-hoc networks. Both WSN and MANET relate to distributed communication between nodes in an infrastructureless environment. Currently, the research focus on Ad-hoc radio techniques have migrated to dual-use and commercial use in areas such as home computing, public wireless LAN and wireless sensor networks. Wireless sensor networking offer a wide range of potential applications including security surveillance, traffic surveillance, environment monitoring, medical systems, robotic exploration, data acquisition in industries, farming and rescue missions in inhospitable terrain [18, 17, 37, 38, 39]. There are numerous factors as to why ad-hoc wireless sensor networks are receiving increased attention in research communities. Among these factors are the significant benefits of rapid deployment, the wide range of potential applications, low setup and maintenance costs, the use of license-free spectrum, along with the continual decrease in size and cost of sensors. These factors have fostered intensive research addressing the potential of associating several sensors to gather and process information via wireless connectivity. Networking unattended sensor nodes is expected to have a high impact on the efficiency of military and civil applications soon[17, 40]. For technological and marketplace success, the low power, inexpensive sensor networks need to achieve or attain energy efficiency and reliable connectivity. Apart from the resource constraints, WSN may be subjected to harsh environment conditions and dynamic network topology that challenge its performance to the point at which a portion of a WSN is disconnected due to link failures. The IEEE 802.11 standards lack the ability to provide all these features (resilience); however these standards provide the base for research communities to work on building or creating new standards able to deal with different applications [8]. Furthermore, given the broad use of the IEEE 802.11x standard, it is expected to have existing nodes using the IEEE 802.11 standard in a real application scenario. Currently an increased number of researchers are working with or on a new IEEE 802.15.4 standard technology, commonly known as ZigBee technology. ZigBee was adopted in 2003, and is based on or derived from the 802.15.4 low-rate, Wireless Personal Area Network (WPAN) standard [41, 42]. Bluetooth (IEEE 802.15.1) is another prominent wireless technology in the area of wireless sensor networks.

2.2 An Overview of Wireless Sensor Networks

Sensor networks are distributed networks made up of small sensing devices equipped with a processor, memory and capability for short range wireless communication. The difference from conventional networks is that they have severe energy constraints, low-rate data, and a wide range of information flows [20, 43, 44]. Normally sensor network consists of large number of distributed nodes that organise themselves into a multi-hop wireless network. Ad-hoc networks self-configuring, infrastructureless and multi-hop mechanism can improve the throughput and power efficiency of the network. The implementation of sensor networks in this research can consequently be tailored to specific applications and can be formed from whatever network nodes available.

Sensor networks, similar to Mobile Ad-hoc networks (MANET), are envisioned to have dynamic, sometimes rapid-changing, randomly distributed, multi-hop topologies that are composed of relatively limited wireless link bandwidth. WSN can be deployed with a large number of unattended nodes and therefore the underlying network architecture has also become one of the challenging areas in wireless sensor networks research [17, 24]. Whilst ad-hoc networks have been the subject of a significant amount of research and development, currently, the emerging field of Wireless Sensor Networks research combines numerous disciplines and poses a combination of challenges facing modern computer science, wireless communication and mobile computing [45, 3, 5, 46]. WSNs can be deployed in large numbers of unattended nodes and therefore the underlying network architecture has also become one of the challenging areas in wireless sensor networks research [17, 24].

It is well established that the wireless medium is characterised with high bit error rates (BER) compared to wired mediums [25]. Errors in wireless mediums occur in bursts while in traditional wired networks errors occur randomly. Furthermore, we cannot assume a fully connected topology between nodes in wireless networks, but rather a logical network topology that is constantly changing depending on node or user movement from one point to another. Therefore, wireless ad-hoc networks are characterised by unreliable links, burst errors and dynamically changing network topologies.

Most of the studies on wireless networks are based on tackling some of the problems associated with wireless networks. Currently, a wide-range of research in wireless networks thrives on ways to improve the quality of service (QoS) of wireless networks for multimedia applications [47, 12]. With wireless sensor networks, one needs to look at all these ongoing research issues along with other issues that are unique to wireless sensor networks (WSN) and ad-hoc networks. The primary performance objectives of wireless sensor networks in most cases are energy conservation, throughput improvement, scalability, and self-configuration, whereas fairness and temporal delay are often secondary issues [20, 18]. Since sensor nodes share a common wireless medium, an efficient medium access control (MAC) operation is required without isolating other issues such as topology changes or mobility, multi-hop communication, self-configuration, unattended nature of wireless sensors (power), connectivity, and throughput improvement.

2.3 Sensor Node Hardware Platform

A low-rate wireless personal area network (LR-WPAN) platform (also referred to sensor node or device) is typically designed with a separate microcontroller (processor), radio transceiver, power supply (battery), sensor, storage and a number of peripherals (Figure 2.1). Currently, most of the sensor nodes commercially available are made up of off-the-shelf components also known as COTS (commodity of the shelf) mounted on a small printed circuit board [48, 49]. However, more single chip solutions with integrated protocol hardware implementation are also becoming more available.

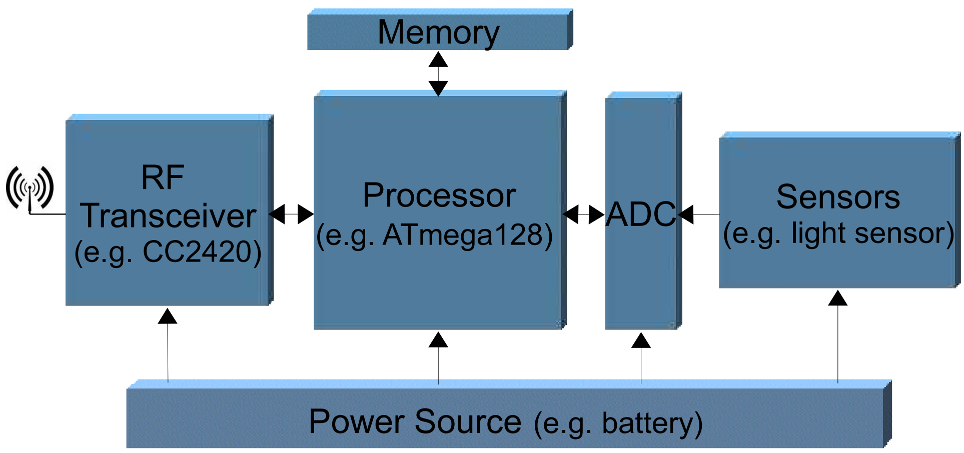


Figure 2.1: Sensor node hardware

2.3.1 Processing module (Micro-controllers & processors)

The processing module is the core of the platform, around which are arranged all sensor node functions and procedures needed to perform a particular sensing task. In the PC era the emphasis was on faster processors; unfortunately, this increased power consumption unacceptable for modern wireless sensor systems. In the current era of connected intelligence, embedded process performance and processing power consumption need to be balanced along with integrated transceiver and sensors. Depending on WSN application requirements such as processing speed, energy efficiency and costs, there are several low-end and high-end processors or microcontrollers that could be selected from the literature [50, 51, 52]. A lower end microcontrollers (MCU) have a simple internal processor with bus width of between 4 and 16 bits, with only on-chip memory, and no interfaces to external RAM. In contrast, microprocessors used in personal computers or other general purpose applications. High end devices contain complex processors with bus width typically 32 or even 64 bit system bus, higher clock rates devices, caches and interfaces to external memories. Moreover, the complex processing module may be capable of energy aware processing and pre-processing of received data as well as featuring multiple CPUs for faster processing.

There is a confusing array of processors or microcontrollers that can be chosen for a particular WSN application, the field to choose from is quite large and can be a confusing task. However, the following guide can assist with choosing the right processing module for an electronics development project. The first task will be to determine the application systems critical priorities, such as processing power, power consumption, operating voltage, operating temperature, flexibility, and cost. The next task is to develop or determine a more suitable solution from available technologies (hardware or protocols) that can support such a project. The choice of a processor should be driven by the desired tradeoff between processing capabilities, energy consumption (for different mode), price and flexibility.

Table 2.1 provides details on the characteristics and capabilities of some of the most popular processing modules employed in various state-of-the-art sensor nodes. Low power, low-cost and simple instruction sets are used such as 8-bit Atmel's ATmega128L CPU on the Mica motes, and the 16-bit Texas Instrument's (TI) MSP430 family on the Telosb motes. The MSP430 from TI has some of the best power saving, and power consumption figures in the industry with a good supply operating voltage range.

The main factors affecting a controller's hardware power consumption include the supply operating voltage, clock frequency at which the controller operates, peripherals enabled, external switching activity, and external components required in the system (particularly power amplifiers). This can be related using the following expression:

$$P_{dynamic} \alpha C V_{dd}^2 f_{clk}, \tag{2.1}$$

where C is the collective switching capacitance, V_{dd} is the supply voltage, and f_{clk} is the clock frequency. Lowering the supply voltage V_{dd} can significantly reduce the amount of energy consumed because of the quadratic relationship between power and V_{dd} as shown in the equation 2.1.

Processors and transceivers have several power down modes or power saving features (Tables 2.1 and 2.2) that can be used to conserve energy. The low power modes such as

Table 2.1: Processor features and comparison

Micro-controller/ Micropro-cessor	CPU	Clock speed (max operating frequency)	Memory (onchip & Ex-ternal/flash memory)	Power saving features	Platform using	Operat-ing volt-age	Operat-ing Temp.	Average Price
MSP430-F5xx (TI) [53]	16-bit AVR microcon-troller	20MHz	16/18 KB onchip RAM & 128/256KB KB external. Interface	5 low power modes (LPM0-LPM4). Normal state power consumption 1.8mA/3mA. Low state current consumption < 1µA	TelosB, EyesIFX, Scatterweb, WISAN, Kmote	1.8 to 3.6V	-40°C to +85°C	$3.92
ATmega128 (Atmel) [52]	8-bit AVR micropro-cessor	16MHz and 8MHz	4 KB onchip RAM & 128 KB external	Sleep 20µA ; Active 8mA	MicaZ, Btnode, Waspmote, EmberNet, Iris Mica2	4.5 to 5.5V and 2.7 to 5.5V	-55°C to +125°C	$14.90 and $12.90
ATmega64/L (Atmel) [52]	8-bit AVR (at-mega64L)	16 MHz and 8 MHz;	64 KB Repro-grammable Flash program memory; 2 KB EEPROM; 4 KB Internal SRAM	Six Sleep Modes: Idle, ADC Noise Reduction, Power-save, Power-down, Standby and Extended Standby.		4.5 to 5.5V and 2.7-5.5V	-40°C to +85°C	$8.90
HCS08 (Freescale) [51]	8-bit microcon-troller using M68HC08	8 MHz at 5V oper. voltage. 4 MHz at 3V oper. voltage	256 bytes of on-chip RAM. 8,192 bytes user program FLASH memory	20 nA power-down mode. Can reduce power to 0.7 microamp (uA) - Up to 40 MHz CPU/20 MHz bus at 2.1 V and 16 MHz CPU/8 MHz bus at 1.8 V		1.8 to 3.6V	- 40 to +125	$6.50
PXA270 (INTEL)	PXA Xscale Processor 32-bit ARMv5 architec-ture processor.	312 MHz, 416 MHz, 520 MHz and 624 MHz.	32 KB instruction cache; 32 KB data cache; 2 KB “mini” data cache; 256 KB of internal SRAM	Dynamically drops the core's voltage and clock frequency according to demand (4 low-power modes). Supply voltage may be reduced to 0.85 V.	HP iPAQ hx2495 Pocket PC	2.25 to 3.7V ; 5V	-40°C to +85°C	$32.97
PXA271-PXA272 (INTEL) [54]	PXA Xscale Processor 32-bit ARMv5	13, 104, 208 MHz or 416 MHz for 271 and 312 MHz, 416 MHz or 520 MHz for 272	32 MB flash & 32 MB of SDRAM; 32 KB data cache; 32 KB instruction cache; 256 KB of internal SRAM	Dynamic voltage and frequency management (4 low-power modes). Supply voltage may be reduced to 0.85 V.	imote2 (A271), Intel Stargate 2 (A271), Pocket PCs, PDAs, GPS Navigation systems	2.25 to 3.7V; 5V	-40°C to +85°C	$50.14

sleeping mode can dramatically increase the battery life span depending on the application. For example, in a periodic sampling application where sensor nodes are most likely to spend 99.9% of their time in sleep mode, the consumption is close to zero [55]. Obviously if the MCU is allowed to run in its normal state at all times, then the coin cell battery will last for less than seven hours, but if it is intelligently switched to its lower power state most of the time, the battery can last more than two years. Thus implementing the power management scheme and using the right hardware can dramatically increase battery life.

For a platform, with a separate microcontroller and a radio transceiver, communication between the microcontroller and the transceiver is via a serial bus such as SPI (Serial Peripheral Interface) or UART (Universal Asynchronous Receiver or Transmitter). The SPI has a full-duplex capability supporting data rates of up to 20 Mbps compared to a common two wire interface, I^2C bus that supports 100 or 400 Kbps data rates. This allows simple, efficient communication among devices controlled by one master (microcontroller).

2.3.2 Transceivers

A wireless communication module (transceiver) is responsible for data transmission and reception via a specific radio channel and modulation or demodulation and spreading or de-spreading techniques. An IEEE 802.15.4 network may operate in one of the three Industrial, Scientific, Medical (ISM) frequency bands: 2.4 GHz, 915 MHz and 868 MHz as illustrated in figure 2.4 in section 2.10.

In this thesis, we focus on transceivers operating in the 2.4 GHz band of the IEEE 802.15.4 standard. Selecting a specific receiver-transmitter architecture for a particular application's performance requirements, requires careful examination of the transceiver's key features such as data rates, the number of channels that can be used, channel bandwidth, energy consumption, modulation type, receiver sensitivity, transmit power levels, link budget, ease-of-integration, and requirement of external components that have significant function and cost implications. In some cases there is a clear tradeoff between a high performance chip-set providing high data rates against a basic communication chip-set with a lightweight protocol and low power cost. For example, the 802.11b transceiver card has higher transmission ability at 11Mbit/s but also consumes more power, while the 802.15.4 on CC2420 chip-set has lower power consumption but with a lower transmission rate, 250kbit/s and communication range [56, 50].

Table 2.2 provides details on the characteristics and capabilities of some of the available transceivers in the literature as a guide into selecting a desirable transceiver for a particular WSN development project. For a example from the table (Table 2.2) we observe that the radio may consists different operation modes (e.g., transmit, receive, idle, and sleep) for power management purposes [22]. In terms of energy consumption, sleep mode power consumption, radio operating voltage will influence the power management algorithms. Also most of the transceivers available operate at Temperature ranging -40 °C to 80, apart from the CC2520 [53] which can operate up to 125 °C, this can be useful when considering application such as fire detection. Other important transceiver features include extensive hardware support for MAC support such as data encryption, data authentication, clear channel assessment, link quality indication and frame timing information; transceiver receiver sensitivity and transmission power will affect the transmission range apart from antenna gains and heights as the link budget is determined by adding together their absolute values [22].

2.3.3 Integrated Chips

There are several commercially-available integrated chips , for example the CC2431, which combines the CC2420 RF transceiver with an industry-standard enhanced 8051 microcontroller [53]. The CC2431 is a true System-On-Chip (SoC) for wireless sensor networking with the most competitive industry leading ZigBee® protocol stack (Z-Stack™) from Texas Instruments. One major drawback of the CC2430 is its limited debugging capability. It offers a very limited low level access through the two-wire debug interface. The ATmega128RFA1 is derived from the ATmega1281 microprocessor combined with the AT86RF231 radio transceiver [52]. Other SoC include the Freescale Semiconductor, its manufacturer provides a variety of 802.15.4 SoCs [51]. The MC1322x series is highly integrated solution with a 802.15.4 compliant on-chip transceiver and an ARM7 processor. With time we expect more integrated chips in the market for WSN platforms.

2.3.4 Power source

The power source module supplies power to a sensor node, which determines a sensor node's lifetime. The electrode material and the diffusion rate of the electrolyte's active material

Table 2.2: Transceivers features and comparison

Trans-ceiver	PHY features	Max RF Power	Receiver Sensit-ivity	Link budget & range (m)	Current drawn/consumption	Platform using	Operat-ing volt-age	Operat-ing Temp.	Average price
CC2420 Chip-con/TI [53]	2.4 GHz band. DSSS baseband modem with 2 MChips/s	0 dBm (1mW)	-94 dBm	94 dBm. Up to 150m	18.8 mA Rx; 17.4 mA TX@ 0 dBm; 14 mA TX@ -5 dBm; 11 mA TX@-10 dBm; 9.9 mA TX@-15 dBm; 8.5 mA TX@ -25 dBm; 20µA Sleep	TelosB, Wisan, iMote2, MicaZ, Sensinode, SunSpot	2.1 to 3.6	-40 to 85	1-$5.88 25-$5.88
CC2520 Chip-con/TI [53]	same as CC2420	+5 dBm	-98 dBm	103 dBm. 400 m	18.5 mA Rx; 25.8 mA TX, 0 dBm; 33.6 mA TX, +5 dBm; <1 µ A power down	Ubimote2, Egs	1.8 to 3.8	-40 to 125	1-$3.89 25-$3.57
Atmel AT86RF230 (ATMEL) [52]	2.4 GHz Band Low Power Transceiver	3 dBm (from -17 dBm)	-101 dBm	104 dBm	16 mA Rx; 10 mA TX, -17 dBm; 13 mA TX, -3 dBm; 17 mA TX, 3 dBm; 20 nA SLEEP;	Iris Mote (cross-bow), Mulle (Eistec)	1.8 to 3.6	-40 to 85	1-$3.70 25-$2.32
AT86RF231 (ATMEL) [52]	2.4GHz band. Supports a non-standard high data rate mode up to 2 Mbps.	3 dBm (from -17 dBm)	-101 dBm	104 dBm. 100m (on-board antenna)	13.2 mA Rx; 10 mA TX, -17 dBm; 13 mA TX, -3 dBm; 17 mA TX, 3 dBm; 0.02 µA SLEEP; 0.4 mA TRX_OFF; 12.3 mA RX_ON; 14 mA BUSY_TX (@ 3 dBm)		1.8 to 3.6	-40 to 85 (indus-trial)and -40 to 125	1-$4.73 25-$2.97
MC13201 (Freescale Semicon-ductor, Inc) [51]	2.4 GHz band RF transceiver	4 dBm (from -27 dBm)	-91 dBm	95 dBm	37 mA Rx; 30 mA TX, 3 dBm; 3 power down modes 1 µA off Current, 1 µA Hibernate current 35 uA Doze current		2.0 to 3.4	-40 to 85	1000-$1.91
MC13202 (Freescale Semicon-ductor, Inc) [51]	2.4GHz band RF transceiver	4 dBm (from -27 dBm)	-92 dBm	96 dBm	30 mA TX, 3 dBm; 37 mA Rx; 3 power down modes 1 uA Hibernate current 35 uA Doze current 3 dBm 1uA Off current	BeeKit, CodeWar-rior	2.0 to 3.4	-40 to 85	1000-$2.24
XBee (Digi In-ternation Inc.) [57]	2.4 GHz band, data rate: up to 115.2 Kbps , 16 Channels	0 dBm	-92 dBm	92 dBm. Up to 30 m	45 mA (@ 3.3 V) boost mode 35 mA (@ 3.3 V) normal mode TX 50 mA (@ 3.3 V) RX Power-down sleep current <10 µA at 25° C	Waspmote (libelium)	2.8 to 3.4	-40 to 85	$19
XBee-PRO (Digi In-ternation Inc.) [57]	2.4 GHz band, data rate: up to 115.2 Kbps, 12 Channels	10 dBm	-100 dBm (all vari-ants)	(118 & 110 dBm Up to 1.6 km	215 mA (@ 3.3 V) TX 55 mA (@ 3.3 V) RX Power-down sleep current <10 µA at 25° C	Meshlium X treme (libelium)	2.8 to 3.4	-40 to 85	$32

affect the battery capacity [58]. Given the battery capacity of a particular battery, and by finding the average current drained by the system, we can approximately obtain the battery life span using the following expression:

$$\frac{Capacity}{I_{pavg}}$$

For example, given the battery capacity of 2850mAh and average drained current of 11.623mA, the expected battery life time is approximately 245.19 hours if running continuously.

2.4 Current State of Wireless Networks Deployment

Despite the wide use of the 802.11 standards for wireless communication , various studies have observed degradation in performance when the IEEE 802.11 standard is used in distributed network scenarios [59, 60]. These studies found the IEEE 802.11 medium access control (MAC) protocols inability to perform well in such environments in terms of energy efficiency and other performance parameters. These findings alerted future research to look at the MAC schemes that will be suitable for wireless sensor network operating in a multi-hop mode without excessive performance degradation. However, one cannot ignore the fact that the exploding success of wireless area networks (WLANs) over recent years, especially in commercial based applications, is due to the products that are based on IEEE 802.11 standard. The IEEE 802.11 standard is well established and has won the market place of wireless networked devices at relatively low prices. Most likely, future standards will still operate in coexistence with the 802.11 networks and also other technologies [59]. The new standards such as the IEEE 802.15.1 (Bluetooth) and 802.15.4 (ZigBee) standards are currently receiving more attention in the development of wireless sensor applications [61, 42, 62].

Choi [61] suggests the use of bluetooth standard for security system wireless sensor network. However, Heng-Chih [62] made a comparison between Bluetooth and ZigBee showing as the latter being more energy efficient and therefore a more appropriate solution for long operation time sensor networks. Furthermore he argues that bluetooth has several other limitations compared to ZigBee that include high-cost, longer latency, and low density. Table 2.3 shows some of the standards in comparison to the IEEE 802.15.4 standard.

Geer [42] quoted a research vice president at Gartner Dataquest, a market research firm, predicted that a worldwide increase in number of devices connected via ZigBee from 400,000 in year 2005 to 150 million in 2010 as shown in figure 2.2.

Table 2.3: A comparison between 802.15.4 and other standards

Market Name	ZigBee®	---	Wi-Fi™	Bluetooth™
Standard	802.15.4	GSM/GPRS CDMA/1xRTT	802.11b	802.15.1
Application Focus	Monitoring & Control	Wide Area Voice & Data	Web, Email, Video	Cable Replacement
System Resources	4KB - 32KB	16MB+	1MB+	250KB+
Battery Life (days)	100 - 1,000+	1-7	.5 - 5	1 - 7
Network Size	Unlimited (2^{64})	1	32	7
Maximum Data Rate (KB/s)	20 - 250	64 - 128+	11,000+	720
Transmission Range (meters)	1 - 100+	1,000+	1 - 100	1 - 10+
Success Metrics	Reliability, Power, Cost	Reach, Quality	Speed, Flexibility	Cost, Convenience

The greatest challenge is developing effective WSN communication systems that will run unattended for years from a limited energy resource. This requires both energy-efficient, robust hardware and an efficient software management system. We expect the emerging WSNs to be more energy-efficient with reliable connectivity, given that the compactness and increasing density of new wireless devices impose greater constraints on battery capacities and connectivity. To minimize the power loss in a node, system components must be optimized and be compatible with efficient algorithms or protocols without affecting the target application requirements, e.g, saving energy [22, 26]. Furthermore, the design must be cost effective in terms of hardware costs, communication efficiency and the complete cost equation including development costs and product life cycle support costs. While technology is still emerging, progress has not been as rapid as predicted. Instead of smart dust sprinkles from aircraft, we have large nodes connected by myriad wires to transducers [4]. Researchers are still concerned with networking and maximizing the lifetime of networks powered by finite electrochemical primary cells. While energy considerations have dominated most WSN research, the increasing interest in real-time applications involving imaging and video sensors poses additional challenges, including specific quality of service (QoS) requirements such as latency, throughput and jitter. Moreover, with the increasing need to connect IP network users to WSNs, a new wave of WSNs known as the Internet of Things (IoT) has engaged researchers in both academic and industrial communities [11].

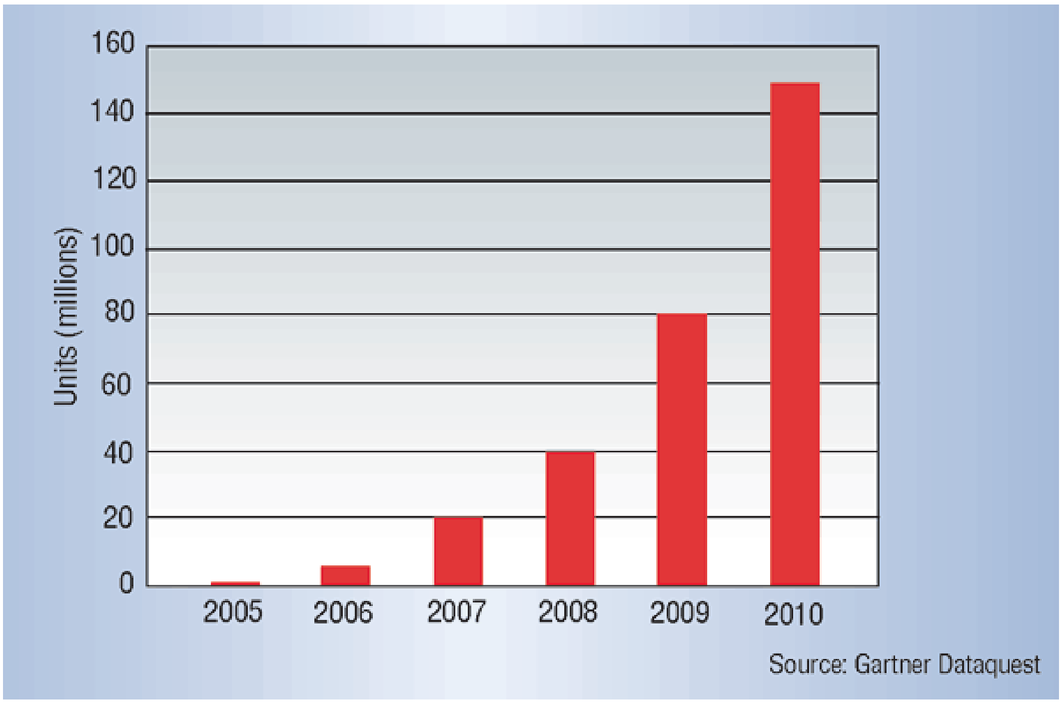


Figure 2.2: Zigbee connected devices prediction [42]

2.5 Transmission Power Control Aspect

The main aim of transmission power control in a communication system is to attempt to use the minimum possible power level to achieve good or acceptable performance in a system. Here the performance will depend on the context, which may include optimizing metrics such as the network's lifespan, geographic coverage or communication range, and link data rate.

In principle, there are merits and demerits of increasing transmission power. Some of the benefits of increasing transmission power include obtaining higher signal-to-noise ratio (SNR) at the receiver, which translates into reducing the bit error rate (BER) of a communication link. With higher SNR, devices can transmit at a higher data rate, resulting in a system with greater spectral efficiency. Using higher transmission power translates into greater coverage. The following subsection lists some of the important theories regarding multi-hop TPC, namely, connectivity and topology maintenance; spatial reuse and detection; and energy consumption. A multi-hop wireless sensor network is defined as a network whereby a packet may have to traverse multiple consecutive wireless links in order to reach the destination [63].

2.5.1 Connectivity and Topology Maintenance

The network topology depends on a number of controllable and noncontrollable factors. Some of noncontrollable factors include node mobility, weather, interference and noise. Some of the controllable factors include transmit power and antenna direction. Topology maintenance aims to reduce transmission range by adjusting the nodal radio transmission range downward while maintaining necessary network properties such as connectivity [64, 35]. A network is constructed having network connectivity whereby each node can communicate with any other nodes in the network, via single a hop or via multiple hops. By minimising transmission power, we control the network topology by reducing the number of links (depending on the network density). If the transmit power is too low, the network might be disjointed, and if we transmit at excessively high power then we use energy inefficiently and cause interference in the shared radio channel. Topology control aims to minimize the number of links that constitute the topology. Power control in terms of topology maintenance, retention of connectivity, reduces power consumption and also reduces MAC level interference. However, as transmission power decreases or carrier sense threshold increases the signal to interference ratio, SINR also decreases as a result either of smaller received signal or an increased interference level. In terms of connectivity then the optimal common transmission power will be power just sufficient to preserve network connectivity [65].

2.5.2 Spatial Reuse and Detection Advantages

The spatial reuse in the case of a wireless network is the network's ability to allow multiple communication to proceed simultaneously [66]. In the physical layer, one can increase the level of spatial reuse to possibly allow higher throughput by either reducing the transmit power or reducing the carrier sense range by an increase in the carrier sense threshold (CSthresh_). In [67] it was found that spatial reuse depends on the ratio of transmission power and carrier sense threshold. Even though spatial reuse characterise the performance of MAC by determining the number of simultaneous communication to proceed, here it shows the need for cross layer improvement since this can be controlled at the physical layer.

2.5.3 Multi-hop and Energy Consumption

Some of the previous research suggest that multi-hop communication in densely deployed sensor networks is expected to consume less power than traditional single hop communication [31, 32, 33]. So if we can use minimum possible power while still maintaining connectivity, we can reduce the energy consumption, Joule/byte transmitted and therefore prolong the lifespan of wireless sensor nodes [68, 67, 33, 32]. Zhao [31] suggests that an N hop multi-hop communication can be more energy-efficient than single-hop communication for same distance, Nr by deriving the following expression:

$$\eta_{rf} = \frac{P_{send}(Nr)}{N.P_{send}(r)} = \frac{(Nr)^{\alpha} P_{received}}{N.r^{\alpha} P_{received}} = N^{\alpha-1}$$

where r , α, P_{send}, and $P_{received}$ are the one-hop distance, radio frequency (RF) attenuation, the power at a transmission node, and the minimum received power at a node respectively.

2.6 A Review on Wireless Medium Access Control Protocols

Data link layer is responsible for establishing a reliable and secure logical link over the unreliable wireless link. The data link is therefore responsible for wireless link error control, security(encryption or decryption), mapping network layer packets into frames, and packet retransmission. A sublayer of the data link layer is known as the media access control (MAC) protocol layer. Like in all shared medium networks, medium access control is responsible for coordinating the access of active nodes or users in the communication channel or channels. Figure 2.3 shows the MAC categories. When dedicated channels are allocated to users it is often called multiple access. Bandwidth sharing using random channel allocation is known as random multiple access or simply random access. All random access techniques use some sort of carrier sensing, such as the carrier sense multiple access with collision detection (CSMA/CD) which is used in the wired IEEE802.3 standard (Ethernet) similar to carrier sense multiple multiple access with collision avoidance

(CSMA/CA) described in section 2.13 used in wireless networks such as WPAN, WLAN and ALOHA [69, 21]. All active users contend for the channel, hence this MAC scheme is sometimes known as a contention based scheme. The Distributed Coordination Function (DCF) of the IEEE802.11 standard [8] and the Contention Access Period (CAP) of the IEEE 802.15.4 standard [7] are good examples of contention based protocols.

In general, the choice of whether to apply a particular multiple access or a particular random access will depend on several factors. Some of these basic factors include the system application, the nature of traffic characteristics of the users in the system, the performance requirements, characteristics of the channels and other interfering systems operating in the same bandwidth. Traditionally, wireless channel access schemes can be classified into two broad categories namely random based or contention based and reservation or dedicated or contention-free based. The channel access schemes are sometimes classified based on their operating principle, for example contention based access mechanism is sometimes referred to as the decentralized or distributed medium access scheme and the centralized mechanisms that use techniques such time-division multiple access (TDMA), frequency division multiple access (FDMA), code division multiple access (CDMA) or hybrid combination of these reservation based channel accesses. An example of reservation based channel access is that of Point Coordination Function (PCF) of IEEE 802.11 that employs polling.

Applications with continuous transmission and delay constraints, such as voice or video, typically require dedicated channels for good performance to ensure their transmission is not interrupted. However, most data users, or in particular sensor networks, do not require continuous transmission. i.e. data is generally generated at random time instances, and therefore dedicated channel assignment can be extremely inefficient. Furthermore, most network scenarios have a total number of users that are active users plus idle users than can be accommodated simultaneously, so at any given time channels should only be allocated to users or nodes that need them. Therefore, random access protocols are more effective with burst traffic where there are many more users than available channels, and when these uses rarely transmit. On the other hand if the users have long strings of packets or continuous streaming data, then random access works poorly as most transmission results in collisions. In such cases performance can be improved by assigning channels to users in a more systematic fashion using one of the dedicated or scheduling channel schemes.

Contention based access schemes are usually used for ad-hoc wireless networks due to their distributive nature, simplicity and lack of synchronization requirements. However, each

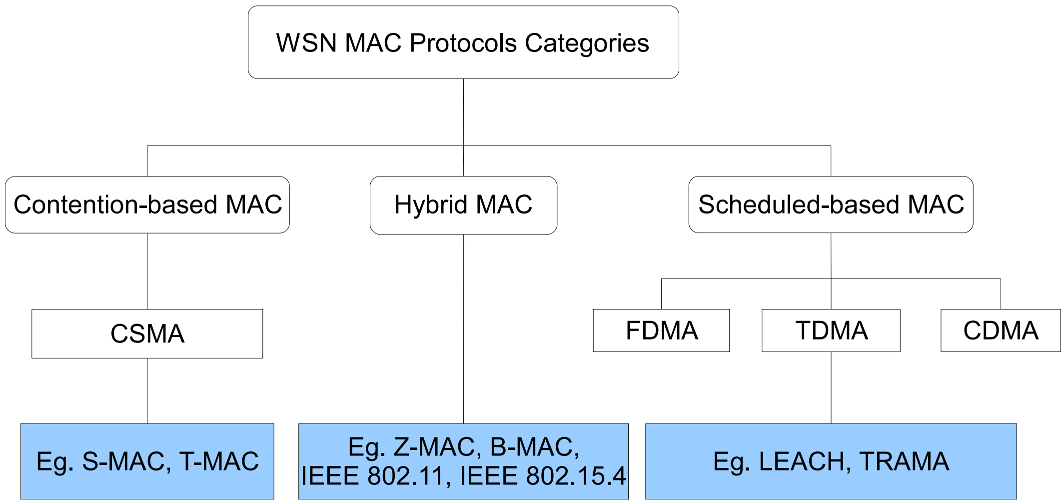


Figure 2.3: Medium access control categories

node must keep its radio on at all times for contention based schemes to ensure reception of the incoming packets[38].

The MAC protocol in wireless sensor networks must achieve three goals. The first goal being the ability to scale to changes in network size, node density and topology creation of network infrastructure. Since thousands of sensor nodes may be densely scattered in a sensor field, the MAC scheme must establish appropriate communication links for data transfer. This forms the basic infrastructure needed for wireless communication hop by hop and gives sensors self-organising ability. The second objective is to fairly and efficiently share communication resources between sensor nodes. Finally, the MAC protocol must also be energy efficient to increase the network lifespan considering most sensor nodes are likely to be battery powered.

2.6.1 Contention based MAC Design for Wireless Networks

In wired networks, collision can quickly be detected by a transmitter during the course of transmission with a technique such as that of CSMA with collision detection (CD) that is used in Ethernet. In contrast, a transmitter in wireless, medium cannot detect collisions when transmitting in wireless networks, but has to rather rely on the receiver's acknowledgment to determine whether collision took place in the transmission duration. Zhao [24] noted that the resulting collision period is quite long and very costly if a long data transmission encounters collisions, thus the need for effective ways to reduce collision becomes one of the key issues for MAC design in this regard.

Several techniques can be used to control collision in random medium access, namely carrier sense, handshaking and backoff mechanisms [70]. Carrier sense requires the transmitter to transmit only when the channel is determined to be idle. Handshaking between transmitter and receiver, which involves an exchange of short frame packets between transmitter and receiver before transmitting data packets to avoid long collision periods of data packets. Furthermore, the backoff mechanism described in section 2.13 forces each node to wait for a random period before attempting retransmission to avoid collision.

2.7 MAC Power Consumption Sources

The sources of power consumption in wireless sensor networks can be classified into two types: communication related and computation related. The understanding of power characteristics of the mobile radio used in wireless devices is important for an efficient design of communication protocols. Unlike wired networks for which the topology is fixed except in the cases of link failures, WSN have dynamic topologies based on the location of the sensor nodes and their range of transmission. For sufficiently dense networks, nodes can restrict communication only to nearby nodes with reduced range of transmission and yet maintain global network connectivity. The mechanism for computing the sufficient transmission ranges for each node is known as topology control, and its main goal is to optimise performance in terms of network lifetime and throughput while maintaining a connected network.

A typical mobile radio may exist in three modes namely: transmit, receive, and standby. Maximum power being used while transmitting and the least power usage occurs during the standby mode. Since the MAC-layer is responsible for allocating the medium so that multiple units do not interfere with each other's transmissions, it is no coincidence that some power saving optimisations need to be looked at in this particular layer. Previous research into MAC layer power optimisation have been investigating four possible ways to reduce power consumption in wireless networks. These include reducing sending time, reducing power while sending, reducing listening time, and reducing switching time.

2.8 MAC Protocols - Related Work

The medium access control is a broad research area, and a good number of researchers have worked in the area of power efficient MACs and wireless sensor networks [71, 18, 72]. One of the pioneers in the area of power efficient MAC protocols is PAMAS, which tries to reduce the overhearing between nodes by using a separate signalling channel [73]. However this requires an extra radio and therefore increases the cost and complexity of sensor nodes. Another MAC known as PCM (Power Control MAC) and PCM does not use a separate signalling channel like PAMAS [74]. This MAC protocol is an extension to the standard IEEE 802.11 MAC protocol, and it can be used by any protocol applying CSMA/CA. The main goal of the PCM is to use less power compared to the 802.11 standard and still retain the same throughput. It does this by transmitting DATA and ACK at minimum possible power and transmitting RTS and CTS at maximum power. To reduce collisions, data transmissions are periodically transmitted at maximum power, so that neighbours can sense the medium as occupied, and refrain from sending RTS packets.

S-MAC is a contention based MAC protocol like IEEE 802.11. This protocol uses a number of techniques to reduce energy consumption by close to 50 percent compared to 802.11 and still maintain a tolerable latency and throughput [18]. In S-MAC all nodes in the network synchronize their respective sleep or wake schedules, and all nodes that maintain the same schedule belong to the same virtual cluster (neighbouring nodes). The main difference between S-MAC and IEEE 802.11 in power save mode is that the latter is designed for single hop networks, whereas S-MAC includes synchronisation between the nodes in the network. S-MAC adds power saving features to the virtual carrier sense. When NAV is nonzero, and the ongoing transmission does not involve the current node, the radio is powered off or down until the NAV reaches zero. The design reduces the energy consumption caused by idle listening and tackles the overhearing problem by sending to sleep interfering nodes once they hear RTS/CTS. However, this design embodies or activates a trade off of latency as latency is increased, since sender nodes must wait for the receiver to wake up before sending out data [18]. Wei's [18] main goal in the design of the S-MAC protocol was to reduce energy consumption, while supporting scalability and collision avoidance. He identifies and describes the causes of energy waste that include idle listening, collisions, overhearing, and control overhead. S-MAC is not only a link protocol, but also a network and organisation protocol. The S-MAC design involves synchronisation that consumes energy and TDMA complexity may not be suitable for simple devices.

T-MAC (Timeout MAC) [75] is another contention-based MAC protocol with a/the main design goal to reduce energy consumption. T-MAC improves S-MAC's energy usage by allowing active nodes to have adaptive or variable duty-cycles rather than fixed ones. The design allows every node to decide its own duty-cycle based on its activation period. T-MAC protocol ends the active time by timing out on hearing nothing for a period known as timeout. The T-MAC protocol has more latency compared to an S-MAC protocol; however it gives much better energy performance for low data rate applications. The design of T-MAC — similar to S-MAC — also uses periodic time synchronisation that consumes much energy.

B-MAC (Berkeley MAC) [76] is another contention-based MAC protocol where the main design goal is to reduce energy consumption, and with an additional goal of keeping the implementation simple with small code and RAM size. B-MAC carrier sensing uses Clear Channel Assessment (CCA) with the sleep or wake scheduling using Low Power Listening (LPL). B-MAC is only a link protocol with network services such as organisation, synchronisation, and routing built above its implementation needs[76]. B-MAC design provides an interface to the user to change different parameters such as CCA, acknowledgments, back-offs and LPL to suit a particular WSN application scenario at run-time. The design emphasis is on keeping the code size small and on providing complete flexibility. Another advantage of this design is that no RTS/CTS and synchronisation packets are required. However, the design causes or creates huge overhead because of overhearing, whereby receiver nodes have to keep themselves on for receiving a long preamble even though they might not be the intended destination.

Z-MAC (Zebra MAC) [77] is a hybrid MAC scheme that combines the strength of CSMA and TDMA. With Z-MAC, nodes within interference range transmit during different times, so as to be collision free, however unlike TDMA, a node can transmit during any given time slot. The main design goal of the T-MAC is to reduce energy consumption by preventing collision caused by hidden nodes, and to control overhead such as RTS/CTS or Data/ACK.

2.9 IEEE 802.15.4 Overview

An increased attention in WSN applications has triggered the development of standard protocols specifically designed for intended range of applications. Among other development, is the recently proposed IEEE 802.15.4 standard, which describes the Physical layer

(PHY) and medium access control (MAC) sublayer specifications for wireless communication standard particularly for low-rate, low-power consumption wireless personal area networks (LR-WPANs). Since the introduction of 802.15.4 standard for wireless personal area network (WPAN) in 2003 by the IEEE 802.15 working group, WPAN has tremendously attracted research and development in wireless sensor networks (WSNs). The standard has been designed to provide low complexity, low cost and low power wireless connectivity, which makes it one of the most anticipated technologies enabling wireless sensor networks (WSNs).

2.10 IEEE 802.15.4 Physical Specification

The IEEE 802.15.4 physical layer is responsible for data transmission and reception using a certain radio channel and according to specific modulation or demodulation and spreading or de-spreading technique. The standard also provides other common provisions such as receiver sensitivity, the ability to adjust transmitter power, ability to dynamically select channel, a channel scan function in search of a beacon, activation and deactivation of radio transceiver, ability to measure received packet energy known as energy detection (ED) , the ability to measure the quality of the received signal for each packet known as link quality indicator (LQI) and the ability to check for activity in the medium known as clear channel assessment (CCA).

IEEE 802.15.4 network may operate in one of the three Industrial, Scientific, Medical (ISM) frequency bands: 2.45GHz, 915MHz and 868MHz as illustrated in figure 2.4 . There is a single channel between 868 and 868.6 MHz in the 868MHz band, 10 channels between 902 and 928MHz in the 915MHz band, in 2 MHz steps, numbered 1 through 10 and 16 channels between 2.4 and 2.4835GHz in 2.45GHz band, in 5 MHz steps, numbered 11 through 26. The center frequency of these 27 channels in three frequency bands is defined as follows:

$F_c = 868.3\text{MHz}$, for $k = 0$

$F_c = 906 + 2\,(k-1)\text{MHz}$, for $k = 1, 2, ..., 10$

$F_c = 2405 + 5\,(k-11)\text{MHz}$, for $k = 11, 12, ..., 26$

where k is the channel number.

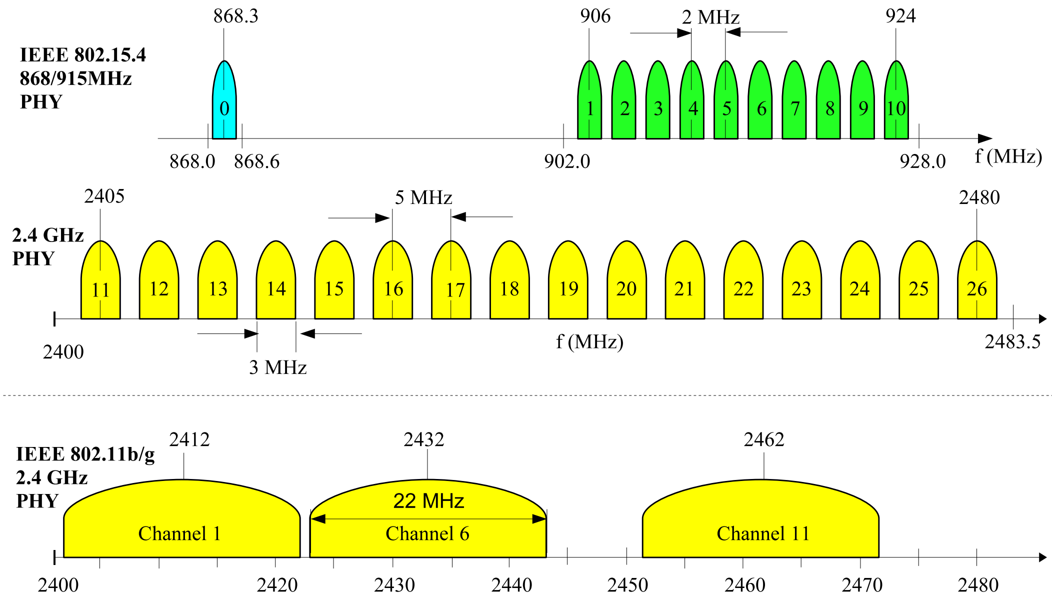


Figure 2.4: IEEE 802.15.4 frequency spectrum

The standard uses direct sequence spread spectrum (DSSS) as a spreading technique for all bands. Frequency bands 868MHz and 915MHz utilise DSSS with a comparatively low chip rate as a spreading technique and binary phase shift keying (BPSK) modulation, which result in maximum attainable data rates of 20 kbps and 40 kbps, respectively. The 2.45GHz band uses a 16-ary quasi-orthogonal modulation technique is used, in which four data bits comprise one modulation symbol and the chip sequence is then modulated onto the carrier using offset quadrature phase shift keying (O-QPSK),attaining data rate of up to 250 kbps (Table 2.4).

We use the 2.45GHz frequency band in this research for three reasons. Firstly, since it provides high radio data rate (250kb/s) which reduces the frame transmission time and therefore reduces the energy per transmitted and received bit. Secondly, because network scalability is improved given that a large number of nodes may communicate with each other within a time period, and lastly, because the band is available in most countries worldwide.

2.10.1 Channel Frequency Selection

The PHY layer should be able to tune its transceiver into a specific channel requested by upper layers. Dynamic channel selection (DCS) involves a number of procedures to enable 802.15.4 devices to change their radio channel based on measurements and regulatory

Table 2.4: IEEE 802.15.4 physical parameters

PHY (MHz)	Frequency bands (MHz)	Channels	Data parameters			Spreading parameters	
			Bit rate (kbps)	Symbol rate (ksymbol-s/s)	Data Modulation	Chip rate (kchip/s)	Chip Modulation
868/915	868 - 868.6	1	20	20	BPSK	300	BPSK
	902 - 928	10	40	40	BPSK	600	BPSK
2450	2400 - 2483.5	16	250	62.5	16-ary Orthogonal	2000	O-QPSK

requirements. When a node first associates with the network, the association frame includes a supported channels information element, which reveals the channels supported by the station. The selection of a particular channel can affect the initial association procedure and ongoing network operations [78, 79, 80]. DCS will periodically test the channel for potential interference from other radio systems by stopping the transmission on the network and measuring potential interference, and if necessary communicating the need for channel change.

2.10.2 Receiver sensitivity and capture threshold

The receiver threshold value or receiver sensitivity is the signal power required to achieve a particular BER or is the least power level of a packet for its transmission to be detected successively; if the received signal power is lower than RXthreshold, it cannot be detected successfully. For example, when a node is presently receiving a packet of power P_a, and a packet at power level P_b arrives, the following comparison must be made to determine whether or not capture occurs:

$10log\left(P_a\right) - 10log\left(P_b\right) > 10db$ or $\frac{P_a}{P_b} > 10$

Receiver sensitivity is measured in dBm, whereby 0 dBm equals 1mW, and power below 1mW are expressed as negative number. For example 0.01 mW would be -20 dBm. Therefore, the lower the power level that the receiver can successfully process, the better the receiver sensitivity [81, 67]. Rxthreshold depend on a function of modulation used, and packet size. For small packets even -80dBm$(1x10^{-11}W)$ is enough, however receiver sensitivity of -85 or better is preferably. For simulation purposes, NS-2 threshold.cc can be used to calculate the value of RXthreshold required for a particular receiver range [82].

However this does not necessary mean there exists a physical card with such value of RX and CS thresholds.

Transmission range of a mobile node can also be changed in the tcl script by simply changing the receiving threshold with the following command line:

```
Phy/WirelessPhy set RXThresh_ <value>
```

For any given receiver, the higher the data rate, the less sensitive will be the receiver, since more power is required at the receiver to support higher data rates. For example, a receiver sensitivity of -98 dBm is better than a receive sensitivity of -95 dBm by 3 dB, or a factor of two. In other words, at a specified data rate, a receiver with a -98 dBm sensitivity can hear signals that are half the power of those heard by a receiver with a -95 dBm receiver sensitivity.

2.10.3 Receiver Energy Detection (ED)/Digital RSSI

Receive Signal Strength Indicator (RSSI) is a transceiver's feature which is able to estimate or indicate Radio Frequency (RF) strength (power) of an incoming signal at the receiving antenna. The RSSI is derived from received signal strength as ratio of received power to the reference power (P_{ref}). Typically, the reference power represents an absolute value of $P_{ref} = 1mW$.

$$RSSI = 10log\frac{P_r}{P_{ref}} \qquad [RSSI] = dBm \tag{2.2}$$

Before a device can transmit a message, it first goes into receive mode to detect and estimate the received signal power (energy level) within the bandwidth of a current channel. This task is known as energy detection (ED). The ED time is equal to 8 symbol periods, and the signal energy in the band of interest is averaged over this period. Most of embedded devices such as telosb, CC2420 has a built-in RSSI yielding a digital value that can be read from the 8 bit, signed 2's complement RSSI_value register. This value is always averaged over 8 symbol periods (128μs @250 kbps), in accordance with the IEEE 802.15.4 standard [50].

Receiver's ED does not attempt to detect the signal type but rather the signal energy level estimated (i.e., ED does not reveal as to whether the signal is an IEEE 802.15.4 standard compliant or not). In addition, ED might not be able to detect weak signals with energy level close to receiver sensitivity level. The MAC request the PHY to perform ED, then the ED results will be reported to the MAC (MLME) using PLME-ED.confirm, which return an 8-bit integer indicating energy level in the frequency channel of interest [7].

2.10.4 Link Quality Indicator (LQI)

A link quality indicator (LQI) indicates the signal strength and/or quality of packets received by the receiver. The received signal strength (RSS) is a measure of the total energy of the received signal, this can be determined using receiver ED. Another way of looking at signal quality is by using a signal to noise ratio (SNR) estimation (where higher SNR is considered a higher quality signal, and so forth). Therefore, LQI measurement may be implemented using receiver ED, a signal-to-noise estimation, or a combination of both methods.

The LQI measurement is performed for each received packet and the result reported to the MAC sublayer using PD-DATA.indication, which return an integer ranging from 0x00 to 0xff. The link quality that is received by higher layers is simply the RSSI value (in dBm) after it has been scaled and offset. This is done to get the value in the 0-255 range rather than the -40 to -95 range typical of RSSI values. The conversion can be found in a mac_radio_defs.h file, defined as MAC_RADIO_CONVERT_RSSI_TO_LQI(x). The value of LQI relates to RSSI value in a linear function. The LQI works in the same way as the ED, except that LQI is measured over $64\mu s$ period after the incoming packet preamble[78]

2.10.5 Carrier Sensing (CS) and Clear Channel Assessment (CCA)

Similar to ED, carrier sense (CS) is a method used to verify as to whether a frequency channel is available to use. Before a device can transmit a message, it goes into the receive mode to detect the type of any possible signal that might be present in the desired frequency channel. In contrast to ED, in CS, the signal is demodulated to verify whether the signal modulation and spreading are compliant with the characteristics of the PHY that is currently in use by the device. If the occupying signal is compliant to IEEE 802.15.4 PHY, the device might choose to consider the channel busy regardless of the signal level.

The Carrier sense threshold (CSthreshold) provides the sensing range of the nodes. CSthreshold value is used by medium access control (MAC), when a node senses the channel and find that the sampled energy or received power is below CSthreshold, the node will perceive the channel to be idle.

The concept of CCA was first proposed as an enhancement ALOHA. CCA is a physical layer activity and is an essential element of the CSMA protocol.The CCA provides two important services: (i) detecting an incoming packet, (ii) ensuring a free channel before transmission. The CCA module processes received radio signals in a suitable time termed CCA window. The CCA processing can be either energy detection or sense of specific features of signal over the channel. It then reports channel state, either busy or idle, by comparing the detection with a threshold.

The 802.15.4 PHY provides the capability to perform clear channel assessment (CCA) to determine whether the channel is busy or idle by comparing the energy in the channel with a threshold. The CCA is part of the PHY management service. In CSMA/CA channel access mechanism, the MAC request the PHY to perform a CCA to ensure that the channel is not in use by any other device. The 802.15.4 compliant PHY perform CCA according to at least one of the following methods:

- Mode 1: Energy above threshold. CCA will report a busy channel if it detects energy above the energy detection (ED) threshold. Whereby, the ED threshold will be at most 10 dB above the specified receiver sensitivity.
- Mode 2: Carrier sense only. CCA will report a busy channel if it detects a signal with comparable modulation and spreading characteristics of IEEE 802.15.4 transmission, regardless of signal's energy being above or below the ED threshold.
- Mode 3: Carrier sense with energy above the threshold. CCA will report a busy channel only if it detects a signal with comparable modulation and spreading characteristics of IEEE 802.15.4 transmission with energy above the ED threshold. This is a combination of the two modes above.

The MAC request is received by the PLME-CCA.request primitive (see subsection 2.10.7) during reception of a PHY protocol data unit (PPDU). A busy or idle channel will be indicated by the PLME-CCA.confirm primitive with status BUSY or IDLE respectively. The CCA detection time will be equal to eight symbols periods. The PHY PIB attribute *phyCCAmode* will indicate the appropriate CCA operation mode(1-3).

MAC uses physical carrier sensing (PCS) whenever a node intend to start transmitting a packet. PCS is performed at the physical layer whereby the medium is sensed before a node initiate transmission. Similarly, 802.15.4 uses clear channel assessment (CCA) or energy detection provided as received signal strength indicator (RSSI) services in 802.15.4 PHY. Figure –shows the CSMA/CA algorithm used by the MAC layer. The node will transmit a packet only when the energy level of the RF medium signal sampled by PCS is below the carrier sense threshold. Consequently, PCS plays an important role in MAC layer collision avoidance algorithm. Usually the PCS threshold is a static constant value in most MAC implementation [83, 81]. We can minimise collision and interference if we properly tune carrier sensing PCS threshold [83], in doing so, we conserve energy as well. Higher value of PCS threshold (CSthresh_) would lead into more collision due to hidden terminal problem and lower value would decrease the level of spatial reuse. Currently most of PCS are configured with fixed very low values that sometimes even a remote communication would generate a signal strong enough to make a station withhold its transmission, as a result very little spatial reuse is possible. Liu [81]argues that independent variable PCS are not suitable for WSNs due to sensor nodes energy limitations and processing capability. An analytical model for deriving an optimal carrier sense threshold for the IEEE 802.11 mesh network is presented by Zhu[83].

2.10.6 PHY Frame Format

The PHY protocol data unit (PPDU) packet is illustrated in Figure 2.5. Each PPDU packet consists of the following basic components:

- A synchronization header (SHR), which allows a receiving device to synchronize and lock into the bit stream. This consists of four bytes of zeros preamble field used for synchronisation and one byte of a predefined start-of-frame delimiter (SFD) used to indicate the end of synchronisation and the start of the data packet.
- The PHY header (PHR), which contains frame length information (from 0 to 127 bytes, inclusive).

- The PHY service data unit (PSDU) which carries the MAC sublayer frame of variable length.

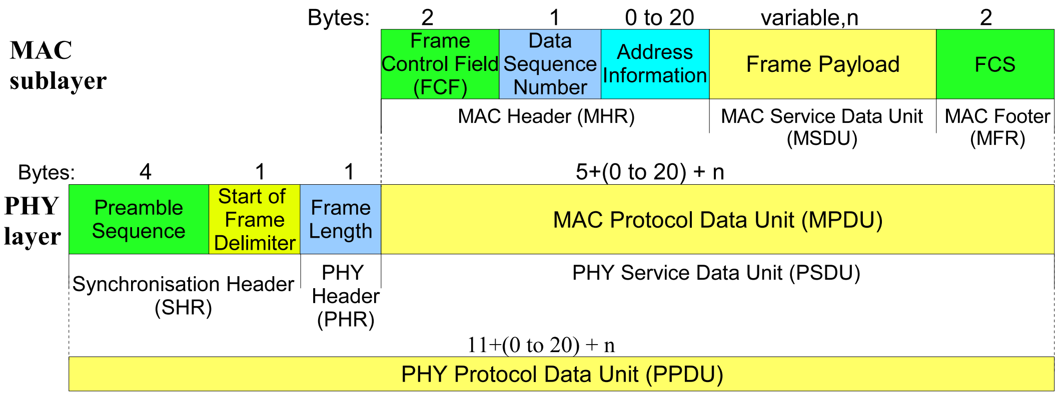


Figure 2.5: IEEE 802.15.4 frame format

2.10.7 Physical Service Specifications

The PHY layer provides an interface between the MAC sublayer and the physical radio channel, via the RF hardware (Figure 2.6). The PHY layer conceptually includes a management entity called the PLME, which provides the layer management services interfaces through which layer management functions may be invoked. The PLME is also responsible for maintaining the PHY layer database known as the PHY PAN information base (PIB), containing PHY managed objects.

PHY provides two services that can be accessed through two Service Access Points (SAPs). These are the PHY data service, accessed through the PHY data SAP (PD-SAP), and the PHY management service, accessed through the PLME's SAP (PLME-SAP).

The standard defines ways through which communication is carried between layers via service primitives having the following form:

- Request-a layer uses this type of primitive to request that another layer perform a specific service.

- Confirm-a layer uses this type of primitive to convey the results of a previous service request primitive.

- Indication-a layer uses this type of primitive to indicate to another layer that a significant event has occurred. This primitive could result from a service request or from some internally generated event.

- Response-a layer uses this type of primitive to complete a procedure initiated by an indication primitive.

The PD-SAP which supports exchange of data packets between MAC and PHY has the following primitives: PD-DATA.request, PD-DATA.confirm and PD-DATA.indication. The PLME-SAP which support the exchange of management commands between MLME and PLME has request and confirm primitives for the followings: PLME-CCA, PLME-ED, PLME-GET, PLME-SET-TRX-STATE and PLME-SET. These primitives are an abstract way of defining the protocol, and they do not imply a specific physical implementation method. Similarly, the MAC layer provides an interface between network or application layer.

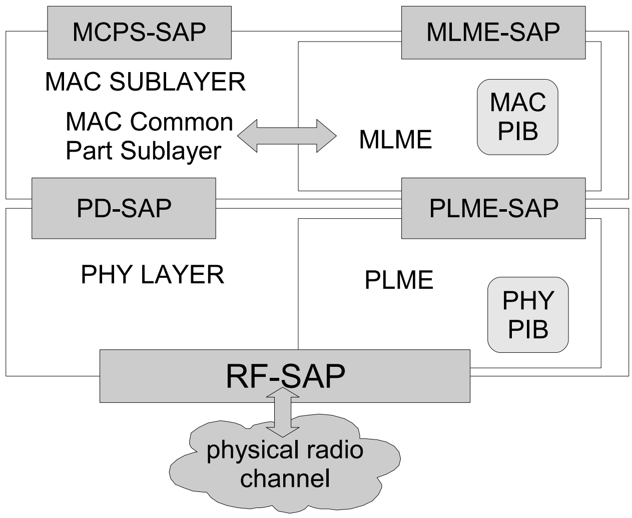


Figure 2.6: PHY layer and MAC sublayer reference model

There are several constants that define characteristics of a particular PHY layer; these constants are hardware dependent and therefore cannot be changed during operation. These constants variables include:

- *aMaxPHYPacketSize*, which is the maximum PSDU packet size the PHY will be able to receive is 127 bytes, and
- *aTurnaroundTime*, which is the RX-to-TX or TX-to-RX 12 symbol periods maximum turnaround time.

There are also several variable attributes in PHY PIB required to manage a device's PHY layer. These attributes can be read or written using PLME-GET.request and PLME-SET.request primitives, respectively. These attributes include:

- *phyCurrentChannel*, which is the desired RF channel out of 27 valid channels to be used for transmissions and receptions
- *phyChannelsSupported*, which is the supported channel or channels amoung 27 valid channels
- *phyTransmitPower*, which is thedifferent power levels
- *phyCCAMode*, which is the CCA mode used out of the three CCA modes

2.11 Supported Network Devices

In the IEEE 802.15.4 specifications, network devices can be classified as full-function (FFDs) or reduced function devices (RFDs). A FFD has more processing ability and contains the full protocol stack with a complete set of MAC services. All PAN coordinators are FFDs that have the ability to communicate with other FFDs and RFDs. In contrast, RFD is an end device operating with minimum implementation of the IEEE 802.15.4 protocol, i.e. contains only a subset of the protocol stack. A RFD cannot associate with more than one FFD concurrently, and is designed for extremely simple applications, such as a light switch or a passive infrared sensor involving small data packages. A FFD can operate in three different network roles: (1) serving as a Personal Area Network (PAN) coordinator, responsible for starting , identifying the network and configuring the network, and operating as a gateway to other networks; (2) as a subset node coordinator providing synchronization services (through beacon transmission), self-organization operations and data routing; (3) as a device, which does not provide the above functions and must associate with a Coordinator before interacting with the network.

2.12 Network Topology

Depending on the application requirements, the standard supports two network topologies, star and peer-to-peer. In star topology, communication is controlled by PAN coordinator that operates as the network master and other devices operates as slaves. A star topology is more appropriate for applications such as home automation, personal computer peripherals, toys and games and personal health care.

In our work we consider both topologies using the IEEE 802.15.4 standard. In peer-to-peer networks devices can communicate with each other as long as they are in range of one another. One special type of peer-peer topology is cluster-tree network as depicted in Figure 2.7. The network consists of clusters, each having a coordinator as a cluster head and multiple devices as leaf nodes. A PAN coordinator initiates the network serves as the root. The network is formed by parent-child relationships, where new nodes associate as children with the existing coordinators. A PAN coordinator may instruct a new child FFD to become cluster head of a new cluster. Otherwise, the child operates as a device as shown in figure 1. One of the advantages of using multicluster topology is increase coverage area by trading off message latency. Node operations in cluster-tree network are specified by ZigBee Alliance document [84].

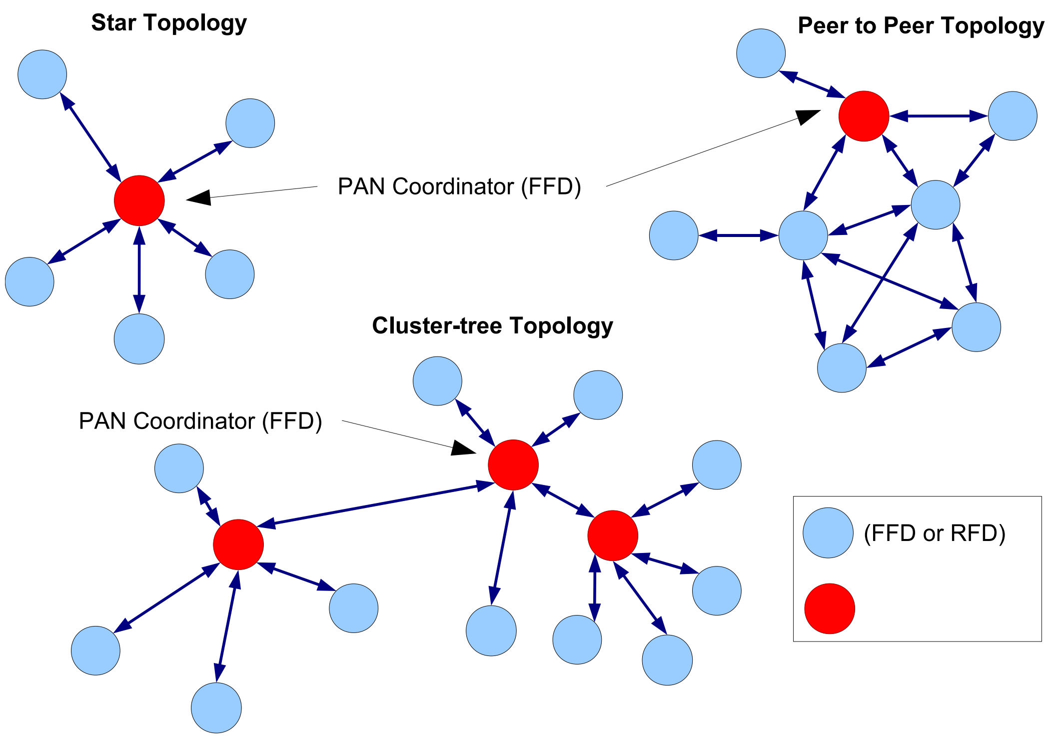


Figure 2.7: IEEE 802.15.4 supported topologies

2.13 IEEE 802.15.4 MAC Sublayer

IEEE 802.15.4 MAC sublayer protocol supports two operational modes, beacon enable mode and non beacon enable mode. A particular mode of operation is selected by central node, i.e. PAN coordinator. In non beacon enable mode, MAC is ruled by a simple non-slotted Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol that require a constant reception of possible incoming data. In beacon enabled mode, MAC is ruled by modified slotted CSMA/CA protocol. We concentrate on the beacon-enable operational mode in this research, since the most important power saving features that are critical to WSNs application can only be supported in this particular mode. In addition, beacon-enable mode offers flexibility and additional features in WSN applications that are not possible in non beacon enable mode. Some of these features include synchronisation service using beaconing and optional contention free period (CFP) using Guaranteed Time Slots (GTS) technique.

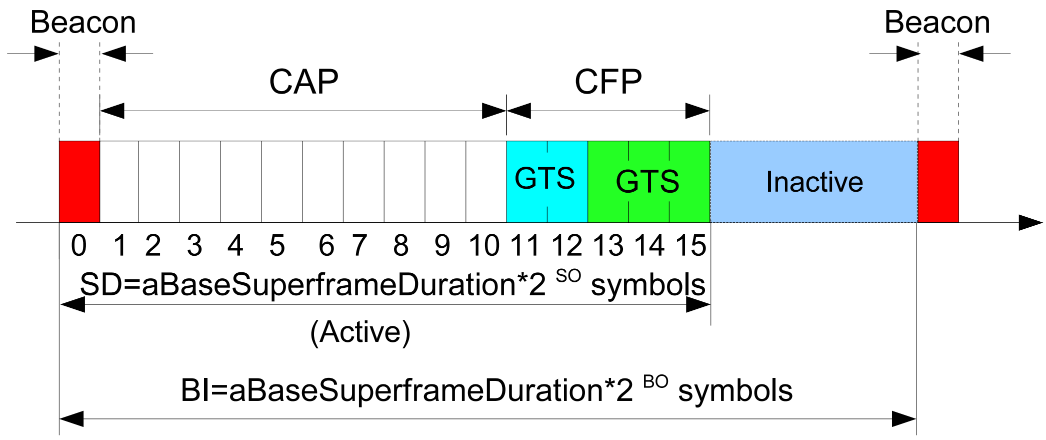


Figure 2.8: Superframe format

In beacon-enable mode all communication must occur within a superframe structure that is maintained by the central device, referred to as PAN coordinator (Figure 5.2) . A superframe is bounded by periodically transmitted beacon frames, used by PAN coordinator to control channel time and allow nodes to synchronise to the network. For example in cluster-tree networks, all coordinators may transmit beacons in order to maintain the synchronisation with their children. In the current mode, beacon frames are also used by central device to identify its PAN.

A superframe is divided into two parts, an active period part and an inactive period part as presented in the figure below. The coordinator can only interact with PAN during the active period part of the superframe, the remaining part of the superframe (if any) is an inactive period part, during which nodes may enter a power (sleep) saving mode to conserve battery power.

The constructed superframe structure is based on (1) Beacon Interval (BI), defining the time between two consecutive beacon frames, (2) Superframe Duration (SD), defining the time period of the active portion of the superframe. An inactive part of the superframe can only be defined when BI is greater than SD. BI and SD are determined by two MAC PAN information base parameters, the macBeaconOrder, BO, describes the interval at which the coordinator transmits its beacon frame and macSuperframeOrder, SO, describes the length of the active portion of the superframe respectively. The value of BO and SO are related to beacon interval, BI, and superframe duration, SD, respectively, as follows:

For 0=<BO=<14, BI = aBaseSuperframeDuration * 2^BO symbols

The values of SO related to the superframe duration, SD, are related as follows: for 0=<SO=<BO=<14, SD = aBaseSuperframeDuration*2^SO symbols The active portion of each superframe is divided into aNumSuperframeSlots equal spaced of duration 2^SO * aBaseSlotDuration and aBaseSuperframeDuration = aBaseSlotDuration x aNumSuperframeSlots. Assuming 250kbps in 2.45 GHz frequency band, aBaseSlotDuration equals to 60 radio symbols resulting 15.36ms minimum SD(SO = 0) with 16 superframe slots. Hence (BI) and SD may be between 15.36ms and 251.7s. In case of non beacon-enable, both macBeaconOrder and macSuperframeOrder are set to 15 by PAN coordinator and therefore an unslotted CSMA-CA mechanism is used to access the channel.

In beacon-enable mode, the 16 contiguous time slots in the active period part of each superframe are composed of three parts: the beacon, contention access period (CAP) and contention-Free period (CFP). The beacon transmitted without the use of CSMA, at the start of slot 0, followed by CAP and CFP to the end of active part of superframe. In addition to the beacon, CAP is mandatory part of a superframe. Coordinators are required to listen to the channel the whole CAP to detect and receive any data from their child nodes. On the other hand, the child node may only transmit data and receive an optional acknowledgement (ACK) when needed, which increases their energy efficiency.

Downlink data from a coordinator to its child require a total four transmissions. The availability of pending data is signaled in beacons. First, a child requests the pending data by transmitting a data request message. The coordinator responds to the request with the ACK frame, and then transmits the requested data frame. Finally, the child transmits ACK if the data frame was successfully received.

All frames, except acknowledgement frames and any data frame that quickly follows the acknowledgement of the data request command, transmitted in the CAP will use a slotted CSMA-CA mechanism to access the channel. A device transmitting within CAP shall ensure that the transaction is complete (i.e including the reception of any acknowledgement) one IFS period before the end of the following superframe. If this is not possible, the device shall defer its transmission until the CAP of the following superframe.

2.13.1 The CSMA-CA procedure

The CSMA/CA procedure is used for each data frame transmission or MAC command frame during contention access period (CAP). The CSMA/CA will not used during the transmission of beacon frames, acknowledgement frames or data frames transmitted during contention free access (CFA) and any data frame that quickly follows the acknowledgement of data request command . In beacon enable mode, the MAC sublayer uses the slotted version of the CSMA/CA algorithm for transmission in the CAP of the superframe. If beacons are not used then unslotted version of CSMA/CA algorithm is used. In slotted CSMA/CA, the backoff period boundaries of every device in the PAN shall be aligned with the superframe slot boundaries of the PAN coordinator. i.e. the start of the first backoff period of each device is aligned with the start of the beacon transmission. In slotted CSMA/CA, the MAC sublayer shall ensure that the PHY commences all of its transmissions on the boundary of a backoff period. In the case of unslotted CSMA/CA, the backoff periods of one device are not related in time to the backoff periods of any other device in the PAN.

The CSMA/CA mechanism is based on a basic time unit referred to as Backoff Period (BP), which is equal to aUnitBackoffPeriod = 80 bits or 20 symbols, i.e. 0.32ms in 2.45 GHz frequency band. The slotted CSMA/CA can be summarized in five steps. To accessing the channel or each transmission attempt, each node maintains three variables: 1) NB is the number of backoff attempts for the current transmission, initialized to 0 before each new transmission attempt. 2) BE is the backoff exponent, which define the number of backoff periods a node should wait before attempting to assess the channel or perform a clear channel Assessment. With macBattLifeExt set to FALSE, BE shall be initialized to the value of macMinBE. In slotted systems with macBattLifeExt set to TRUE, this value shall be initialized to the lesser of 2 and the value of macMinBE. 3)CW is the contention window length, which define the number of consecutive backoff periods a channel needs to be silent before transmission can commerce (Default value = 2) CW=2 before each transmission attempt and reset to 2 each time the channel is accessed to be busy. The CW variable is only used for slotted CSMA/CA. The backoff period length (tBOP) is defined as 0.32ms in the 2.4GHz band.

When using slotted CSMA/CA First, the MAC sublayer initializes NB, CW, and BE, and then locates the boundary of the next backoff period.

Second, The MAC sublayer delay for a random number of complete backoff periods in the range 0 to 2^BE – 1

Third, MAC request that the PHY perform a CCA, in slotted CSMA/CA, the CCA shall start on the backoff period boundary. In unslotted, the backoff starts immediately.

Fourth, if channel is assessed to be busy, the MAC sublayer shall increment both NB and BE by one, ensuring BE shall not be more than the aMaxBE. MAC in slotted shall also reset CW to 2. CSMA/CA will return to step two if the value of NB is less than or equal to macCSMABackoffs. CSMA-CA will terminate with a Channel Access Failure status if the value of NB is greater than macCSMABackoffs.

Fifth, if the channel is accessed to be idle, the MAC sublayer in slotted CSMA/CA system will ensure that the contention window has expired before commencing transmission. To do this CW is decremented by 1 and if it reaches zero then the data is transmitted otherwise the algorithm goes back to step 3. This ensures that CCA is performed twice to prevent potential collisions of acknowledgement frames. If the channel is again sensed to be idle, the node attempts to transmit provided that the remaining BPs in the current CAP is sufficient to complete the transaction (i.e including the reception of any acknowledgement) one IFS period before the end of the following superframe. If this is not possible, the device shall defer both CCAs and frame transmission until the next CAP of the following superframe.

2.13.2 The Self-Organisation and Self-Configuration Aspect

One of the very important aspects of wireless sensor networks is that of an ad-hoc property whereby wireless networks should exhibit self-organising and maintaining of the network. The major activities that an ad-hoc network is required to perform to achieve self-organisation are neighbour discovery, topology organisation and topology reorganisation. During the neighbour discovery phase, every node in the network gathers information about its neighbors and maintains that information in appropriate data structures. This information is obtained periodically either by sending short packets called beacons, or by promiscuous snooping on the channel to detect any neighbours' activities.

2.14 Conclusions

The literature review focused on a range of WSN research and development in both physical layer and medium access control (MAC) sublayers, the IEEE 802.15.4 standard, and key concepts and theories relating to this research. The literature review included a review on the transmission power control, IEEE 802.15.4 medium access control (MAC), and self-configuration. The IEEE 802.15.4 is designed for low rate wireless personal area networks (LR-WPANs), making it the first WSN-enabling standard. However, the development of a particular WSN application will require solutions, integrated to a high degree, for both robust hardware and efficient protocols or software to achieve effective communication. So far there have been no clear guidelines or design rules that had to be followed in designing sensor network architectures because of the wide range of sensor applications, with each application having its own unique purpose and performance requirements (i.e., various hardware and network capabilities). Furthermore, both the general WSN architecture and hardware architecture for WSNs with a detailed comparison of some of the currently available hardware components were presented. The object of such a comparison is to provide information about some of the latest innovations, and the challenges to face and solutions to consider when developing new ones. These forefront initiatives require a balance between power consumption and other performance parameters. The optimal choice of sensor system, processor, wireless interface, and memory technology is not only application dependent, but also exhibits temporal dependence for a given application.

Chapter 3

Problem Formulation and Background

3.1 Introduction

In Chapter 1, the purpose of this study was defined "to investigate strategies to improve the performance of WSNs to maintain reliable network connectivity, improve scalability and save energy". Having established the background literature framing in Chapter 2, this Chapter directs the emphasis on the research questions and the approach used to address them or the research methodology.

The structure of the chapter can be summarised as follows. Section 3.2 of this chapter provides an overview of the background and motivation for this research. Section 3.3 includes a detailed presentation to research questions, background and the approach used to address the questions. Section 3.4 presents a summary of research contributions. Section 3.5 describes the methods and tools used in this research, and Section 3.6 describes some of the essential performance parameters in this study. Section 3.7 presents the general research assumptions and Section 3.8 discusses some of the research limitations and future research directions. Section 3.9 concludes the chapter.

3.2 Background to the Research

Traditionally, sensor networks have been connected via considerably reliable wired networks. However, establishment and maintenance costs for these networks comprise 33~70% of the entire system cost [1, 2, 3, 4]. The advantages of wireless connectivity include the likelihood of saving the network's establishment and running costs . In the near future, sensor networks will be able to support new opportunities or applications for interaction between humans and their physical world. Specifically WSNs are expected to contribute significantly to pervasive computing and space exploration. Deploying sensor nodes in an unattended environment will provide tremendous possibilities for the exploration of new applications in the real world. However, this area of study is still underdeveloped. Furthermore, the lack of relevant guidance and practical approach when dealing with WSN applications means that solutions are needed.

The main motivation behind this research study is a belief that the performance of WSNs may benefit from further cross-layer protocol improvements and further knowledge regarding the operation of a particular protocol. The initial research cycle identified general problems in wireless sensor networks. Thus investigation of how performance of WSNs could be improved and how this could be better integrated into the working IEEE 802.15.4 standard was required. While a wide-range of research in wireless networks thrives on ways to improve the quality of service (QoS) of wireless networks for multimedia applications. The primary performance objectives of wireless sensor networks in most cases are energy conservation, throughput improvement, scalability and self-configuration, whereas fairness and temporal delay are often secondary issues [20].

We anticipate that to achieve technological and marketplace success, the low power, inexpensive sensor networks need to achieve energy efficiency and reliable connectivity. Enhancing communication networks for reliable wireless connectivity, self-configuration, cost effectiveness and energy efficiency is the challenge for WSNs. For example, ability to work with minimum energy consumption will prolong the network lifetime. Since sensor nodes share a common wireless medium, an efficient medium access control (MAC) operation is required; however other issues which cannot be ignored include topology changes or mobility, multi-hop communication, self-configuration, unattended nature of wireless sensors (power), connectivity, and throughput improvement. In particular, a WSN application will require a high level of system integration, performance, and productivity.

3.3 Research Main Objective and Questions

The main purpose of this research is to investigate means to improve the performance of WSNs to maintain reliable network connectivity, scalability and energy efficiency. The study focuses on the IEEE 802.15.4 MAC/PHY layers and the carrier sense multiple access with collision avoidance (CSMA/CA) based networks. So the main research question is "how and what can be done to improve the performance of WSNs to maintain reliable network connectivity, scalability and energy efficiency in the IEEE 802.15.4 based networks?" To answer this question, this research consists of four semi-independent areas of study and therefore four backgrounds to the problem. The following subsections present the four main research areas of the study and questions that this research set out to explore. For the purpose of clarity, each of these four areas of study including results is addressed separately in Chapter 4, Chapter 5, Chapter 6 and Chapter 7 of this thesis (see Table of Contents).

3.3.1 The impact of multi-hop and transmission power control in 802.15.4

This first major theme connects directly to the discussion in the literature review that an N hop multi-hop communication can be more energy-efficient than single-hop communication for same distance, Nr by deriving the following expression:

$$\eta_{rf} = \frac{P_{send}\,(Nr)}{N.P_{send}\,(r)} = \frac{(Nr)^{\alpha}\,P_{received}}{N.r^{\alpha}P_{received}} = N^{\alpha-1}$$

where r , α, P_{send}, and $P_{received}$ are the one-hop distance, radio frequency (RF) attenuation, the power at a transmission node, and the minimum received power at a node respectively. We take the relationship between the number of hops and transmission power control, and pay particular attention to the likelihood that multi-hop might be beneficial for energy saving in WSNs. In consideration of these points and the specific literature review in Chapter 4, the basic research questions which are addressed in Chapter 4 are:

1. How can we specifically test multi-hop TPC communication versus single-hop communication using typical wireless sensor node hardware parameters?
2. What is the performance advantage of using multi-hop TPC in energy constraint WSNs instead of a single-hop in terms of energy efficiency and other important performance parameters? Essentially, I what to determine as to whether transmission power control in multi-hop communication is more energy superior than single hop

communication and by how much with an increasing number of hops. Further questions concerning multi-hop TPC grow out of these, for instance, are there any ways that we can use TPC to improve energy efficiency in WSNs ?

3.3.2 The impact of beacon interval in association and synchronization

This second major theme is the self-configuration aspect of WSNs, which also connects directly to the discussion in the literature review in Section 2.13. One of the key aspects of a wireless sensor network is its ability to self-organize and maintain connectivity. Medium Access Control (MAC) protocol manages network self-configuration, which includes establishing a personal area network (PAN), finding a network to associate or disassociate with, and synchronizing if required. In beacon-enable mode all communication must occur within a superframe structure that is maintained by the central device, referred to as PAN coordinator. A superframe is bounded by periodically transmitted beacon frames, used by PAN coordinator to control channel time and allow nodes to synchronise to the network.

Currently, there is limited research addressing the network initialization phase or self-configuration phase. This appears to be the first investigation of the performance of the 802.15.4 MAC beacon interval setting and the number of associating nodes. The performance evaluation is based on the number of nodes associating with a coordinator and beacon intervals in terms of the time required for a node to associate with its coordinator (association delay) and energy consumed by a node to associate and synchronize with the coordinator. In consideration of these points and the specific literature review in Chapter 5, the basic research questions addressed in Chapter 5 are:

3. What is the impact of beacon interval (BI) and number of nodes during WSN association and synchronization stages in terms of energy and association or synchronization time?
4. How can we improve the performance of WSNs during association and synchronization stage (self-configuration)?

3.3.3 Clear channel assessment and enhanced MAC

This third major theme connects directly to the discussion in the literature review on the IEEE 802.15.4 MAC protocol standard controlling radio channel access using the Carrier

Sense Multiple Access with Collision Avoidance (CSMA/CA) algorithm. To avoid collisions, the standard adjusts the backoff exponent (BE) based on two consecutive clear channel assessments (CCA) before packet transmission. The CCA part is carried out at the physical (PHY) layer, and used by the MAC protocol as part of the CSMA/CA algorithm, whereby a node is required to perform a CCA for a predetermined duration to determine if the channel is available for transmission before transmission of the data frame.

In consideration of these points and the specific literature review in Chapter 6, the basic research questions addressed in Chapter 6 are:

5. What is the impact of the number of times the clear channel assessment (CCA) is performed in the 802.15.4 MAC during frame transmission in terms of throughput, packet error rate, delay and energy consumption for both hidden and non-hidden nodes in a network ?
6. What can be done to improve the performance of the 802.15.4 MAC during frame transmission stage?

3.3.4 Analysis of CSMA/CA using Markov chain

The last major theme, similar to the previous section connects directly to the discussion in the literature review on the IEEE 802.15.4 MAC protocol standard that controls radio channel access using the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) algorithm. However, Markov Chain theorems were used to model the CSMA/CA operation in order to be able to forecast the performance outcome for CSMA/CA. This is of prime importance to protocol designers since one can use the insight gained using Markov Chain to fine-tune ones design strategies. Obviously in analytical mathematical modelling, one relies on assumptions and approximations made to simplify mathematical expressions while closely modelling/describing an original protocol or process.

Considering these points and the specific literature review in Chapter 7, the basic research questions addressed in Chapter 7 are:

7. How can Markov chains be used to accurately model the IEEE 802.15.4 slotted CSMA/CA ?
8. What is the relationship between different performance variables and the MAC parameters derived from the Markov Chains?

3.4 Significance of the Study

This section provides a brief description on various significances of the study. This research is beneficial to students, researchers and network designers as it contributes further knowledge to the WSN area of research particularly on network connectivity, scalability, energy efficiency, self-configuration and possible MAC and physical layer cross layer enhancements. The research serves future researchers baseline information on the recent advancement of WSNs and their possible performance improvements. This research provides a practical outcome to assist network engineers or designers in developing and improving more effective protocols for WSNs. Several works relating to this thesis have been published during the course of candidature. The list of publications can be found on pages xi-xii of the thesis.

The main contributions of this research have been described in Chapter 1 and also reviewed in the final chapter. The significance of the research relates to the outcomes of the four semi-independent areas of study described in Section 3.3 above.

In summary, the main research contributions listed according to the research question number (Section 3.3) are:

1. This study has developed a novel approach to testing multi-hop and single-hop transmission power control (TPC) at the physical layer using typical wireless sensor node hardware parameters.

2. One of the more significant findings to emerge from this study is the evidence that contrary to what has been reported from previous studies, in multi-hop networks, TPC did not save energy. Both the radiation and electronic components of the energy consumption were investigated, and results indicated that sending packets using a short-range multi-hop path, instead of a single-hop, does not necessarily save energy as suggested by some researchers. The results of this study support the idea that a better topology such as cluster topology is required rather than flat topology

3. The study has added to the body of knowledge as it appears to be the first investigation of the performance of the 802.15.4 MAC beacon interval setting and the number of associating nodes. The study findings suggest that over a longer period, shorter beacon intervals will consume more of the node's energy while long beacon

intervals will spend less energy, at least for BO=0 to BO=11. The associating energy consumption increases with increased number of nodes for all beacon intervals (B0=0-15). For longer beacon intervals, BO=12 to BO=14, there is an abrupt increase in energy consumption as the number of associating nodes increases, even for a small number of nodes, such as four. This study has shown that it will take about 42 minutes for 7 nodes requesting association to associate with the coordinator, when BO=14. Such long delays are not suitable for real time and mobile WSN applications.

4. The findings of this study raised a question as to whether the association energy consumption will outweigh the benefit of duty cycle power management for larger beacon intervals, as the number of associating nodes increases. The evidence from this study suggests a need for a better protocol design to resolve this.

5. The most obvious finding to emerge from this study is that there is serious network performance degradation even for a small number of hidden nodes in a network. The results of this study also indicate that there is some improvement in terms of: 1) throughput; and 2) average packet delay, when sensing the channel for shorter duration (once), instead of twice or thrice as the traffic load increases; however there is no significant difference in energy consumption and packet error rate. An implication of this is the possibility that that likelihood of a channel being idle or busy the second or third time is smaller once it has been sensed busy or idle the first time.

6. The study provides a proposed cross layer (PHY-MAC) mechanism to save energy, reduce interference, improve scalability and reliability, and reduce packet collisions due to hidden terminals.

7. The study developed an analytical model for the IEEE 802.15.4 slotted CSMA/CA scheme using Markov chains. The body of knowledge was increased by the development of theoretical understanding related to IEEE 802.15.4 operational and performance of CSMA/CA.

8. The study developed model captures essential features of the slotted CSMA/CA that can be used to forecast some of the performance parameters such as successful transmission probability, throughput and average energy consumption.

3.5 Research Methods and Tools

The design and investigation in the current research has been carried out using a combination of simulation, numerical method and Markov chain modelling. To answer the research question posed above different methods were used given that the research consists of four semi-independent areas of study as described in Section 3.3 above. The methods and findings for each study area are covered in Chapter 4, 5, 6 and 7 respectively. The objectives and research questions elaborated in the previous section will mainly be addressed via NS 2 simulations, which is the main research instrument for this thesis. Where possible theoretical mathematical numerical and analysis will be provided.

The research methods involved investigation, analysis and proposed improvements in the MAC and Physical layer, particularly in the IEEE 802.15.4 based WSNs. Both strengths and weaknesses of the protocols are determined. Experiments, implementations and research questions were addressed using NS 2 simulations and where possible numerical mathematical expressions and analytical modelling was carried out using Markov Chain theorem. NS 2 is the main methodological approach used in this research. We use NS 2 for implementation, modelling and simulation of a real system to help us answer research questions.

There are numerous software tools used in our research. Some of these software tools include Eclipse, which was used to develop and debug our C++ implementation code [85]. Doxygen [86] was used extensively for documentation of existing protocol implementation in ns-2 and our implementation. We provide an overview description of ns-2, which is the main simulation and protocol implementation design tool used throughout the research. Furthermore, we provide the steps involved in implementing and simulating a particular network scenario using ns-2 simulator and discuss some of the ns-2 limitations.

3.5.1 Network Simulator 2 (NS 2)

NS-2 is one of the most widely used publicly available object oriented, discrete event driven network simulators used in education and research today. The ns simulator project was started as a variant of the REAL network simulator in 1989 and evolved substantially ever since. The simulator is written in C++ and it uses OTcl interpreter as a command and configuration front-end. It supports a large number of packet switching protocols and also provides a very rich flexible platform for developing and testing new protocols. Using ns-2 flexibility, one can simulate variants of available network protocols or design a new protocol using available flexible models.

NS-2 is capable of simulating mobile nodes connected by wireless interfaces using 802.15.4 standard protocol. In the current research thesis, ns-2 with the wireless extension implemented by the Rice monarch Project was used [82]. Given all these features, i.e. open source, flexibility and great design potential, ns-2 was chosen as the developing and testing platform in the current research.

In this we describe some of the tools and methods used in the current research for the investigation and protocol design using a Network Simulator (NS-2) [82]. It focuses on development of a framework for designing, optimising, analysing and carrying out performance measurement of 802.15.4 standard and proposed design for wireless sensor networks.

Supplementary information about the simulator can be found in an Appendix A, which includes the following sections: Installation and Settings, Simulator Internal Architecture, The Concept of Discrete Event Driven, Ns-2 Simulation, Extending New Implementation/-Coding, Extracting Information from the Trace Files, and Simulation Visualization.

3.5.2 Research Framework/Simulation Environment

The summary of overall simulation environment is shown in Figure 3.1. The text editor is used for writing awk scripts and OTcl script to setup the network, traffic and other simulation parameters. Variable specification and implementation changes can be done solely using OTcl or by changing the C++ network elements code. Upon running tcl script in ns-2, ns-2 will generate trace files that contain events record (tracefile) and for NAM (NAM trace file). These files are then processed for further analysis. Note that in the Figure 3.1, gnuplot, Eclipse, awk or perl script and doxygen are not part of the ns-2 simulator. These tools are used for further processing of information produced by the ns-2 simulator. For example, doxygen was used to produce documentation for the NS 2 C++ code. Awk scripts are used to extract relevant information and obtain a particular performance parameter of interest from the large trace file. The relevant information obtained can then be analysed and plotted using one of the graphics tools.

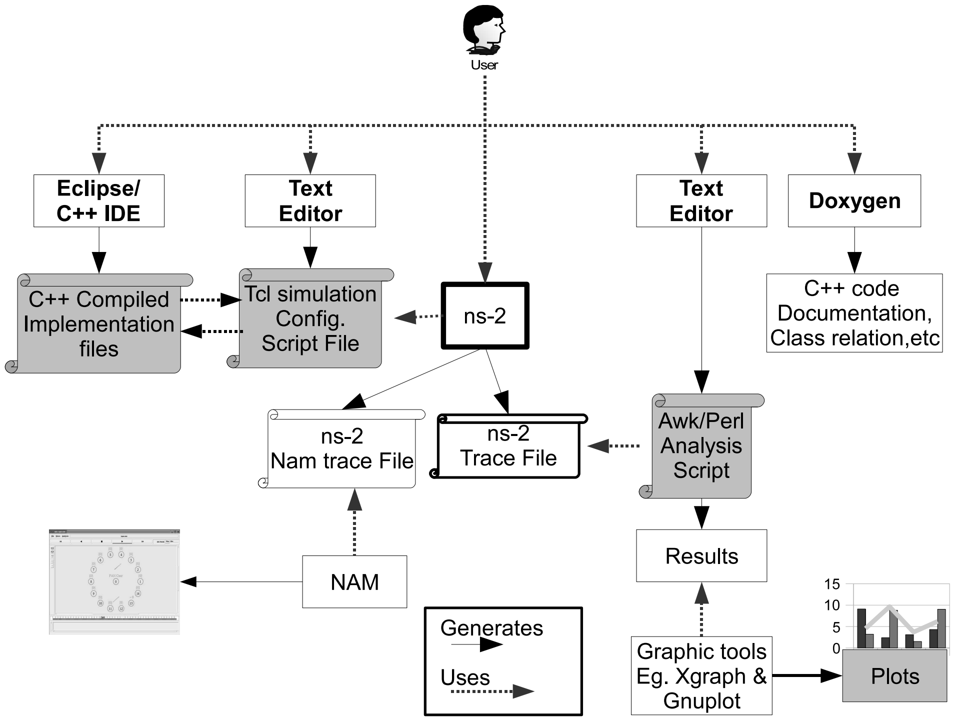


Figure 3.1: Research framework

3.5.3 Markov Chain Analysis

A discrete Markov chain model was used in the last study area as a methodological approach to answer the research questions. Generally, a discrete Markov process $\{X_n\}$ is a stochastic process with the property that the probability of any particular future behaviour of the process, when the current state is known exactly, is not altered by additional knowledge concerning its past behaviour. From the definition $\{X_n\}$ is Markov chain if

$$P_r\left\{X_{n+1}=j \mid X_0=i_o, ...X_{n-1}=i_{n-1}, X_n=i\right\}=P_r\left\{X_{n+1} \mid X=i\right\}$$

For all time points n and all states i_0.......i_{n-1}, i, j.

Notation : $P_r\left\{X_{n+1}=j \mid X_n=i\right\}=P_{ij}$, where

$P_{ij} \geq 0$ for $i, j=$ 0,1,2.... and $\sum_{j=0}^{\infty} P_{ij}=1$ for $i=0,1,2,3,...$

Once all the transition probabilities have been obtained, the Markov chain can be numerically solved to obtain the stationary probability distribution of each state using recursive solution, $\pi=\pi A$, where A is the initial state condition and $\pi$is the transition matrix.

3.6 Performance Metrics and Analysis

Performance measurements are carried using results obtained from ns-2 simulations and where possible, analytical and numerical models were used in the analysis of our findings.

3.6.1 Throughput

Network performance is a measure of a network's performance throughput, which is the amount of data transferred from one place on the network to another or the amount of data processed over a specified amount of time. Data transfer rates for network are measured in terms of throughput. In general, throughput is measured in kilobits per second (Kbps), megabits per second (Mbps) and gigabits per second (Gbps). Apart from measuring the bandwidth of a network, network performance also takes into account how fast a piece of data travels from one part of a network to another. Furthermore, network performance takes into account dropped (lost) network packets. The throughput thus equals the offered load multiplied by the probability of successful packet reception, $throughput = load * probability$, where this probability is a function of the random access protocol in use as well as the channel characteristics, which can cause packet error in absence of collisions. Performance of random access techniques is typically characterized by the throughput of the system. A high performance network, has therefore, high bandwidth, quick transfer rates, and low rates of packet loss. The achieved throughput in an ad-hoc network is affected by numerous factors that include radio interference between hops, ability of the routing protocol to react to topology changes and a complex interaction between the application and underlying protocols. Furthermore, UDP and TCP performance is reduced in a multi-hop 802.15.4 WPAN environment because of radio interference between hops.

Throughput is the rate at which network sends or receives data and a good measure of channel capacity.

The aggregate throughput, S in a simulation study can be obtained by using the following expression:

$$S = \frac{TotalReceivedBytes \times 8}{Simulation\,Time \times Bit\ Rate} \tag{3.1}$$

3.6.2 Packet delivery ratio or Bit Error Rate

This performance metric presents the ratio of total data packets successfully received or delivered to the destinations application layer to total packets generated or sent by sources. It is desirable to have a high packet delivery ratio for efficient bandwidth utilization in wireless networks where available bandwidth is a limiting factor. This performance measurement is important because it reveals the loss rate seen by transport protocols and also characterises the completeness and correctness of the MAC and routing protocols. There are number of factors that can cause high BER, such as signal interference caused by devices in the same frequency spectrum, multipath fading, packet collision, the quality of the channel and established links. For wireless sensor networks, a BER of less than 10-5 is acceptable. Delivery ratio in a simulation study can be obtained by using the following expression:

$$Delivery\,ratio = \frac{Number\ of\ delivered\,packets}{Total\ number\ of\ transmitted\,packets} \tag{3.2}$$

3.6.3 End-to-end delay

End-to-end delay of data packets is another important metric of performance that involves sources and receivers. The end-to-end delay is the total delay that a data packet experiences as it is traveling through the network from the sources through wireless media to the destination. This delay is built up by several smaller delays in the network that add together. These delays include buffering delay during route discovery latency, the time spent queuing at the interface queue, forwarding delays, propagation delay and the time needed to make retransmissions in the case of packet lost.

End-to-end delay in a simulation study can be obtained by using the following expression:

$$Delay = Packet\,destination\,arrival\,time - Packet\,source\,send\,time \tag{3.3}$$

3.6.4 Energy Efficiency

A sensor network is expected to have a long operational life to further reduce the cost of maintenance and deployment. Energy efficiency (normalised energy) is often the key performance parameter in most WSN applications due to limited battery life. We define energy efficiency or the effective transmission energy per packet as the ratio of total amount of data delivered and total energy consumed or by determining the total transmission energy spent in transferring an amount of traffic load, e.g. 20 byte, from a source node to a destination node. Similarly, the energy per bit is defined as the energy consumed by the network to successfully deliver a bit of data to the sink averaged over all nodes. It is desirable to have energy efficient hardware and protocols to improve energy efficiency and prolong the life time of wireless sensor networks.

Energy efficiency in simulation study can be obtained by using the following expression:

$$E = \frac{Total\ amount\ of\ data\ delivered}{Total\ amount\ of\ energy\ consumed} \tag{3.4}$$

3.7 General Research Assumptions

The general assumptions made in the following research include:

- No multipath fading: Multipath fading is when we consider Radio Frequency (RF) signals travelling in all directions, which results into multipath fading and therefore may affect wireless communication. Because of complexity and difficulty of simulating and modelling multipath fading. In this research, Freespace and Two-ray ground propagation models were used to provide easy modelling and simulation while providing significant accuracy. However, the issue of multipath fading is a good candidate for future work.

- Homogenous network: the investigations and design development in this research considered homogeneous sensor networks, i.e. it is assumed that all nodes in the sensor network have the same capability. However, there are important WSN applications where this is not the case. Future studies should include heterogeneous sensor networks that consist of several nodes with extra capability in a network.

- No interference: Most of WPANs or WSNs communications use the Industrial, Scientific and Medical (ISM) frequency band. This frequency band is unlicensed and it is widely used by many other electronic devices. Since it is not easy to control interference from other devices, we assumed that there is no interference due to devices that operate in the same frequency band. Future studies should include other conditions that wireless channels are likely to encounter, such as noise, interference, and other environmental factors, such as temperature, humidity, and wind.

Since there are four areas of study, several other research assumptions unique to those study areas are addressed in the succeeding Chapters 4, 5, 6 and 7 respectively.

3.8 Research Limitations and Implications for Further Research

Apart from the research limitations drawn from the assumptions made in the section above. Our findings in this research are subjected to at least two limitations. First, obviously the time period of my candidature where this research was conducted. Secondly, is the fact that the current investigation was conducted using a simulator and mathematical theories and not a hardware platform. However, the research has been conducted careful to closely reflect the hardware systems.

Further investigation and experimentation using suitable hardware platforms in the experimentation and implementation phases of the current and future work is recommended. The following sections provide important insights for those interested in using hardware investigation and experimentation in the current area of research.

3.8.1 Challenges of implementing MAC in embedded systems

Embedded system applications are highly integrated and constrained to minimize cost among other factors. Currently, most of the MAC protocols are running on the main processor. Many challenges exist when porting or implementing a new MAC protocol in a particular platform including the variety of existing operating systems (OS) with variety services and system software interface for MAC, the diversity in radio transceiver interfaces and features, the diversity of instruction set architecture features and compiler support, and the degree of flexibility and network performance inherent tradeoff.

The MAC protocol implementation to a greater extent depends on the radio transceiver and microprocessor or processor in use. The number of available hardware features for transceivers, microprocessors and interfaces require different MAC instruction set for MAC implementation and compiler support. From a view point of the OS and a portable MAC implementation, the primary differences are the interfaces to time facilities, memory management, interrupt handling, interprocessing communication and hardware peripheral access. Most of IEEE 802.15.4 MAC implementation are targeted at microcontrollers allowing nesting prioritization of interrupts. For example freescale provides such an IEEE 802.15.4 MAC implementation, which is independent of operation system [87]. TI also provides an interrupt based implementation of 802.15.4 MAC for its CC2420 transceiver. When migrating these implementation to hardware platforms with limited interrupt handling capabilities, rewriting of possibly a large portion of the code will be necessary.

Another challenge is on cross-layer coupling of functions, since there is a strict interdependence among functions handled at all layers of communication protocol stack. This has to be explicitly considered when designing communication protocols aimed at QoS provisioning on resource constrained.

3.8.1.1 Designing, debugging and Programming tools

Most of the popular hardware vendors provide their own IDE for developing and debugging their systems. One example is the Atmel AVR, which offers several options for debugging, mostly involving on-chip debugging while the chip is in the target system. AVR Studio® 5 makes editing and debugging source code easier by seamlessly bringing together an editor with assisted code writing, a wizard for quickly creating new projects, an AVR software framework source code library, a GNU C or C++ compiler, a powerful simulator, and a front-end visualizer for all of Atmel's AVR programmers and in-circuit debuggers [52]. AVR Studio 5 combines the best features of the current 8-bit AVR Studio 4 and 32-bit AVR32 Studio into one environment that covers all 8- and 32-bit AVR MCUs. It also gives the user easy access to online documentation including device data sheets, tools user guides, example project documentation, and kit shopping directly from the Atmel online store. Atmel's AVR Studio 5 further provides an integrated offering of third party plug-ins for embedded development tools.

A common debugging interface is JTAG (Joint Test Action Group), which is often used in Microcontrollers [88]. JTAG provides access to on-chip debugging functionality while the chip is running in the target system. JTAG allows accessing internal memory and registers, setting breakpoints on code, and single-stepping execution to observe system behavior. Atmel provides a series of JTAG adapters to program AVR chips, however the methods to program AVR chips varies from AVR family to family. Other ways include the In-system programming (ISP) programming method, which is functionally performed through SPI, plus some twiddling of the Reset line, debugWIRETM is Atmel's solution for providing on-chip debug capabilities via a single microcontroller pin. It is particularly useful for lower pin count parts which cannot provide the four "spare" pins needed for JTAG.

3.9 Conclusion

In this chapter, a research methodological framework layout is presented. The research is concerned with developing and evaluating techniques for improving the performance of WSNs to maintain reliable network connectivity, scalability and energy efficiency. The research questions were presented under four areas of study, and their justification or evaluation phase and results was linked to the four areas of study in the succeeding Chapters 4, 5, 6 and 7. The evaluation process was briefly described which involved simulation studies, numerical and mathematical analytical modelling. Lastly, the main research contributions, performance parameters, research assumptions, limitations and future methodological research were addressed.

Chapter 4

Transmission Power Control for Sensor Networks

Because of the need to minimise energy consumption of sensor nodes to prolong battery life in sensor network. Power control has been one of the main techniques used to conserve energy in wireless sensor networks, particularly in star topology or cellular networks. This chapter provides a conclusively demonstration of some relevant advantages of single-hop transmission power control (TPC) over multi-hop. TPC is investigated in multi-hop and single-hop WSNs using typical Telosb platform parameters, which are IEEE 802.15.4 standard compliant. A new detailed approach is also presented for testing TPC for multi-hop and single-hop WSNs at the physical layer. Following this approach, energy consumption performance results via simulation and a numerical analysis are presented, and results indicate that sending packets using a short-range multi-hop path, instead of a single-hop, does not necessarily save energy as suggested by some researchers [31, 32, 33]. Moreover, transmitting in single-hop networks at lower transmission power levels, while still maintaining reliable connectivity, reduced energy consumption by up to 23%. Both the radiation and electronic components of the energy consumption are characterised. Furthermore, the research shows that both packet collisions and delays affect the performance of WSNs that have an increased number of hops. Since the use of TPC in star topology or cellular networks transmission can save energy, we recommend cluster based (hybrid) or similar topology over completely multi-hop topology. The relationships among protocol layers are also revealed, possible improvement suggested, insights are provided into challenges associated with developing wireless sensor networks protocols and the significance of TPC is highlighted;

4.1 Introduction

A major challenge in sensor network protocol design is minimizing energy consumption by nodes to prolong network endurance, while still maintaining effective communication. We expect the emerging WSNs to be more energy-efficient, given that the compactness and increasing density of new wireless devices impose greater constraints on battery capacities.

There are several techniques for minimizing energy consumption in a WSN, which can be categorized into: efficient data aggregation, efficient routing, MAC layer power management, and topology management using transmission power control. This chapter focuses on TPC, which is one of the promising and effective techniques for minimizing interference and reducing sensor node energy consumption. TPC allows a transmitter to dynamically change the transmission output power to the minimum level, depending on the receiver proximity, and still maintain a reliable link. TPC has been widely studied in the literature, particularly in cellular networks and IEEE 802.11 networks. Our work, based on the 802.15.4 physical layer, relies on all sensor nodes having adjustable transmission power levels. While researchers have addressed cellular TPC algorithms in cellular networks, no comprehensive published work was identified which compares energy efficiency in multi-hop communication over equal distances from source to sink. Although some researchers suggest that short-range multi-hop communication is more energy-efficient [31, 32, 33], our simulation and numerical results do not support this conclusion.

Earlier studies have sought to improve WSN performance (such as throughput, and power consumption) by varying transmission power. In[74, 89, 90], Power control in 802.11 standard was used to increase the channel efficiency rather than prolong battery life. Their work is based on RTS/CTS protocols and considered the issues of exposed and hidden terminals in networks. While 802.11 is power-hungry and therefore unsuitable for WSN applications, these studies can be extrapolated and used for WSN protocol design.

In [91, 92], transmission range adjustment was adopted to avoid overlapped sensing area while still maintaining effective coverage. The objective was to minimize energy consumed by the sensing function rather than during communication. In this chapter, we energy consumed to transmit information from source to destination is addressed.

Zhao [31] suggests that multi-hop communication can be more energy-efficient than single-hop communication. He derives an expression to show the power advantage of a N-hop transmission over a single-hop transmission over the same distance. This simplified model favors the multi-hop scenario. Monks [33] and Kai [32], also suggest that information from a source should go through one or more intermediate hops to reach its destination in order to achieve desired power savings.

Various models have been used to address transmission power, Bandai [93] using a Friis transmission equation, suggesting that a shorter distance hop greatly decreases transmission power, while Liu [81] considered a variable Physical carrier sense (PCS), based on background noise to minimize collision and therefore minimize energy consumption.

Our derived energy model is based on research by Heinzehman [94]. We address transmission power control at the lowest general PHY layer and therefore our findings can be used in the implementation of MAC or the network layer. We consider commercially available low-energy sensor nodes (Telosb), in which PCS is fixed not variable. In practice, the number of power levels is limited, and therefore the optimum value will approximate one of them if the levels are discrete, rather than continuous as in most transmission power optimization research.

The main contribution of this chapter is to characterize, by a numerical analysis and simulation, the performance of transmission power control, in single-hop and multi-hop communication, using real sensor node hardware parameters (Telosb) [95, 50]. A new detailed approach is presented for testing TPC in multi-hop networks at the physical (PHY) layer, which can also be used to test 802.15.4 standards and related protocols. In contrast to other studies [31, 32, 33], the research results indicate that TPC in multi-hop communication does not necessarily save energy. In addition, by using TPC in single-hop networks, battery life was extended by up to 23%. Furthermore, the results show the impact of multi-hop communication in terms of packet delay and collision.

4.2 Transmission Power Control Optimization and Related Models

A node can transmit a packet at a minimum possible power requirement to reach nearby nodes and use multi-hop path to reach a more distant data sink or user. In other words we can save energy in data transmission by using multiple short range transmission (less transmission power) rather than one large hop transmission (more transmission power).

Multi-hop communication in densely deployed sensor networks is expected to consume less power than traditional single-hop communication. So if we can use minimum possible power while still maintaining connectivity, we can reduce the energy consumption, Joule per byte transmitted and therefore prolong the lifespan of wireless sensor nodes[68, 67, 96].

In the following subsections, we introduce TPC related models and a derived energy model that has been used in our experiments to help us in answering some of these questions:

- Does the physical transmit power play a significant factor in the overall energy consumption?
- Is ad-hoc short distance communication more energy efficient as supposed to single-hop infrastructure star network?

4.2.1 Channel propagation model

A radio channel model is important for analyzing the performance of a wireless system. In a wireless channel, the signal strength or energy level decays as the distance from the source to destination increases. This fading can be modeled as a power law function[1] of the distance between the transmitter and receiver. Moreover, if there is no direct line-of-sight path between the transmitter and the receiver, the electromagnetic waves will bounce off objects around and arrive at the receiver, from a different paths at different times. The interaction between these waves causes multipath fading, which can also be roughly modeled as a power law function of the distance between the transmitter and receiver. No matter which model is used, that is, direct line-of-sight or multipath fading, the received power decreases as the distance from the transmitter to receiver increases[97].

The Two-ray ground reflection model takes into account both the direct path and the ground reflection path. This model yields better prediction over longer distance, than the freespace model. However, Two-ray model does not give a good prediction for a short distance due to the oscillation caused by the constructive and destructive combination of the two rays.

In this Chapter, we take into account both the free space model (direct path) and the multipath fading model (reflection path), depending on the distance between the transmitter

[1] Power law distributions are usually used to model data whose frequency of an event varies as a power of some attribute of that event. In our case, it is the signal strength and distance between the transmitter and receiver.

and receiver [97, 98]. If this distance is less than a certain distance, known as cross-over distance, then the Friis free space model is used. If the distance is greater than the cross-over distance, then the two-ray ground propagation model is used. The cross-over distance is defined as follows:

$$d_{xover} = \frac{4\pi h_r h_t}{\lambda}, \tag{4.1}$$

where

h_t is the height of transmitting antenna above the ground,

h_r is the height of the receiving antenna above the ground, and

λ is the wavelength of the carrier signal.

If the distance between transmitter and receiver is less than d_{xover}, that is $d < d_{xover}$, then the received signal power at the receiver is modeled using the Friis freespace model as follows:

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}, \tag{4.2}$$

where

G_t is the transmitter antenna gain,

G_r is the receiver antenna gain,

$L \geq 1$ is the system loss factor not related to propagation, and

$P_r(d)$ is the received power given a transmitter-receiver distance separation of d.

If the distance between transmitter and receiver is greater than d_{xover}, that is $d > d_{xover}$, then the received signal power at the receiver is modeled using the two-ray ground model as follows:

$$P_r\left(d\right) = \frac{P_t G_t G_r h_t^2 h_r^2}{d^4 L} \tag{4.3}$$

Under this propagation model, a receiver can successfully receive a packet with an acceptable error rate only if the received signal power is greater than receiver sensitivity (RXthresh_) and SNR is above a threshold.

In our experiments we assumed omnidirectional antennas with $G_t = G_r = 1$, $h_t = h_r =$ 1m, no system loss (L=1), and 2.45 GHz radios. Using these values, $\lambda = \frac{3\times10^8}{2.45\times10^9} =$ 0.12244898m, the cross over distance (d_{xover}) is approximately 103 meters (the exact value is 102.62536 m) and equation 4.2 and 4.3 can be simplified to:

$$P_r(d) = \begin{cases} 9.4949 \times 10^{-5}\frac{P_t}{d^2} & : \ d < 103\,m \\ \frac{P_t}{d^4} & : \ d > 103\,m \end{cases} \tag{4.4}$$

From equation 4.4, knowing the transmission power and receiver sensitivity, we can estimate the communication range.

4.2.2 Physical layer energy model

Here we describe the energy numerical model that was used in our work. To understand and optimize physical energy consumption, we use an energy model similar to that used by Heinzelman [94] and Holger [21]. The energy consumption for transmitting one packet (E_p) comprises: the energy consumed by the transmitter, when sending a packet (E_{tx}) and receiver energy consumption for receiving the packet (E_{rx}). That is,
$E_p = E_{tx} + E_{rx}$.

In general, the energy consumed by a transmitter is due to two sources. The first is the energy dissipation due to RF signal generation, which depends mostly on the modulation technique used and the distance from the source transmitter to destination. Power control can be used by setting the power amplifier to ensure a specific power level at the receiver. In this case, energy consumed depends on the transmission power, that is, power radiated by the antenna.

The second source is the energy consumed by electronic components necessary for frequency synthesis, frequency conversion, filters and others. This will remain constant for the specific electronic components used.

The sensor node transmission energy can be modeled as the sum of constant electronic components energy and an amplifier energy proportional to the receiver distance. Thus, energy per packet required for a node to transmit a packet of length, l bits over a distance d between two nodes, is the product of the total transmission power and the packet transmission duration:

$$E_{tx} = (P_{tx-elec} + P_{tx-amp})t_{tx} \tag{4.5}$$

where time spent to send a packet is $t_{tx} = \frac{l}{R_b}$, determined by the nominal bit rate R_b.

We can write the above equation in terms of energy as:

$$E_{tx}(l,d) = E_{tx-elect}(l) + E_{tx-amp}(l,d) \tag{4.6}$$

$$E_{tx}(l,d) = (\beta + \mu d^n)l \tag{4.7}$$

where

β is constant energy consumed by electronics,

μd^n accounts for radiated power necessary to transmit over a distance d, between two nodes (source and destination) and

n is the path loss index.

The parameter μ is a proportional constant that will depend on the receiver sensitivity and the receiver noise figure, therefore transmit power needs to be adjusted so that the power at the receiver is above a certain threshold.

The energy consumed by the receiver is the energy consumed by receiver electronics $E_{rx}(l) = E_{rx-elec}(l)$, given by:

$$E_{rx}(l) = lE_{elec} \tag{4.8}$$

Considering the discussion in section 4.2.1, for short distances, the propagation loss can be modeled as inversely proportional to d^2, whereas for longer distances, the propagation loss can be modeled as inversely proportional to d^4, that is to say that the amount of energy necessary to go distance d decreases as d^2 for short distances and d^4 for longer distances. Relating equation 4.7 and propagation models, we get:

$$E_{tx}(l,d) = \begin{cases} (E_{elect} + \mu_{friss-amp} d^2)l & : d < d_{xover} \\ (E_{elect} + \mu_{two-ray-amp} d^4)l & : d \geq d_{xover} \end{cases} \tag{4.9}$$

If the radio bit rate is R_b, then the transmit power, P_t is equal to the transmit energy per bit times the bit rate:

$$P_t = E_{tx-amp}(1,d)R_b \tag{4.10}$$

Now if we consider only the radiating part of equation 4.9 and substituting the value of $E_{tx-amp}(1,d)$, we have:

$$P_t = \begin{cases} \mu_{friss-amp} R_b d^2 & : d < d_{xover} \\ \mu_{two-ray-amp} R_b d^4 & : d \geq d_{xover} \end{cases} \tag{4.11}$$

Using the propagation model, described previously, the received power is:

$$P_r = \begin{cases} \frac{\mu_{friss-amp} R_b G_t G_r \lambda^2}{(4\pi)^2} & : \ d < d_{xover} \\ \mu_{two-ray-amp} R_b G_t G_r h_t^2 h_r^2 & : \ d \geq d_{xover} \end{cases} \tag{4.12}$$

Since the receiver sensitivity is constant (-94dB), the parameters $\mu_{friss-amp}$ and $\mu_{two-ray-amp}$ can be determined by solving equation 4.12:

$$\mu_{friss-amp} = \frac{P_{r-thresh}\,(4\pi)^2}{R_b G_t G_r \lambda^2} \tag{4.13}$$

$$\mu_{two-ray-amp} = \frac{P_{r-thresh}}{R_b G_t G_r h_t^2 h_r^2} \tag{4.14}$$

Hence, we can estimate the required transmit power, P_t, as a function of receiver threshold and the distance between transmitter and receiver as:

$$P_t = \begin{cases} \alpha_1 P_{r-thresh} d^2 & : d < d_{xover} \\ \alpha_2 P_{r-thresh} d^4 & : d \geq d_{xover} \end{cases} \tag{4.15}$$

Where

$\alpha_1 = \frac{(4\pi)^2}{G_t G_r \lambda^2}$ and

$\alpha_2 = \frac{1}{G_t G_r h_t^2 h_r^2}$.

In our experiments, receiver threshold remains constant at -94dBm. Substituting values used in our experiments, that is, $G_r = G_t = 1$, $h_r = h_t = 1.5$, $R_b = 250\,kbps$ and frequency 2450 MHz into equation 4.13 and 4.14 we get:

$$\mu_{friss-amp} = 1.6771 \times 10^{-14} J/bit/m^2$$

and

$$\mu_{two-ray-amp} = 3.1455 \times 10^{-19} J/bit/m^4$$

4.3 Performance Evaluation

To observe the impact of transmission power control in multi-hop and single-hop scenarios, NS-2 simulator [82] is used and the derived numerical model to obtain the average energy consumed per packet and the average energy consumed per packet per node, taking into account all nodes involved in sending packets from a source node to a data sink node. For example, in a 2 hops communication, three nodes exist i.e. one source node, one relaying node, and one destination or sink node. The percentage of energy storage used by each node involved in a multi-hop communication and the percentage contribution of energy spent due to the radiation and electronic components are obtained. In addition, we obtain the average end to end transmission delay and the average number of collisions as we increase the number of hops.

4.3.1 Simulation environment

Our radio model uses characteristics similar to Telosb interface and using ad-hoc routing. Telosb uses a CC24-20 chip [50], supporting eight different transmission power levels. Energy consumption for different transmission power levels can be calculated using Table 4.2 values. Note that node's radio consumes power not only when sending or receiving a packet, but also when in idle or listening to the channel. In our experiments we have considered power consumption when transmitting, receiving and, in idle states. To simulate the typical Telosb energy model in NS-2, we calculate the energy consumption by each power level, using values in Tables 4.1 and 4.2, whereby energy is the product of power and time ($E = Pt$). Here the time t is the amount of time spent transmitting, receiving or listening, and power is the product of the voltage and current drained at that particular state or power level ($P = VI$). For example, when transmitting at maximum power (0 dBm), power consumption due to transmission is the product of the node's operating voltage and the current drained, 3 Vx17.4 mA.

The power consumption for receiving a packet and being in an idle state is 3.0 Vx18.8 mA and 3.0 Vx0.426 mA respectively. Likewise, we obtain numerical approximation results using our derived numerical energy model (Section 4.2.2) by considering a constant receiver energy consumption for all transmission power levels (Table 4.2), number of hops, number of nodes, and the time taken to transmit or receive a packet (packet size divided by data rate or average packet delay).

4.3.2 Experiment 1: multi-hop

We consider optimum transmission power control, whereby there is no overhearing during transmission since the nodes are using the minimum available transmission power to reach nearest neighbour. A well controlled environment was necessary in order to test multi-hop Vs single-hop and to rule out the possibility of any other factors such as network density that might hinder or improve the performance of multi-hop communication. We simulate a basic peer-to-peer chain topology network, where the distance from a source node to a destination node (sink) is kept constant at 120 m. We also use the same traffic load from the source to the destination. First, we simulate two nodes transmitting at maximum power (0 dBm) for single-hop communication, and measure energy consumption for each node. We then reduce transmission power to one of the supported Telosb, CC2420 chip

Table 4.1: Simulation parameter settings

Parameter	Value
Channel carrier frequency	2450 MHz
Data packet size	100 bytes, 28 bytes
Channel rate	250 kbps
Data rate	12 kbps
RXthresh_	-94 dB
Max Queue length	256
Antenna gain	0
Simulation area	250m x 250m
Simulation time	24,000 seconds
Radio propagation model	Freespace and reflection
Transmission power (Pt_)	0,-1,-3,-5,-7,-10,-15,-25 dB
macSuperframeOrder (SO)	15
macBeaconOrder (BO)	15
macMinBE	3
macMaxBE	5
macMaxCSMABackoffs	4
macMaxFrameRetries	3
Symbol interval	16μs
aUnitBackoffPeriod	20 symbols (320μs)
Current consumption in transmit mode	depending on the transmission power (see Table 4.2)
Current consumption in receiving mode	18.8 mA
Current consumption in idle mode	0.426 mA
Typical node working voltage	3.0 V

Table 4.2: Telosb transmission power and current

PA_level	Output power(dBm)	Current drained (mA)
31	0	17.4
27	-1	16.5
23	-3	15.2
19	-5	13.9
15	-7	12.5
11	-10	11.5
7	-15	9.4
3	-25	8.5

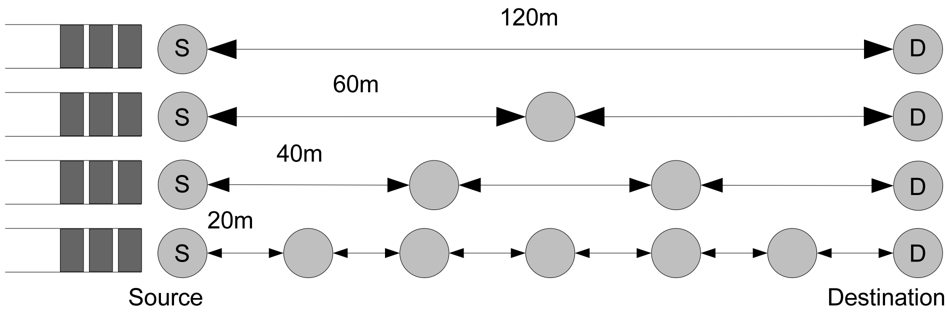


Figure 4.1: Chain ad-hoc scenario

power levels. This will automatically reduce the node's communication range. To maintain the link between the source and the sink, which are 120 m apart, a node is strategically placed between the source and sink, and transmission power is adjusted to establish a two hop communication link (Figure 4.1). This process is repeated for other lower power level values and more intermediate nodes are strategically placed between the source and the sink, thus increasing the number of hops between them. The range between nodes, and transmission power levels, can be approximated using propagation models, whereby P_r is the node constant receiver sensitivity (-94 dBm). Furthermore, we maintain reasonably low (12 kbps) source node data sending rate to avoid packet loss due to a queue overflow.

This is a basic topology but it is quite sufficient to show the basic characteristics of transmission power control in a multi-hop communication.

4.3.3 Experiment 2: single-hop

We simulate a pair of transmitter-receiver nodes, such that the distance from the transmitter to the receiver is small enough to enable the use of the lowest power level (Table 4.2) to transmit packets and therefore the radiation part remains constant. Using the same traffic load and same Tx/Rx range, we measure energy consumption for sending packets at different power levels. Again the radiation part will remain constant. The energy consumption using the lowest level will obviously be minimum, however, we want to find by how much this contributes to the energy savings and to compare our simulation and numerical results.

4.3.4 Results

Figure 4.2 shows numerical and simulation results for average energy consumed per packet for each node as the number of hops increases.

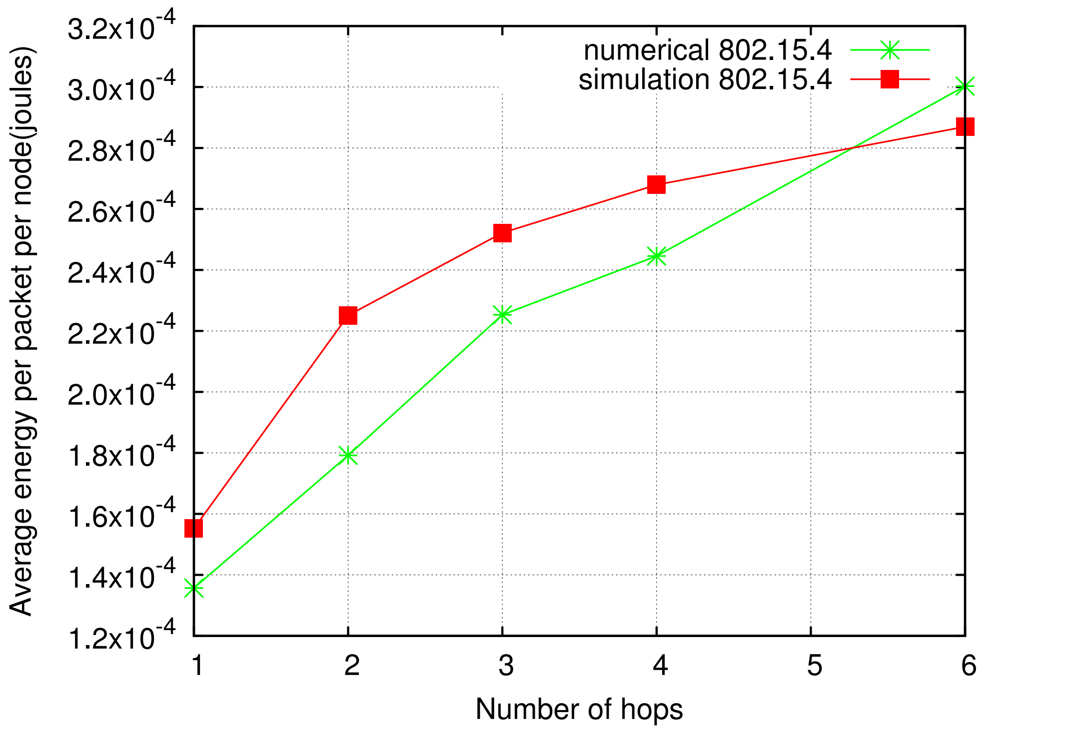


Figure 4.2: Multi-hop average energy consumption (packet size 28 bytes, data rate 12kbps)

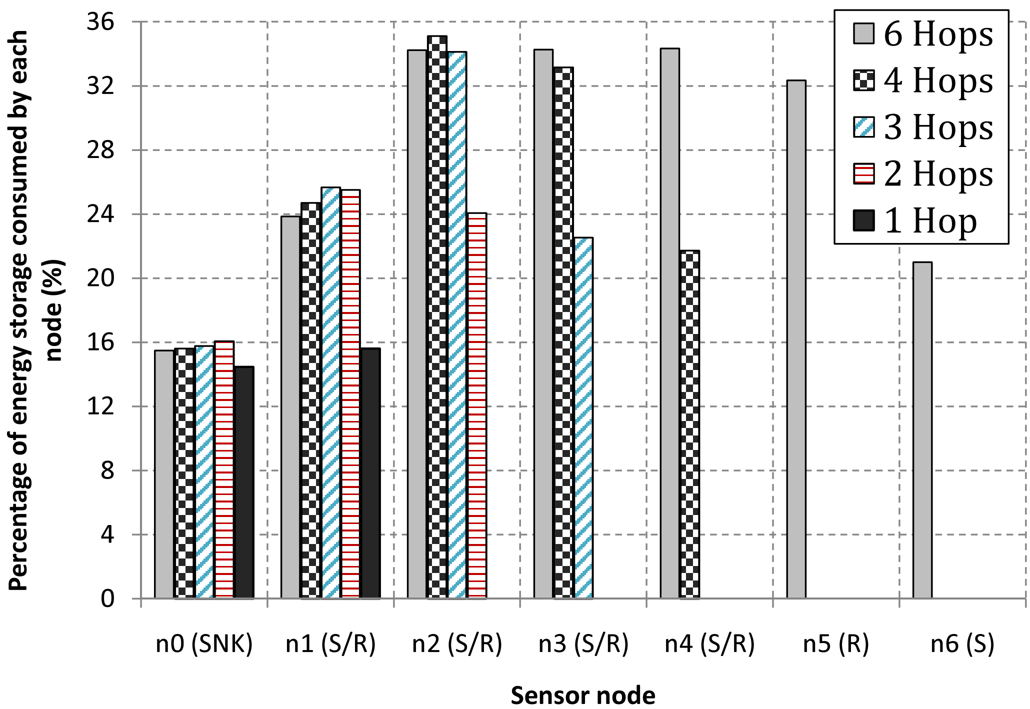


Figure 4.3: Comparison of percentage of energy storage used for different number of hops

Figure 4.3 shows percentage of energy storage spent by each individual node as we increase the number of hops. The x-axis label shows each individual node, where SNK, S and R denote sink node, source node and relaying node respectively.

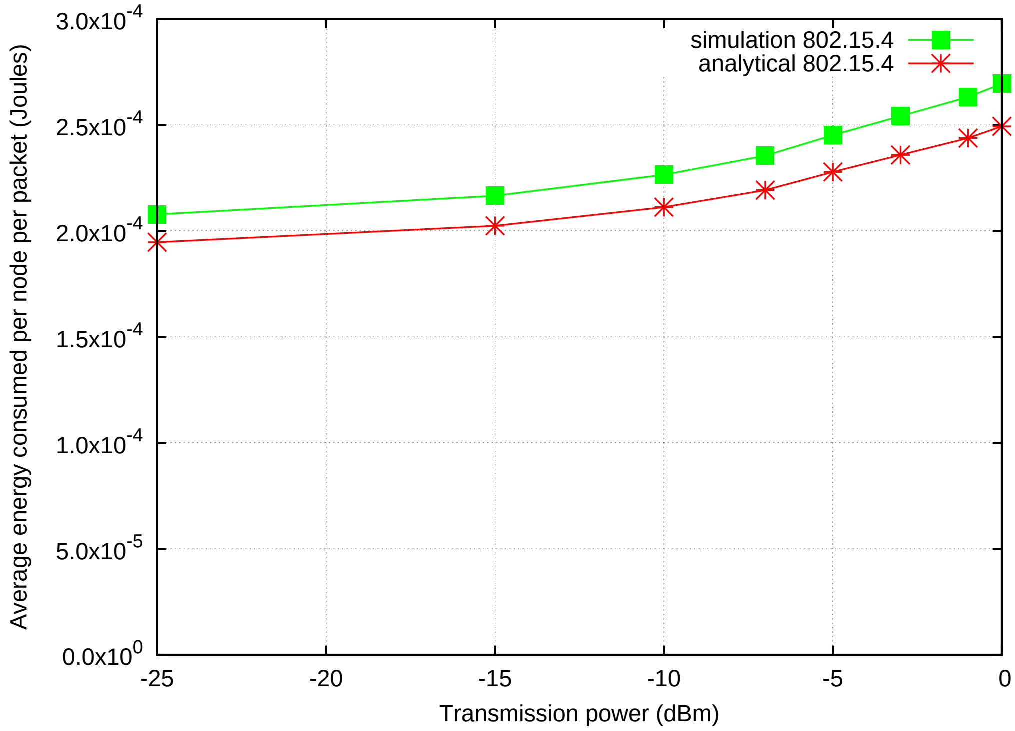


Figure 4.4: Average energy consumption per node per packet (single-hop, data rate 64kbps, packet size 100 bytes)

Figure 4.4 shows average amount of energy consumed per packet for each node as a function of transmission power.

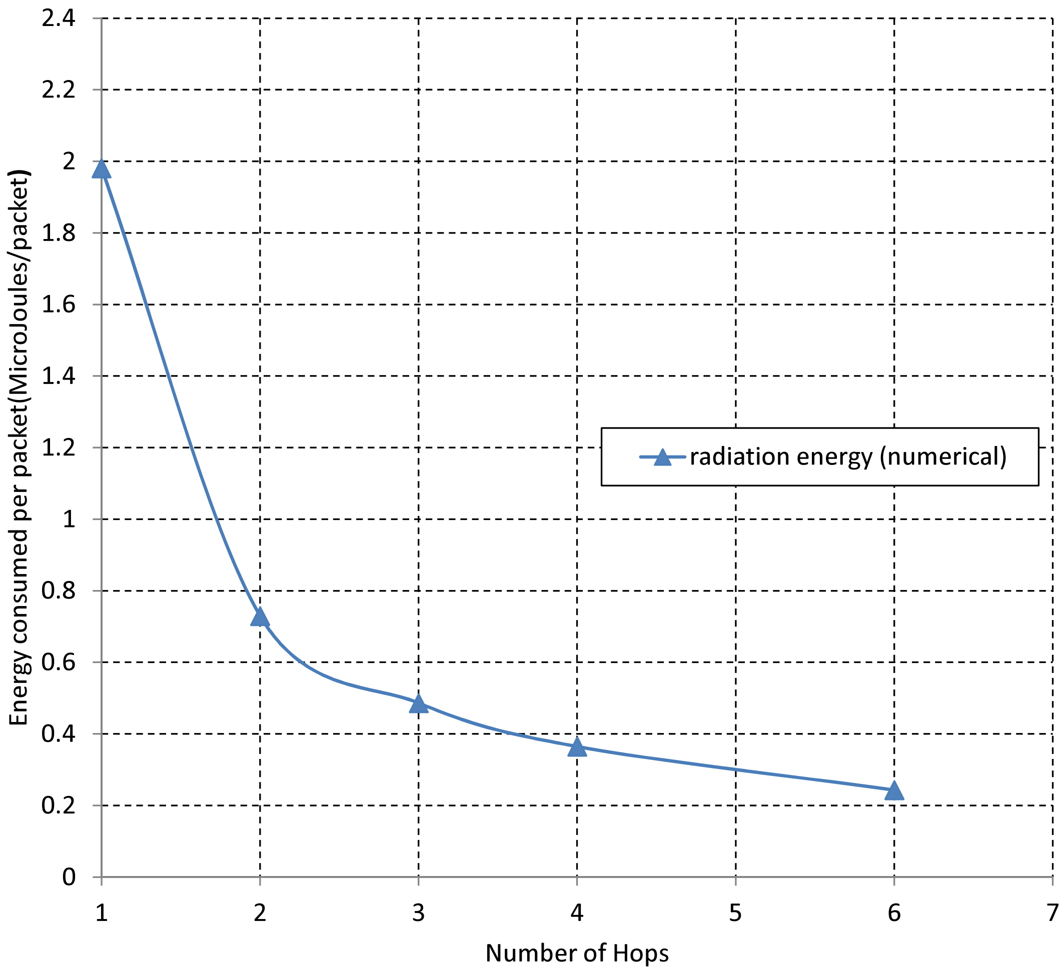


Figure 4.5: Radiation component energy consumption

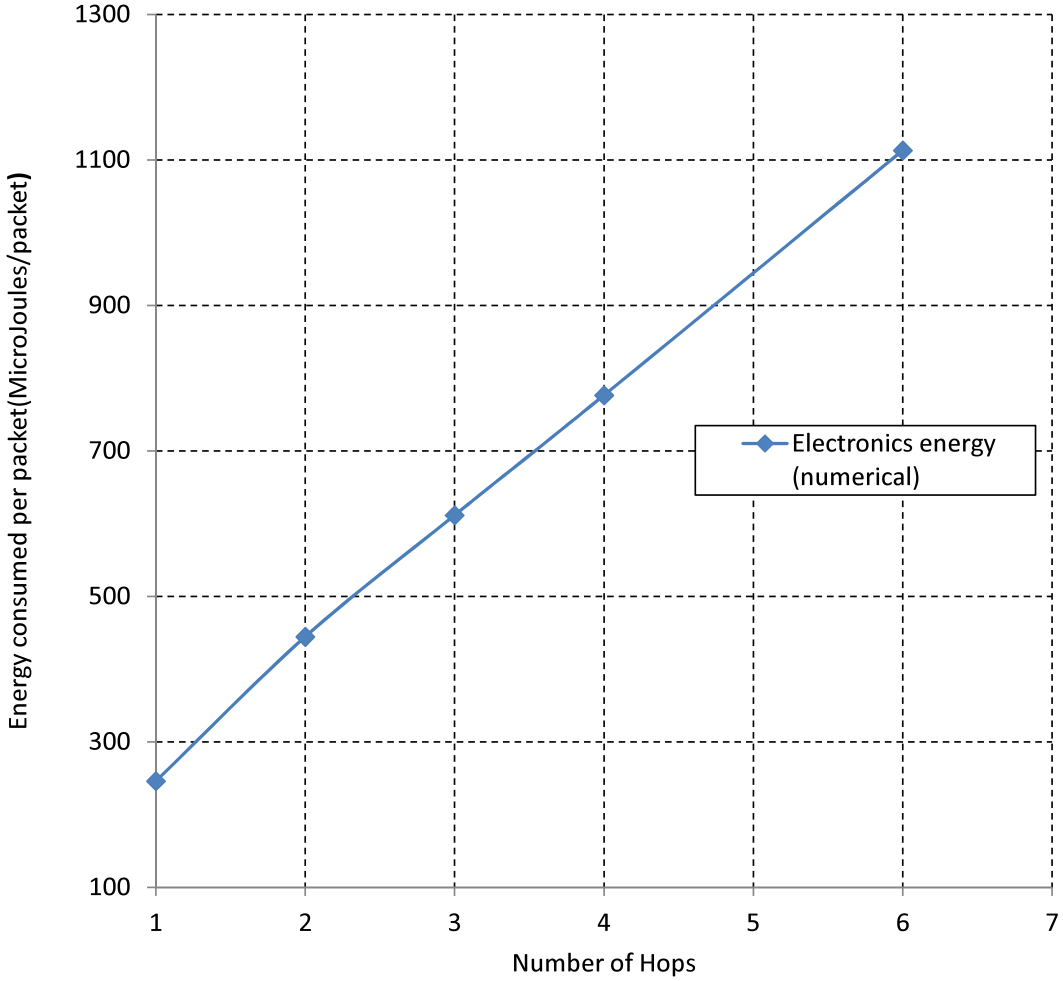


Figure 4.6: Electronic component energy consumption

Figure 4.5 and Figure 4.6 show energy per packet consumed in a multi-hop network as we increase the number of hops for both radiating and electronic parts respectively. These results were obtained using our derived numerical model.

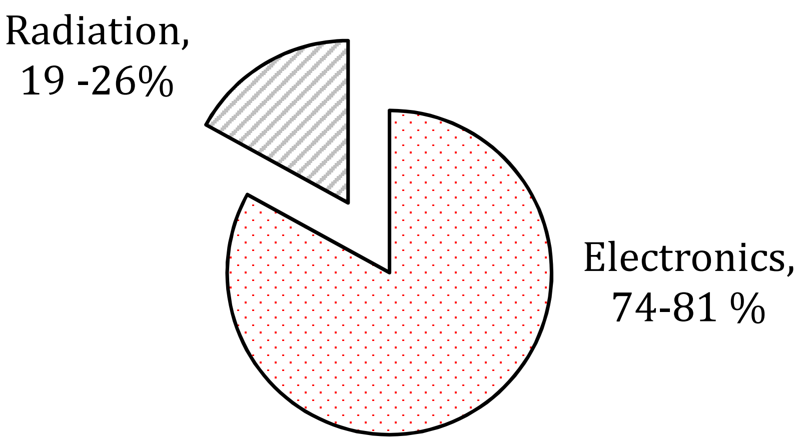


Figure 4.7: Radiation energy percentage

Figure 4.7 shows the amount of energy contributed by radiation and electronics part using different transmission power levels in a single-hop experiment.

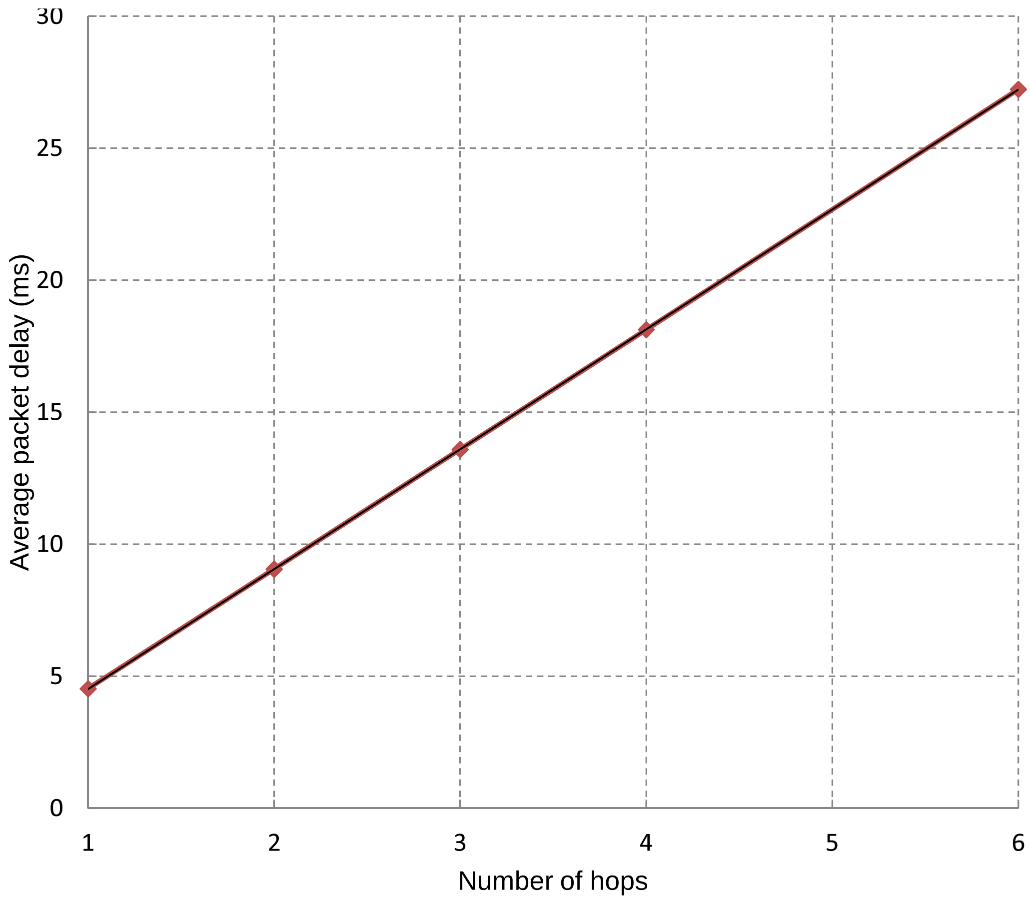


Figure 4.8: Delay comparison

Figure 4.8 shows the average end to end transmission delay as we increase number of hops. This can be a major network degradation for time critical applications and for sensor nodes with low memory or buffer size.

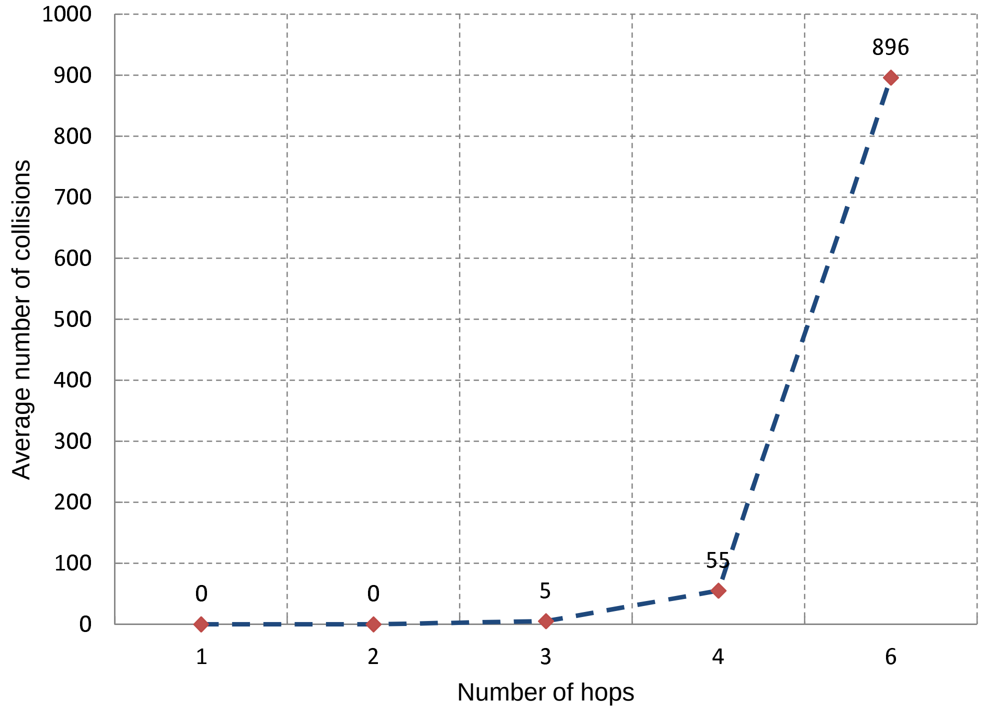


Figure 4.9: Number of collisions at the MAC/PHY layer versus number of hops

Figure 4.9 shows the average number of collisions versus the number of hops in a multi-hop experiment.

4.4 Discussion

Other researchers [31, 32, 33] anticipated a benefit of using multi-hop instead of single-hop by suggesting that nodes in multi-hop can share the load, i.e. energy consumed sending information will be shared among nodes in multi-hop resulting into lower energy per node cost and longer lifetime. We agree with this findings if one only considers the energy spent due to radiation or propagation or if the radiation part dominates the total energy consumption (Figure 4.5 and 4.7) and not the node's electronics component (Figure 4.6 and 4.7).

Our findings confirm that using TPC short-range multi-hop instead of single-hop does not prolong nodes' lifespan in this case (Figure 4.2. and Figure 4.3). We used our well controlled environment for testing, and derived numerical model and simulation results to support our findings. Using multi-hop will increase coverage due to limited sensor node ranges but not save energy. There can be several reasons why multi-hop short-range fails to reduce the power consumption: energy is consumed by node's electronics not only when sending packets but also when receiving packets; the International Organization for Standardization (ISO) communication stack and layered protocols interact as the packet transverses from one node to another, for example, the CSMA/CA in MAC sublayer is performed per packet and per hop as packets go through several hops. Furthermore, by increasing number of hops, we increase the number of nodes contending in the channel and the number of nodes that cannot hear one another; this increases the chance of packet collisions due to hidden terminals (Figure 4.9). Furthermore, by increasing the number of hops we increase packet delay (Figure 4.8). Depending on the application traffic, sensor nodes' buffer size can also cause performance degradation as we increase the number of hops. Using our approach, results presented in this chapter can be related to those found in [99].

TPC is effective in single-hop cellular or star networks and can increase the network's lifespan because the power level can be changed based on single-hop receiver or sink proximity (radiation part remains constant) and no other complexity exists compared to the multi-hop case (Figure 4.4). This has been recognized for many years [100, 74, 96, 101]. Furthermore, TPC has been used in cellular networks for controlling co-channel interference among devices in the shared radio channel [101]. In Figure 4.4, if we compare energy spent when sending at the maximum power level (0 dBm) and the lowest power level (-25 dBm); it shows that we can save energy by up to 23% compared to the single level maximum transmission power.

These results suggest that a cluster based (hybrid topology) or similar topology would be preferable. Instead of having every node relay the information, specific nodes would be responsible for relaying the information and sensor nodes will pass the message in one hop to the cluster head or relaying node which will not have the same energy restrictions as the sensors nodes. Each node associated with a cluster head or relaying node will control transmission power based on its distance from the cluster head or relaying node.

Our numerical model gives only an approximation of the results, it does not include other control packets such acknowledgment, PAN association and retransmitted packets. It also lacks the analysis of the energy spent due to the random nature of CSMA/CA. These components are incorporated in our simulation results. Future work will include other sources of energy consumption in the numerical model or analysis and results from a hardware-based testing platform.

4.5 Conclusion

WSNs is a burgeoning area of research with many challenges, including managing energy consumption and network connectivity. In this chapter, a new approach to transmission power control was presented for multi-hop and single-hop WSNs. While some researchers have suggested that short-range multi-hop communication can extend the sensor node's lifespan, our results, both numerical and simulation, differ from those findings. The research showed that if the distance between source and destination is fixed, then the total energy consumption in the WSN, packet collisions and packet delay all increase as we increase the number of hops and reduce the transmission power for each hop. Results indicate that, in a simulation scenario when a single-hop is used in conjunction with optimization of the transmission power, the node's energy consumption decreases by up to 23%. The difference between our results and the published literature is due to the fact that we consider most components of energy consumption and not just the component related to the power radiating from antennas. Furthermore, we used a basic simulation scenario that is effectively maintained to test TPC in multi-hop communication.

Chapter 5

Association and Synchronization Efficiency

A key aspect of a wireless sensor network is its ability to self-organize and maintain connectivity. Medium Access Control (MAC) protocol manages network self-configuration, which includes establishing a personal area network (PAN), finding a network to associate or disassociate with, and synchronizing if required. Currently, there is limited research that addresses the network initialization phase. This chapter provides a performance evaluation of the 802.15.4 MAC during device association and synchronization with the PAN coordinator; this shows the impact of beacon interval is shown for the number of associating nodes in terms of association time delay and energy consumption in stationary wireless sensor networks. Results illustrate that energy consumption and association time increase with increasing number of nodes associating with a coordinator. Moreover, short beacon intervals consume more energy due to the frequency of beacon frames that nodes have to keep track of to maintain synchronization. However, short beacon intervals reduce the time required for the nodes to associate, in contrast to longer beacon intervals that are undesirable for real time and mobile applications. Furthermore, for longer beacon intervals, BO= 12 to BO=14, there is an abrupt increase in energy consumption as the number of associating nodes increase, even for as few as four nodes as supposed to many expected nodes in sensor networks.

5.1 Introduction

Wireless Sensor Networks (WSN) are a major technology that promises solutions for various industrial and domestic applications. A typical WSN is a distributed network formed by sensor nodes deployed in a certain geographical region to collect and disseminate data. Generally, the network will be composed of many scattered sensor nodes, from which data will be routed from the original sensors to a remote sink in a single or multi-hop ad hoc fashion. A typical WSN node (also referred to LR-WPAN platform) is composed of a sensing module, a radio communication interface or transceiver module, a data processing module, and a limited power supply module. The sensing module would most likely have multiple on-board sensors for environmental variables such as temperature and humidity. The data processing module is composed of a controller or microcontroller to process all relevant data and codes. Usually the memory is a component of the data processing module for storing programs and data. The power supply module may be battery or power generator; however, often it will be quite limited. Generally, sensor nodes have serious resource constraints including battery life, communication bandwidth, CPU capacity, and storage [22].

This chapter focuses on the IEEE 802.15.4 standard for WSNs. The research provides a study of the 802.15.4 standard the during the nodes' association and synchronization stage in terms of synchronization time and energy consumption for a particular beacon interval. Currently, insufficient work has been done in the area of network initialization, i.e., association and synchronization. Most research focuses on the performance of the 802.15.4 standard after the nodes' association and synchronization stage, during contention access period (CAP) of the 802.15.4, by evaluating and analyzing 802.15.4 MAC CSMA/CA. In [102, 103, 104, 105], the authors have developed mathematical models based on Markov chains to analyze the performance of CSMA/CA. In [106], the suitability of 802.15.4 in mobile networks was tested with respect to beacon order and node speed. Since the standard has been designed for LR-WPAN with minimum complexity, performance degradation for sophisticated mobile WSNs is expected. In this chapter , we consider stationary sensor nodes and evaluate the performance of 802.15.4 based on beacon order and the number of nodes associating with the PAN coordinator. Fan & et al [107] presented an improved association scheme by reducing the number signaling between the PAN coordinator and devices, thus shortening the total time to join the PAN to 0.20438 seconds compared to the 0.5752 seconds obtained while using the 802.15.4 standard scheme. The authors used fixed time values for every stage of association with a PAN coordinator and subtracted the fixed time values for every stage that is redundant for an improved scheme. This approach does not address the random nature of the association procedure as the values are fixed. The 0.5752 seconds value reported is actually the scanning channel time and not the total association time (section 5.3). Furthermore, in [107], the results do not include the impact of beacon interval, as the authors used fixed beacon interval, i.e. beacon order (BO) equal to three, and the study does not assess the impact of increased number of PAN coordinator associating nodes as occurs in this study.

This appears to be the first investigation of the performance of the 802.15.4 MAC beacon interval setting and the number of associating nodes. The performance evaluation is based on the number of nodes associating with a coordinator and beacon intervals in terms of the time required for a node to associate with its coordinator (association delay) and energy consumed by a node to associate and synchronize with the coordinator.

The rest of the chapter is organized as follows. Section 5.2 introduces the IEEE 802.15.4 standard. In section 5.3, an overview of PAN creation is presented, and node association and synchronization procedures. In Section 5.4 presents the performance simulation results for IEEE 802.15.4 (beacon-enabled and non-beacon-enabled modes) in terms of synchronization or association energy consumption and association time delay. In section 5.5, the discussion of the significance of our findings and future research directions. Finally, chapter conclusions are drawn in section 5.6.

5.2 The IEEE 802.15.4 Standard

The IEEE 802.15.4 standard describes the Physical layer (PHY) and medium access control (MAC) sublayer specifications for wireless communication particularly for low-rate, low-power consumption, wireless, personal area networks (LR-WPANs) [7]. The standard has been designed with low complexity and cost wireless connectivity, making it a greatly anticipated technology for wireless sensor networks (WSNs). A PAN involves one coordinator which manages the whole network, but may involve one or more coordinators for a network's subset nodes. The standard supports star, cluster- tree and mesh (peer-to-peer) network topologies. This chapter considers only the star topology investigation.

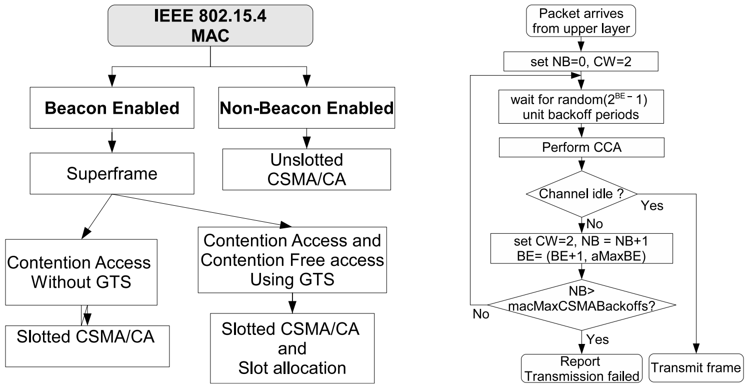
In the IEEE 802.15.4 specifications, network devices can be classified as full-function

(FFDs) or reduced function devices (RFDs). A FFD has more processing ability and contains the full protocol stack with a complete set of MAC services. All PAN coordinators are FFDs that have the ability to communicate with other FFDs and RFDs. In contrast, RFD is an end device operating with minimum implementation of the IEEE 802.15.4 protocol, i.e. contains only a subset of the protocol stack. A RFD cannot associate with more than one FFD concurrently, and is designed for extremely simple applications, such as a light switch or a passive infrared sensor involving small data packages. A FFD can operate in three different network roles: (1) serving as a Personal Area Network (PAN) coordinator, responsible for starting , identifying the network and configuring the network, and operating as a gateway to other networks; (2) as a subset node coordinator providing synchronization services (through beacon transmission), self-organization operations and data routing; (3) as a device, which does not provide the above functions and must associate with a Coordinator before interacting with the network.

5.2.1 Channel access methods

A node wishing to send information has to listen to the channel for a predetermined number of times to check for any activity on the channel. If the channel is sensed as "idle" the node is permitted to send. If the channel is sensed as "busy", the node has to defer its transmission for a random interval. This is the essence of CSMA, which is used in both the carrier sense multiple multiple access with collision avoidance (CSMA/CA) and the carrier sense multiple access with collision detection (CSMA/CD), to gain access to the channel and reduce the probability of collisions [22]. The IEEE 802.15.4 standard specifies a CSMA/CA for contention-based channel access while CSMA/CD is for Ethernet networks.

IEEE 802.15.4 MAC sublayer protocol supports two operational modes for channel access, beacon enabled mode and non beacon enabled mode (Figure 5.1a). A PAN coordinator will select a particular mode of operation. Every node in a PAN uses the CSMA/CA algorithm for every new data packet or MAC frame transmission during the contention access period (CAP). Based on whether beacons are used or not, the CSMA/CA will choose either a slotted or non-slotted procedure. In beacon enabled mode, the MAC sublayer uses the slotted version of the CSMA/CA algorithm for transmission in the CAP of a superframe (section 5.2.2). If beacons are not used, or are not detected, then non-slotted version of CSMA/CA algorithm is used. Figure 5.1b depicts the flowchart describing the non-slotted CSMA/CA mechanism.



(a) MAC operational modes

(b) Unslotted CSMA/CA algorithm

Figure 5.1: MAC operating channel assess modes and the Unslotted CSMA/CA algorithm

5.2.2 Superframe structure

In beacon-enable mode all communication must occur within a superframe structure that is started and maintained by the PAN coordinator . As depicted in Figure 5.2, a superframe is bounded by network beacons and divided into 16 equally sized slots. The first time slot (slot 0) of each superframe is used to transmit the beacon. The main purpose of the PAN coordinator using beacon is to control channel time usage and allow attached devices to synchronize to the network. For example in cluster-tree networks, all coordinators may transmit beacons to maintain the synchronization with their children, i.e. subset nodes. In the current mode, beacon frames are also used by the coordinator to identify its PAN. The remaining time slots are used by competing devices for communications during the contention access period (CAP). All communication between devices must be completed by the end of the current CAP and the beginning of the next network beacon.

To support applications with strict latency and bandwidth requirements, the PAN coordinator may dedicate groups of continuous time slots of the active superframe as guaranteed time slots (GTSs). The number of GTSs cannot exceed seven slots, but a single GTS allocation may occupy more than one time slot. The GTSs form the contention free period (CFP) part of the superframe. Network devices that require GTS can send requests during the CAP period to reserve a desired number of continuous time slots.

To reduce energy consumption, the PAN coordinator can also issue a superframe containing both active and inactive (idle) periods, thus the superframe divides into active and an inactive parts (Figure 5.2). The coordinator can only interact with PAN during the active part of the superframe. During the inactive period , the nodes, including the coordinator, may enter a power (sleep) saving mode to conserve battery power. In this mode, network devices switch off their power and set a timer to reactivate just before the next beacon frame is announced.

The configuration of the superframe will very much depend on the applications' requirements. In 802.15.4 standard, the length of the active and inactive periods, the time slot duration, and the inclusion of GTSs are all configurable network parameters.

The constructed superframe structure is controlled by the duration of the beacon interval (BI), which defines the time between two consecutive beacon frames, and the superframe duration (SD), which in turn defines the active portion of the superframe. An inactive part of the superframe can only be defined when BI is greater than SD. The durations of BI and SD are controlled through two MAC layer attributes known as the beacon order (macBeaconOrder), and superframe order (macSuperframeOrder) SO, respectively, using the following formulae:

$$\begin{gathered} BI = aBaseSuperframeDuration \times 2^{BO} symbols \\ 0 \leq BO \leq 14 \end{gathered} \tag{5.1}$$

$$\begin{gathered} SD = aBaseSuperframeDuration \times 2^{SO} symbols \\ 0 \leq SO \leq BO \leq 14 \end{gathered} \tag{5.2}$$

The beacon enabled mode provides a power management mechanism based on the duty cycle (DC) of each node which can be obtained by taking the difference between BO and SO, i.e.$DC = \frac{SD}{BI} = 2^{SO-BO}$.

The active portion of each superframe is divided into *aNumSuperframeSlots* of equal duration $2^{SO} \times aBaseSlotDuration$, where $aBaseSuperframeDuration = aBaseslotDuration \times aNumSuperframeslot$. For 250 kbps in a 2.45 GHz frequency band, *aBaseSlotDuration* is equal to 60 radio symbols duration resulting in 15.36 ms minimum SD(SO=0) with 16 superframe slots. Hence (BI) and SD may be between 15.36 ms and 251.66 s, and doubles from the previous value of BO and SO (Table 5.1).

In case of non beacon-enable, both *macBeaconOrder* and *macSuperframeOrder* are set to 15 by the PAN coordinator and therefore the unslotted CSMA/CA mechanism is used to gain access to the channel.

A beacon is transmitted without the use of CSMA, at the start of slot 0, followed by CAP and CFP to the end of the superframe's active part. As with the beacon, CAP is a mandatory part of a superframe. Coordinators are required to listen to the channel for the whole CAP to detect and receive any data from their child nodes. Conversely, the child node may only transmit data and receive an optional acknowledgment (ACK) when needed, thus increasing their energy efficiency.

All superframe settings are sent to network devices through beacon frames (Figure 5.4). In the superframe specification field (Figure 5.4), beacon order, superframe order, number of CAP slots, power saving settings, PAN coordinator bit and association permit bit are specified [7].

Table 5.1: Superframe duration

BO/SO	BI/SD	BO/SO	BI/SD	BO/SO	BI/SD
0	15.36ms	5	491.52ms	10	15.72864s
1	30.72ms	6	983.04ms	11	31.45728s
2	61.44ms	7	1.96608 s	12	62.91456s
3	122.88ms	8	3.93216s	13	125.82912s
4	245.76ms	9	7.86432s	14	251.65824s

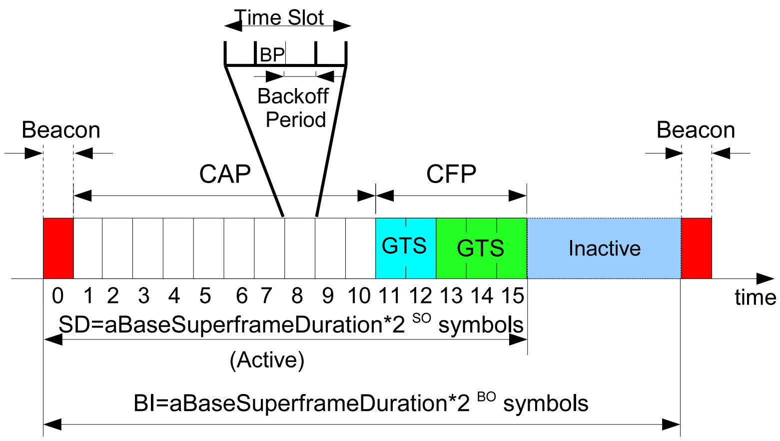


Figure 5.2: Superframe format

5.3 Initialization of a PAN Coordinator, Node Association and Synchronization

One key aspect of a wireless sensor network is its ability to self-organize and maintain connectivity. The MAC protocol manages the self configuration of the network, i.e., ability to start a new PAN, associate or disassociate with an exiting network, and synchronize if required. Figure 5.3 illustrates a simulation of a PAN initialization, node association and synchronization stages.

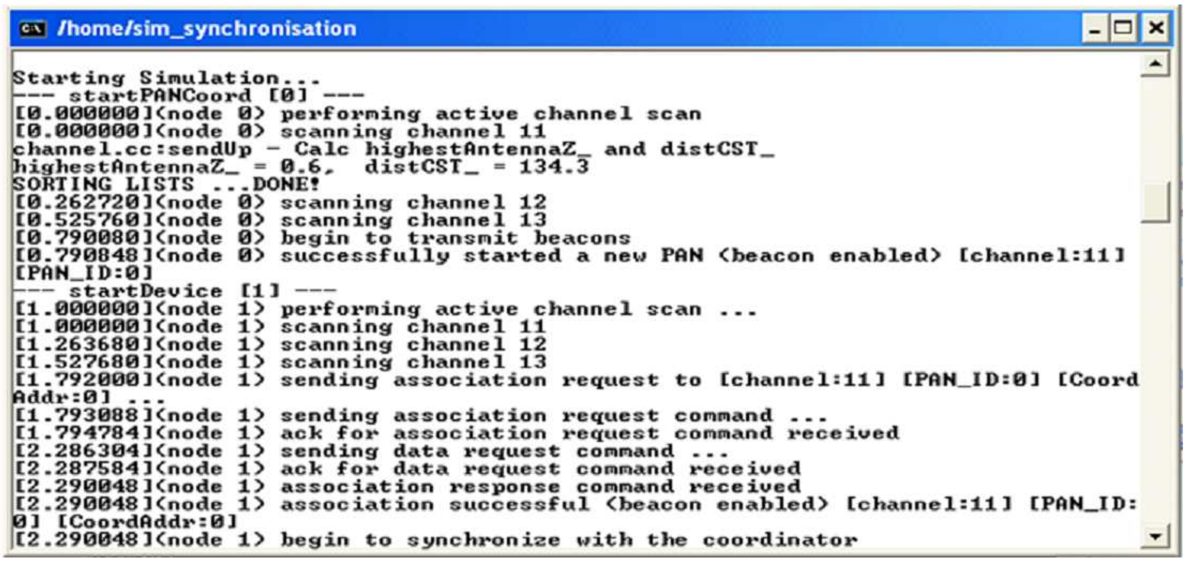


Figure 5.3: PAN creation, association and synchronization steps

Before any communication can take place, devices have to find a channel or channels for communication. This is achieved by scanning through a selected number of channels for a specific scan duration. For example, a device can scan all 16 channels available in 2.4 GHz band or scan some of the selected channels (Figure 5.3). In the 802.15.4 standard there are four types of scanning that can be performed: energy detection scan (FFD only), active scan (FFD only), passive scan, and orphan scan. The duration of scanning is the time spent scanning each channel for ED, active and passive scans; however, for orphan scan this duration is ignored. The time to scan each channel is given by $[aBaseSuperframeDuration \times (2^n + 1))]$ symbols duration, where n is the value of scan duration parameter, and 1 symbol duration is equal to 16 microseconds in 2.4 GHz band. Energy detection (ED) scan is used to find an unused channel or channels while active (AS) and passive scans (PS) are used to locate beacon frames containing any PAN identifier, i.e. allows a device to locate any coordinator transmitting beacon frames within its personal operating space (POS). The AS is also used to select the PAN Identifier before starting a new PAN or could be used by a device prior to association to determine if there is any coordinator transmitting beacon frames within its POS. Orphan scan is used to locate a PAN to which the device is currently associated [7].

5.3.1 PAN Creation

To start any PAN, the first step involves establishing a PAN coordinator. Any FFD can be the sole PAN coordinator. The following is a summary of the steps used when establishing a PAN coordinator (creating a new PAN):

1. Upon power up, a FFD transceiver may begin ED scan and then an active scan on each of the available channels to find a suitable frequency for communicating within its personal operating space (POS)

2. During active scan (AS), a device sends out a beacon request command and then sets a scan duration

3. If no beacon is detected within the scan duration, the FFD believes that there is no coordinator in its POS

4. The PAN coordinator will lock on a suitable channel, select an identification number for the PAN known as the PANid, assign itself a short address (less than 0xffff), and begin to operate as a PAN coordinator by broadcasting its periodic beacon frame. At this stage the superframeOrder beaconOrder parameters are set and now devices can associate with the PAN coordinator. The PAN coordinator will control device association by assigning short addresses to devices and coordinators

5.3.2 PAN Association and Synchronization

A FFD or RFD device can request to join an existing PAN within its POS by initializing an association procedure. In order to optimize the association procedure on a beacon-enabled PAN, a device is allowed to start tracking the beacon of the coordinator of interest in advance[7]. The following is a summary of the steps used when a device wants to associate with an existing PAN (section 5.3.1):

1. Device's PAN association starts with a device performing either an active or passive channel scan to determine if there is any coordinator transmitting beacon frames within its POS. It also has to find a PAN coordinator that is accepting incoming association requests when using an AS. For passive scan the beacon request command is not required

2. From scan results above, if a PAN coordinator/s exists the device will select a suitable PAN and attempt to join a PAN as long as PAN coordinator allows association (Figure 5.4), as determined through the scan procedure. A device can then transmit an association request command for an association with a coordinator

3. The coordinator will then send an acknowledgment frame confirming that it received the request command and then make a decision within aResponseWaitTime symbols duration ($aResponseWaitTime = 32 * aBaseSuperframeDuration$ symbols = 30,720 symbols $\approx$ $0.49s$) as to whether to allow association or not. This decision will depend on whether there are sufficient resources available

4. For beacon-enabled mode, the device will wait for the maximum aResponseWaitTime symbols duration for the coordinator to make the decision. Within aResponseWaitTime symbols duration, the device will seek information about the decision made by the coordinator whenever a beacon frame appears. In the case of a non-beacon enabled mode, the device will seek the association response command after aResponseWaitTime symbols duration. If there is no response, the association attempt has failed

5. On receiving the association response command, the device requesting association will send an acknowledgment frame confirming receipt. If the status of an association response command indicates the association was successful, the device will configure the PHY and MAC attributes, to the value necessary for association (used when a device transmits data) that include the channel to use (phyCurrentChannel), PANid (macPANid) and the short address of the coordinator

Note that all devices in PAN, come with a pre-assigned long address, the PAN coordinator must be assigned a short address to itself before it can allow the start request . A FFD that is not a PAN coordinator can only begin transmitting beacon frames when it has successfully associated with a PAN coordinator (Figure 5.3).

Once devices have associated with the coordinator, all devices will be allowed to acquire beacon synchronization only with beacons containing the PAN identifier specified in macPANId. If macPANId specifies the broadcast PAN identifier (0 x ffff), a device shall not attempt to acquire beacon synchronization. All devices operating in a beacon-enabled PAN (i.e., macBeaconOrder$<$15) have to maintain beacon synchronization to detect any pending messages or to track the beacon. Synchronization is maintained by all devices by receiving and extracting beacon frames (Figure 5.4). All devices operating on a non beacon-enabled PAN (macBeaconOrder=15) must be able to poll the coordinator for data at the discretion of the next higher layer (5.2.2).

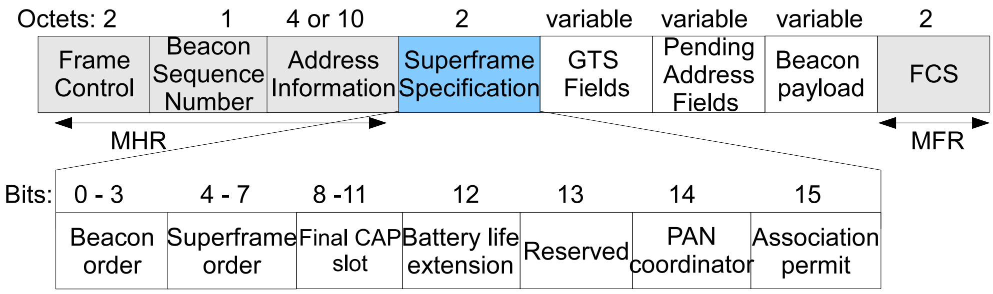


Figure 5.4: Beacon frame format

5.4 Performance Evaluation

To observe the impact of beacon interval (BI) and number of nodes associating with the PAN coordinator, we obtained the average energy consumed per node to associate and synchronize with the coordinator, and the average time required by a node to associate with the PAN coordinator.

5.4.1 Simulation model

NS-2 [82] simulator was used to study the impact of beacon interval and the non beacon case during node association and synchronization. It involved a star network topology, using 802.15.4 standard, where the sink node in the middle acts as the PAN coordinator and all surrounding items are associating nodes. The PAN coordinator and associating nodes are all stationary. All nodes in the ideal star topology are in range with the PAN coordinator and there is no channel interference. The coordinator starts at 0.0 seconds, followed by each associating node in turn, 1 second apart. Each simulation ran for 5000 seconds. No data are sent by nodes that have joined the PAN as we are interested with the association and synchronization part only. Table 5.2 shows our simulation parameters.

5.4.2 Results

Figure 5.5 and Figure 5.6 show average node's association and synchronization time for different beacon interval (BI) as we increase the number of nodes associating to one PAN coordinator.

Table 5.2: Simulation Parameter Settings

Parameter	**Value**
Frequency Band	2400-2483.5 MHz
Channel Rate	250 kbps
macSuperframeOrder (SO)	0-15
macBeaconOrder (BO)	0-15
macSuperframeSlots	16
aBaseSlotDuration	60 symbols (960 μs)
Symbol interval	16μs
aUnitBackoffPeriod/slot duration (T_{slot})	20 symbols (320μs)
macAckWaitDuration	54 symbols (864μs)
aResponseWaitTime	30,720 symbols (0.4915s)
SIFS	12 symbols (192μs)
ACK reception duration (T_{ack})	544μs
ACK timeout ($T_{acktout}$)	864μs
Current consumption in transmit mode (@ 0 dBm)	17.4mA
Current consumption in receiving mode	18.8 mA
Current consumption in idle mode	0.426 mA
Typical node working voltage	3.0V
Simulation area	150m x 150m
Simulation time	5,000 seconds
Number of random seeds per simulation	50

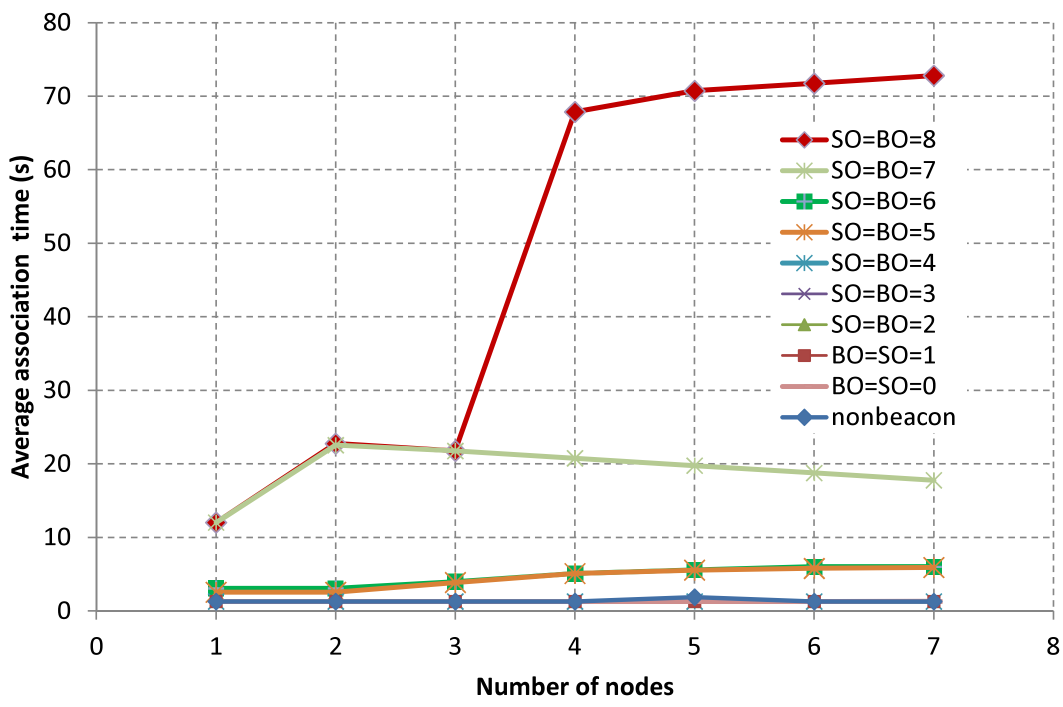


Figure 5.5: Devices' PAN association and synchronization durations for beacon orders up to 8 and 15

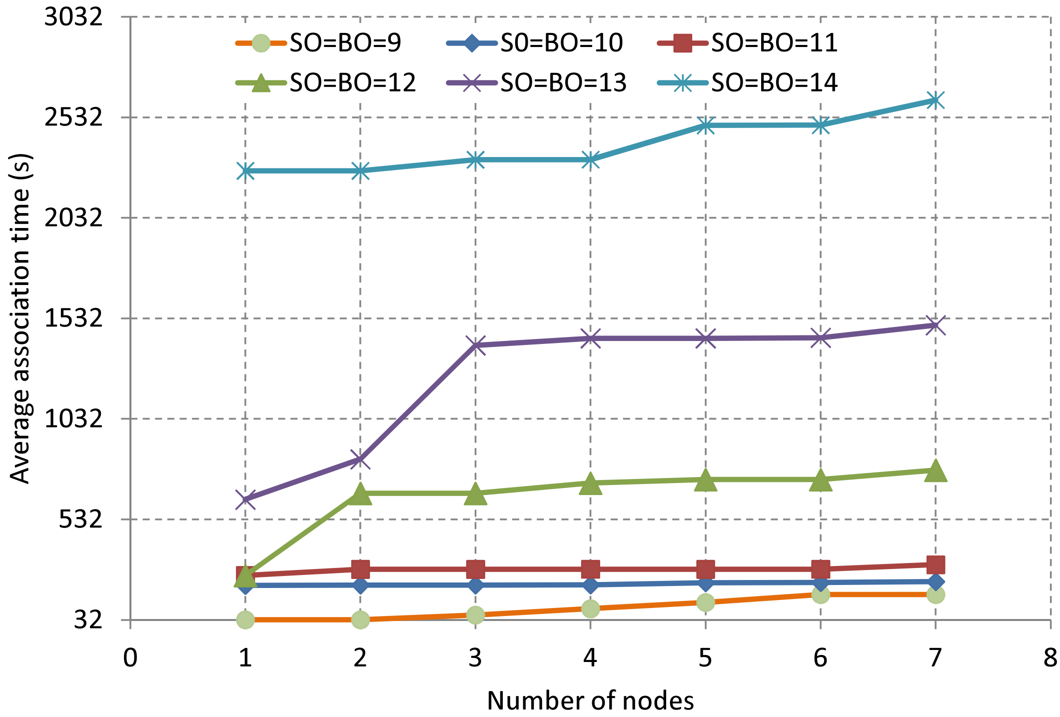


Figure 5.6: Devices' PAN association and synchronization durations for beacon orders 9-14

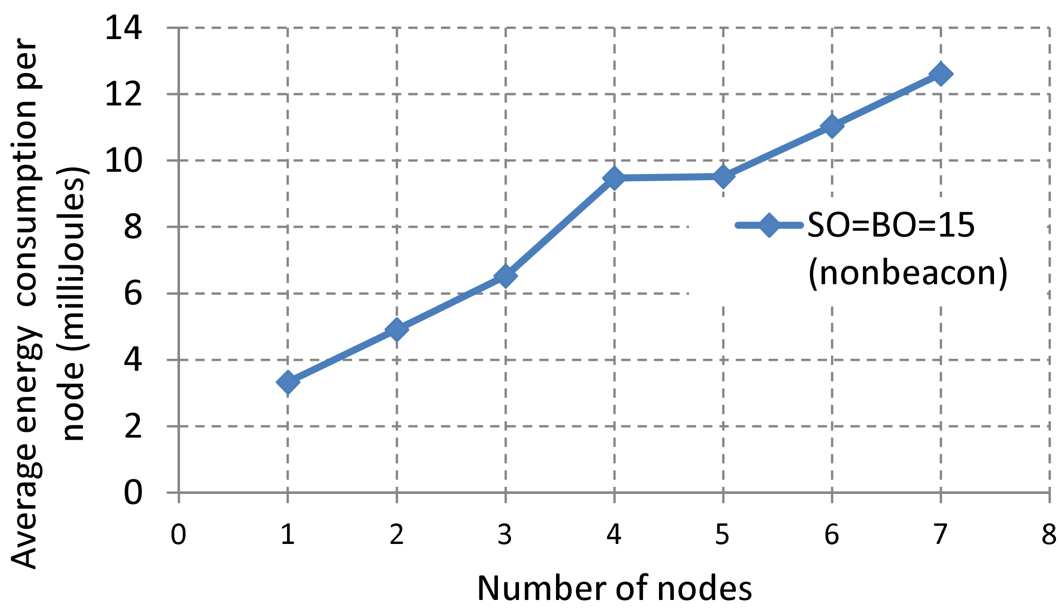


Figure 5.7: Energy consumption for non beacon enabled mode

Figure 5.7 shows the average amount of energy consumed by a node in order to associate with the PAN coordinator when using non-beacon enabled mode.

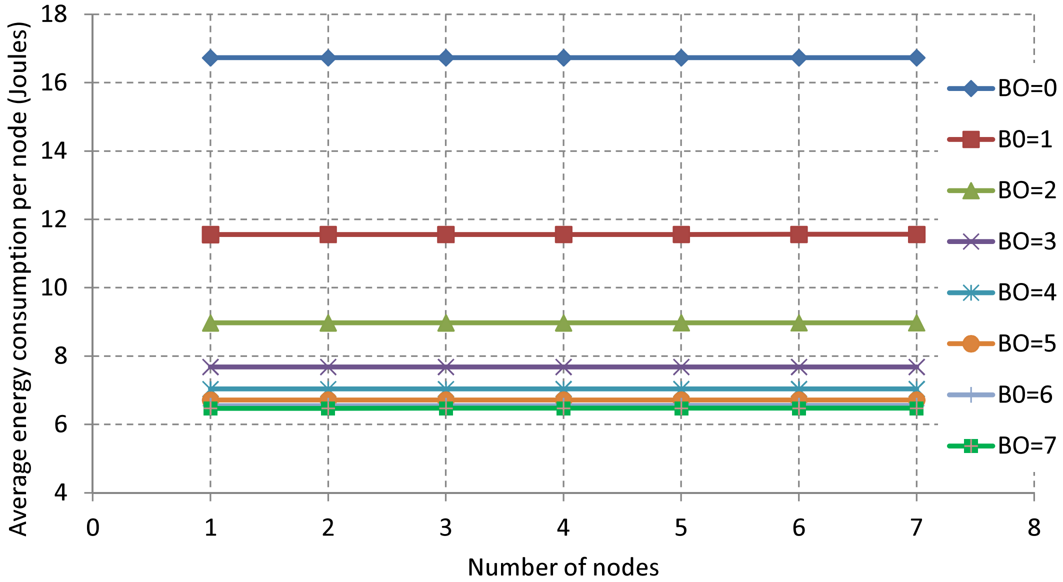


Figure 5.8: Association and synchronization energy consumption

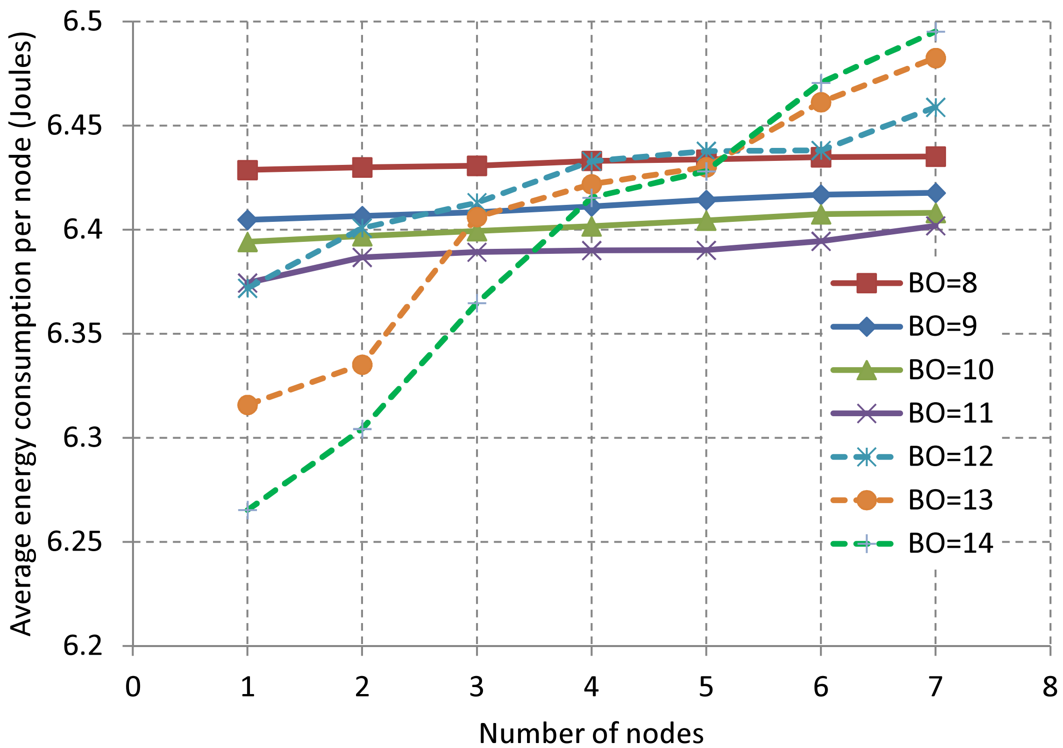


Figure 5.9: Association and synchronization energy consumption

Figure 5.8 and Figure 5.9 show average energy consumption per node for different BI as we increase the number of nodes associating to one PAN coordinator when using beacon enabled mode.

5.5 Discussion

Results illustrate that over a longer period, shorter beacon intervals will consume more of the node's energy while long beacon intervals will require less energy. Short beacon intervals consume more energy due to the frequency of beacon frames with which nodes have to keep track of to maintain synchronization; our results suggest that this is valid for BO=0 to BO= 11 (Figure 5.8 and Figure 5.9). However, for longer beacon intervals, BO= 12 to BO=14, there is an abrupt increase in energy consumption as the number of associating nodes increases, even for as few as four nodes. The energy consumption increases in the order of about 1 millijoule for every additional associating node for all beacon order (BO) values ranging from 0 to 11. Results also illustrate that non-beacon mode consumes less energy to associate to the PAN coordinator compared to the beacon enabled. The main reason low association energy for non-beacon enabled mode is that there is no beacon transmission to maintain synchronization as opposed to beacon enabled mode (Figure 5.7).

The results demonstrate that the average node's association delay time increases with increased number of nodes and increased beacon intervals (Figure 5.5 and Figure 5.6). However, there is a very small time difference between non-beacon enabled PAN and beacon enable PAN for values of beacon order (BO) between 0 and 4. Furthermore, our results demonstrate that as the number of associating nodes increases, longer beacon interval cases suffer longer association delays (Figure 5.6) compared to shorter beacon intervals, and the energy consumption for association and synchronization increases. For example, it will take about 42 minutes for 7 nodes requesting association to associate with the coordinator, when BO=14. Such long beacon intervals are unsuitable for real time and mobile WSN applications.

To conserve energy in WSNs, we expect to use longer beacon interval (BI) and shorter active periods (SD) so that the nodes can go into inactive or sleep state during CAP to save energy. To date the longest beacon interval is 251.66s (about 4 minutes). Our results demonstrate that even with 7 nodes connected to the PAN coordinator, the association delay and energy consumption due to synchronization, increase. The question is whether the association energy consumption will outweigh the benefit of duty cycle power management for larger beacon intervals, as the number of associating nodes increases?

5.6 Conclusions

WSNs are a research hotspot with many challenges, including managing energy consumption and network connectivity. In this chapter, performance evaluation of the 802.15.4 MAC beacon interval settings during devices' association and synchronization with the PAN coordinator was presented. Overall, non-beacon mode consumes less energy to associate to the PAN coordinator compared to beacon enabled.

It has been demonstrated that over a longer period, shorter beacon intervals will consume more of the node's energy while long beacon intervals will spend less energy, at least for BO=0 to BO=11. The associating energy consumption increases with increased number of nodes for all beacon intervals (B0=0-15). For longer beacon intervals, BO=12 to BO=14, there is an abrupt increase in energy consumption as the number of associating nodes increases, even for a small number of nodes, such as four. Results demonstrate that it will take about 42 minutes for 7 nodes requesting association to associate with the coordinator, when BO=14. Such long delays are not suitable for real time and mobile WSN applications. The question here is whether the association energy consumption will outweigh the benefit of duty cycle power management for larger beacon intervals as the number of associating nodes increases. Future work will further investigate possible solutions to improve the performance of 802.15.4 during PAN association and synchronization stage and during data sending stage.

Chapter 6

Clear Channel Assessment and Enhanced MAC for Hidden Nodes

The IEEE 802.15.4 MAC protocol standard controls radio channel access using the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) algorithm. To avoid collisions, the standard adjusts the backoff exponent (BE) based on two consecutive clear channel assessments (CCA) before packet transmission. The CCA part is carried out at the physical (PHY) layer, and used by the MAC protocol as part of the CSMA/CA algorithm, whereby a node is required to perform a CCA for a predetermined duration to determine if the channel is available for transmission (i.e. check whether the channel is busy or idle) before transmission of the data frame. This chapter provides an investigation on the impact of the number of times the CCA is performed in the 802.15.4 MAC sublayer during frame transmission; in terms of throughput, packet error rate, delay, and energy consumption. The study considers both hidden and non-hidden nodes in a network system. Results show a serious network performance degradation, even for a small number of hidden nodes in a network. In this chapter a proposed cross layer (PHY-MAC) design is presented, aimed at improving network: energy efficiency, reliability, and scalability; by reducing packet collisions due to hidden terminals/nodes.

6.1 Introduction

The IEEE 802.15.4 standard describes the physical layer (PHY) and the medium access control (MAC) sublayer specifications for wireless communication; in particular for low-rate, low-power consumption, wireless personal area networks (LR-WPANs) [7]. The standard represents a significant milestone in promoting deployment of wireless sensor networks (WSNs) for a variety of commercial uses [108].

The MAC sublayer is a broad research area, however, this chapter focuses on the efficiency of the MAC sublayer for WSNs. Earlier studies have sought to improve WSNs in the area of a power efficient MAC sublayer[71, 18, 72, 73, 74, 77]. In [73], the authors developed a power efficient MAC protocol known as PAMAS. PAMAS was designed to reduce the overhearing between nodes by using a separate signaling channel. The PAMAS method requires an extra radio interface and therefore increases the hardware costs and the complexity of the MAC sublayer for a sensor node. In [74], an extension to the standard 802.11 MAC protocol known as power control multiple access (PCMA) was presented. PCMA unlike PAMAS, does not use a separate signaling channel, and can also be used by any other protocols that use CSMA/CA. The main aim of the PCMA is to use less power compared to the 802.11 standard, and still retain the same throughput. This was achieved by transmitting DATA and acknowledgment (ACK) frames at the minimum transmission power, and transmitting request-to-send (RTS) and clear-to-send (CTS) frames at the maximum transmission power. Moreover, to reduce collisions, data transmissions are periodically transmitted at maximum power, so neighboring nodes can sense the medium occupied, and refrain from sending RTS frames.

Wei et al. [18] developed a power efficient protocol known as S-MAC (schedule MAC), which is a contention based MAC protocol like the IEEE 802.11 MAC protocol. However, the main difference between them is the power saving mode of S-MAC, which adds power saving features to the virtual carrier sense. When a NAV (Network Allocation Vector) shows that the remaining time of the ongoing transmissions is nonzero, and that the transmission does not involve the current node; the radio is powered off until the NAV reaches zero (Fig 6.4). The S-MAC design reduces the energy consumption caused by idle listening, and tackles the overhearing problem by sending interfering nodes to sleep once they hear a RTS/CTS signal; however latency is increased (tradeoff between energy and latency), since the sending nodes must wait for the receiver to wake up before sending out data [18]. In summary [18] identified and described areas of energy wastage including: idle listening, collisions, overhearing, and control overhead; and aimed to reduce energy consumption, while supporting network scalability and collision avoidance.

Dam & Langendoen [75] presented another contention based MAC protocol called T-MAC

(Timeout MAC), which aims to reduce energy consumption by allowing active nodes to have adaptive/variable duty-cycles rather than fixed ones. The design allows every node to decide its own duty-cycle based on its activation period, and to end the active time upon hearing nothing on the channel (for a period known as timeout). The T-MAC protocol causes more latency in a network compared to the S-MAC protocol; however, the authors claim to give much better energy performance results for low data rate applications. Both T-MAC and S-MAC use periodic time synchronization that can consume a lot of energy.

B-MAC (Berkeley MAC) [76]is also a contention based MAC protocol, but is only a link layer protocol design, with network services such as organisation, synchronisation, and routing being built above its implementation. B-MAC performs carrier sensing using Clear Channel Assessment (CCA), and the sleep/wake scheduling by using Low Power Listening (LPL). Significant B-MAC design considerations include: keeping MAC implementation code size small for small storage, saving energy, and providing users with complete flexibility to change different MAC parameters, such as CCA, acknowledgments, backoffs, and LPL to suit a particular WSN application. These changes can be made using the B-MAC configuration interface at run-time. Other advantages of this design include: no RTS/CTS signalling requirement, and no synchronisation of packets requirement. However, the design causes a huge overhead because of overhearing, whereby receiver nodes have to stay awake while receiving a long preamble, even when they are not the intended destinations.

Z-MAC (Zebra MAC) [77] is a hybrid MAC scheme that combines the strengths of CSMA and time division multiple access (TDMA). The design allows nodes that are within interference range and in a high contention scenario to transmit during different times/slots to avoid collisions, i.e. it's collision free. However, unlike TDMA, a node can transmit during any given time slot. T-MAC's main design goals are to reduce energy consumption, by tackling frame collisions caused by hidden nodes, and controlling overhead frames such as RTS/CTS or Data/ACK.

This chapter presents a study on the impact of the number of times the CCA is performed in the 802.15.4 MAC during frame transmission; in terms throughput, packet error rate, delay, and energy consumption. Both hidden and non-hidden nodes in a network system are considered in the experiments, and a new cross layer (PHY-MAC) design is proposed. The purpose of the new cross layer is to improve network energy efficiency, interference, reliability, and scalability; by minimising packet collisions due to hidden nodes. The proposed changes can coexist with the legacy 802.15.4 CSMA/CA, and can also be used by

CSMA/CA MAC protocols.

6.2 IEEE 802.15.4 MAC Layer

The IEEE 802.15.4 MAC sublayer controls radio channel access using the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism. Every PAN node uses the CSMA/CA algorithm for every data packet or MAC frame transmission during the contention access period (CAP). This is achieved through the standard modes of operation: beacon enabled and non-beacon enabled. The mode is selected by the central node (PAN coordinator). In non-beacon enabled mode, the MAC protocol uses a simple non-slotted CSMA/CA algorithm for transmission in the CAP, which requires constant reception for potential incoming data. In beacon enabled mode, the MAC protocol uses a modified slotted CSMA/CA algorithm that requires all nodes to be synchronized through beacon frames[7]. Based on whether beacons are used or not, the CSMA/CA will choose either a slotted or non-slotted procedure. If beacons are not used, or are not detected, then the non-slotted version of the CSMA/CA algorithm is used. The CSMA/CA algorithm is not used during beacon and acknowledgment frame transmissions. The data frame is transmitted during the contention free access (CFA) period, and the data frame quickly follows the acknowledgment of a data request command. Figure 6.1 depicts the flowchart describing slotted and non-slotted CSMA/CA mechanisms.

The 802.15.4 MAC protocol is also responsible for: flow control via acknowledgment of frame delivery; frame validation (as well as maintaining network synchronization); network association and dissociation; administering device security; and the scheming of the guaranteed time slot mechanism.

6.2.1 The CSMA/CA algorithm

A node, wanting to send information, first listens to the channel for a predetermined amount of time to check for any activity. If the channel is sensed as "idle" then the node can send. If the channel is sensed as "busy" the node defers its transmission for a random interval. In both CSMA/CA and CSMA/CD, this technique allows access to the

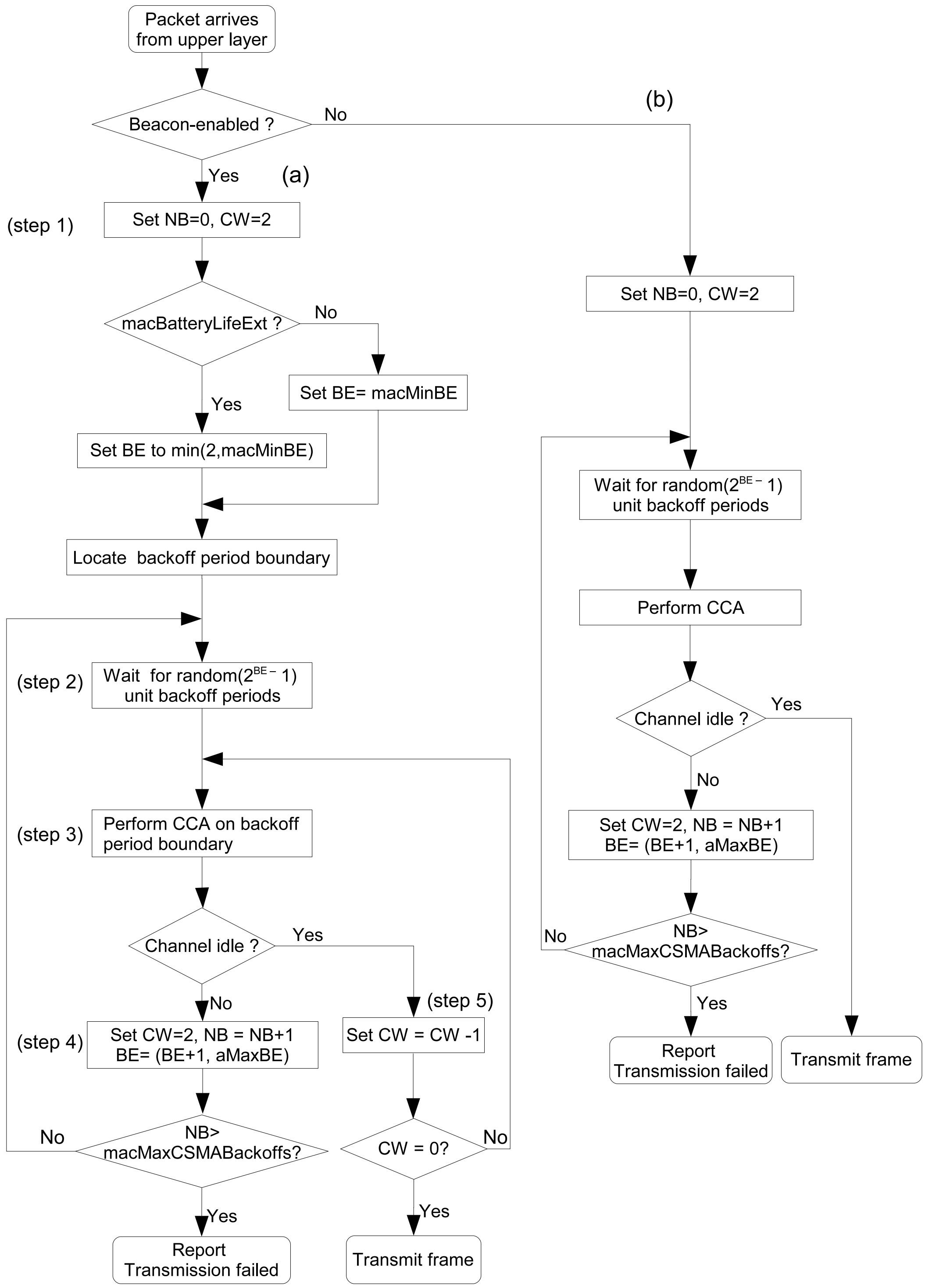


Figure 6.1: Slotted (a) and non-slotted (b) CSMA/CA algorithm

channel while reducing the probability of collisions [46, 26]. The CSMA/CA is used by the IEEE 802.15.4 standard for contention-based channel access, while CSMA/CD is used by Ethernet networks.

The CSMA/CA mechanism is based on a basic time unit called a unit backoff period (BP) or backoff slot [7]. Each backoff slot, aUnitBackoffPeriod, lasts for 20 symbols (80 bits); equivalent to 320 microseconds in a 2.45 GHz frequency band. Any node that has a packet ready to send has to wait for a randomly chosen number of slots (BP). This backoff period/-counter is decremented by one at the beginning of every slot that follows. At the end of the backoff period, the node performs a clear channel assessment (CCA) for a predetermined period to monitor the channel status before sending the packet; i.e. to check whether the channel is busy or idle. The channel sensing mechanism ensures that the channel is clear of activity for a predetermined duration known as the contention window (CW) duration, expressed in terms of backoff slots, before the node can attempt transmission. Similarly, the CW begins from a specified value (default 2), and is decremented by one at every idle contention window slot until it reaches zero.

In order for a node to access the channel for a transmission attempt, the CSMA/CA algorithm requires each node to maintain three counters: 1) NB, which is the number of backoff attempts/trials (backoff stage) for a particular frame transmission, initialised to 0 before each new transmission attempt. 2) BE, which is the backoff exponent that defines the uniformly distributed random number of backoff durations, for which a device has to wait, before performing a CCA. In slotted PAN, if macBattLifeExt is set as FALSE, then BE is initialised to the value of macMinBE; otherwise if macBattLifeExt is set as TRUE, the BE value will be initialised to the value of macMinBE minus 2. In the 802.15.4 the default BEmin is 3, and BEmax is 5. 3)CW, which is the contention window duration, expressed in terms of backoff slots, defining the number of consecutive backoff periods for which a channel needs to be silent before transmission can commence.

The 802.15.4 standard defines the default CW duration to be 2 backoff slots ($640\,\mu s$). The slotted CSMA/CA algorithm can be summarized as follows (Figure 6.1):

1. A node initialises NB=0, CW=2, and BE=MacMinBE, and then locates the backoff period boundary of the next backoff period.
2. A node delays for a random number of complete backoff periods/slots in the range 0 to $2^{BE}-1$, i.e. $\textit{Backoff time}=\textit{Random}([0\text{-}2^{BE}-1])\times \textit{aUnitBackoff Period}$, before sensing the

channel. This randomly chosen counter or backoff period is decremented by one at the beginning of every slot that follows, until the counter is zero; before sensing the channel.

3. A node requests the PHY layer to perform a CCA to sense the channel, i.e. check whether the channel is busy or idle. In slotted CSMA/CA, the CCA starts on the backoff period boundary; while in unslotted, the backoff starts immediately.

4. If the channel was sensed as "busy" in step 3, the value of CW will be reset to its original value, e.g. CW=2; BE will be increased by one after each transmission fails until it reaches a maximum value BEmax (default BEmax =5); NB will be incremented by one, ensuring NB is less or equal to MacCSMABackoffs (the standard default=4), and then the algorithm will return to step 2. If the value of NB is greater than macCSMABackoffs, CSMA/CA will terminate with a channel access failure status and the current packet will be discarded. If the channel was sensed as idle in step 3, we jump to the next step (step 5).

5. If the channel was previously sensed as idle (step 3), the MAC sublayer in a slotted CSMA/CA system will ensure that the specified contention window has expired before commencing transmission. To do this, the CW value is checked, if its value is not equal to zero, the CW is decremented by one and the algorithm goes back to step 3. If its value is equal to zero, then the frame will be transmitted and the process recommences (step 1) for another data frame.

A frame transmission is considered to be a success or a failure (collision) depending on whether an optional ACK frame is successfully received after the frame transmission. To deal with such a problem, the 802.15.4 standard supports an optional retransmission scheme based on acknowledgments and timeouts. When the retransmission mechanism is enabled, the destination node must send an acknowledgment after receiving a correct data frame. The acknowledgment will not be sent if a collision or corrupted frame reception occurs. The sender will wait for an acknowledgment, and if it does not receive it within a specified period (timeout), a retransmission will be scheduled. The standard default maximum number of retransmissions (macMaxFrameRetries) is 3. If the maximum number of retransmissions is reached, then the data frame will be dropped. This retransmission scheme applies when a node fails to transmit a frame either: 1) due to five consecutive busy channel outcomes, i.e. NB>*macCSMABackoffs;* or 2) due to collisions.

In the CSMA/CA algorithm, BE is the main parameter used in the backoff procedure, to reduce or control the probability of a collision among contending nodes in a multiple access, broadcast channel. This backoff procedure is sometimes known as a truncated binary exponential backoff (BEB).

The CSMA/CA algorithm provides a distributed access mechanism in the sense that each station independently executes the algorithm to decide whether to transmit in the given time slot. In this regard 802.15.4 CSMA/CA is similar to IEEE 802.11 CSMA/CA; however, in the former, a backoff counter value for the device decreases automatically at every slot until it become zero, regardless of the channel status (busy or idle), and then performs a CCA. This is one of the power saving features of 802.15.4 wherein devices can conserve power during the backoff period, in contrast to the conventional CSMA/CA mechanism used in IEEE 802.11 WLANs [109]. Figure 6.2 shows the channel access timings for the 802.15.4 and the 802.11 basic access (without RTS/CTS).

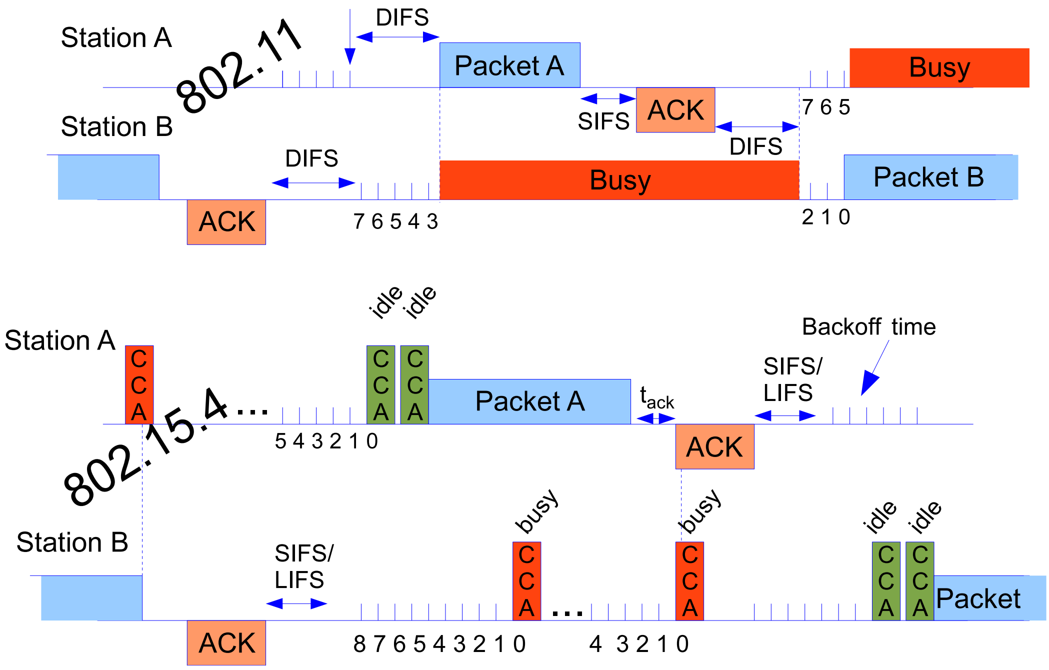


Figure 6.2: IEEE 802.11 and IEEE 802.15.4 channel access

6.3 Hidden Terminals Problem

The wireless medium has some special properties that affect the performance of contention based MAC protocols. The wireless receiver requires the received signal to meet a certain minimum signal threshold/strength in order to be detected. Therefore, if the distance between two stations exceeds some threshold, they cannot hear each other. Thus for protocols incorporating carrier sensing (e.g. CSMA/CA) to be effective, detection time and propagation delays in the system must be small; given that the user waits to transmit a random time period after sensing the channel is free. The CSMA only works when all users can detect each others transmissions (within range), and delays are small. However, the nature of the wireless channel may prevent a given node from detecting the signal transmitted by all other nodes, especially for nodes with low transmission/sensing range. This gives rise to the hidden terminal scenario, as illustrated in Figure6.3

Consider three stations A, B, and C; with transmission radii as indicated by the solid circles. Station B can communicate with both A and C since they are in range of B, but A is not in the range of C, and vice versa. If C starts to transmit packets to B, A cannot detect the transmission using the carrier sense mechanism, and considers the medium to be free. Hence A also starts packet transmission and therefore a collision will occur at B. To avoid packet collisions due to possible hidden terminals, techniques such as the one used in the 802.11 standard networks, by using the four handshake request to send-clear to send (RTS-CTS) exchange and furthermore use ACK for reliability, can be useful as illustrated in Figure 6.4. All nodes that hear a RTS or CTS will not transmit for the duration of the transfer. For example, in Figure 6.3, station A will hear the CTS sent by station B to C, and therefore backoff to avoid collision.

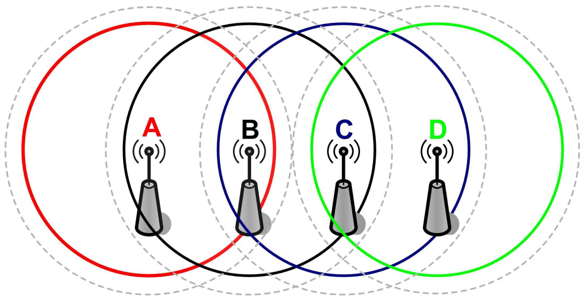


Figure 6.3: Hidden terminal problem

There exists a second scenario, where carrier sensing leads to false predictions about the channel state at the receiver, known as the exposed terminal problem/scenario; also depicted in Figure 6.3. The four stations A, B, C, and D are placed in such a way that only the pairs A/B, B/C, and C/D can hear each other, while all remaining combinations cannot. Consider the situation where station B transmits to A, and a short period later

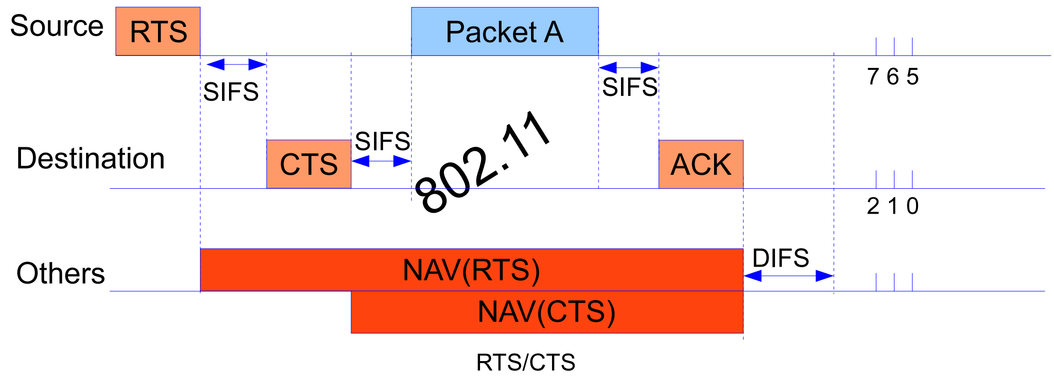


Figure 6.4: 802.11 four-way handshake mechanism

C starts to transmit to D. Station C performs carrier sensing and senses the medium is busy due to B's transmission to A. As a result C postpones its transmission. However, C could have safely transmitted its packet to D, without disturbing B's transmission to A. This scenario leads to inefficiencies in channel utilization.

The packet collisions introduced by hidden terminals are often avoided in CSMA wireless networks by using the four-way handshake during transmission. This technique avoids large sized packet collision by sending small control packet (RTS/CTS), which are less likely to collide and even if a collision occurs it won't impact the system as much as the large sized packet collision would. Although the RTS/CTS procedure efficiently reduces collisions in traditional wireless networks, it has some drawbacks in wireless sensor networks. The data packet sizes in sensor networks are usually small, and therefore their collision probability is in the same order as the control packets, RTS-CTS. Moreover, the use of four-way handshake introduces more control packets, RTS/CTS, which increases the energy consumption of the MAC protocol.

6.3.1 Proposed MAC design

To maintain the IEEE 802.15.4 MAC's limited number of control packets, and to leave the fundamental MAC paradigm unchanged, instead of introducing (RTS-CTS) like in the 802.11 standard, we have proposed the following algorithm. When a node is sensing the channel (i.e. performing CCA), it will do so by always using the minimum configurable CCA threshold to increase the sensing coverage area. This will reduce the number hidden terminals in a network. Moreover, a node will transmit packets using the minimum required transmission power assigned by a coordinator/base station, to save energy and reduce interference. The coordinator will use its receiver signal threshold and the node packet received signal strength indicator (RSSI) or Link quality indicator (LQI), to assign a node with the minimum required transmission power. The proposed design is given in Algorithm 6.1.

Algorithm 6.1 Setting CCA and packet transmission power to reduce hidden terminals and save energy

Require: beacon_mode, phyMode, opt_tx_power, and min_CCA_threshold
Read: beacon_mode, PhyMode

```
if beacon_mode = beacon_enabled then
    while phyCCAMode do
        phyCCAThreshold ← min_CCA_threshold
    end while
    while phyTXMode or phyACKMode do
        phyTransmitPower ← opt_tx_power
    end while
else
    if beacon_mode = beacon_disabled then
        while phyCCAMode do
            phyCCAThreshold ← phyCCAThreshold
        end while
        while phyTXMode or phyACKMode do
            phyTransmitPower ← max_tx_power
        end while
    end if
end if
```

6.3.2 Proposed transmission power control algorithm

The following algorithm is used to determine whether the transmit power of a node needs to be changed. Since in the 802.15.4 standard transmission can only start after an idle CCA, which implies that no other transmissions are taking place, RSSI for neighbouring nodes is not considered. The coordinator will listen for an incoming packet from a source node, and record its received signal strength or LQI and packet transmit power level.

Determining the minimum transmission power that maintains connectivity is conceptually simple, but challenging to implement. Conceptually, the receiver simply subtracts the received signal strength indicator (RSSI) from the transmitted power of the packet to obtain the current path loss, and then informs the sender to transmit at the "current path loss + RXthreshold", where RXthreshold is the minimum power at which the receiver can decode a packet. However, this would keep the coordinator and the source node barely connected and therefore may cause frequent triggers to change the transmission power. In practice, the noisy RF reception environment results in fluctuations in the RSSI/path loss between packets even when both the client and base station are stationary [110]. The proposed TPC algorithm can adapt to node mobility and RF noise/fading by incorporating a configurable buffer. Therefore, the optimal transmit power should have a buffer above the tight bound given by equation 6.1.

$$opt\_tx\_power = pass\,loss + RXthreshold + Buffer \tag{6.1}$$

In this algorithm, the buffer added to the minimum receiver threshold is a fraction of the device's minimum transmit power. This will allow devices to operate in different environments, such as within mobile applications and while experiencing extreme environmental conditions, without being required to frequently change transmit power updates. For example, the buffer value can be set to 10% of the minimum transmission power in a normal condition, and increased to say 30-50% of the minimum transmission power for an extreme condition.

The path loss is the difference between the measured received signal power and the transmit power level obtained from the received packet. The computed path loss need not be calculated for every packet, for example it can be calculated for every 10th or 100th packet. The decision to adjust the transmission power level is determined by the previous path loss and the updated path loss; by taking the absolute difference between the two, and checking if its above a configurable trigger value. Figure 6.5 shows the algorithm flow diagram given in Algorithm 6.2.

Algorithm 6.2 Adaptive optimal transmit power

Require: RXthreshold, tx_power, received power or LQI, trigger_value, buffer_value
Read: node_listed
return opt_tx_power

```
while Receiving frame from a source node do
    if node_listed = false then
        add to the list
        record received power or LQI
        record tx_power
        PL ← tx_power − received power
        record PL
        opt_tx_power ← PL + RXthreshold + buffer_value
        send opt_tx_power
    else
        if node_listed = true then
            record received power or LQI
            record tx_power
            PL_new ← tx_power − received power
            if (abs(PL_new − PL) > trigger_value then
                PL ← PL_new
                record PL
                opt_tx_power ← PL + RXthreshold + buffer_value
                send opt_tx_power
            else
                no change
            end if
        end if
    end if
end while
```

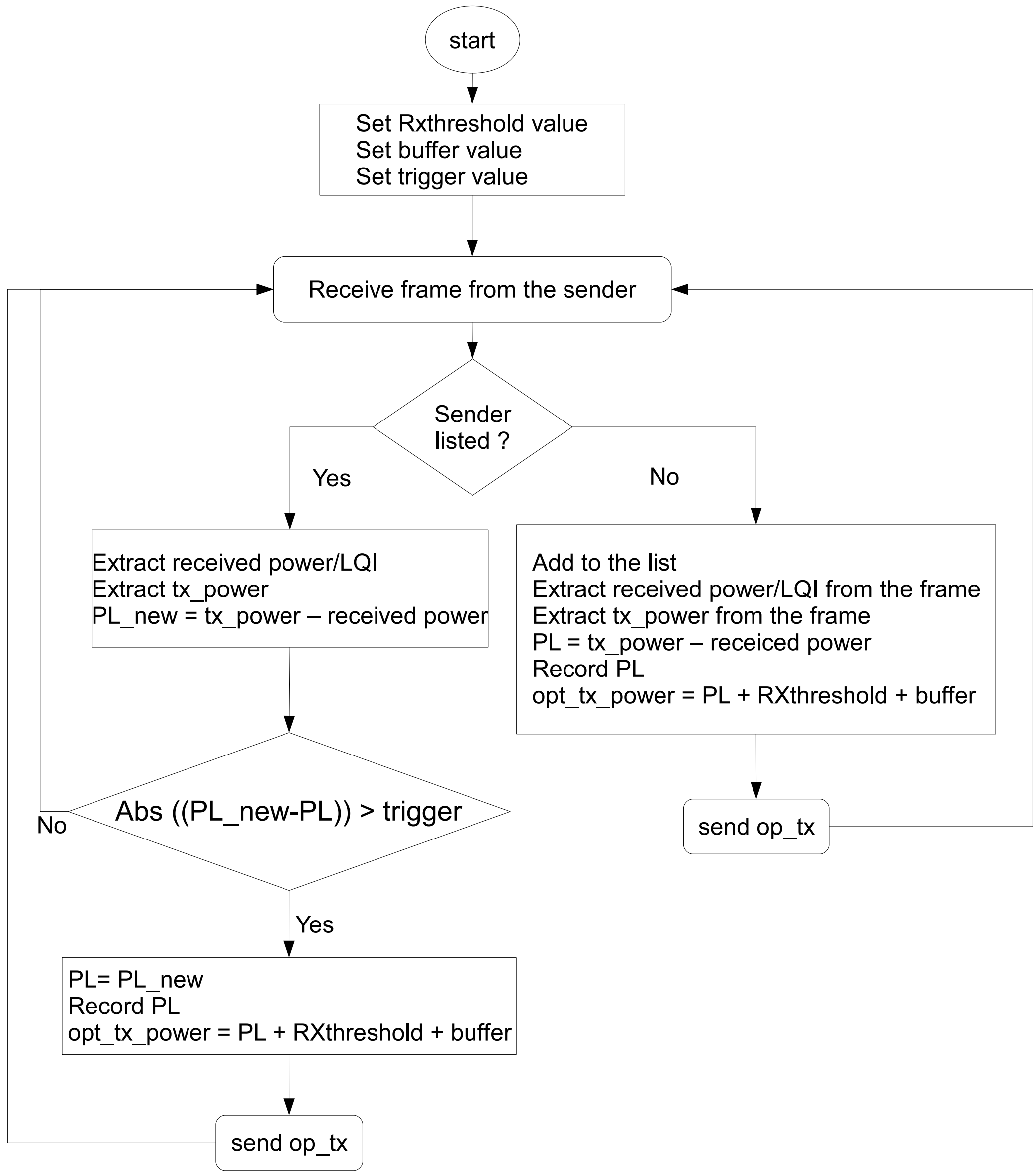


Figure 6.5: Proposed adaptive transmit power

6.4 Performance Evaluation of Slotted CSMA/CA under Different Number of CCA Settings

In the following section, we present the performance evaluation of the number of times that CCA is performed during frame transmission in terms of: throughput, packet error rate, delay, and energy consumption. A comparison is made for a single, triple, and the

IEEE 802.15.4 standard legacy double CCA; for both hidden and non-hidden node network scenarios.

6.4.1 Simulation model

Using a Network Simulator (NS-2) [82], we assume an ideal stationary star network topology, using the 802.15.4 standard, where the sink node in the middle receives traffic from all surrounding nodes, i.e. all nodes are in range of the sink node. For the non-hidden scenario, all nodes are also in range with one another. For the hidden-node scenario, we assume that all nodes are in range with one another except for only one pair that cannot hear each others transmissions. Each node sends data at 40 kbps, i.e. packet interval of 0.02s with 100 bytes packet size, which is less than the channel capacity of 250 kbps. We increase the traffic by increasing the number of traffic connections from the surrounding nodes to the sink. All sensor nodes are associated to the PAN coordinator before starting to send packets, and stop before the end of simulation time to allow enough time for packets sent to be received. Table 6.1 shows our simulation parameters. All simulations were run independently and their results averaged under different seeds.

6.4.2 Performance metrics at MAC level

The performance metrics analysed in this chapter are as follows:

- Average energy consumption per packet, which is the ratio of the total energy consumed over the number of delivered data packets.
- Throughput and average throughput, which is the fraction of data traffic correctly received by the coordinator over a specified period of time.
- Packet Error Rate (PER), which is the percentage delivery ratio, defined as the number of data packets correctly received by the destination node, over the total number of packets generated by source nodes. This reflects the degree of reliability achieved by the network for successful transmissions.

Table 6.1: CCA Simulation Parameter Settings

Parameter	**Value**
Frequency Band	2400-2483.5 MHz
Channel Rate	250 kbps
macSuperframeOrder (SO)	4
macBeaconOrder (BO)	4
macSuperframeSlots	16
aBaseSlotDuration	60 symbols (960 μs)
Symbol interval	16μs
aUnitBackoffPeriod/slot duration (T_{slot})	20 symbols (320μs)
macMinBE	3
macMaxBE	5
macMaxCSMABackoffs	4
macMaxFrameRetries	3
CCA Detection Time	8 symbols (128μs)
Clear channel assessment duration(T_{cca})	320μs ,640μs and 960μs
aResponseWaitTime	30,720 symbols (0.4915s)
SIFS	12 symbols (192μs)
ACK reception duration (T_{ack})	544μs
ACK timeout ($T_{acktout}$)	864μs
Current consumption in transmit mode (@ 0 dBm)	17.4mA
Current consumption in receiving mode	18.8 mA
Current consumption in idle mode	0.426 mA
Typical node working voltage	3.0V
Simulation area	150m x 150m
Simulation time	12,000 seconds
Number of random seeds per simulation	25

- end-to-end delay, which is the average time taken by a data packet, from the start of packet generation by the application layer at the source node, to the destination node (coordinator).

6.5 Results

Figures 6.6, 6.7, and 6.8 show the average energy consumed per packet as the traffic load increases when using different number of CCA, for non-hidden nodes, hidden nodes and both hidden and non-hidden respectively.

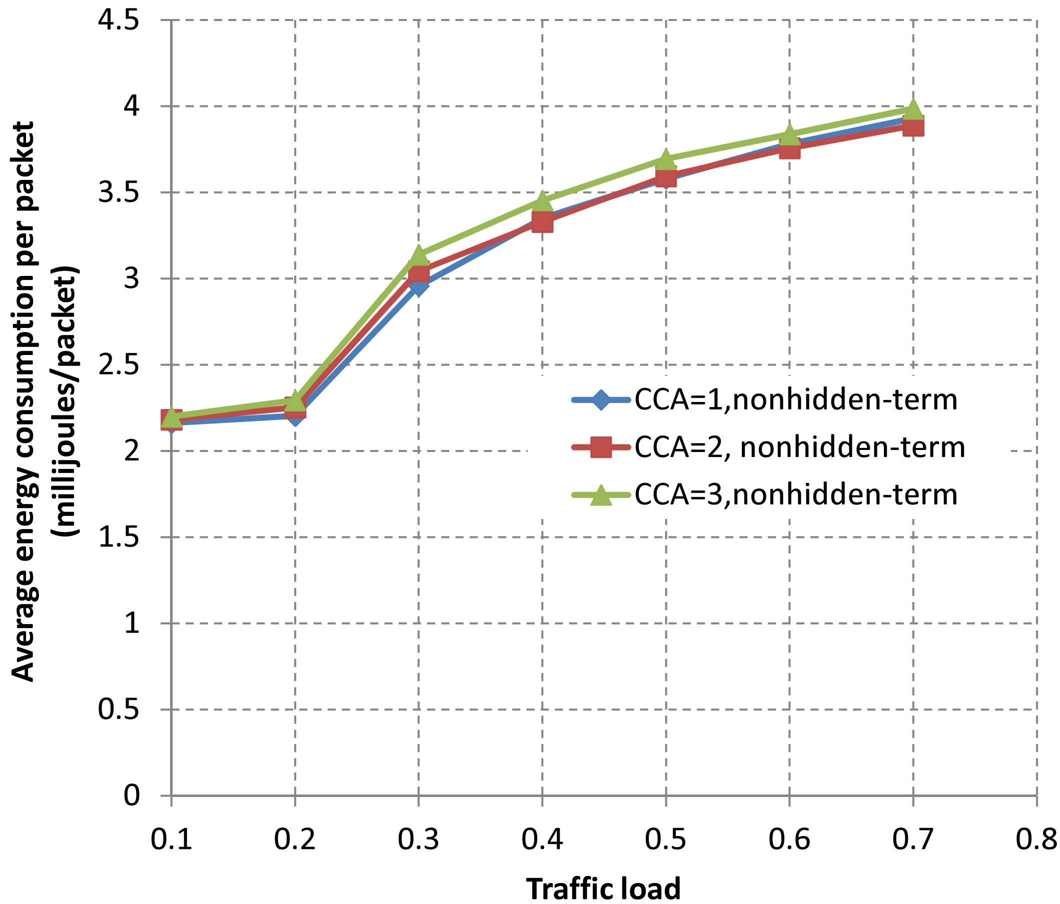


Figure 6.6: Average energy consumption for non-hidden nodes scenario

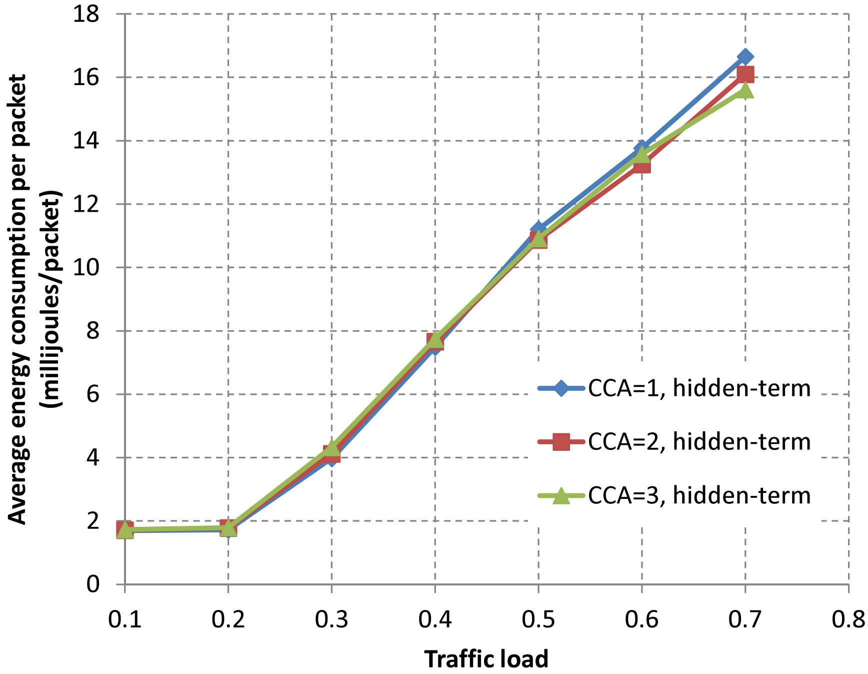


Figure 6.7: Average consumption for hidden nodes scenario

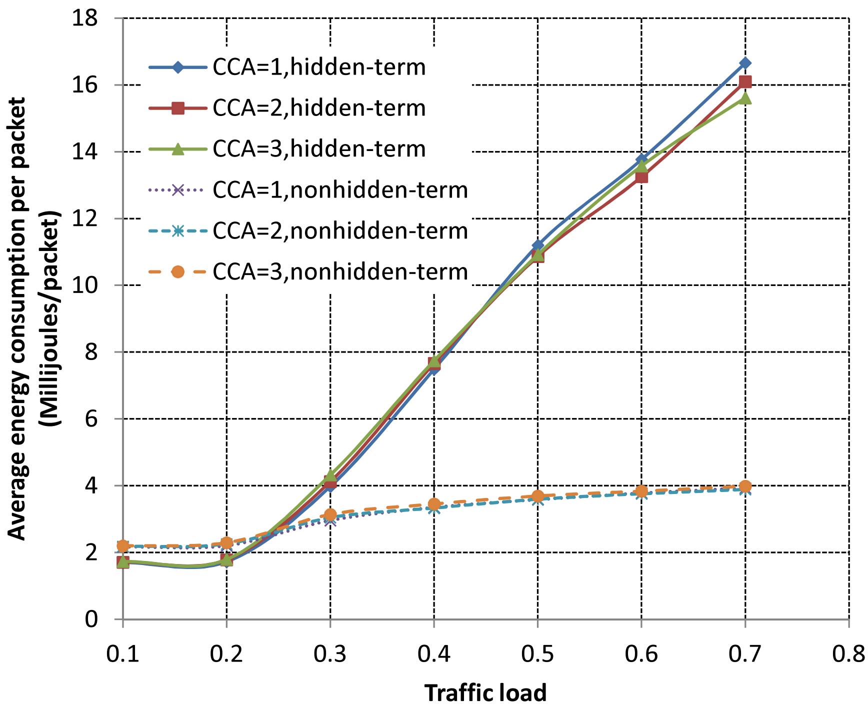
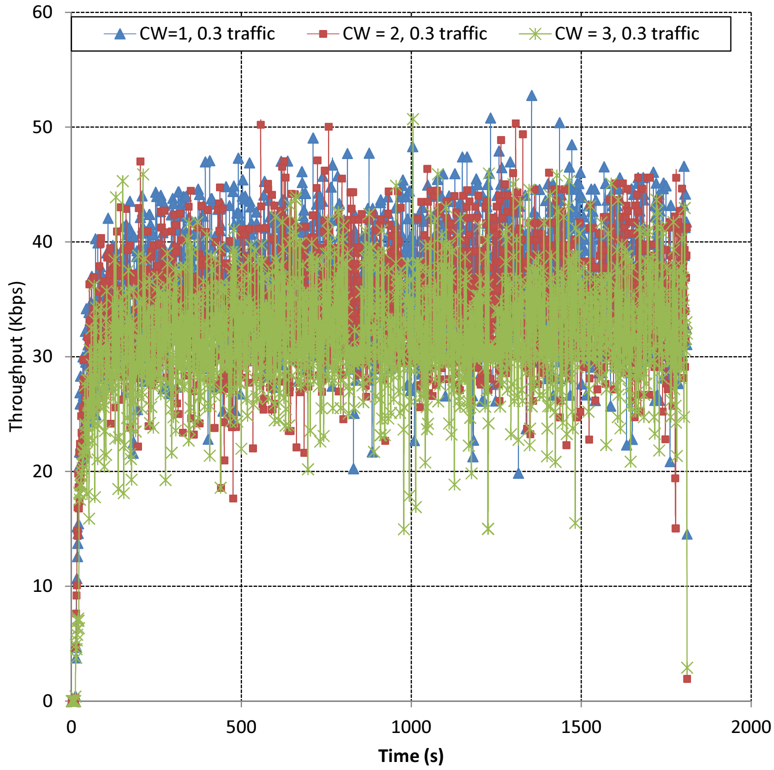
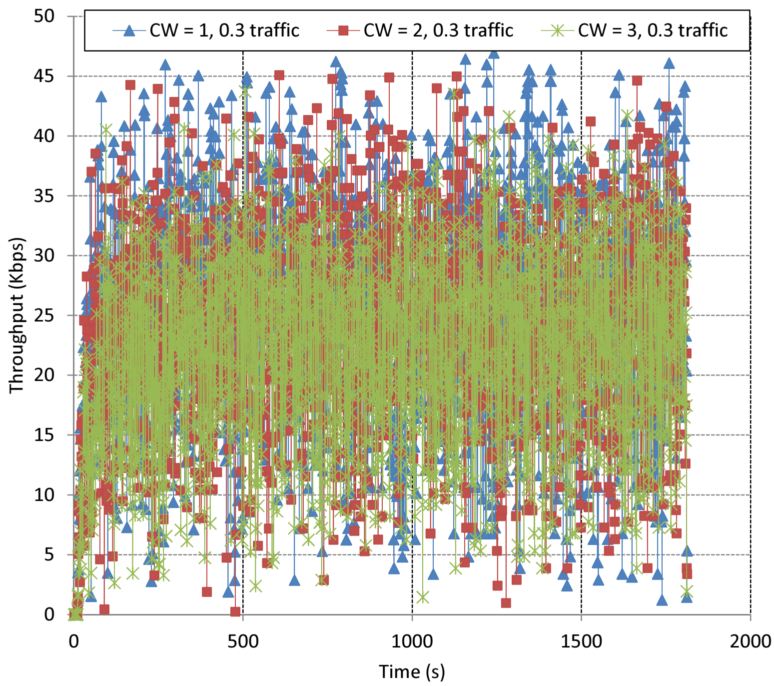


Figure 6.8: Comparison of hidden and non-hidden nodes energy consumption

Figures 6.9 (a) and (b) show throughput at 0.3 traffic load for non-hidden nodes and hidden nodes scenarios respectively.



(a) Non-hidden nodes



(b) Hidden nodes

Figure 6.9: Throughput, 0.3 traffic

Figures 6.10, 6.11 and 6.12 shows the average throughput as the traffic load increases when using different number of CCA, for (a) non-hidden terminals, (b) hidden terminals, and (c) both hidden and non-hidden terminals respectively.

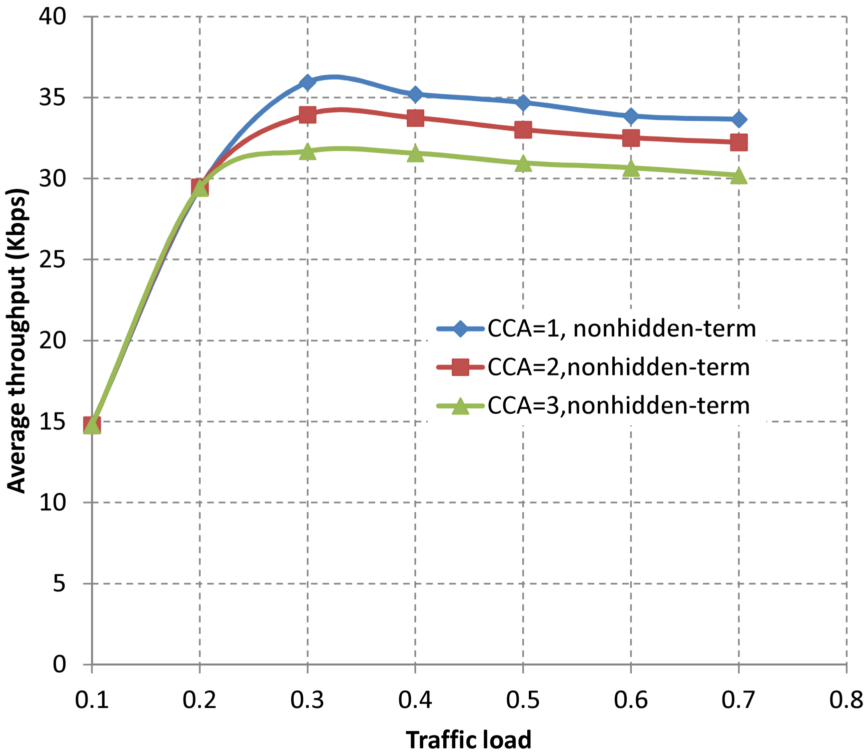


Figure 6.10: Average throughput for non-hidden nodes

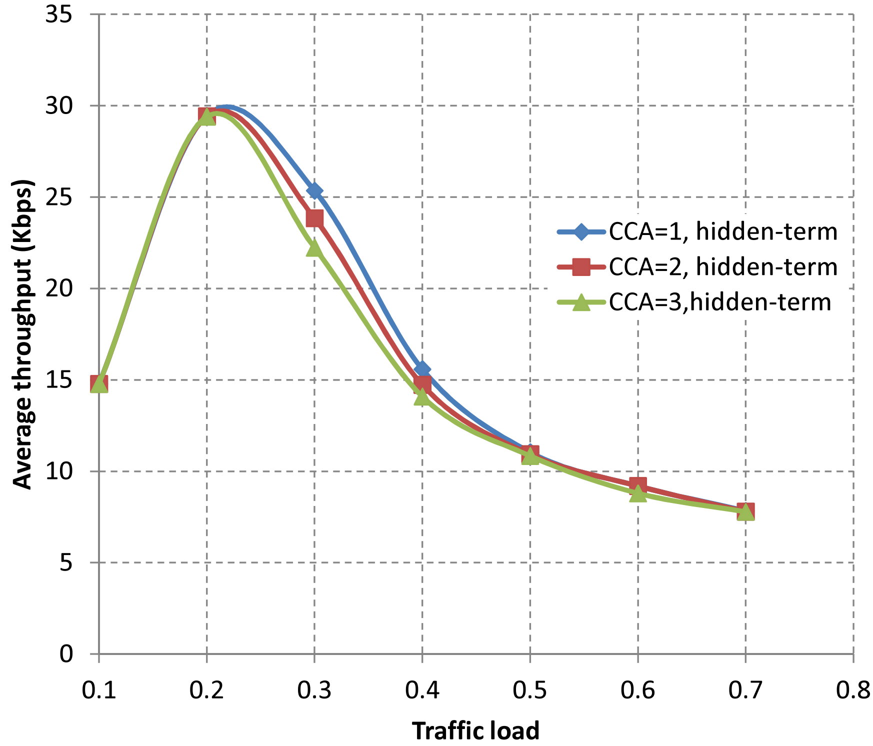


Figure 6.11: Average throughput hidden nodes

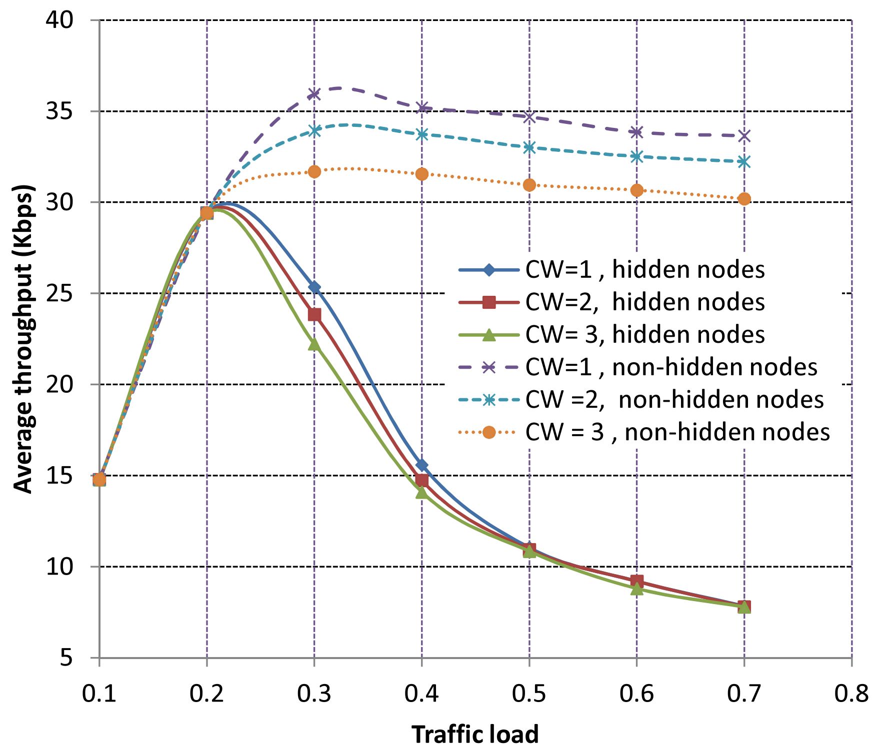


Figure 6.12: Comparison of hidden and non-hidden nodes average throughput

Figures 6.13, 6.14 and 6.15 show the percentage of packet collision as the traffic load increases when using different number of CCA, for (a) non-hidden terminals, (b) hidden terminals, and (c) both hidden and non-hidden terminals respectively.

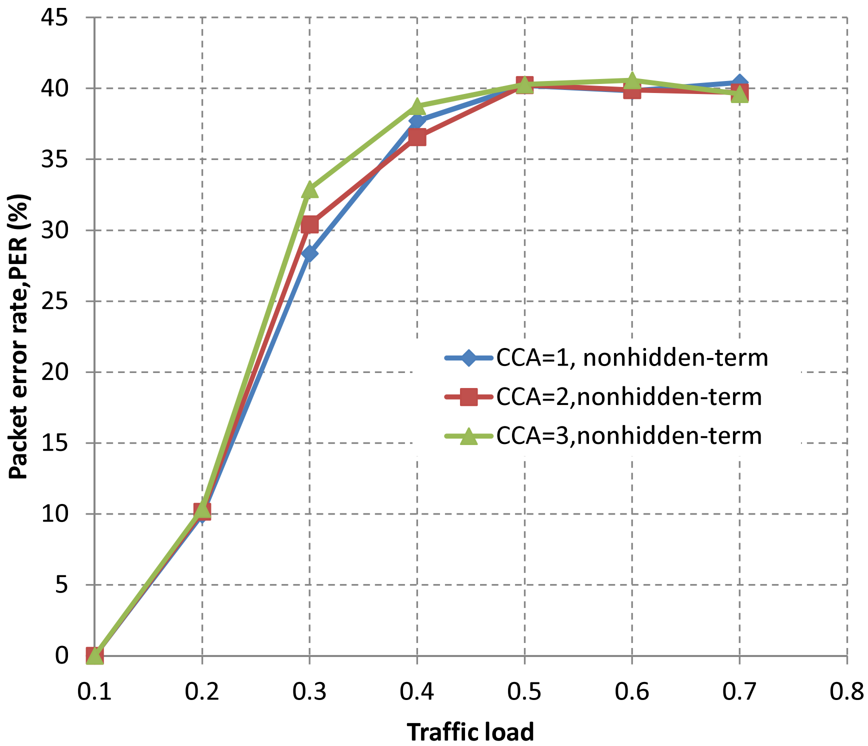


Figure 6.13: Percentage of packet collision at MAC/PHY layer for non-hidden nodes scenario

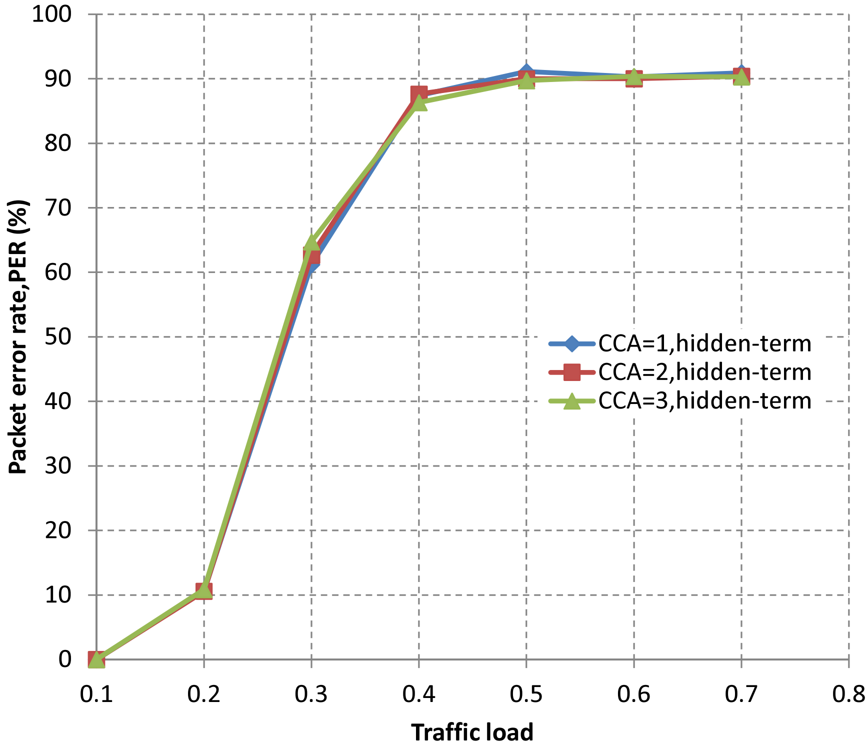


Figure 6.14: Percentage of packet collision at MAC/PHY layer for hidden nodes scenario

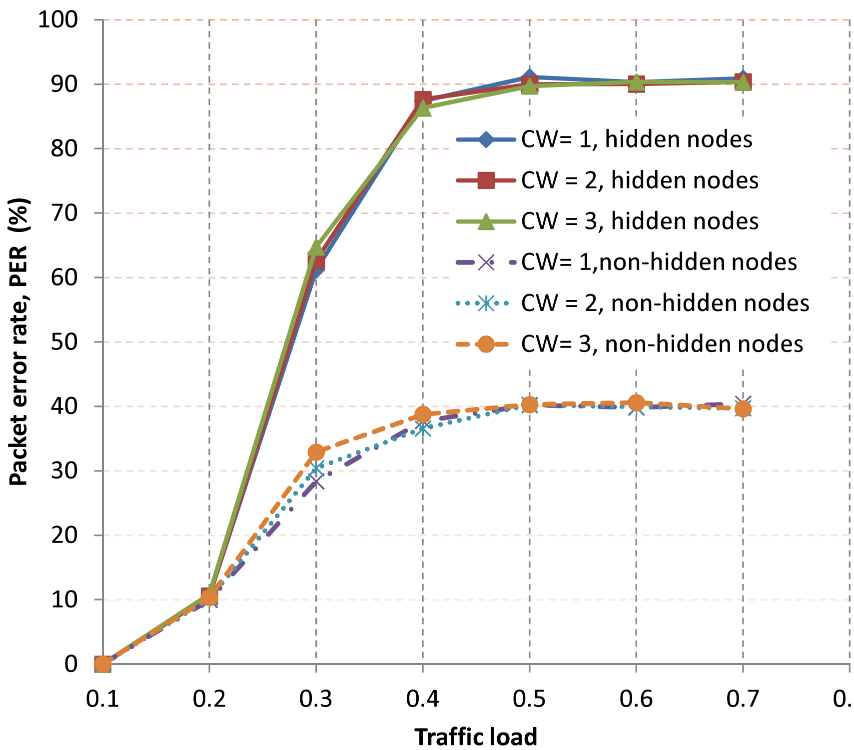


Figure 6.15: Comparison of hidden and non-hidden nodes percentage of packet collision at MAC/PHY layers

Figures 6.16, 6.17 and 6.18 show the average packet delay as the traffic load increases when using different number of CCAs, for non-hidden terminals, hidden terminals and both hidden and non-hidden terminals respectively.

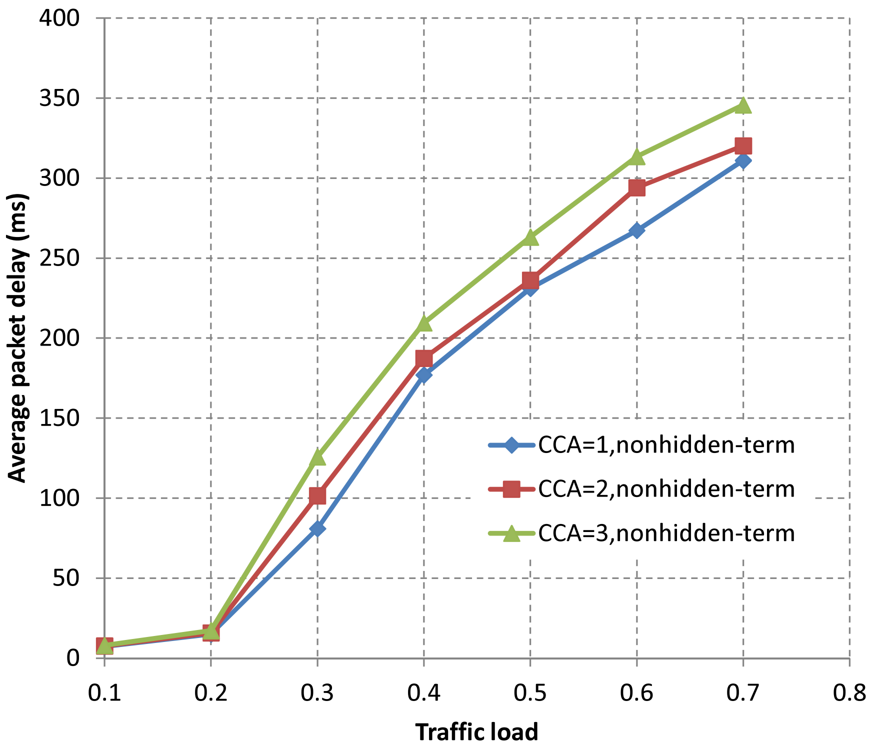


Figure 6.16: Average packet delay for non-hidden nodes

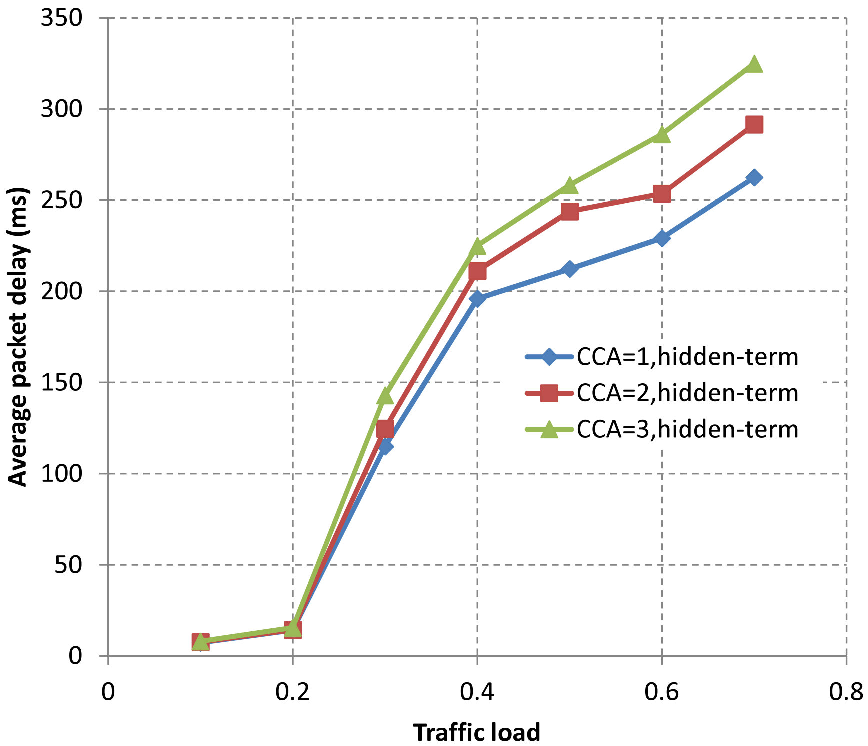


Figure 6.17: Average packet delay for hidden nodes

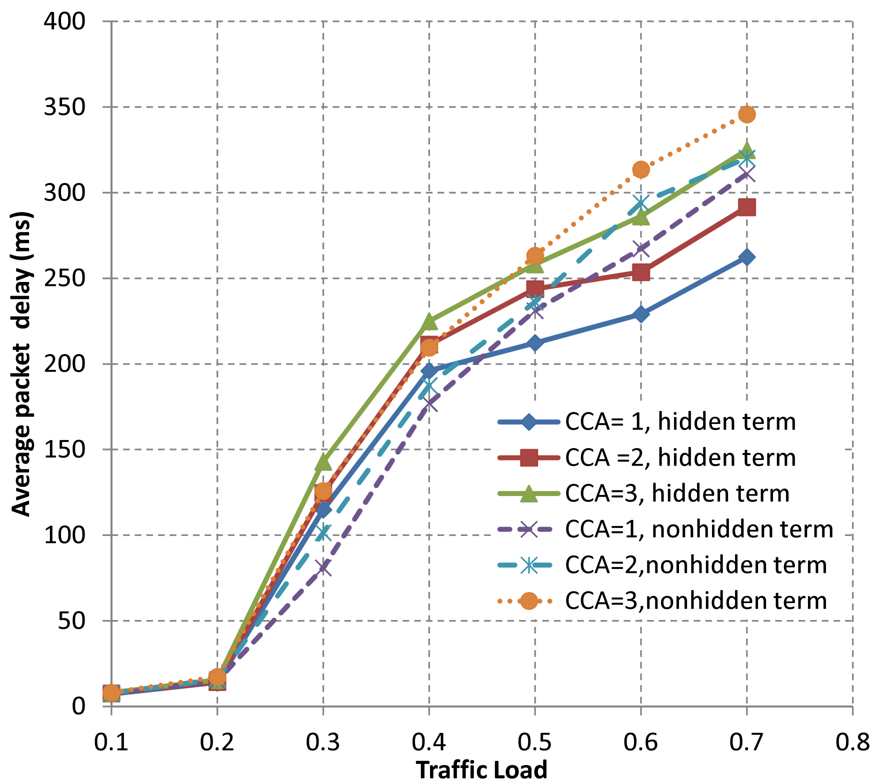


Figure 6.18: Average packet delay for hidden and non-hidden nodes

6.6 Discussion

The 802.15.4 CSMA/CA MAC is prone to two types of collisions, collisions caused by hidden node phenomenon, and collisions caused by the selection of the same backoff slot with another node. In CAP neither of these collision can be avoided by the standard. This reduces the reliability of IEEE 802.15.4 even for the case of a lightly load WPAN.

While we can conclusively say that there is some improvement in terms of: 1) throughput; and 2) average packet delay, when sensing the channel for shorter duration (once), instead of twice or thrice as the traffic load increases; there is no significant difference in terms of energy consumption and packet error rate. This can be explained in terms of probability as described in chapter 7, section 7.2.2. The likelihood of a channel being idle/busy the second or third time is smaller once it has been sensed busy/idle the first time. The reason for employing the standard default value when consecutively checking the channel, is to avoid packets colliding with an acknowledgment frame; which is possible (with small probability) when packet size is big, i.e. taking longer to transmit. However for small packet size, even checking the channel only once does not appear to cause a problem. Furthermore, in the case of non-hidden terminals; effective collision resolution is achieved by adjusting the backoff exponent (BE), based on consecutive clear channel assessment (CCA) busy/idle results, and therefore CCA has a small part to play. In case of hidden nodes, the standard does not tackle the collision problem, and therefore network performance in terms of: energy consumption, throughput, packet error rate, and delay degrades tremendously. The proposed design will be effective for low data traffic WSN applications, for high traffic applications, traffic scheduling will be a more appropriate choice.

6.7 Conclusion

In this chapter, we presented an investigation aimed at determining the impact of the number of times the CCA is performed in the 802.15.4 MAC during frame transmission in terms of: throughput, packet error rate, delay, and energy consumption. Both hidden and non-hidden nodes in a network system are considered. Results indicated a serious degradation in network performance, even for a small number of hidden nodes in a network. Following these results, a proposed cross layer (PHY-MAC) mechanism to save energy, reduce interference, improve scalability and reliability, and reduce packet collisions due to hidden terminals has been presented. The proposed design uses a new algorithm to increase the sensing coverage area, and therefore greatly reduces the chance of packet collisions due to hidden nodes. Moreover, the design uses a new dynamic transmission power control (TPC) to further reduce energy consumption and interference. The proposed changes can be easily integrated, with minimal or no disruption into the legacy 802.15.4 CSMA/CA design.

Chapter 7

Analysis of Slotted CSMA/CA Using Markov Chain

The design and performance evaluation of MAC protocol can be carried out using several approaches, including simulation, hardware platform, theoretical mathematical model, or a combination of such approaches. This chapter contains a proposed model to capture essential features of the IEEE 802.15.4 slotted CSMA/CA by using the Discrete Markov chain. Accurately modelling the CSMA/CA will result in better performance predictions for parameters, such as throughput, delay, and energy consumption. Moreover, it will offer deeper insights into the strengths and weaknesses of the multiple access control operation as well as possible enhancement opportunities. Previous studies [70, 111, 102, 109, 112, 103, 104, 113, 105] have, to a certain extent, provided an inspiration in developing the current proposed model.

7.1 Introduction

In analytical mathematical modelling, one relies on the assumptions and approximations made to simplify mathematical expressions while closely modeling/describing an original protocol or process. In Bianchi's [111, 70] approach, a Markov chain is proposed to model the IEEE 802.11 Distributed Coordination Function (DCF) while the packet transmission probability is computed given the network configuration and contention window size. Note that in IEEE 802.15.4 the DCF is known as the Contention Access Period (CAP).

Bianchi [70, 111] presented a Markov chain model describing the performance of 802.11 DCF using the probability that a device is in the channel-accessing state, using the key approximation that each transmission attempts, regardless of the retransmission experienced; thus, all packets collide with a constant and independent probability. In light of the 802.11, when using this model, it is possible to compute the probability that a given station attempts transmission in a given time slot. The transmission probability can then be used to obtain the probability of an idle, successful, and collision slot for a number of contending stations. However, in 802.15.4, it is not appropriate to use this key approximation because the channel sensing is performed according to the value of CW before entering the transmission state. Markov chain modelling for 802.15.4 differs from 802.11 CSMA/CA DCF because, in 802.11, nodes continuously monitor the channel and are therefore continuously aware of the channel state [103]. In the 802.15.4 standard, a node does not listen to the channel continuously; thus, it is possible to switch to low-power mode during a random back-off delay to save some energy. Only after such a random delay does the contending node wake up to listen to the channel for CW back-off slots. Therefore power consumption during channel listening is minimised.

Ziouva and Antomakopolas [114] modelled 802.11 DCF assuming that the channel access probability and station collision probability are independent of channel status. Chuan [115] corrected the model presented in [114] using Bianchi's improved model by considering the busy medium condition.

Currently, the literature on the IEEE 802.15.4 analytical evaluation models is insufficient. Most of the existing literature has drawn considerable inspiration from Bianchi's work [111, 70] on the modelling of 802.11 MAC DCF.

Park [102] proposed a new 802.15.4 Markov chain model in saturation conditions using the probability of a device in the channel-sensing states (CCAs) instead of the channel-accessing states, relying on the same assumptions as in [70]. The key approximation is the busy probability of the channel at the first and second CCA regardless of the stages.

In [109], the Markov chain model was derived by considering which embedded points were correct after the completion of a frame transmission of any device, regardless of success or failure, which is also different from the conventional 802.11 model [70, 111].

Pollin [103] assumed that each device carrier sensing probability, rather than its packet sending probability, was independent.

One of the difficulties in analysing the 802.15.4 CSMA/CA in CAP lies in modelling its exponential backoff behaviour. Apart from different approaches, the main parameter that brings different results is that of finding the probability of a node to be on the first CCA as well as assumptions made that lead to different results.

The scope of this chapter lies in the construction of a mathematical model based on the discrete Markov chain in describing the performance of slotted 802.15.4 CSMA/CA during CAP. The relationship among the successful transmission probability, throughput, and average energy consumption was derived. The model is more accurate, is simple, and has rectified some of the minor issues that emerged in previous work, such as:

- The time used to calculate CCA energy consumption (equation 14) in [116] is incorrect; the authors utilised the time used to send the packet (i.e., payload divided by data rate) instead of the appropriate time spent to perform CCA.
- The transition matrix, equation 4 in [117, 103], is incorrect as, once the node finds the channel busy in the first CCA, it will move straight to the next stage and not perform the second CCA. Similarly, equation 3 in [108] defines the probability of a channel being idle if it was busy in the previous slot; however, according to the standard, once the channel is found to be busy, the algorithm moves to the next stage (increases BE and NB).
- The backoff time is included in both the time to successfully receive a packet and collision time as this is part of the time spent to transmit a packet (equation 7.12 and 7.13).

Discrete Markov Chain Definition

Definition 1.A discrete Markov process $\{X_n\}$ is a stochastic process with the property that the probability of any particular future behaviour of the process, when the current state is known exactly, is not altered by additional knowledge concerning its past behaviour. From the definition $\{X_n\}$ is Markov chain if

$$P_r\{X_{n+1} = j \mid X_0 = i_o, ...X_{n-1} = i_{n-1}, X_n = i\} = P_r\{X_{n+1} \mid X = i\}$$

For all time points n and all states $i_0.......i_{n-1}, i, j$.

Notation : $P_r\{X_{n+1} = j \mid X_n = i\} = P_{ij}$, where

$P_{ij} \geq 0$ for $i, j=$ 0,1,2.... and $\sum_{j=0}^{\infty} P_{ij} = 1$ for $i = 0, 1, 2, 3, ...$

Once all the transition probabilities have been obtained, the Markov chain can be numerically solved to obtain the stationary probability distribution of each state using recursive solution, $\pi = \pi A$, where A is the initial state condition and $\pi$is the transition matrix.

7.2 Performance Modeling and System Description

This section presents the proposed two-dimensional discrete time Markov chain model to analyse throughput, reliability and energy consumption of the slotted CSMA/CA. For a complete slotted CSMA/CA algorithm, refer to chapter 6, section 6.2.1.

Consider a star network topology with a group of WPAN devices that use slotted CSMA/CA with an optional acknowledgment (ACK) in sharing a radio channel when transmitting to the PAN coordinator. The standard specifies that all nodes ensure that any transmission initiated should be complete before the end of the beacon interval. Therefore the probabilities of channel access and success transmission are evaluated as a function of time, starting from the reception of the beacon sent by the coordinator, until the end of the superframe.

Generally, a node accessing the channel during the CAP portion of the superframe can be in one of the five states, which include:

- backoff
- carrier sensing
- transmit
- collision
- idle

7.2.1 Model assumptions and mathematical modeling

The following are the assumptions made in the proposed model:

- The network consists of finite number of N contending nodes associated with a common coordinator in a one hope star topology.
- All nodes are perfectly synchronised at backoff period boundaries, and the inactive period does not exist (i.e., BO=SO).
- An ideal channel condition, where all nodes are within the carrier sense range of each other (i.e., no hidden nodes).
- Each node always has a packet available for transmission, which implies operating in a saturation condition.
- Using fixed size data packets of the L-backoff slot duration.
- The probability to start sensing the channel is constant and independent of all other nodes and independent of the retransmission this packet has suffered in the past. This is the main approximation assumption, which is different from Bianchi's [111], where the packet sending probability is assumed to be independent.

Let *s(t)* be the stochastic processes representing the backoff stage *(0...m)* for a given node at time *t*, where *m* is the maximum backoff stage (NBmax), and let *b(t)* be the stochastic process representing backoff time counter for a given node at time *t*. The time *t* corresponds to slot time and is related to system time. Table 7.1shows different symbols and parameters used in the current model.

Note that *b(t)* and *s(t)* are time discrete stochastic processes in a chain; however, *b(t)* is not memory less (not Markovian) as its value depends on the history (e.g., how many times the node has tried to access the channel with or without success and the number of retransmission). However for convenience:

Let $b_{ij} = \lim_{t \to \infty} P_r \{s(t) = i, b(t) = j\} \; i = \epsilon(0.m)$

is the steady state probability of any state. Then the random process of the backoff stage *s(t)* and the backoff counter *b(t)* constitute a two dimensional Markov chain *X(t) = {(s(t), b(t))}*

The delay window W_i is initially $W_0 = 2^{MacMinBE}$, a device with a pending frame for transmission, will select a random backoff counter value between $[0, W_0 - 1]$and doubled at every stage until $W_i = W_{max} = 2^{macMaxBE}$. Therefore, the size of the backoff window at the backoff stage s(t) = iϵ {0...m} is $W_i = 2^{min(MacMinBE+i, macMaxBE)}$.

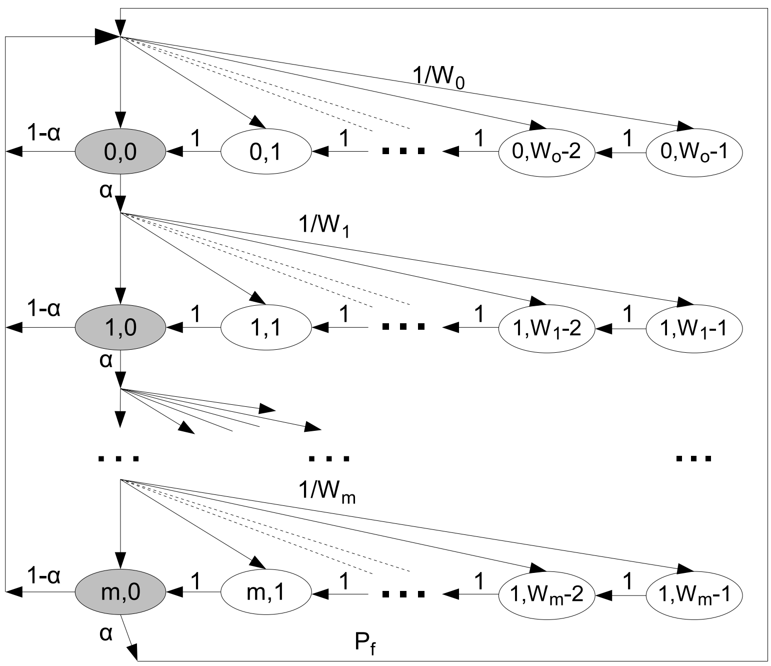


Figure 7.1: Markov chain states for single CCA

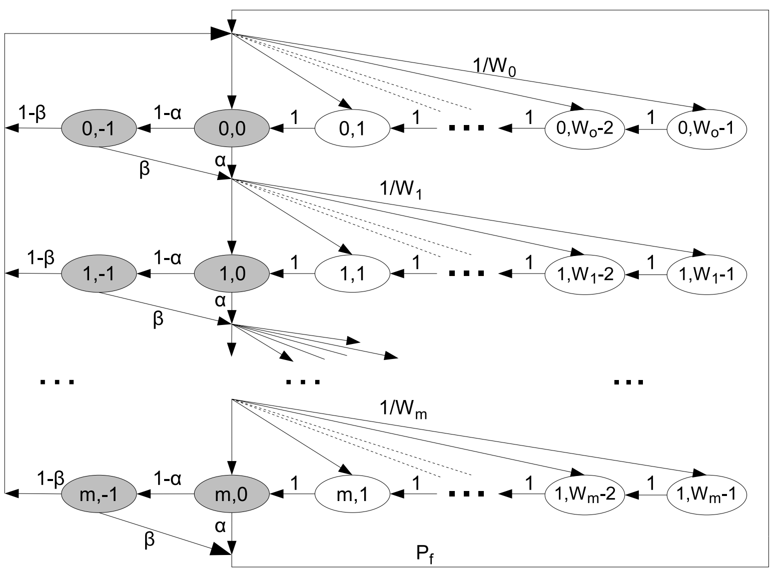


Figure 7.2: Markov chain states for double CCA

7.2.1.1 State Transition Probabilities

The total number of states is higher than five, as illustrated in Figure 7.2. Using the probabilities defined in table 7.1 and the identified assumptions, the state transition probabilities associated with the Markov chain are a two-dimension Markov chain with the following transition probabilities:

$$\begin{cases} P\left(i,j \mid i,j+1\right) = b_{i,j|i,j+1} = 1 \qquad i = \epsilon\left[0,m\right] \qquad j = \epsilon\left[0,W_i-2\right] \\ P\left\{i,-1 \mid i,0\right\} = b_{i,-1|i,0} = (1-\alpha) \qquad i = \epsilon[0,m] \\ P\left\{i,j \mid i-1,0\right\} = \alpha/W_i \\ P\left\{i,j \mid i-1,-1\right\} = \beta/W_i \\ P\left\{0,j \mid m,0\right\} = \alpha/W_0 \\ P\left\{0,j \mid m,-1\right\} = 1/W_0 \qquad j = \epsilon\left[0,W_0-1\right] \\ P\left\{0,j \mid i,-1\right\} = b_{0,j|i,-1} = (1-\beta)/W_0 \qquad i = \epsilon[0,m-1] \quad j = \epsilon\left[0,W_0-1\right] \end{cases} \tag{7.1}$$

Equation 1 of the transition probability is the condition to the decrement of the delay back-off counter, regardless of whether the channel is idle or not.

Equation 2 is the condition for performing the second CCA given during the first CCA when the channel was idle.

Equations 3 and 4 show the move to the next stage whereby the back-off exponential (BE) is increased because of the busy channel at the first or second CCA, respectively.

Equations 5 and 6 are the condition when the maximum stage is reached and, as a result, the packet is dropped and the transmission process starts again in the first stage.

Equation 7 is the case of the packet being transmitted after the channel is found to be idle in the first and the second CCA.

From expression 7.1 , we have

$$b_{i,j} = \frac{W_i - j}{W_i} b_{i,0} \tag{7.2}$$

Table 7.1: Different symbols and parameter used for the model

τ	The probability that a node attempts a first carrier sensing to transmit a frame
α	The probability that a node finds the channel busy during the first CCA
β	The probability that a node finds the channel busy during the second CCA
P_{tx}	Probability that at least one node is transmitting in any given time slot
P_s	Probability that at least one node is transmitting successfully in any given time slot
p_c	Collision probability
P_{idle}	Probability that the node is idle
ACK+PHR+SHR, T_{ACK}	11 bytes = $352\mu s$
t_{ack}	12 PHY symbols = $192\mu s$
σ	a unit backoff slot duration

7.2.2 Probability of transmitting

Before transmitting a packet, each contending node performs the back-off algorithm, where each node is randomly delayed by extracting an integer from a uniformly distribution between 0 and Wo-1; before sensing the channel a node enters, with the probability 1/Wo, one of the states is {0,j,w-1} with j E [0,Wo-1]. If there is no random delay j= 0, then the node enters the first carrier sensing straight away.

After the random delay, in order for a node to transmit a packet, it first performs a predetermined number of CCAs to determine if the channel is idle in all CCAs performed (in this case, CW=2 or 1). After sensing the channel to be free, the node immediately enters the transmission state. At this stage, the packet transmission duration in slots, L, is included, followed by a sequence of idle slots until the end of the superframe duration. The focus is on finding the probability that the node is in the sensing state, which can be determined using the state transition diagram (Figure 7.2 or 7.1) and the transition matrix that describe all possible nodes' states. The probability of transmitting P_{tx} will depend on the probability of being in a sensing state and the probability of finding the channel idle during CCA.

When a node attempts to send a frame, its backoff counter has reached zero and it is no longer idle as it has a frame to send. Here we consider τ, instead of the product of $(1 - P_{idle})\tau$ as at this stage $P_{idle} = 0$. τ is different from that of 802.11 in [70], whereby the node is always listening to the channel when not transmitting. Therefore, we do not model the transmission state, but focus on the probability that a device is in the sensing states. In the case of 802.15.4, τ is a function of exponential delay line, as explained in the previous section 7.2.1.1.

The probability that a node starts to transmit is

$$P_{tx} = \tau(1 - \alpha)(1 - \beta) \tag{7.3}$$

Which requires the node to be sensing with the probability τ, and the channel to be idle during the two CCAs, with the probability $(1 - \alpha)(1 - \beta)$. We define τ, as the conditional probability that a device is at one of the first CCA states $b_{i,0}$, out of the backoff states as follows:

$$\begin{aligned} \tau &= \frac{\sum_{i=0}^{m} b_{i,0}}{\sum_{i=0}^{m}\sum_{j=0}^{W_i-1} b_{i,j}} \\ &= \frac{2(1-(\alpha+\beta-\alpha\beta)^{m+1}}{\sum_{i=0}^{m}(W_0 2^{min(i,BE_{max}-BE_{min})}+1)(\alpha+\beta-\alpha\beta)^i} \end{aligned} \tag{7.4}$$

since the Markov chain normalised condition

$$\sum_i \sum_j b_{i,j} = 1 \tag{7.5}$$

Now we need to find the remaining two unknowns, α and β. Let T_L and T_{ACK} denote time duration in the number of slots for transmitting an L-slot frame and receiving ACK frame, respectively. Similar to [117], the probability α, the probability that a node finds the channel occupied either due to data transmission or ACK transmission in the first CCA can be estimated as follows:

$$\alpha = \alpha_L + \alpha_{ack} \tag{7.6}$$

where α_L is probability of finding the channel busy during the first CCA due to data transmission, which is:

$$\alpha_L = L\left[1-(1-\tau)^{N-1}\right](1-\alpha)(1-\beta) \tag{7.7}$$

and α_{ack} is probability of finding the channel busy during the first CCA due to ACK transmission, equal to:

$$\alpha_{ack} = L_{ack}\frac{N\tau(1-\tau)^{N-1}}{1-(1-\tau)^{N}}\left(1-(1-\tau)^{N-1}\right)(1-\alpha)(1-\beta) \tag{7.8}$$

Finally, the probability of finding the channel occupied during the second CCA is not independent like the first CCA, it depends on the probability of finding the channel idle during the first carrier sense, which is:

$$\beta = \frac{1-(1-\tau)^{N-1}+N\tau(1-\tau)^{N-1}}{2-(1-\tau)^{N}+N\tau(1-\tau)^{N-1}} \tag{7.9}$$

The expression for the sensing probability τ and the busy channel probabilities α and β form a system of non-linear equations that can be solved through numerical method. To evaluate other target probabilities, we model how the number of nodes contending to the channel varies with time.

7.2.3 Probability of successful transmission

The probability that a node transmit successfully ($P_s = 1 - P_c$), P_s is the probability that a node start sensing alone and finds the channel idle for predetermined CCA slots (i.e., the probability that exactly one node transmit on the channel), given by:

$$P_s = \tau(1-\tau)^{N-1}(1-\alpha)(1-\beta) = P_{tx}(1-\tau)^{N-1} \tag{7.10}$$

A transmission is considered a successful one if an acknowledgment frame is received in time (before ACK timeout). The frame transmission starts from the time a node perform random backoff to the time an ACK frame is received, including an Inter-Frame Space (IFS) time after ACK frame transmission.

7.2.4 Probability of collision

For an ideal channel condition, unsuccessful transmission is only due to collision ($P_c = 1 - P_s$). If we consider N nodes in a network system, the collision probability can be derived as the probability that at least one of the N-1 remaining nodes transmit a packet in the same time slot (i.e., two or more nodes start the first cca at the same time). If all nodes sense the channel with the probability τ, then P_c is defined as:

$$P_c = 1 - [1 - (1 - P_{idle})\tau]^{N-1}$$

For saturation conditions, $P_{idle} = 0$, and therefore:

$$P_c = 1 - (1 - \tau)^{N-1} \tag{7.11}$$

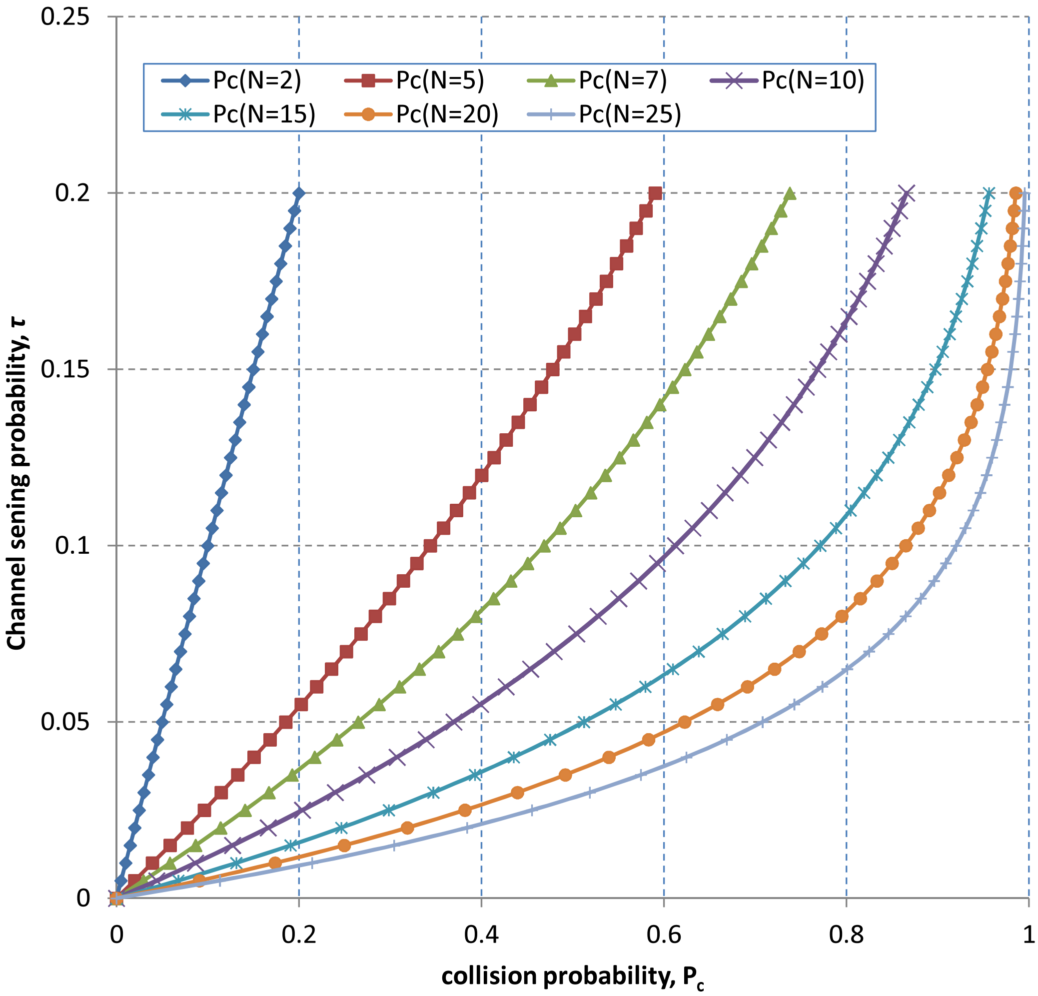


Figure 7.3: Channel sensing probability and collision probability

Figure 7.3 shows the relationship between sensing probability and collision probability as the number of contending nodes increases.

7.3 Transmission and Collision Timings

In this model, for accuracy, the average backoff period and interframe space (LIS/SIF) are considered as part of the time to successfully transmit a frame. This is contrary to previous models derived in [113, 118, 111, 70, 109]. The total number of time slots required for a single successful transmission is:

$$T_s = E[Backoff\, period] + no.\, of\, cca \times T_{CCA} + L + L_{ACK} + t_{ack} + T_{IFS} \tag{7.12}$$

where T_{CCA}, T_L, t_{ack}, and L_{ACK} are time duration in number of slots for performing a CCA, transmitting data frame, waiting for an acknowledgment frame and receiving an ACK frame respectively. $E[Backoff\, period]$ is the average backoff period in terms slots as shown in the Table 7.2. $no.\, of\, cca$ is the number of times CCA is performed (default 2), and T_{IFS} is the Inter-Frame Spacing, depending on the size of the data frame, either Short Inter-Frame (SIF) or long (LIF) is used (Figure 7.4).

Similarly, the total number of time slots for a single collision transmission is

$$T_c = E[Backoff\, period] + no.\, of\, cca \times T_{CCA} + L + T_{ack,tout} \tag{7.13}$$

where $T_{ack,tout}$ is ACK timeout of ACK [7]. In 802.15.4 ACK waiting duration is specified by macAckWaitDuration (2.7 slots in 2.4 GHz channel).

Table 7.2: Binary exponent values

BE	Backoff Interval 0 to $2^{BE}-1$	Average no. of backoff periods	Average backoff (symbols)	Average backoff (time)
0	No Backoff	n/a	n/a	n/a
1	0 to 1	0.5	10	$160\mu s$
2	0 to 3	1.5	30	$480\mu s$
3	0 to 7	3.5	70	$1120\mu s$
4	0 to 15	7.5	150	$2400\mu s$
5	0 to 31	15.5	310	$4960\mu s$

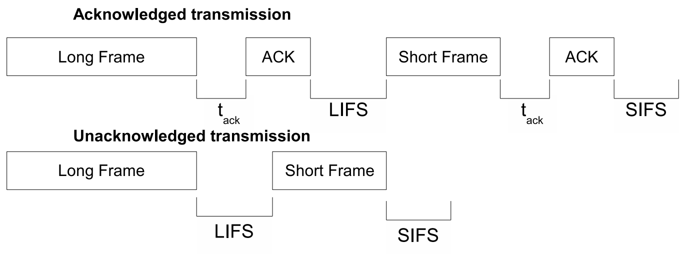


Figure 7.4: Packets Interframe Spaces

7.4 Throughput Analysis

Here, the channel efficiency or throughput is defined as the fraction of time that the channel is used to successfully transmit a payload in bits. Similar to [111, 70], let S be the normalised throughput defined as the ratio of successful transmitted data payload (in backoff slots) to the average number of the backoff slots used to successfully transmit a data frame, S can be estimated as follows:

$$S = \frac{E[succefully\, payload\, information\; transmitted\; in\; interval]}{E[length\; of\; a\, renewal\; interval]} \tag{7.14}$$

$$S = \frac{LP_s}{(1-P_{tx})\,\sigma + P_sT_s + (1-P_s)\,T_c} \tag{7.15}$$

and the system aggregate throughput by N contending nodes is given by the following expression:

$$S = \frac{NLP_s}{(1-P_{tx})\,\sigma + P_sT_s + (1-P_s)\,T_c} \tag{7.16}$$

where T_s is the average time the channel is sensed busy due to successful transmission (equation 7.12), T_c is the average time the channel is sensed busy by each node during a collision (equation 7.13), and σ is the duration of an empty slot. To convert equation 7.15 and 7.16 to bit per second (bps), multiply by a normalised constant, $C = \frac{80bits}{0.32ms}$ for the 802.15.4 2.4GHz band, 250kbps data rate.

7.5 Average Energy Consumption Analysis

In order to determine the average energy consumed by a node, we have to determine the average time (probability) the node occupies each state (i.e., transmit, receive, idle, sleep, CCA and collision) and multiply by each state associated power expenditures. The transmit power P_{TX}, receive and sensing power P_{RX} and idle power P_{IDLE} can be readily obtained from the node's data sheet such as the one in chapter 2, Table 2.2. In the saturated condition, nodes always have a data frame to transmit; thus, P_{IDLE} is the power used when the node is in the exponential delay time (backoff) and for the remaining slots after the frame transmission between the two consecutive transmissions. Note that the power consumed while receiving and performing CCA is larger than the transmit power consumption [103, 119]. Furthermore, in the current model the sleeping power $P_{SLEEP} \approx 0$, because superframe BO= SO.

To find the individual state energy consumption, simply use the appropriate state probability and multiply with associated power consumption. Here, the interest is in finding the average energy consumption for packet transmission including both successful transmission and packet collision. Using equations 7.3, 7.10 and 7.11, the average energy for packet transmission is given by

$$E = \tau (1 - \alpha) (1 - \beta) [(1 - P_{tx}) P_{IDLE} + LP_{TX} + L_{ACK} (P_s P_{RX} + P_c P_{IDLE})] \quad (7.17)$$

7.6 Discussion

In wireless sensor networks, it is important to minimize energy consumption, maximise the number of successful transmissions (reliability), and minimise the probability of collisions.

The duration of collision is as long as the length of the packet involved in the collision; it is therefore essential to reduce the number of collisions to improve network reliability, energy consumption and throughput.

In CSMA/CA, as the number of nodes increases, the chances that two or more nodes transmit on the same slot increase, which subsequently increases the chance of transmission loss due to the increased number of collisions. In addition, the probability of finding the channel idle in the sensing slots decreases when the number of nodes, N, increases as a large part of time is spent in the back-off; thus, the network throughput will downgrade with the significant increase in the frame service time.

Binary exponent, BE, is the main parameter for avoiding collision; basically, the contention window adapts to the high value by increasing BE when the active population of nodes is large. This reaction reduces the load on the network and should decrease the collision probability. The MAC latency is high if the contention window is large. The issue is when a station successfully transmits as it resets the contention window to a small, fixed minimum value of W_0. Consequently, the node has to rediscover the correct contention window size, thereby wasting bandwidth. The 802.15.4 standard BE back-off does not assume the advantage of shared learning when the number of nodes increases or decreases. Although BE back-off improves fairness because after completion of each successful packet transmission, a node needs to wait for a random back-off time, which can help other nodes seize the channel. A technique such as IEEE 802.11e can be used to dynamically tune the value of BEmin and BEmax to adapt to the number of contending nodes. Obviously, small contention windows are desirable when the number of contending stations is low to keep the number of empty unused slots relatively low. However, an empty slot is much more desirable than collision as the duration of an empty slot is comparatively smaller than collision duration. A larger contention window offers better performance because it reduces the collision probability.

The waste of channel utilisation is the other factor in slotted CSMA. When the remaining number of back-off periods in CAP are not enough to process the transmission of a data frame, the channel will remain idle because the sensor node waits for the next superframe. Obviously, the number of remaining back-off periods will depend on the length of the superframe BO or beacon interval, the size of the data payload and the number of CCA performed. To increase channel utilization, a fragmentation scheme can perhaps be used to divide the data frame to fit into the remaining number of back-off slots in a superframe

CAP.

To get a more accurate analytical model result, future models need to include the real operation value of a superframe SO and BO, which determines the total number of slots in CAP. The CAP slots specify the number of available slots for packet transmission and therefore can impact the probability that there are not enough slots left in the current CAP for transmission and the overall performance in general. For example when SO=BO=3, the number of CAP slots, $CAP_{slots} = \frac{16*60*2^3 symbols}{20\, symbols} = 384$. Although the proposed model remains to be validated using simulation or hardware tools, some of the findings in chapter 6, section 6.5 on the probability of collision when using single CCA or double CCA reflect the proposed model probability of finding the channel busy in the second CCA, which is much smaller as given in equation 7.9. These results demonstrate that changing the default CW from 2 to 1 can bring benefits in terms of throughput. However, performing the second CCA does not show significant improvement in terms of collisions.

7.7 Conclusion

In this chapter, a more accurate model has been proposed based on discrete Markov chain describing the performance of slotted 802.15.4 CSMA/CA during CAP. The relationships among the successful transmission probability, throughput and average energy consumption are derived. Some of the minor issues apparent in previous studies have been rectified while maintaining the model's simplicity. Future work and some of the 802.15.4 CSMA/CA CAP issues have been thoroughly discussed.

Chapter 8

Conclusions and Future Work

This chapter contains a summary of contributions of this thesis and some of future research directions in wireless sensor networks.

8.1 Concluding Remarks

The emerging field of WSN research combines numerous disciplines and addresses a combination of the major challenges in sensor techniques, embedded techniques, distributed information processing, and wireless communication. WSNs is a burgeoning area of research with many challenges, including managing energy consumption and network connectivity. While the wireless channel has enabled cheap establishment and maintenance costs of WSNs, it adds constraints that are not found in wired networks. Specially, limited bandwidth, channel errors, and nodes that have limited operating energy.

Developing new WSN applications with severe resource constraints will require innovative solutions to overcome the above issues as well as improving the robustness of network components, and developing sustainable and cost effective implementation models. New developed WSN protocols/algorithms and components will have to further improve energy efficiency, bandwidth efficiency and connectivity.

The IEEE 802.15 standard was designed for low rate wireless personal area networks (LR-WPANs), making it the first WSN enabling standard. However, the development of a particular WSN application will require a high degree of integrated solution to achieve desirable and effective communication. This requires both robust hardware and efficient protocols/software solutions. So far there has been no clear guidelines or design rules that have been followed in designing sensor network architectures because of the wide range of sensor applications, with each application having its own unique purpose and performance requirements (i.e, various hardware and network capability). Similarly, the general IEEE 802.15.4 standard and the likes have been implemented for a broad range of wireless PAN applications and therefore not optimised for a specific application.

The main aim of this thesis has been to investigate techniques for improving the performance of WSNs to maintain reliable network connectivity, scalability and energy efficiency. Results and the overall work presented in this thesis form a part of an emerging WSN research and establish contribution in achieving more efficient WSNs and applications. Specifically, the following areas have been examined in detail: WSN transmission power control, self-configuration, MAC design in the presence of hidden nodes and CSMA/CA analytical modeling.

The study sought answers to the following questions which are addressed in four areas of study (Section 3.3):

1. How can we specifically test multi-hop TPC communication versus single-hop communication using typical wireless sensor node hardware parameters?
2. What is the performance advantage of using multi-hop TPC in energy constraint WSNs instead of a single-hop in terms of energy efficiency and other important performance parameters?
3. What is the impact of beacon interval (BI) and number of nodes during WSN association and synchronization stages in terms of energy and association or synchronization time?
4. How can we improve the performance of WSNs during association and synchronization stage (self-configuration)?
5. What is the impact of the number of times the clear channel assessment (CCA) is performed in the 802.15.4 MAC during frame transmission in terms of throughput, packet error rate, delay and energy consumption for both hidden and non-hidden nodes in a network ?
6. What can be done to improve the performance of the 802.15.4 MAC during frame transmission stage?

7. How can Markov chains be used to accurately model the IEEE 802.15.4 slotted CSMA/CA ?

8. What is the relationship between different performance variables and the MAC parameters derived from the Markov Chains?

The following section highlights the major contributions of this thesis.

8.2 Main Research Contributions

The main contributions of this thesis are summarised as follows:

- The transmission power control (TPC) was investigated in multi and single-hop WSNs using typical hardware platform parameters via simulation and numerical analysis. A novel approach to testing TPC at the physical layer was developed, and results have shown that contrary to what has been reported from previous studies, in multi-hop networks TPC did not save energy. Both the radiation and electronic components of the energy consumption were investigated, and results indicated that sending packets using a short-range multi-hop path, instead of a single-hop, does not necessarily save energy as suggested by some researchers. Moreover, transmitting in single-hop networks at lower transmission power levels, while still maintaining reliable connectivity, reduced energy consumption by up to 23%. Furthermore, we have shown that both packet collisions and delays affect the performance of WSNs that have an increased number of hops. Since the use of TPC in star topology/cellular networks transmission can save energy, we have recommended cluster based (hybrid) or similar topology over completely multi-hop topology. Relationship among protocol layers was also revealed; possible improvement suggested; insight when developing wireless sensor networks protocol and the significance of TPC;

- The performance evaluation of the 802.15.4 MAC during device association and synchronization with the PAN coordinator, showing the impact of beacon interval and the number of associating nodes in terms of association time delay and energy consumption in stationary wireless sensor networks has been investigated. Results illustrated that energy consumption and association time increased with increasing number of nodes associating with a coordinator. Moreover, short beacon intervals consumed more energy due to the frequency of beacon frames that nodes have to keep track of to maintain synchronization. However, short beacon intervals reduced the time required for the nodes to associate, in contrast to longer beacon intervals that are undesirable for real time and mobile applications. Furthermore, for longer beacon intervals, BO= 12 to BO=14, it has been shown that there was an abrupt increase in energy consumption as the number of associating nodes increased, even for as few as as four nodes. This appeared to be the first investigation of the performance of the 802.15.4 MAC beacon interval setting and the number of associating nodes. To conserve energy in WSNs, we expect to use longer beacon interval (BI) and shorter active periods (SD) so that the nodes can go into inactive/sleep state during CAP to save energy. To date the longest beacon interval is 251.66s (about 4 minutes). Our results demonstrated that even with 7 nodes connected to the PAN coordinator, the association delay and energy consumption due to synchronization, increased. The question was whether the association energy consumption will outweigh the benefit of duty cycle power management for larger beacon intervals, as the number of associating nodes increases.

- A study to determine the impact of the number of times the CCA was performed in the 802.15.4 MAC during frame transmission in terms of throughput, packet error rate, delay and energy consumption has been presented. Both hidden and non-hidden nodes in a network system were considered. Results indicated a serious network performance degradation even for a small number of hidden nodes in a network. Following these results a proposed cross layer (PHY-MAC) mechanism to save energy, reduce interference, improve scalability and reliability, and reduce packet collisions due to hidden terminals has been presented.

- Finally, an improved two dimensional discrete time Markov chain has been proposed to capture essential features of the IEEE 802.15.4 slotted CSMA/CA. This model has rectified some of the issues apparent in previous studies. Important relationship for the successful transmission probability, throughput and average energy consumption have been derived. Moreover, the proposed model provided greater insight into the strengths and weaknesses of the MAC operation, and future possible enhancement opportunities.

8.3 Future Work

WSNs have a promising future, but additional research is needed so that the remaining challenges can be addressed. Future WSNs will still be constrained by modest power supplies provided by both passive (e.g., solar and vibration) and active (e.g., battery power and external power source) sources of energy. Thus, energy efficiency and reliable connectivity will continue to receive significant attention in the research and design of WSNs. We believe that such research will contribute to the development of a new, inclusive paradigm within the field of wireless communications. Following the current research, a starting point for this work will be the inclusion of additional cross-layer designs at multiple layers of the communication protocol stack due to the interdependence that exists among all of the layers. This has to be explicitly considered when designing communication protocols aimed at quality of service (QoS) provisioning on resource-constrained WSNs. In the current research, the work is limited to the PHY-MAC cross-layer.

There is also a need to use suitable hardware platforms in the experimentation and implementation phases of this work. This is important because the optimal choices of sensor system, processor, wireless interface, and memory technology are application dependent and exhibit temporal dependence for a given application. The concept is to get all the bits right across layers, hardware, and algorithms/software. Also, it is important for the newly-designed protocols to relate effectively to available hardware as opposed to sounding good on paper while failing the test of successful implementation with current or future technologies. Future work will validate the proposed CSMA/CA Markov chain model using a simulator or hardware platforms.

Most of the existing research in the field has been restricted to the star topology, in which devices in a PAN can always reach the coordinator in one-hop distance; however, for a large WSN, not all devices will be able to communicate with the coordinator directly; rather, they must communicate through intermediate devices (routers) to forward messages. There is a need to consider different application scenarios and to incorporate harsh environmental conditions in future studies. For example, reasonable designs must include appropriate considerations of conditions that wireless channels are likely to encounter, such as noise, interference, and other environmental factors, such as temperature, humidity, and wind. Furthermore, since sensor networks will become a seamless part of larger networks, so additional investigations should be conducted focusing on the combination of WSNs with existing and future technologies, such as the Internet and GPSs.

The investigations and design development in this research considered homogeneous sensor networks. However, there are important WSN applications in which this is not the case. Future studies should include heterogeneous sensor networks that consist of several nodes with extra capability in a network.

There is also a need for further investigation to determine possible approaches that would improve the performance of 802.15.4 during the PAN association and synchronization stages. This research raised important issues during network self-configuration. Future studies should consider improvements in self-configuration designs. For example, such studies could evaluate the implementation of an adaptable beacon interval to make use of both short intervals for a quick association time and suitable large beacon intervals for saving energy. The coordinator could start with a short beacon interval repetitively to allow nodes to quickly associate with the coordinator; then, after a predetermined period of time, the coordinator could switch to a large beacon interval to save energy. Subsequently, the coordinator could switch again to a short beacon interval to allow new nodes to associate and disassociated nodes to re-associate.

Work also is needed to improve the 802.15.4 standard BE backoff, which does not take the advantage of shared learning when the number of nodes increases or decreases. For example, a technique such as the one in the IEEE 802.11e standard could be used to tune the value of BEmin and BEmax dynamically to adapt to the number of contending nodes. A fragmentation scheme also can be used to divide the data frame to fit into the remaining number of backoff slots during the contention access period (CAP) to increase channel utilization. While protocols that are implemented for specific wireless applications can be advantageous in the future, flexibility is vitally important in future applications in which sensors will be able to adapt to changing objectives and to evolving applications. Future studies should focus on determining the appropriate balance between a protocol's adaptability, complexity, and performance in WSNs.

Finally, while energy considerations have dominated most research related to WSNs, one of the technology trends is towards increasingly higher bandwidth. This emphasis has resulted from the increasing interest in real-time applications that involve imaging and video sensors, which pose additional challenges, including specific quality of service (QoS) requirements, such as latency, throughput, and jitter. Moreover, although authentication and privacy are not always complementary objectives, the misuse of private information must always be a prime concern, e.g., the possibility of a patient's medical sensor being hacked, data tampering, and computer viruses. Security is an essential system requirement in various applications, such as healthcare networks in which the sensitivity of the data is a major concern. Eventually, WSNs will enable new applications in a wide array of areas to an extent that has never occurred before.

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Appendix A

NS 2 Supplementary Material

A.1 Installation and Settings

Installing NS-2 can be a bit length and time consuming process. Before installing NS-2 in windows environment, one needs to first install cygwin containing gcc compiler. In the current research we downloaded all-in-one -withpass version 2.34 package from the NS-2 download page [120] into cygwin local directory, usr/local/. The following are steps and commands used to install ns-2:

- Install cygwin with gcc
- download ns-allinone-withpass-2.34.tbz
- unzip ns-allinone-withpass-2.34.tbz
- tar -jxvf ns-allinone-withpass-2.34.tbz
- cd ns-allinone-2.34 and type ./install

Figure A.1shows a part of the directory structure of ns-2 once installed.

A.2 Simulator Internal Architecture

Ns-2 is written in C++, with an OTcl interpreter as a frontend interface to create and control the simulation environment. The simulator supports a class hierarchy in C++,

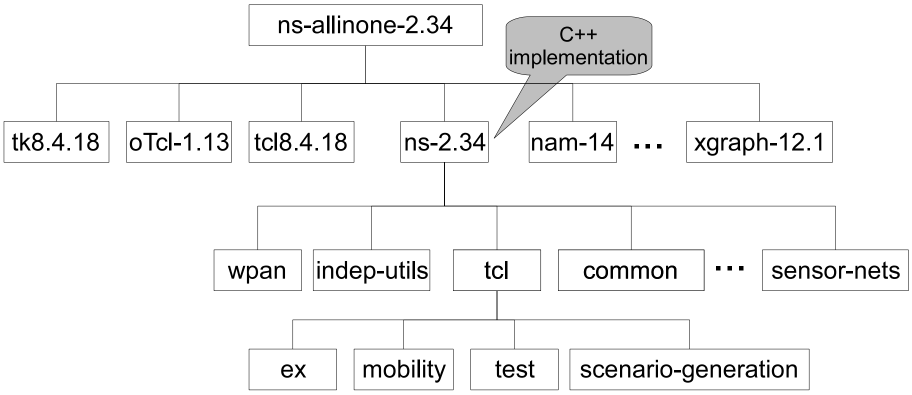

Figure A.1: NS-2 directory structure

and similar class hierarchy within the OTcl interpreter. The two hierarchies are closely related, with one-to-one correspondence between the C++ compiled hierarchy and the interpreted hierarchy [82]. The root of this hierarchy is the class TclObject. The interpreted hierarchy is automatically established through methods defined in the TclClass, while user instantiated objects are mirrored through methods defined in Class TclObject. These dynamic binding methods make it possible for the compiled member variables to be directly accessed in the interpreter. That is whenever the compiled object is instantiated; it is automatically accessible by the interpreter object as an instance variable. When one creates a new simulator objects through the interpreter, these objects are instantiated within interpreter, and closely mirrored by a corresponding object in the compiled C++ hierarchy. The code to interface with interpreter resides in a separate directory, tcl and the rest of the code reside in the ns-2.x directory (Figure A.1).

To maintain flexibility and interaction in the current thesis, both C++ and OTcl languages were used. The C++ language was mainly used for protocol implementation alteration. The OTcl language was used for dynamic configuration of protocol objects, scenario generation and simulation configuration setup.

A.3 The Concept of Discrete Event Driven

The discrete event driven nature of ns-2 simulator means that the advancement of time relies entirely on the timing of events maintained by the scheduler. In ns-2, an event is any object in the C++ hierarchy with a unique ID, a scheduled time with the pointer indicating an object that handles the event. The class event is defined by time, uid, next and handler, where time is the scheduled time of the event, uid is the unique id of the event. Next is the following scheduled event in the queue, and handler points to the function to handle the event when the event is called. The actual definition of an event is found in ns-2.x/common/scheduler.h.

A scheduler is basically an event-driven time management mechanism that launches the earliest scheduled event, executes it to completion and returns to execute the next event. In the event scheduler, events are in the queue event and sorted according to their firing time one after another. The scheduler is the primary part of the simulator. When simulator is started, the first task of the scheduler is to schedule events already predefined by the user. These events include creating a new simulator object, start simulator node/traffic, node configuring, traffic and scenario.

The packet class is the subclass of the class event as packets are received and transmitted at some time. Furthermore, all network components are subclasses of the class handler and use scheduler as they need to handle events such as packets handling delay or need to use time at some point.

In ns-2, there two types of event schedulers: real time for emulating which allows the simulator to interact with a real network and non-real time. There are three available for non-real time scheduling, namely Heap, List and Calendar.

Currently, the simulator is single-threaded, meaning only one event is in execution at any given time. The overall framework architecture of ns-2, showing a discrete event scheduler as implemented in ns-2 indicated in Figure A.2. Note that a network object that issues an event is the one handling the event later at the scheduled time. Also note that the data path between network objects differs from the event path. Packets are actually handed from one network object to another using send (Packet* p) {target_->recv(p)}; method of the sender and recv(Packet*, Handler* h = 0) method of the receiver.

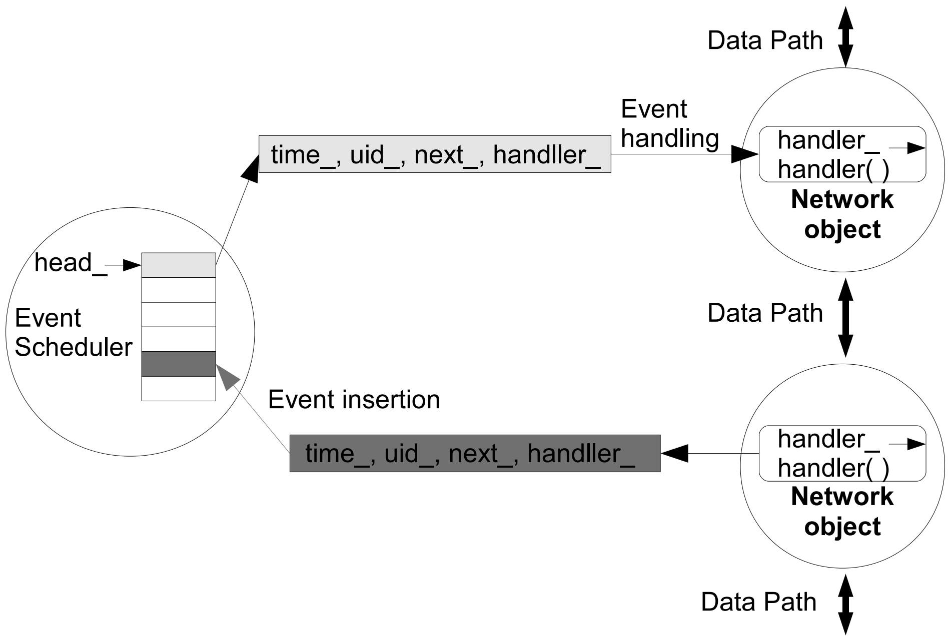

Figure A.2: Discrete Event Scheduler implementation in NS 2

A.4 ns-2 Simulation

The ns-2 is initialised using OTcl interface, whereby each simulation requires a single instance of a TCL class simulator to control and operate simulation. The TCL class simulator provides a set of interface for configuring a simulation. A simulation tcl scriptfile (*.tcl) to be interpreted by ns generally begin by creating an instance of this class and calling various methods and varibles required required in the simulation process. For example methods to create nodes, topology, scenario, traffic,channel type, propagation model, queue length, and all other configuration aspects required to run a particular wireless simulation.

When a new simulation object is created in OTcl, the initialization procedure performs the following operations:

1. initialize the packet format (calls create_packetformat)
2. create a scheduler
3. create a "null agent" (a discarding sink used in various places)

A.4.1 Packet

Packet is a subclass of the class event. Objects in the Packet class are the fundamental unit in exchange between objects. NS-2 packet is composed of stack of headers and optional data space, which is initialised when a simulator object is created. So a network object can access any header in the stack of a packet it processes it using offset value.

The initialization of the packet format will set up the field offsets used for the entire simulation. Given that ns-2 is an event-driven simulator, from this point on, the scheduler takes over.

A null agent is created to act as a sink for packets, both successfully transmitted and dropped. Packets may be handled to NsObjects at scheduled points in time since a node is an event handler and task performed over a packet is an event. Tasks over a packet should the only type of event scheduled on a node.

Testing protocols under an appropriate set of network conditions is critical in achieving valid and meaningful results. Using automatic created complex scenarios can help to achieve such appropriate scenarios. In ns-2, a scenario defines the input configuration for the simulator to run. A Scenario is made up of several components including network topology and traffic model. The network topology include the physical interconnects between nodes and the static characteristics of links and nodes. The traffic model defines the network usage patterns and unicast and multicast senders locations. The key challenge in the topology generation is coming up with a topology that embodies relevant characteristics.

For example, TCP and CBR traffic between mobile nodes can be setup manual or by using random traffic connections using CMU's traffic-scenario generator scripts available under ns-2.34/indep-utils/cmu-scen-gen, called cbrgen.tcl and tcpgen.tcl. These scripts can be used to generate CBR or TCP traffic connections between wireless nodes respectively by using the following command:

```
ns cbrgen.tcl [-type cbr/tcp] [-nn nodes] [-seed seed] [-mc connections]
[-rate rate]> file_to_store
```

A.4.2 Scenario and mobility models

In order to carry meaningful study and different network analysis such as performance of MAC protocol, effect of network dynamics, scalability etc it is important to carry simulation on the right kind of scenario, which includes but is not limited to topology size, density distribution, traffic generation, membership distribution, real-time variance of membership, and network dynamics.

Different scenario generated may be used to emphasise the different design criterion while studying protocol behaviour.

Nodes positions can be set manually inside tcl script or generated from a scenario file. The scenario file containing the positions of all nodes. Currently there are a number of scenario files in ns that can be used. These are simple text files that can be easily edited to place the nodes at desired positions.

For large topologies, node position, movement and traffic are defined in separate files for convenience. These files are generated using CMU's movement and connection generations found in ns-2.x/indep-utils/cmu-scen-gen/setdest.

The scenario generator file command allows one specify number of nodes in the simulation, x and y position of the node with respect to topology dimension, and distance from the coordinator, used main for single hop. By running

```
scen_gen [number of nodes] [x-position coordinate] [y- position
coordinate][personal operating space]
```

will produce a file wpan.scn, to be used in source scenario file (*.tcl)

For mobile node scenario we can run:

```
./setdest -n [number of nodes] -p [pause time] -M [maximum speed]
-t [simulation time] -x [max x] -y [max y]> [output dir]/[scenario-file]
```

for version 1.

A.4.3 NS 2 mobile node model

A simple unicast node consists of Two TclObjects: an address classifier (classifier_) and a port classifier (dmux_). The main function of these classifiers is to distribute incoming packets to the correct agent or outgoing link. By default nodes in ns are constructed for unicast simulations. In order to enable multicast simulation, the simulation should be created with an option "-multicast on", i.e. set ns [new simulator -multicast on]

The function "Simulator::node-config{}" accommodates flexible and modular construction of different node definitions within the same base Node class.

To create a node capable of wireless communication we use wireless communication configuration support

```
$ns_ node-config -adhocRouting dsdv
```

It is essential to define the node characteristics through configuration before creating them. This includes the address structure, type of routing and energy model.

Mobile nodes are derived from the basic ns Node object with added functions such as movement or mobility, periodic position updates, ability to maintain topology boundary and ability to transmit and receive on a channel that allows it to be used to create mobile, wireless simulation environments.

The network stack for mobile node consists of link layer (LL), an ARP module connected to LL, an interface priority queue (IFq), a mac layer (MAC), a network interface (netIF), all connected to the channel.

In the wireless model the core of the simulation environment generally consists of a mobile node with additional support features allowing simulation of multi-hop ad-hoc networks, wireless LANs and other networks. NS nodes support other added functionalities like movement, and power management. When creating mobile nodes in NS-2 environment firstly one needs to create a mobile node object, secondly the mobile node must be configured by creating a particular ad-hoc-routing agent that will be used by the node or nodes, next the network stack consisting of a link layer, interface queue, mac layer, network interface with an antenna, and propagation model must be created, we then interconnect these components and lastly, connect the stack to the channel.

The class MobileNode is used too simulate wireless nodes in wireless ad hoc networks or sensor networks on wireless channel. The class MobileNode inherits from the class Node, however there are no links in MobileNode, the receiving and sending packets are based on Wireless Channel not links

Figure A.3 illustrates the schematic of a mobile node under the CMU monarch wireless extension to NS. Note the mobile structure used in the case of DSR protocol is slightly different.

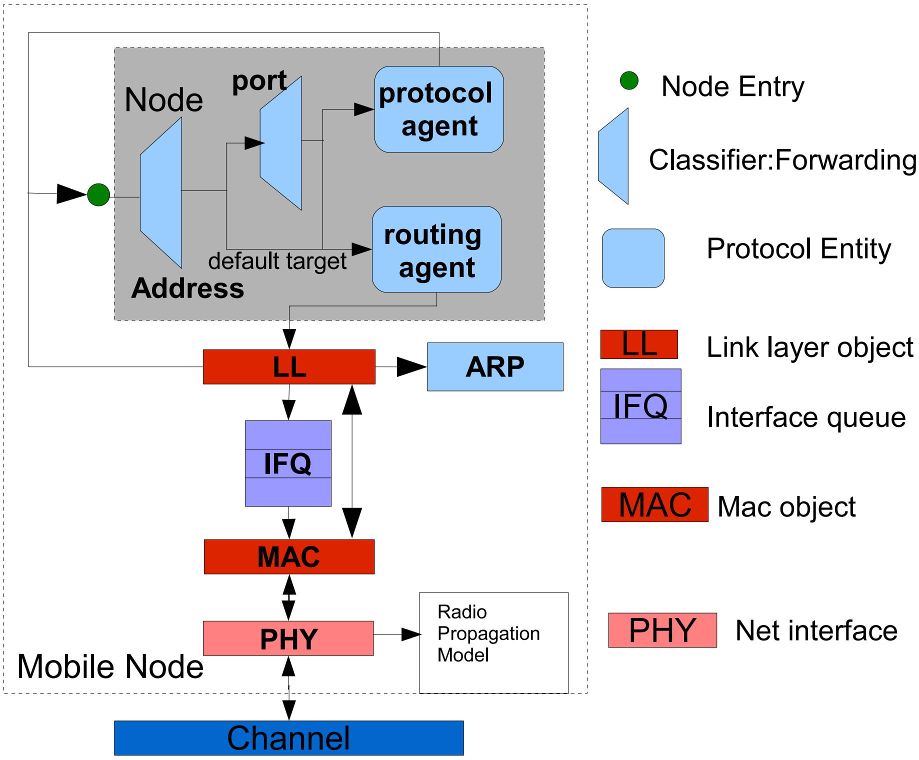

Figure A.3: Schematic node extended to implement mobile node

A.5 Extending New Implementation/Coding

Using doxygen or similar software, the ns-2 class hierarchy for 802.15.4 protocol standard or any other protocol can easily be revealed. A protocol implementation in a ns-2 follows object oriented approach. Therefore any changes or implementation of code needs to be done in a structured manner.

The overall documentation for 802.15.4 exist in NS-2 implementation. In this section, the fundamental of extending the 802.15.4 standard protocol is described as follows:

- Derive class from mac and/or wirelessPhy
- Create C++ class, fill the methods
- Define OTcl linkage if any -In order to access private variables you need to export the C++ variables to OTcl as follows
- Write OTcl code if any
- Save the new *.h and *.cc files in ns-2.34 directory
- Edit the Makefile of ns-2.34 directory to add the object file newagent.o
- Execute "make" command
- Build and debug the code
- Test using tcl script

The folder containing all modification is added in the ns-2.34 folder, then one needs to make few more changes such as editing the Makefile by adding new object files inside OBJ_CC variable before recompiling ns-2.

A.5.1 Linking C++ implementation and OTcl objects

Modification and implementation done in C++ are only accessible through Tcl script if there are bond. To bind our implementation to Tcl interface so that our implementation can be instantiated from Tcl. To do this we use the class TclClass, for example:

```
static class p804_15_4new : public TclClass{
public:
        p802_15_4new():TclClass(802.15.4new){}
        TclObject* create(int argc, const char*const* argv){
       return (new 802.15.4new)
}class_p802_15_4new
        //
```

Although most of the binding is done when a class object is initiated, the other way to establish link between OTcl and compiled C++ objects is to use binding funstion. The binding function takes to argunments, the name of the OTcl variable and the address of the C++ compiled variable.

- Define the newAgent class in C++
- In C++ class definition:Define a static class, NewAgentClass that inherits the class "TclClass" that aims to define a new OTcl object of specified name and make a linkage between this OTcl object and C++ object
- In order to access private variables you need to export the C++ variables to OTcl as follows
- Save the newagent.h and newagent.cc in ns-2.34 directory
- Edit the Makefile of ns-2.34 directory to add the object file newagent.o
- Execute "make" command
- Run the newagent.tcl script

A.5.2 Debugging and variable tracing

In NS 2 architecture, programming error can be classed into runtime errors and C++ compilation errors. Run time errors occur during NS 2 simulation caused by error in OTcl or/and C++ programming. Compilation errors occur during the compilation process when C++ header and source files are converted into object files with the extension ".o" and when compiler links the created object files to create NS executable file. In the case of the compilation process, errors may occur if the compiler is unable to understand the C++ codes. The compiler will show error messages on the screen, indicating where and why the error occurred. Examples of compilation errors include incorrect C++ syntax and a use of undefined variable and/or function. In the case of when compiler links created objects, error may occur due to improper linkage of C++ files. Example of linking error include instantiate an object from an abstract class and modifying a base class without creating object files of the child classes whereby this error usually occurs when dependency in the Makefile is not properly defined.

A.6 Extracting Information from the Trace Files

Compilation of simulation results refers to the process of collecting information from simulation and compute performance measures under consideration. There are three main approaches to collect simulation results in NS2, include through C++ code, through Tcl codes and through trace file.

The trace file format defines how the variable details are recorded in a trace file. The format of the file is defined in a function trace(v) of the class TclObject.

Upon simulating a particular scenario, trace files recording detailed information on events such as traffic and information about mobile nodes are generated. Awk scripts were then used in order to analyse or extract relevant information or measure a particular metric from the trace files. Figure A.4 shows the format of an example trace file (new trace format). In the trace file each column separated by a space represents some information, for example here we have a packet sent(s) at time (-t) sec, from source node (Hs) 0 to destination node (Hd) 1. The source node id (Ni) is 0, the node x, y and z coordinates are specified by (Nx), (Ny) and (Nz) respectively. The node energy level (Ne) is 19.986414J, the trace level (Nl) is RTR (shows the network level). The node event (Nw) is blank. The MAC level information is given by duration (MA) 0, destination Ethernet address (Md) 0, the source Ethernet address (Ms) is 0 and Ethernet type (Mt) is 0. Following the MAC level information is the IP packet level information like packet id (li), source (address.source port number) given by (Is) and the destination (address.destination port number) is given by (Id).

```
s -t 2.260000000 -Hs 0 -Hd 1 -Ni 0 -Nx 200.00 -Ny 10.00
-Nz 0.00 -Ne 19.986414 -Nl RTR -Nw --- -Ma 0 -Md 0 -Ms 0
-Mt 0 -Is 0.0 -Id 2.0 -It cbr -Il 230 -If 1 -Ii 48 -Iv 30 -Pn cbr
-Pi 48 -Pf 0 -Po 0
```

Figure A.4: Trace file output format (new trace format)

A.7 Simulation Visualization

NS comes with animation tool called Network Animator. We used Network animator (NAM) to visualize mobile node position, direction of movement and speed. NAM is animation tool that comes with NS 2 for viewing network simulation traces and real world packet trace data. NAM is designed to read simple animation event commands from a large trace file. Xgraph, Excel or Gnuplot can be used to plot graphs. Figure A.5 shows a typical NAM display with a coordinator in the middle of surrounding nodes.

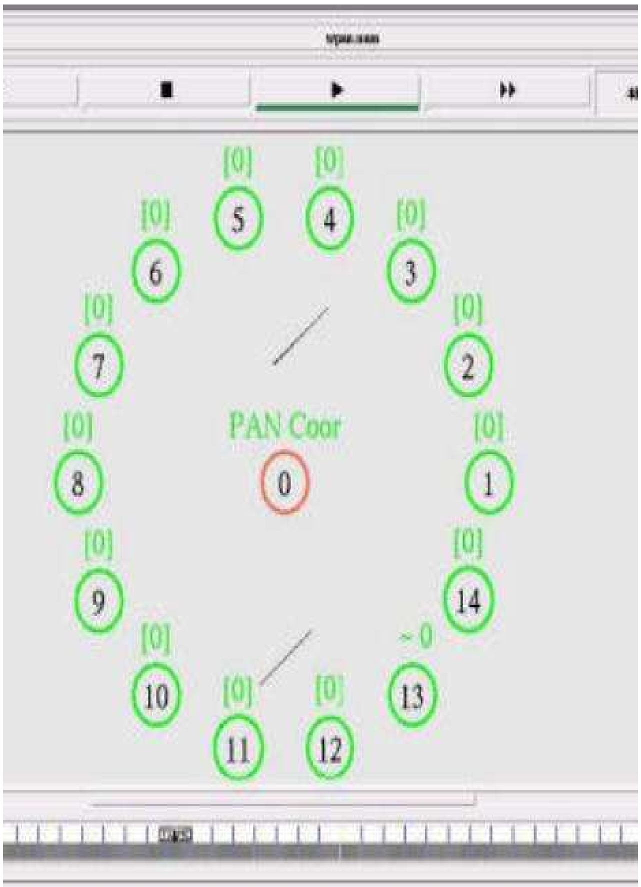

Figure A.5: NAM