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CROSS-LAYER DESIGN AND OPTIMIZATION FOR WIRELESS SENSOR NETWORKS

by

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March 2006

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Cross-layer design and optimization is a new technique which can be used to design and improve the performance in both wireless and wireline networks. The central idea of cross-layer design is to optimize the control and exchange of information over two or more layers to achieve significant performance improvements by exploiting the interactions between various protocol layers. In this thesis, a cross-layer design and optimization framework was proposed and the concept of using the optimization agent to provide the exchange and control of information between the protocol layers was also introduced. The approach for this thesis is to investigate the effects of the wireless channel and the performance of a small scale wireless sensor network (WSN) to develop insights that can be used in the design and development of the optimization agent in the proposed cross-layer framework. A tap delay line (TDL) model was developed and simulated in MATLAB to investigate the effects of the wireless channel impairments due to mobility and multipath fading. Performance measurements were also conducted to study the effects of interference and transmission range for a group of networked wireless sensors.

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CROSS-LAYER DESIGN AND OPTIMIZATION FOR WIRELESS SENSOR NETWORKS

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ABSTRACT

Cross-layer design and optimization is a new technique, which can be used to design and improve the performance in both wireless and wireline networks. The central idea of cross-layer design is to optimize the control and exchange of information over two or more layers to achieve significant performance improvements by exploiting the interactions between various protocol layers. In this thesis, a cross-layer design and optimization framework was proposed and the concept of using the optimization agent to provide the exchange and control of information between the protocol layers was introduced. The approach for this thesis was to investigate the effects of the wireless channel and the performance of a small scale wireless sensor network (WSN) to develop insights that can be used in the design and development of the optimization agent in the proposed cross-layer framework. A tap delay line (TDL) model was developed and simulated in MATLAB to investigate the effects of the wireless channel impairments due to mobility and multipath fading. Performance measurements were also conducted to study the effects of interference and transmission range for a group of networked wireless sensors.

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EXECUTIVE SUMMARY

The rapid evolution of wireless network technology and the explosive growth of wireless network services have made wireless communications an ubiquitous means for transporting information across many different domains. In the context of Wireless Sensor Networks (WSNs), there are many potential possibilities where WSNs can be deployed to support numerous applications in both civil and military areas. However, there are still some fundamental challenges that need to be overcome in the design of the next generation of wireless networks. For example, these challenges include the dynamic time varying nature of the wireless channel, co-channel interferences, mobility issues, resource contention, quality of service (QoS) provisioning and energy efficiencies, etc.

The traditional method of designing networks using the layered approach might be unsuitable and inefficient for designing wireless networks. Cross-layer design is an emerging methodology, which can help to improve and optimize the performance of a wireless system by exploiting the interactions between the various protocol layers. In this thesis, a cross-layer design and optimization framework was proposed and the concept of utilizing an optimization agent to facilitate the exchange and control of information between the protocol layers was introduced.

A tap delay line (TDL) model was developed and the simulation was performed in MATLAB to study the performance of a system (e.g., a wireless sensor) under the influence of multipath fading and mobility. Performance measurements were conducted for a group of Micaz motes (from Crossbow Technology Incorporated) to study and investigate the effects of interference and co-existence between IEEE 802.15.4 ZigBee and IEEE 802.11b Wireless Local Area Network (WLAN) operating within the 2.4 GHz ISM band. The transmission range profiles for the Micaz motes were also measured and characterized when they were configured to three different power transmission levels.

Simulations of the bit error rate (BER) performance for the two-tap TDL channel model and 12-tap TDL channel model using GSM Rec. 05.05 were performed, and it was observed that there was a degradation in BER performance as the velocity increased and the system performance started deteriorating rapidly when the velocity was increased to

above 10 mph due to the effects of mobility and impairments caused by the wireless channel. In the performance measurement study, the effects of interference were observed as there was a reduction of about 23% in the packet received rate (i.e., packets lost) for the Micaz mote that is positioned at 10 meters away from the central base station when there was a nearby interfering source (e.g., IEEE 802.11b device). The transmission range profiles for three different transmit power ratings were also measured to determine the effective operating distance that the Micaz motes could support. At the maximum transmit power of 0 dBm, the achievable transmission range was approximately 60 to 65 meters.

Several useful insights were developed and envisioned on how the optimization agent could be used, designed and further developed to fit into the proposed cross-layer optimization framework to improve and maximize the performance in a WSN.

I. INTRODUCTION

In traditional communication networks, the Open Systems Interconnection (OSI) layered architecture has been widely adopted and has served many communications systems well in the past; however, evolving wireless networks of today are seriously challenging this design philosophy. The layered architecture defines a stack of protocol layers in which each layer operate within its well-defined function and boundary, and thus allowing changes to the underlying technology at each layer without imposing the need to change the overall system architecture. This approach has been successful in its ability to provide modularity, transparency and standardization in the wireline networks but might be unsuitable in the wireless networks domain.

Although wireless networks, such as cellular networks, wireless local area networks (WLANs), mobile ad-hoc networks (MANETs) and wireless sensor networks (WSNs) are considerably different in terms of their applications and architecture, a common theme in all these networks is the use of the wireless channel for communication. Unlike the wireline networks, the wireless channel has several unique characteristics that need to be taken into account when designing wireless networks [1]. First, the broadcast nature of the wireless channel requires elaborate medium access control (MAC) protocols for channel access and second, the transmitted signal that propagates through the wireless medium is affected by attenuation and degrades more rapidly with distance as compared to the wireline channels. In addition, the wireless channel is often affected by factors, such as interference, mobility issues and multipath fading. All these factors need to be taken into consideration when designing protocols at different layers of the protocol stack. For example, rapid time variations in channel characteristics due to fading may require a more advanced modulation and coding techniques at the physical layer to avoid frequent packet losses, and it will be more difficult to provide quality of service (QoS) to support future applications, such as multimedia streaming, which demands higher data rates over heterogeneous wireless networks with different transmission characteristics. Hence, designing for wireless networks poses more stringent requirements than wireline networks, and when the layered approach to designing wireline network is applied to wireless networks, it might often lead to a sub-optimal solution and inefficient use of network resources. One typical assumption is that each layer can be optimized independently and performance gains within each layer will be sufficient for the wireless networks as in the equivalent wireline networks.

As there are some direct couplings and interactions between the physical and upper layer, cross-layer design is one of the emerging themes in recent studies that researchers are exploring to optimize the performance in wireless networks. Previous research work focuses on many different areas in wireless networking; this new technique of optimizing the performance by cross-layer interactions aims to achieve gains in overall system performance in wireless networks, such as increase in network capacity, energy efficiencies and QoS to support a wider range of services, and the technique may be deployed to support across a variety of wireless and wireline networks [2]. The central idea of cross-layer design is that by jointly optimizing the control and exchange of information over two or more layers, significant performance improvements can be achieved by exploiting the interactions between various layers of the protocol stack. However, the drawback to such a design is the potential to destroy modularity, and thus making the overall system fragile [3]. The study of cross-layer design for wireless networks is an interesting research area and it will be the theme for this thesis.

A. THESIS GOALS AND METHODOLOGY

The goal of this thesis is to develop a framework for the study of cross-layer design and optimization and to explore the various areas where performance gains can be achieved in the context of WSNs. We will first study and model the effects of the wireless channel and its impact on the system performance. A performance study is conducted using the wireless sensors (Micaz motes) from Crossbow Technologies, where the effects of interference and transmission range are explored. Insights gained from the performance study can be used to design and develop the optimization agent. The development of such a generic cross-layer design framework proposed in the study can be used and adopted to design any other wireless networks.

B. MOTIVATIONS

The study of cross-layer optimization is a relatively new research area. Cross-layer design across the various layers of the protocol stack poses many difficult and challenging problems. An important question in the area of cross-layer design is what parameters need to be shared among different layers of the protocol stack and how can each layer be made robust to the changing network conditions.

The benefits and advantages from relaxing the rigid layered structure needs to be quantified, and the associated complexity and stability issues with implementing such cross-layer design need to be studied more thoroughly. Hence, it will be essential to fully understand the impact of the outputs from one layer on the functions of other layers. The parameters in a particular layer that shaped the functions in other layers need to be identified, and a design methodology for such cross-layer approach that exploits the inter-layer relationships also need to be developed.

Cross-layer design in wireless networks is strongly recommended where the characteristics of the wireless channel permeate the functions of all protocol layers in the traditional protocol stack. Other characteristics of the wireless environment, such as mobility, fading, and interferences, also introduce a strong inter-layer relationship and their effects need to be fully understood and considered in the network design.

There are numerous advantages for implementing a cross-layer design and optimization technique. To name one, the technique can help improve efficiency at both the node and system level by improving the efficiency of protocol functions that utilize critical information from other protocol layers and thus creating a more optimized performance at each protocol layer. For example, this technique can help increase a node or network capacity and make it more flexible and robust to bandwidth variations and more tolerant to data losses since data transmission is dependent on the state of channel conditions and data losses may occur frequently in wireless networks. It can also help lengthen the lifetime of wireless devices by improving the power efficiency in portable wireless devices, such as handheld terminals in cellular networks or sensor nodes in WSNs. The cross-layer design and optimization technique can also enhance the capability of the network to support a wider range of applications; for example in the context of WSNs, a sensor node may support multiple functions for both sensing and ad-hoc operations.

In this thesis, a cross-layer optimization framework is proposed. It allows a systematic and holistic approach to study the interactions between various different protocol layers in any wireless network. The structure of the optimization agent in the proposed framework provides a modular and scalable framework when changes or modifications need to be made to accommodate different requirements or applications for various different types of networks and the benefits of such study will help to provide valuable insights into the design of next generation algorithms and protocols for wireless systems, especially for WSNs.

C. THESIS ORGANIZATION

The remainder of this thesis is organized into four chapters. The physical layer model, wireless channel characteristics, design challenges and overview of WSNs are covered in Chapter II. Chapter III introduces the concept of cross-layer design, proposed framework and highlights some of the optimization approaches in this particular research area. Performance analysis for a group of wireless sensors and simulation of the TDL model are covered under Chapter IV. Finally, Chapter V reviews the results and concludes with recommendations for future studies.

II. WIRELESS SENSOR NETWORKS

Research and development in Wireless Sensor Networks (WSNs) has received much attention from both the academia and the industry because of thesis potential to support a wide range of applications in both civilian and military areas. A WSN consists of a large number of small sensor nodes with sensing, data processing, and communication capabilities. These devices can be deployed under various conditions or at different locations and will collaborate with each other in order to accomplish a pre-defined task, such as environmental monitoring or battlefield surveillance. WSNs are usually characterized by dense node deployment, unreliable sensor nodes, frequent topology changes and severe power, computation and memory constraints. These unique characteristics and constraints present many challenges and obstacles in the design and implementation of WSNs [4, 5, 6, 7]. This chapter provides an overview of WSNs, design challenges, physical layer and wireless channel characteristics and limitations.

A. OVERVIEW

The advancement in micro-electromechanical systems (MEMS) technology and miniaturization of integrated circuit chips has brought about an emergence of tiny embedded processors with wireless interfaces and micro-sensors that are able to perform a variety of sensing functions, such as event detection, measurements, tracking and monitoring. Each sensor has the ability to interact with the physical surroundings, process gathered data and to communicate with each other. A typical wireless sensor node is usually small in size and self-contained, and it consists of a power supply, radio frequency (RF) transceiver, micro-controller, memory, and sensor modules [4, 6]. Figure 1 shows an overview of a wireless sensor node.

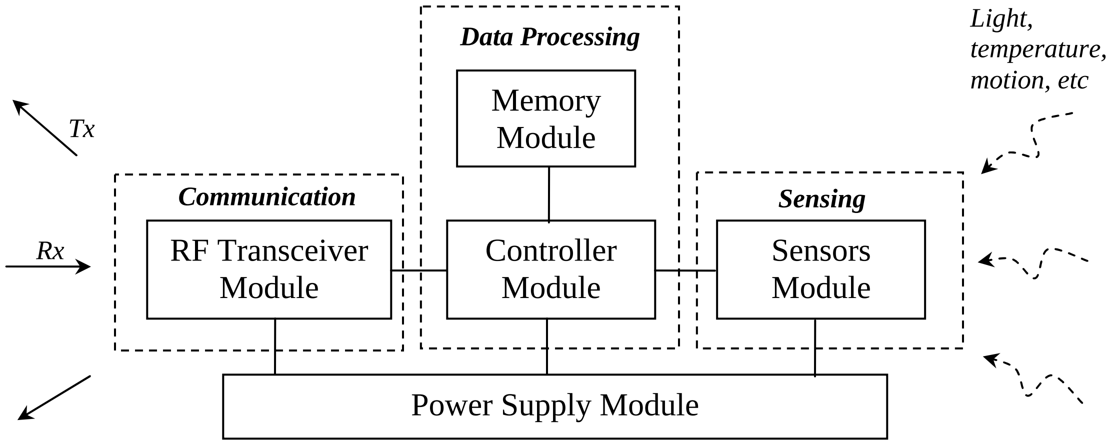

Figure 1. Overview of a wireless sensor node (After Ref. [4, 6].).

The sensor module contains a transducer that performs the sensing operation of the physical environment. The sampled data is processed by the controller where it is stored in memory. In some applications, it may require relaying or forwarding of raw sampled data to a target sink; in such cases the requirements on the processor are minimal. However, there are also cases in more sophisticated applications; it may require the preprocessing of data to extract important information so that transmission bandwidth can be preserved by simply transmitting only the essential information. The RF transceiver module is typically a short range radio communication device that performs both data transmission and reception. The power supply module is usually some form of power source such as batteries that provides the energy to power the other modules. All the four modules are inter-related to each other and their functions are dependent on the role of the sensor node.

The operations of a sensor node usually involve three main areas: sensing, communications and data processing as described earlier and a sensor node can operate in three different roles: data collector, cluster head, or data relay. If a sensor node is a data collector, the sensor module passes the sampled data directly to the RF transceiver module for transmission. If a sensor assumes the role of a cluster-head, it will gather the sensed data from the cluster members and performs data processing to aggregate multiple signals into one signal. If a sensor node works as a relay, it receives the data from nearby nodes and transmits the data to other nodes or to a target sink. A typical sensor network consists of many distributed sensors that are used to monitor conditions at different locations and possesses self-organizing capability so that little network setup and organization is required. These sensor devices also have to be small and inexpensive so that they can be produced and deployed in large numbers and can be left unattended for long hours of operations. Figure 2 shows a diagram of a generic sensor network [4, 7].

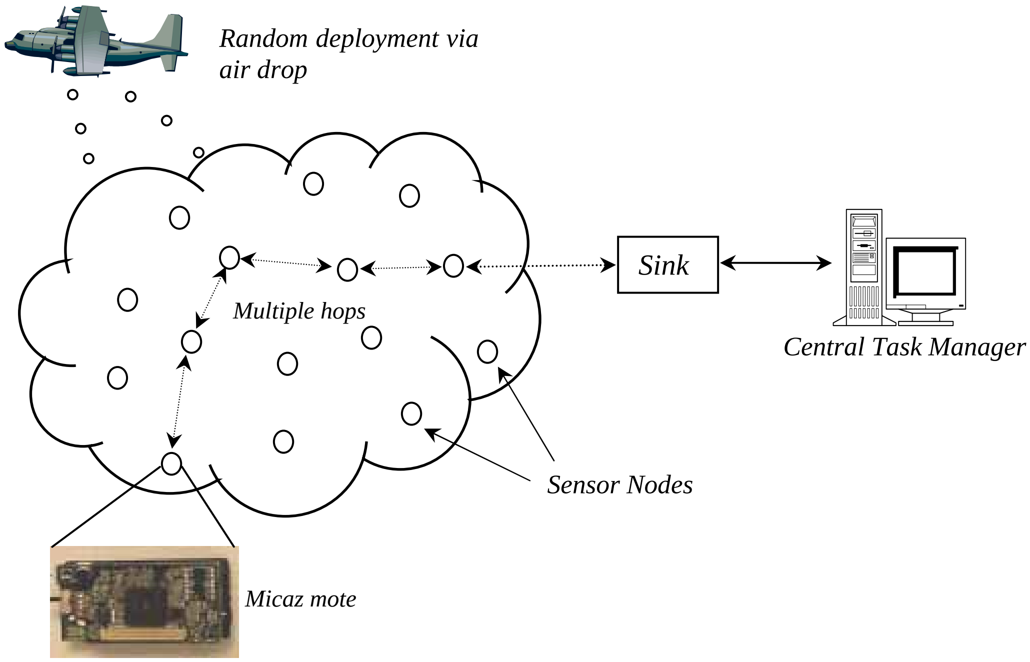

Figure 2. Generic diagram of a sensor network (After Ref. [4, 7].).

Networking these sensor nodes brings about possibilities to support numerous military and civil applications and also in human-inaccessible scenarios. Some application areas include: commercial and industrial applications (e.g. inventory and facility management, manufacturing, automation and intrusion detection, etc), environmental control and monitoring (e.g. seismic detection, disaster area and habitat monitoring, etc), medicine and health care applications, military applications (e.g. battlefield surveillance, tracking of friendly or hostile forces, etc) and also in deep space explorations (e.g. an area where WSNs are in position to contribute because they can be sent to the distant far planets and remain unattended for long durations). Deployment of a sensor network in these applications can be in random fashion (e.g. dropped from an airplane) or in a systematic and sequential order (e.g. sensors installed in conveyor belts in manufacturing plants). For example, in the military context, a large number of sensors can be dropped off randomly from an airplane to cover a hostile territory of interest in battlefield surveillance [4].

A number of different wireless sensor nodes have been developed in the WSN research and development area. Some examples include the Berkeley motes developed by the University of California at Berkeley with collaboration with Intel, the EYES (Energy Efficient Sensor Networks) nodes developed by Infineon, the BTnodes developed at the ETH Zurich and Scatterweb sensor nodes developed at the Computer Systems and Telematics group at the Freie Universitat Berlin [6].

1. Characteristics and Design Challenges of WSNs

The basic function of WSNs is to support the operations of the sensor network as highlighted earlier in Section A. However, this is a non-trivial task as WSNs have several unique characteristics. Firstly, sensor nodes are small in size and have limited amount of energy. Furthermore, sensor nodes are often subjected to failures due to depleted power supplies as it is difficult to replenish the depleted batteries for a large number of deployed sensor nodes. This limited size and energy constraints places a requirement on the amount of resources (e.g. processor performance, memory, communication bandwidth and range) that can be incorporated into a sensor node.

Secondly, sensor nodes are prone to failures due to mobility and physical obstructions and this would create a highly dynamic environment with frequent network topology changes and partitions. Mobility issues can be caused by either the sensor node, sink movement or due to event movement, such as in tracking applications where the target object is moving [6]. As the sensor nodes are also densely distributed and randomly deployed, communication between sensor nodes will be a problem in WSNs as these devices not only need to support various types of communication (e.g. broadcast, multicast or unicast traffic), it will also need to have some form of routing algorithms to support collaborative operations for data aggregation through the network in order to carry out a specific task. Information will be carried through the sensor network in multiple hops and such multi-hops wireless communication is expected to consume less power and can effectively overcome some of the signal propagation effects experienced in the traditional long-distance single hop wireless communication [4].

WSNs may consist of a large number of different nodes in terms of sensors, computing power, and memory. The large number of sensor nodes and dense network size raises the issue of scalability and cost and in many cases, these nodes will have to operate unattended for long durations and it will be impossible to service such a large number of nodes in remote and possibly inaccessible locations. Another problem that may arise is how to support various types of applications over such heterogeneous network.

To meet the new challenges, innovative protocols and algorithms are needed to achieve energy efficiency, flexible scalability, adaptability, and good network performance. For example, it is highly desirable to develop new energy-efficient protocols for topology discovery, self-organization, medium access control, route discovery, and data dissemination for the sensor network. An efficient query processing and data aggregation algorithm can also significantly reduce the number of transmissions of sensor nodes and thus provide substantial energy savings and prolong the lifetime of the WSN [7]. The low-energy, high fidelity and dynamic operation characteristics of WSNs pose great design challenges for researchers. In the following Sections B and C, we will cover some aspects of the physical and wireless channel characteristics that may affect the design, performance and operation of WSNs.

B. PHYSICAL LAYER

WSNs share many of the problems and challenges faced by the traditional wireless networks, such as the challenges presented by the time varying nature of the wireless channels. WSNs also have characteristics that are different from traditional wireless networks. For example, sensor nodes have more severe power constraints compared to traditional wireless network devices such as Wireless LANs (WLANs) even though their range of operation is much shorter and may transmit at a much lower data rate. In addition, there are also additional constraints imposed when working with WSNs. In traditional wireless networks where the devices are designed for high reliability and have the luxury of constant power and have higher processing powers to perform more complex functions, WSNs on the other hand have more tighter constraints as the sensor nodes are more constricted in terms of size and power, processing power and memory and in some scenarios (e.g. hostile environment) maybe less reliable. Hence, for different types of wireless networks and applications, the physical layer technology may be designed differently.

1. Physical Layer Model

The block diagram of a physical layer model is shown in Figure 3. In designing wireless networks, the physical layer is mainly concerned with signal detection, modulation techniques, operating frequency, hardware aspects of RF transceivers and techniques for source and channel coding, etc. In sensor networks, one of the challenges is to find a suitable energy efficient modulation scheme and RF transceiver architectures that are simple, low cost and robust enough to overcome the signal propagation effects through the wireless medium [6].

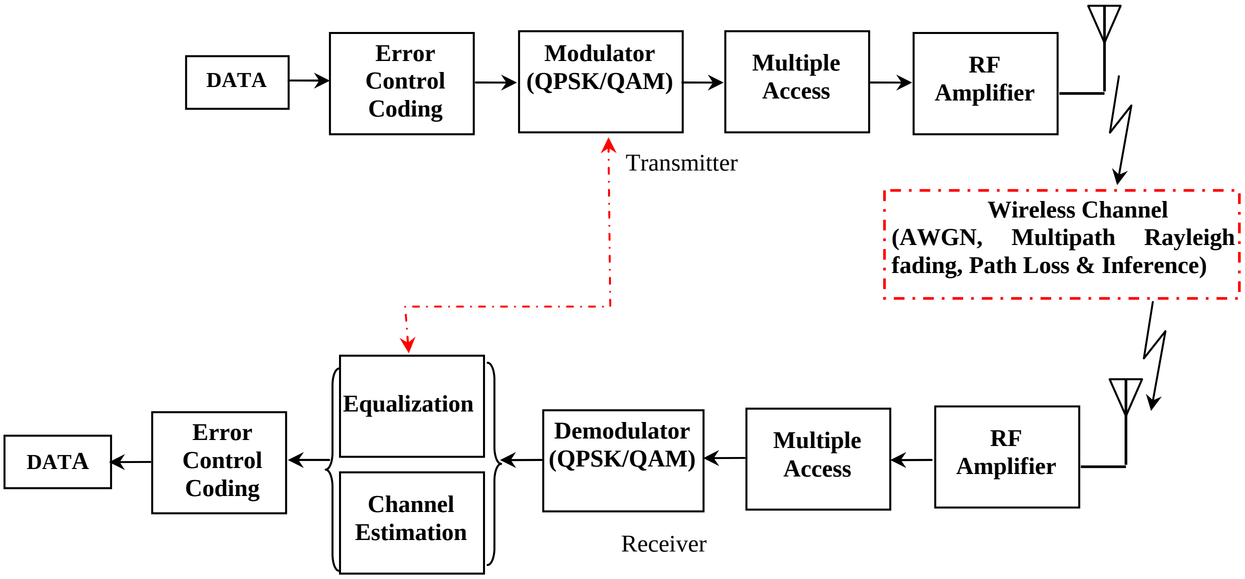

Figure 3. Physical layer model.

There is a variety of different physical layer transmission technologies used in wireless networks and some examples of which include narrowband, spread spectrum and ultra-wideband (UWB) techniques, etc. Generally, spread spectrum technologies meet the requirements much better than narrowband technologies and is one of the more popular techniques used in wireless networks and Wireless Personal Area Network (WPAN) [8]. UWB technology is a technique that is gaining more attention in the wireless research domain and the technique is said to offer higher data rates at short distances and low power consumption while also offering the same robustness against interferences [9].

Several air interface standards are currently being used and new standards are also being proposed for a variety of different wireless networks (e.g. WLANs, WiMAX and WPANs, etc) such as WiFi (IEEE 802.11), Bluetooth (IEEE 802.15.1), UWB (IEEE 802.15.3) and ZigBee (IEEE 802.15.4), etc.

The IEEE 802.11 standards define four different physical layer techniques for WLANs: Diffused Infrared (IR), Frequency Hopping Spread Spectrum (FHSS), Direct

Sequence Spread Spectrum (DSSS) and Orthogonal Frequency Division Multiplexing (OFDM). The infrared technique operates at baseband while the other radio-based techniques operate at the 2.4 and 5.8 GHz bands [10].

Bluetooth uses the FHSS and the modulation technique that it uses is Gaussian Frequency Shift Keying (GFSK). GFSK is based on Frequency Shift Keying (FSK) and the GFSK modulation used in the Bluetooth system is a type of binary partial response continuous phase modulation, which is a slight generalization of the GMSK modulation used in the GSM cellular system [11].

The physical layer for ZigBee (low data rate and low power WPAN) is defined under IEEE 802.15.4 and it specifies two physical layer interfaces, one at 2.4 GHz, and the other at 915 MHz. The 2.4 GHz physical layer interface uses offset quaternary phase shift keying (OQPSK) modulation with operations at a data rate of 250 kbps and the 915 MHz (North America or 868 MHz for European) ISM bands uses BPSK modulation and is able to provide a data rate of between 20 to 40 kbps [12].

2. Frequency Bands

The wireless spectrum consists of both licensed and unlicensed bands. With the introduction of the Industrial, Scientific, and Medical (ISM) bands, many wireless devices have become readily available. These devices have become popular because designers or users do not need to register them if they operate within certain parameters limits as governed by Federal Communications Commission (FCC). In 1985, FCC first authorized the operation of non-licensed spread spectrum systems in the 902-928 MHz, 2400-2483.5 MHz, and 5725-5850 MHz bands under Part 15 of the rules at a power level of one watt, which is significantly higher than previously permitted unlicensed use in other bands [13].

In the ISM bands, unlicensed users are secondary users and so must cope with interference from primary users when such users are active. At 900 MHz, it is one of the noisiest frequency bands, with cordless telephones and hundreds of consumer devices occupying this small spectrum (26 MHz from 902 MHz to 928 MHz). Within the available ISM bands, several competing technologies are available. The current most popular ISM band is 2.4 GHz and interest in the 5.6 GHz ISM band is gaining as the 2.4 GHz band is already becoming crowded with cordless phones, security cameras and other non-network devices. The frequency bands available for unlicensed spread spectrum, unlicensed PCS, millimeter-wave and U-NII devices are summarized in Table 1 [13].

Bands	Year Authorized	Frequencies (MHz)
ISM/Spread Spectrum	1985	902-928, 2400-2483.5 & 5725-5850
Unlicensed PCS	1993	1910-1930 & 2390-2400
Millimeter-wave	1995	59,000-64,000
U-NII	1998	5150-5350 & 5725-5825
Millimeter-wave (Expansion)	2001	57,000-59,000

Table 1. ISM frequency bands (After Ref. [13].).

Within the 2.4 GHz ISM band, there are several wireless systems that share the same frequency band such as IEEE 802.11b, Bluetooth and IEEE 802.15.4 WPAN. Therefore, for systems operating within the same frequency band, they will not only need to be robust against interference but they will also need to be able to coexist and operate within close proximity to each other. Figure 4 shows the overlapping of frequency bands between the IEEE 802.11b and IEEE 802.15.4 channels. The frequency spectrum of the IEEE 802.11b standard shown in the figure occupies channels 1, 6, and 11 that are non-overlapping with each other. In the IEEE 802.15.4 standard, there are only two frequency channels (channels 25 and 26) that are not overlapping with any of the IEEE 802.11b channels. Channels 15 and 20 of the IEEE 802.15.4 standard can also be considered non-overlapping if the IEEE 802.11b systems are configured to operate in non-overlapping channels 1, 6, and 11 to avoid potential adjacent channel interference. The frequency channels that are overlapping may cause potential interference problems and this problem exists in every ISM band and not just in the 2.4 GHz spectrum.

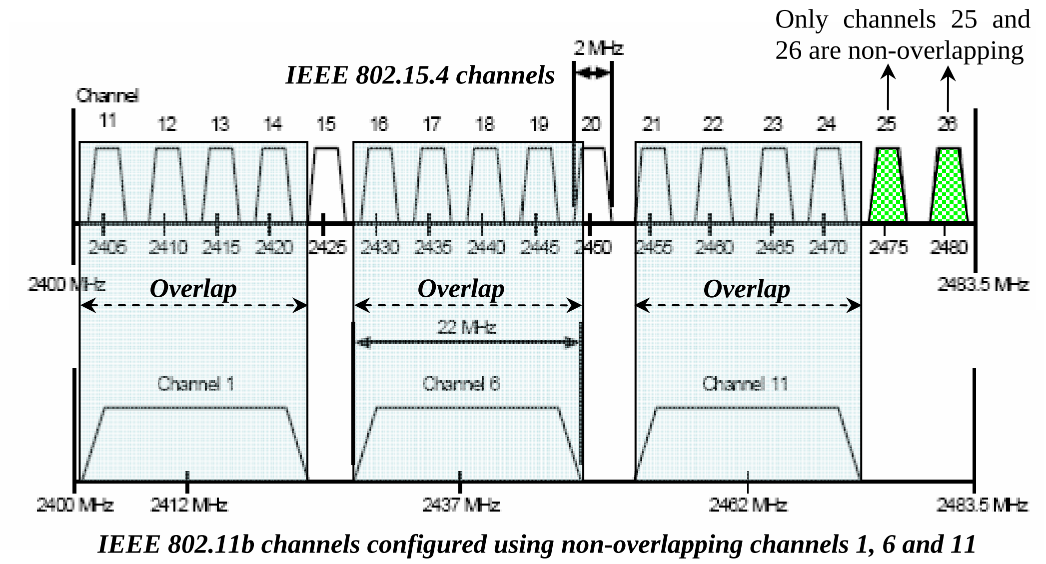

Figure 4. Overlapping frequency bands between IEEE 802.11b (configured using non-overlapping channels 1, 6 and 11) and IEEE 802.15.4 channels.

On February 14, 2002, the FCC amended the Part 15 rules which govern unlicensed radio devices to include the operation of UWB devices. The FCC ruling allows UWB devices to operate at low power (an EIRP of -41.3 dBm/MHz) in an unlicensed spectrum from 3.1 to 10.6 GHz. This low emission limit is meant to ensure that UWB devices do not cause harmful interference and are able to coexist with licensed services and other radio operations, which includes cellular, PCS, GPS, IEEE 802.11a, satellite radio, and terrestrial radio [14]. This new amendment offers tremendous capacity potential (in order of several Gbps) over short ranges (less than 10 meters) at low radiated power for WSNs.

3. Spread Spectrum Communication

Many modern radio communication systems employ the use of spread spectrum communication techniques because of its ability to provide an effective means for communicating reliably over channels that exhibit strong interference and multipath propagation. This technique has several interesting properties, for example, it is able to provide good anti-jamming performance (i.e. offering low probability of detection (LPD) as it has good resistance to interference and jamming signals), to provide a means of masking the transmitted signal in the background noise in order to lower the probability of intercept (LPI) by an adversary, to provide resistance to signal interference from multipath propagation, to provide multiple access schemes by allowing more than one user to access a common communication channel, for example, in cellular systems such as IS-95 and CDMA systems, and to provide a means for measuring location and timing acquisition in applications such as Global Positional System (GPS) [15].

In spread spectrum systems, it uses special modulation techniques that spread the energy of the transmitted signal over a very wide bandwidth. The information to be transmitted is modulated onto a carrier by conventional techniques, which is usually a digital modulation technique, and the bandwidth of the signal is deliberately widened by means of a spreading function. The spreading technique used in the transmitter is duplicated in the receiver to enable detection and decoding of the signal. Spread spectrum systems offer two important technological advantages over conventional transmission schemes. First, the spreading reduces the power density of the signal at any given frequency within the transmitted bandwidth, thereby reducing the probability of causing interference to other signals occupying the same spectrum. Secondly, signal processing in spread spectrum systems can help to suppress undesired signals, thereby enabling such systems to tolerate against any strong interfering signals. However, spread spectrum does not provide any processing gain over white noise. This is because white noise has the same power within the transmitted spectrum and it affects the transmitted signal by the same amount regardless of how widely the signal is spread.

Spread spectrum techniques achieve higher effective signal-to-noise ratio (SNR) than narrowband systems at the cost of excess signal bandwidth. The two most commonly used spreading techniques are direct sequence spread spectrum (DSSS) and frequency hopping spread spectrum (FHSS). In a DSSS system, the original baseband signal is multiplied by a pseudo-random chipping sequence, which has a much higher bit rate than the original baseband signal and this will spread the spectrum of the signal and making it look like a noise-like wideband signal. The spread signal is then modulated by means of binary phase-shift keying (BPSK) or quadrature phase-shift keying (QPSK) and transmitted. At the receiving end, the receiver uses the same pseudo-random chipping sequence to de-spread the received signal and the resulting signal is then demodulated to extract out the original data. The presence of any interferers or jamming signals at the receiver will be spread out by the pseudo-random chipping sequence and making it appear like ordinary wideband noise. Figure 5 shows the frequency channels in the IEEE 802.15.4 standard and the spreading and de-spreading operations that are used in the DSSS technique to overcome a narrowband interference signal. At the receiver, the de-correlation due to the spreading and de-spreading operations will make a narrowband interference signal appear like a wideband noise-like signal which will be filtered off by the receiver. In order to enjoy a high processing gain, complex digital signal processing (DSP) circuitry must operate at a high speed and also under conditions of low data rate. Furthermore, timing and synchronization in a DSSS system must be established within a fraction of the chip interval. The DSSS technique is adopted in both the IEEE 802.15.4 ZigBee standard and IEEE 802.11 standards [10, 12].

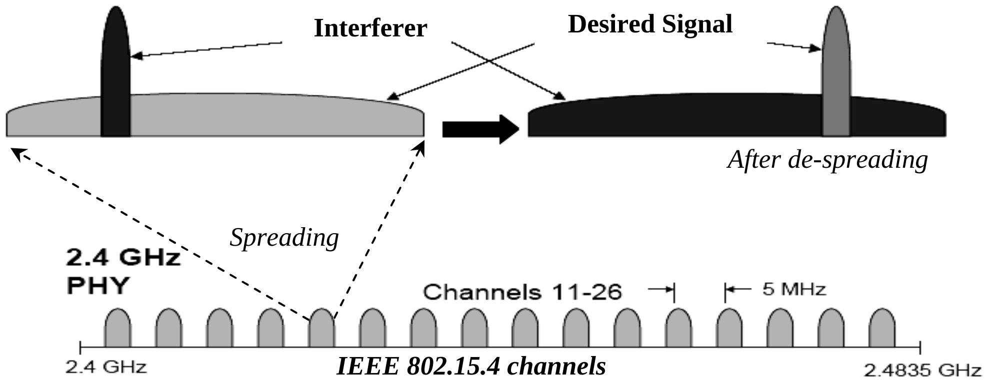

Figure 5. Direct sequence spread spectrum technique used in IEEE 802.15.4.

The FHSS technique, which is adopted in the Bluetooth standard, generally has a more simplified baseband hardware requirement and synchronization protocols compared to the DSSS systems. In the FHSS system, it uses a pseudo-random chipping sequence to shift the carrier frequency in a random manner and modulating portions of the data signal with different carrier frequencies by means of binary frequency shift keying (BFSK). This technique is able to provide an improved multipath performance by transmitting signals over a broad range of frequencies and it may also avoid a particular strong interference signal by selecting interference free channels in its hopping sequence. While the FHSS technique appears attractive for WSN applications, there are challenges in their implementation as WSN require low power operations over a broad range of operating frequencies which might not be suitable with conventional FSK systems.

There is also a third method, which is hybrid combination of the two methods mentioned earlier. Direct sequence with frequency agility (DS/FA) combines the best features of DSSS and FHSS without most of the problems caused by frequency hopping because frequency changes are not necessary most of the time; rather they are appropriate only on an exception basis. Frequency agility offers the ability to change frequencies to avoid interference from a known interferer or from any other signal source. This method is being proposed as the new physical layer recommendation for IEEE 802.15.4 ZigBee standard.

C. WIRELESS CHANNEL

The wireless channel is known to be unreliable and stochastic in nature and is often characterized by path loss, multipath fading, doppler spread, and interference (e.g. co-channel and adjacent channel interference). The performance of a wireless network is mainly affected by interferences and the time varying nature of the wireless channels. Interference such as co-channel interference (CCI) is caused by users sharing the same channel due to the multiple access schemes in wireless networks. The effects due to multipath fading, shadowing, path loss, propagation delay, and noise can substantially reduce the received signal at a receiver output, and the received signal level can fluctuate in the order of tens of decibels.

An important requirement for assessing the performance of any wireless system is to have an accurate depiction of the wireless channel. Hence, characterization of the operating environment is important, because effects of multipath and interference attenuate the received signal. Thus, a good understanding of the channel response allows an accurate and realistic modeling of the wireless channel for the study of the physical layer performance in any wireless system, and it can also help to mitigate the multipath effects in the design of a WSN.

1. Wireless Channel Model

WSNs are especially vulnerable to multipath due to the adverse environment and power constraints placed on the wireless sensors. For example, sensor nodes are often mounted to a surface which may act as a reflector. In addition, in areas of close proximity where the WSN are being deployed, movement from humans, animals, vehicles or rainfall will constantly change the transmission channel. Such dynamic changes can significantly alter the operating environment, either degrading or improving a signal. For example, in the case where there is no single dominant signal contribution (non-line of sight, NLOS) at the receiver, the received signal will follow a Rayleigh distribution. If there is a dominant signal contribution at the receiver (LOS), the signal will then follow a Ricean distribution. In addition to the impairments experienced by the signal as a result of the multipath propagation, the channel can also be affected by Additive White Gaussian Noise (AWGN) and the interference from other wireless sensors within the vicinity of the transmission radius. There is also a path loss factor to be considered as the signal propagates through free space and an additional attenuation factor as the signal passed through various types of terrain (e.g. urban, rural, forest, hilly, etc).

A typical wireless channel will consists of a combination of signal impairments and attenuations as a transmitted signal passes through the wireless medium. Figure 6 shows the block diagram of a typical wireless channel model and it can consists of a combination of the five different components as described earlier in the section. This model can be used in various simulation environments to investigate the performance of a wireless system through the wireless medium.

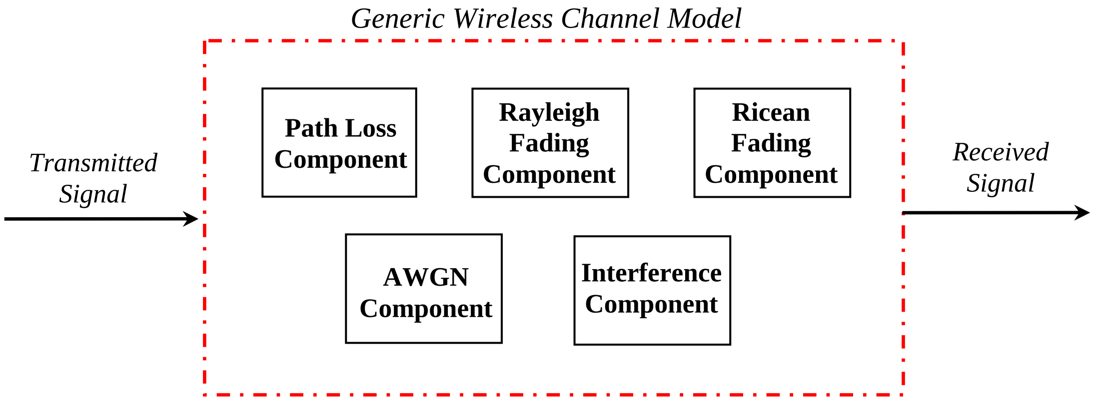

Figure 6. Wireless channel model.

2. Propagation, Path Loss, and Fading

The physical medium between a pair of transmitting and receiving antennas where the transmitted signal (in the form of electromagnetic waves) is propagated is called the propagation channel. The electromagnetic waves that propagate through the wireless channel will experience a certain amount of attenuation and distortion due to the effects of path loss, shadowing, and fading. These effects are generally dependent on the frequency, location, mobility, and reflection coefficients of the surrounding objects, etc. The surrounding objects that influence the propagation of electromagnetic waves can be either static (man-made or natural obstacles such as tall buildings or mountains) or time varying (moving vehicles, wind-blown trees or atmospheric variations) and are considered to be part of the propagation channel. For mobile and portable applications, it is often assumed that the channel varies with time, making it a linear time-variant (LTV) system. In some applications, the channel variations can be slow as compared to the transmission rate and such channels are called quasi-static. In general, it does not matter what type of wireless technology is used, whether it is cellular radio, microwave radio, cordless telephony, or WLANs, the physical principles that govern the propagation of electromagnetic waves is still the same.

Two types of propagation models: large-scale and small-scale propagation models are often used to give estimations of the average received signal strength from the transmitter. Large-scale propagation models estimate the mean signal strength for different distances between a transmitter and receiver in the order of several hundreds or thousands of meters and the models are quite simple and do not take in account the small variations such as fading caused by multipath propagation. These models are useful in predicting the coverage of a radio system. Examples of large-scale models include distance path loss and shadowing [16].

Path loss is caused by propagation loss, where the signal is attenuated due to the distance between the transmitter and the receiver. An often-used approximation of path loss is the log-distance model [16]. In the case of free space propagation, the received power can be calculated from the Friis free space transmission equation:

$$\begin{aligned} P_{rec}(d) &= \frac{P_{tx} \cdot G_t \cdot G_r \cdot \lambda^2}{(4\pi)^2 \cdot d^2 \cdot L} \\ &= \frac{P_{tx} \cdot G_t \cdot G_r \cdot \lambda^2}{(4\pi)^2 \cdot d^2 \cdot L} \cdot \left(\frac{d_o}{d}\right)^2 = P_{rec}(d_o) \cdot \left(\frac{d_o}{d}\right)^2 \end{aligned} \tag{2.1}$$

where P_{tx} is the transmission power, G_t and G_r are the transmitter and receiver antenna gains, λ is the wavelength, d is the actual distance between transmitter and receiver, d_o is the reference distance and L is the loss through the transmitter and receiver circuitry. For environments other than free space, Equation 2.1 can be generalized to:

$$P_{rec}(d) = P_{rec}(d_o) \cdot \left(\frac{d_o}{d}\right)^{\gamma} \tag{2.2}$$

where γ is the path-loss exponent and it typically varies between two (free-space) and six (shadowed and obstructed in-building scenarios). Table 2 shows some typical values of the average path-loss exponent and shadowing variance at different locations [17]. Equation 2.2 can be expressed in decibel form, which gives the log-distance path loss model:

$$PL(d)[dB] = PL(d_0)[dB] + 10\gamma \log_{10}\left(\frac{d}{d_0}\right) \qquad (2.3)$$

Location	**Average Path-loss exponent, γ**	**Average shadowing variance, σ^2 [dB]**
Engineering building	1.9	5.7
Apartment hallway	2.0	8.0
Concrete Canyon	2.7	10.2
Sandy flat beach	4.2	4.0
Dense bamboo	5.0	11.6
Dry tall underbrush	3.6	8.4

Table 2. Average path-loss exponents (After Ref. [17].).

The effect of shadowing occurs when the transmitted signal experiences random variations in the received power due to blockage from large objects or obstacles such as hills and tall buildings in the signal's path. The log-distance path loss model can be extended to include the shadowing effect (lognormal fading), which can be described as:

$$PL(d)[dB] = PL(d_0)[dB] + 10\gamma \log_{10}\left(\frac{d}{d_0}\right) + X_\sigma[dB] \qquad (2.4)$$

where X_σ is a zero-mean Gaussian distributed random variable (in decibels), that describes the shadowing with a standard deviation σ (in decibels) [16].

On the other hand, propagation models that characterize rapid changes of the signal strength over very short distances (a few wavelengths) between a transmitter and receiver over short durations (in the order of seconds) are called small-scale propagation or fading models. Small-scale fading describes the rapid changes of the amplitude of radio waves over a short period of time or traveled distance. Multipath fading is caused by interference between multiple receptions of the same signal as it travels along different paths and is received at different times at the receiver due to reflection, diffraction and scattering. These multipath components combine at the receiver to give a resulting signal that varies widely in amplitude, phase or polarization. In general, small-scale propagation channels are time and environment specific. These models require heavy measurement and the results are correct only for a given location at the measured instant. These channel models can be divided into narrowband and wideband channel models.

Fading models with Rayleigh or Ricean distributions are commonly used to describe the wireless environment. In the case when there is no dominant line of sight (LOS) component in the received signal, the received signal can be modeled by a Rayleigh distribution:

$$p(r_o) = \begin{cases} \dfrac{r_o}{\sigma^2} \exp\left[-\dfrac{\left(r_o^{\,2}\right)}{2\sigma^2} \right] & \text{for } r_o \geq 0, A \geq 0 \\ 0 & \text{otherwise} \end{cases} \tag{2.5}$$

where σ^2 is the time-average power of the received signal before envelope detection, r_o is the Rayleigh fading signal envelope and $r_o^2/2\sigma^2$ is the instantaneous power.

Alternatively, when the received signal is made up of multiple scattering components as well as a dominant LOS path, the received signal amplitude can be modeled by a Ricean distribution:

$$p(r_o) = \begin{cases} \dfrac{r_o}{\sigma^2} \exp\left[-\dfrac{\left(r_o^{\,2} + A^2\right)}{2\sigma^2} \right] I_o\left(\dfrac{r_o A}{\sigma^2} \right) & \text{for } r_o \geq 0, A \geq 0 \\ 0 & \text{otherwise} \end{cases} \tag{2.6}$$

where A is the dominant LOS component of the signal and I_o is the modified Bessel function of the first kind and zero order. The Ricean distribution is often described in terms of a parameter K (Ricean factor), which is defined as the ratio between the deterministic LOS signal power and the variance of the multipath signal and is given by:

$$K = \frac{A^2}{2\sigma^2} \tag{2.7}$$

In addition to the losses of signal strength, a transmitted signal can also be affected by the attenuation from trees, forested woodlands and atmospheric fluctuations**.** Trees can be a significant source of path loss and there are a number of factors involved, such as the specific type of trees, whether it is wet or dry, and in the case of deciduous trees, whether the leaves are present or not. Isolated trees do not usually contribute much to the attenuation, but a dense forest will have a significant amount of attenuation. The attenuation depends on the distance the signal must penetrate through the forest, and it increases with frequency. According to ITU-R P1411 report, the attenuation is of the order of 0.05 dB/m at 200 MHz, 0.1 dB/m at 500 MHz, 0.2 dB/m at 1 GHz, 0.3 dB/m at 2 GHz and 0.4 dB/m at 3 GHz [18].

3. Channel Models

Various radio wave propagation channel models have been developed to estimate the path attenuation and other parameters of the propagation channel. There are variations in calculation methods, initial values, and results between different models. Channel models can be categorized in many ways, for instance according to how they are created.

Empirical models are based on statistical analysis of a large amount of measurements. Usually the simplest models estimate the path loss with the aid of a set of diagrams that are based on empirical measurements. These models can be scaled to a certain environment using simple parameters such as antenna heights. COST231 Hata-model (European Co-operation in the field of Scientific and Technical Research, action 231) is an example of such a model. It uses frequency, distance between transmitter and receiver, and antenna heights as initial parameters. The environment is also characterized by selecting the environment type from dense city, city, suburban or rural environment [19].

Semi-deterministic models are more complex and are based on theoretical calculations and statistics in addition to empirical measurements. The environmental impacts can be modeled more accurately by adding some theoretical aspect to the models. Therefore, these models require extra parameters to characterize the environment. This leads to the case where the channel models are more environment-specific and need to be recalculated if the conditions change. COST231 Walfisch-Ikegami model is one such semi-deterministic channel model used for an urban environment. It uses additional parameters, such as building height, street width, block size and direction of the streets [19].

Deterministic models are based on electromagnetic simulation of the environments. The simulation approach tries to estimate all the characteristics of the radio channel including delays, polarizations and directions of the multipath components. The simulation approach is based on three-dimensional maps of the environment and requires complex calculations in order to model the radio channel thoroughly. Deterministic channel models are environment dependent, and it is difficult to find a model that would suit all environments. Finite difference time-domain (FDTD) methods, used for deriving the impulse response, and ray-tracing approach, where dominant propagation paths are predicted, are two well-known methods that are used to create deterministic channel models.

Often a tap delay line (TDL) model could be used to model the wireless channel when the system bandwidth exceeds the channel coherence bandwidth. It is able to provide insights into the channel distortions caused by scattering components with different propagation delays [20]. Each tap represents a signal from reflected path, having a time delay, phase change, path and attenuated amplitude. The received signal will be the sum of all signals from different paths. Figure 7 shows a model of the tapped delay line structure.

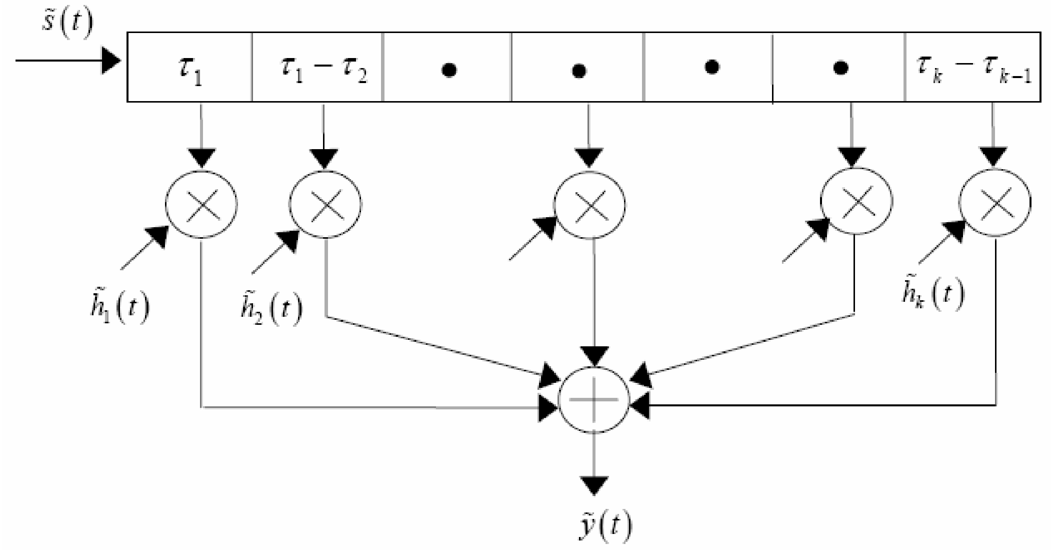

Figure 7. Tapped delay line model (After Ref. [20].).

In summary, this chapter presented an overview of WSNs and highlighted some of the challenges involved in the design and operations of a WSN. In particular, we discussed and looked at some of the physical and wireless channel characteristics that might affect the design, performance and operations of WSNs. In the next chapter, we will highlight the concept of cross-layer design, proposed framework and provide an overview of some of the approaches in this particular field.

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III. CROSS-LAYER DESIGN

In the layered approach to designing networks, the network can be organized as a series of different layers. The purpose of each layer is to offer certain services to the next higher layer, and this provides a level of transparency by shielding the higher layers from the details of how the lower layer services are being implemented. This approach helps reduce complexity by splitting the network into smaller modules with different functionalities such that each function can be dealt with more manageably, and indirectly it also facilitates the development of new protocol standards at various layers of the protocol stack. Such a structured approach to network design helps to provide easy standardization, inter-layer interoperability and peer-to-peer relationships among different networks and equipment [21, 22].

With wireless networks, the dynamic behavior of the wireless channel poses many difficult challenges. The conventional protocol stack is inflexible as various protocol layers communicate in a strict manner. In such a case, the layers are designed to operate under the worst conditions as opposed to adapting to changing conditions and this often leads to inefficient utilization of available frequency spectrum and energy resources. A paradigm shift is also beginning to take place as wireless communications evolves from a circuit-switched infrastructure to a packet-based infrastructure [1], and a certain level of QoS may be required to support future applications in wireless networks. The question now is how to provide and maintain a certain level of QoS in a dynamic environment? One possible alternative is by cross-layer design and adaptation.

A. CONCEPT OF CROSS-LAYERING

The concept of cross-layer design is about sharing of information among different protocol layers for adaptation purposes and to increase the inter-layer interactions. Here, adaptation refers to the ability of network protocols and applications to observe and respond to changes in channel conditions. A common misconception is that the layered approach must be completely eliminated and all layers must be integrated and jointly optimized.

In wireless networks, there is a tight interdependence between layers. Cross-layer design can help to exploit the interactions between layers and promotes adaptability at various layers based on information exchanged. However, such a design process needs to be carefully coordinated to avoid unintentional and undesirable consequences. It is often hard to characterize the interactions between protocols at different layers and the joint optimization across layers may lead to complex algorithms, which would later result in problems with implementation, debugging, upgrading and standardization [3]. As the performance of adjacent layers is inter-related, it is equally important to fully understand this interdependency relationship and carefully analyze their responses as optimization processes at different layers could go in opposite directions.

We consider a simple example in the case of WSNs, which consists of wireless sensor nodes that communicate with each other using multi-hop routes. Routing protocols in WSNs might differ depending on the type of application and network architecture, and there are numerous routing protocols that address the problem of establishing and maintaining the routes in a dynamic network topology. However, most routing protocols are designed with less emphasis on the issues at lower layers like the variable link capacity at the physical layer or the fluctuating contention level at the MAC layer [23]. By exploiting the lower layer information through a cross-layer concept, performance benefits may be obtained. Figure 8 shows the cross-layer concept. At the physical layer, channel estimation is performed to obtain the instantaneous signal-to-noise ratio (SNR) of a link, and this information is used to select the data rate, which affects the transmission delay. At the network layer, the routing protocol then makes a decision based on the delay associated with each link, which it will then evenly spread the network load distributions across the available links and thus optimizing the performance of the lower layers.

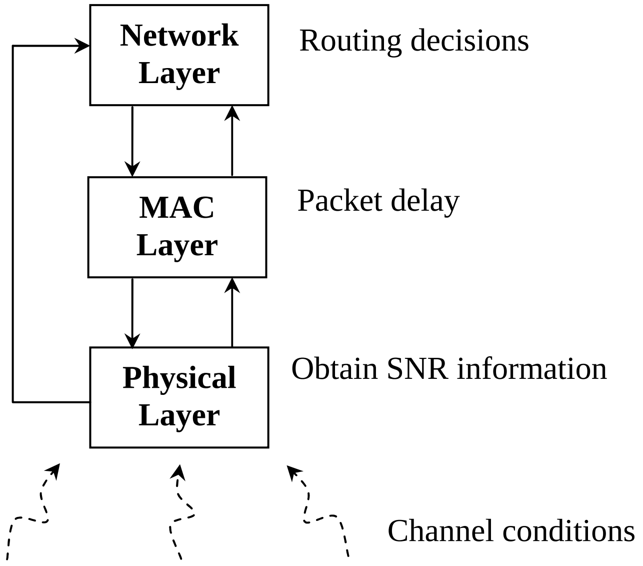

Figure 8. Cross-layer concept.

B. PROPOSED FRAMEWORK

Currently, there is no well defined framework in the study of cross-layer optimization as myriad combinations of optimization techniques exist and can be performed at various layers of the protocol stack and each combination will be unique to a specific optimization goal. Some examples of cross-layer design frameworks are presented in [22, 24, 25, 26, 27] where they discussed various cross-layer possibilities, potential benefits and drawbacks for various approaches and reviewed some existing work in this particular area. A survey on the benefits of cross-layer design optimizations in wireless protocol stacks was presented by [24] where they proposed the use of cross-layer feedback to improve the performance of mobile devices to support future heterogeneous networks as the existing protocol stacks are architected and implemented in a layered manner and do not function efficiently in mobile wireless environments.

Dynamic multi-attribute cross-layer design (DMA-CLD) framework was proposed by [25] for cross-layer interactions in wireless ad-hoc and sensor networks, in which multiple, and possibly conflicting (single-layer, cross-layer, nodal, and networking) objectives can be met. DMA-CLD allows interactions between the network layer to both upper and lower layers of the OSI model. It utilizes Analytic Hierarchy Process (AHP) for making multiple, and possibly conflicting decisions. Cross-layer optimization can also be classified into several categories, based on the order in which the optimizations are performed; for example, top-down, bottom-up, application centric, MAC centric and integrated approaches [26].

We propose a generic framework for our study of cross-layer optimization for WSNs as shown in Figure 9. The architecture consists of a proposed optimization agent (OA), which facilitates interactions between various protocol layers by serving as a core repository or database where essential information such as node identification number, hop count, energy level, link status, etc, are maintained temporary and are used as *side information,* which are fedback to other layers across the protocol stack. This is slightly different from the layered model approach as information can only be exchanged directly across two adjacent layers in a sequential manner.

Interactions between various layers can be categorized as intra-layer (between adjacent layers) or inter-layer interactions (across two or more adjacent layers) and these interactions can be either from bottom up or top down. Bottom up interactions can be described as the typical feedback mechanism used in control systems, such as the sending of feedback information to the upper protocol layers to stabilize the system performance. For example, information obtained about the channel conditions at the physical layer maybe used to update and feedback to the link layer to adapt its error control mechanisms or to the application layer to adapt its sending rate. Top down interactions can be described as the sending of urgent messages such as prioritized traffic (e.g., link down and forwarding of re-routing table entries to other wireless sensors) from the normal operation or data flow, in such a case the direction of the data flow can be directly from application layer straight down to the MAC layer. In another example, the transmit power at the physical layer can be fine tuned by the MAC layer to increase the transmission range.

Our proposed framework is similar to the wireless deployable network system (WIDENS) architecture proposed in [22] with the difference that in [22] interactions between non-adjacent layers is controlled via the adjacent layers and thus allowing cross-layer optimization without affecting the regular functionality of the layer whose response is not intended.

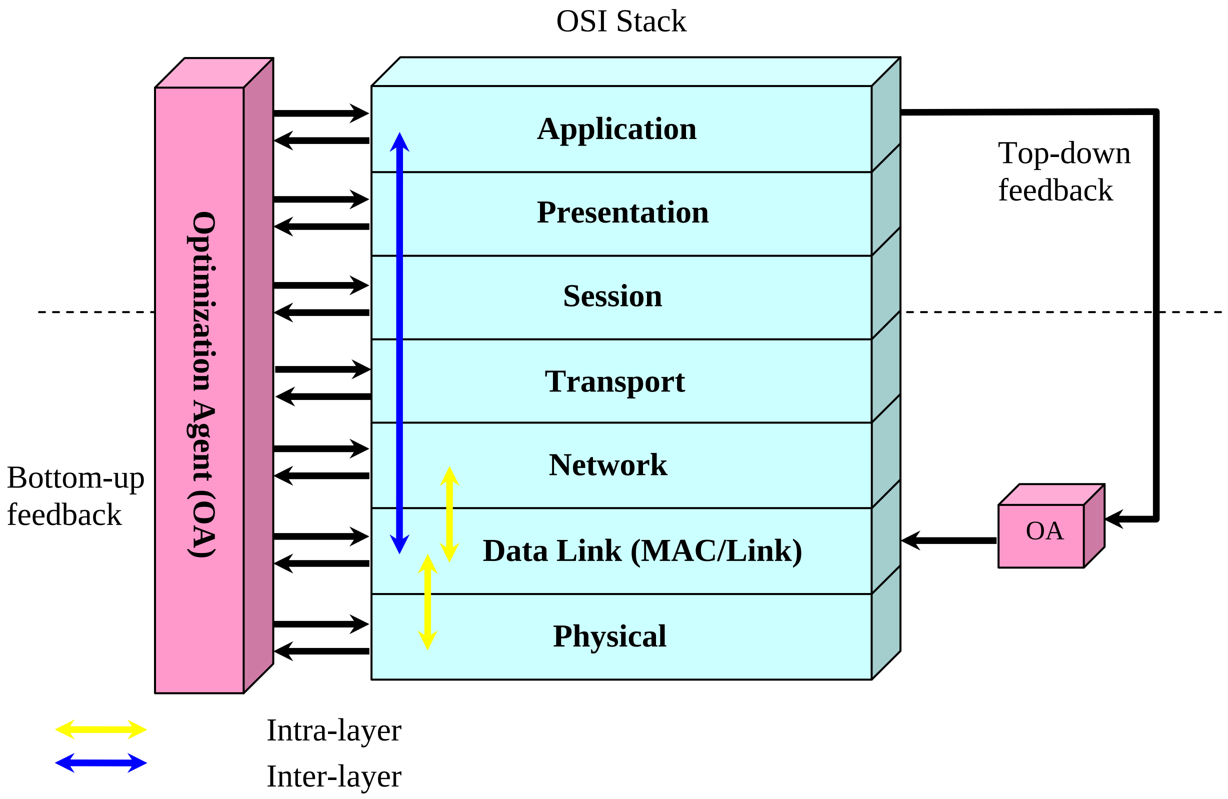

Figure 9. Cross-layer optimization framework.

The structure of the OA provides a modular and scalable framework that accommodates changes or modifications to the protocol stacks for different network requirements or applications. Unlike in some of the proposed cross-layer approaches (e.g., in [30, 31]) that intend to optimize the performance between two adjacent layers (e.g., MAC and network layers), our proposed approach extends the cross-layering process to all protocol layers as critical information can be exchanged across the layers such that the performance at each individual layer can be fully optimized. To support future applications for ubiquitous wireless networking where they demand high QoS and reliable packet delivery over the highly dynamic environment, it would entail the OA to provide the flexibility to accustom and adapt itself to changes in the environment and also to the changes in the performance at each individual protocol layer (e.g. such as adapting to changing network conditions or adapting to the application needs). Such adaptability across all protocol layers is different from other proposed techniques where the main emphasis is on the optimization across one or two protocol layers and they do not consider the effects caused by the changing operating environment.

Our proposed framework and concept of using the OA provides a flexible and adaptive approach for the joint optimization across all protocol layers and it does not need to redesign any existing protocols at each layer.

C. OVERVIEW OF OPTIMIZATION TECHNIQUES AND APPROACHES

Research on cross-layer optimization techniques has recently received much attention by the research community. Previous work concentrates mainly on optimizing the performance at a single layer, for example, smart antenna solutions and diversity reception techniques, such as multiple-input multiple-output (MIMO) and cooperative MIMO, have been proposed at the physical layer to improve the link quality by combating the effects of multipath propagation and to increase capacity by mitigating interference and allowing transmission of different data streams from different antennas [28]. Smart antennas solutions may be considered unsuitable for integration with wireless sensors as they consist of more than one antenna element and may require a larger amount of space than traditional antennas. In addition, the processing of more than one signal also requires more computational power and electronics circuitry. Nevertheless, the use of smart antenna systems in WSNs to achieve reliable and efficient data delivery was proposed in [29] where the authors suggested that the use of smart antennas in sensor networks is not only possible but necessary in some cases and potential benefits can be achieved with minimal additional cost.

Most of the ongoing research work in the area of cross-layer optimization focuses on joint optimization of the lower three layers (e.g., physical, data-link/MAC and network layers) [21, 29, 30, 31, 32] while there are also proposals which consider a combination of optimization techniques between the application and the lower layers [2, 26, 27, 33, 34]. A cross-layer design approach was developed in [30], which combines adaptive modulation and coding at the physical layer and truncated automatic repeat request protocol at the data-link layer. This was done in order to maximize spectral efficiency under a prescribed delay and error performance constraints for wireless links considered in HIPERLAN/2 and IEEE 802.11a standards. In a similar work, [31] analyzes the performance of a MAC-physical scheme for WLANs that makes use of distributed queues and cross-layer concepts to improve radio channel utilization. The results obtained from the proposed scheme outperform throughput bounds achieved when using a legacy 802.11 MAC protocol. The usage of distributed queues and cross-layer information eliminates back-off periods and collisions in data packet transmissions and it makes the performance of a system independent of the number of transmitting stations and it also provides stability under high load conditions.

Cross-layer optimization technique has also been a popular topic in both sensor networks [32, 33] and ad-hoc networks [2, 22, 25, 27, 34] as potential benefits can be achieved in areas such as power efficiency, QoS fairness and resource allocation. An overview of cross-layer network design in MANET was provided by [27] and project MobileMan was discussed and developed that aims to exploit MANET’s protocol stack by allowing protocols belonging to different layers to cooperate, sharing network status information while still maintaining separate layers by using the cross-layer concept. In the proposed approach, it also addresses security, cooperation, energy management, and QoS issues. A methodology for studying the performance of wireless ad-hoc networks with multi-hop routing is introduced in [34] where the interactions of power control at the physical layer, queuing discipline at the MAC layer and the choice of routing protocol at the network layer are being investigated. In [2], a joint integration of middleware, network and application layers is being performed to solve the data accessibility problem in a dynamic MANET environment by considering QoS routing protocols that facilitates data advertising, lookup and replication services in order to achieve a high data access rate.

In [32], a joint optimization approach across the network, MAC and physical layers was proposed to achieve efficient flooding for WSNs due to the high node density and stringent constraint on the energy consumption in WSNs environment. The study of application oriented cross-layer protocol design and optimization was done by [33] with the goal to provide a feasible and flexible approach to solve the conflicts between the requirements of large scale, long lifetime, and multi-purpose WSNs and the constraints of small bandwidth, low battery capacity, and limited node resources. Table 3 from [33] provides some valuable insights into the possible areas where optimization improvements could occur at each OSI layer and the approaches are classified according to the three main optimizations goals of network scalability, system life and node versatility. For example, new modulation technique such as ultra-wide band (UWB) is being proposed at the physical layer to make use of its potential benefits in terms of power savings and high data rate. In another example, the issue of power usage in WSNs can be improved by designing power saving routing protocols at the network layer, which can help to improve energy efficiency of WSNs by considering power-aware and load-aware routings at the network wide and individual sensor node levels.

Layer	**Network Scale**	**System Lifetime**	**Node Versatility**
Application	Data fusion, compression	Power-aware mode control	Load detection, automatic mode decision
Transport	Bounded delay	QoS-power tradeoff	Load-aware transport control
Network	Node naming, efficient routing, efficient node discovery	Power-aware routing, reduced overhead	Load-aware routing, simplified node discovery, distributed storage
MAC	Contention control, channel reuse	Synchronized sleep, transmission range control	Load-aware channel allocation
Physical	Ultra-wide band	Low-power design, powerful battery	Attach specific accessories (GPS)

Table 3. Optimization approaches at each OSI layer (After Ref. [33].).

Other on-going research includes physical-MAC cross-layer strategies that have been proposed by [21] to improve system efficiency by automatic transmission rate adaptation in cellular network. The proposed schemes have shown interesting properties that could be very useful for future multimedia wireless communication systems, where power efficiency of the handheld units will be a significant issue.

The various techniques and approaches covered so far has been on wireless networks, cross-layer design has also been proven to be effective in fixed networks [33]. For instance, the Integrated Layer Processing (ILP) principle [35] permits data manipulation at end-systems to be performed in a few integrated processing loops using application level framing. In general, some of the concepts and approaches proposed for cross-layer optimization can be modified and adapted across the different domains of wireless networks; however, some of these approaches may exhibit different advantages or drawbacks for different types of applications or environment in which it is operating in. Joint optimization across the various OSI layers is possible and could yield significant results. A variety of different techniques have been proposed and there are still many unexplored areas in this particular domain.

In summary, there are many possible approaches in the study of cross-layer design and optimization. Cross-layering, interoperability and the ability to reconfigure are three important properties for the next generation of communications systems [22]. Cross-layer design is a new trend in wireless networking and will be a key design choice for improving network performance to deal with the major challenges of high-data-rate wireless networks, limited radio resources, unreliable wireless channel, and the increasing demand for QoS. However, some cautionary perspectives must be taken into account [3] and an in-depth understanding of the wireless channel is often necessary to study the impacts it has on the overall system performance. In the next chapter, we discuss the simulations that were performed to investigate the performance degradation due to mobility and fading, and we also investigate the performance issues related to interference and power transmission levels for a small scale wireless sensor network.

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IV. PERFORMANCE ANALYSIS

This chapter discusses the results of the tap delay line (TDL) model that is used to simulate the effects of wireless channel impairments due to mobility and multipath fading. Performance measurements were also conducted to study the effects of interference and transmission range for a group of wireless sensors. The approach for this thesis study is to investigate the effects of the wireless channel and the performance of a small scale wireless sensor network by using the Micaz motes from Crossbow Technology Incorporated to develop insights and ideas that can be used to design and develop the OA for the cross-layer design and optimization framework as proposed in Chapter III.

A. WIRELESS CHANNEL SIMULATION

The aim of this simulation is to study the performance of a system (e.g., a sensor node) under the effects of multipath fading and mobility. As highlighted in Chapter II, mobility in sensor networks can be in three forms, either due to the sensor node, sink movement or due to event movement. The dynamic and time varying nature of the wireless channel and mobility issues may cause significant degradation in bit error rate (BER) performance and may affect the overall performance of a WSN. A two-tap delay line channel model was created and the simulation was performed using MATLAB.

1. Simulation Model and Approach

In the tap delay line implementation, a two-tap model was created to simulate the effects of the wireless channel under varying mobility conditions. The block diagram of the model is shown in Figure 10. Time shifted and delayed versions of the transmitted signal are multiplied with the tap gains of a doppler filter. The doppler filter is realized using the Jakes model as defined by Equation 4.1 [20]. The wireless channel is also modeled with an exponential power delay profile and the effects due to AWGN are also included in the simulation model.

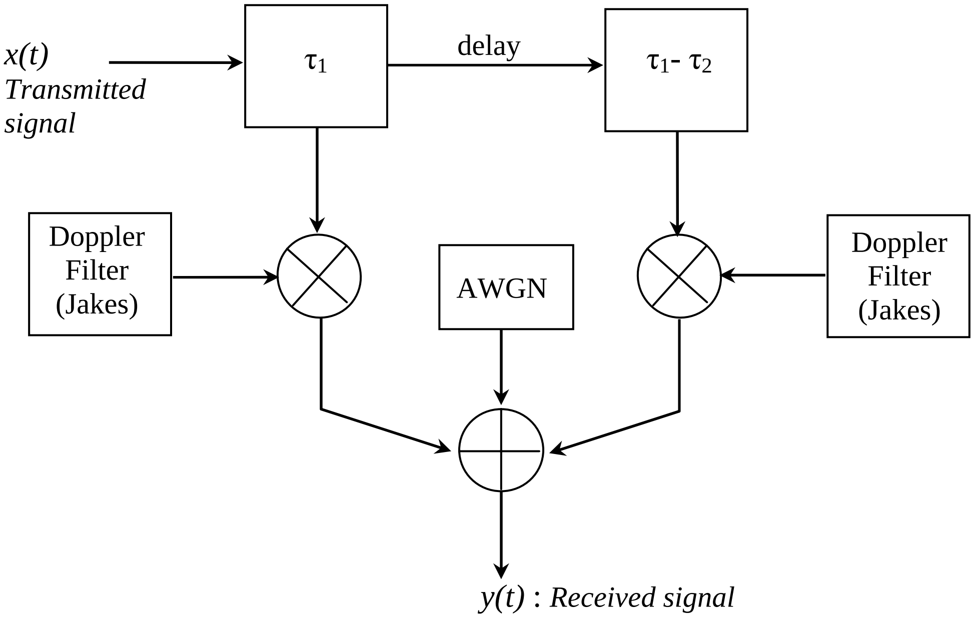

Figure 10. Two-tap TDL channel model.

There are two different kinds of doppler shifts that are often used to model different radio environment. The classic Jakes doppler spectrum is often used in vehicular and pedestrian environment and the flat doppler spectrum is often used in indoor office environment. The Jakes doppler spectrum was first used by Jakes and many others at Bell Laboratories to derive the first comprehensive mobile radio channel model for both doppler and amplitude fading effects [20] and it has the form:

$$S_d(f) = \frac{K}{\sqrt{1-\left(\frac{f}{f_d}\right)^2}}, \qquad -f_d \le f \le f_d \qquad (4.1)$$

where $f_d = v/\lambda$ is the maximum doppler shift, v is the velocity in meters per second, and λ is the wavelength of the carrier. The doppler spectrum defined in Equation 4.1 is appropriate for dense scattering environments like urban areas and in cases where there is a strong LOS component in the received signal, the Ricean doppler spectrum is used and it is often used to model the rural environment. The Ricean doppler spectrum has the form:

$$S_d(f) = \frac{K}{\sqrt{1-\left(\frac{f}{f_d}\right)^2}} + 0.91\delta\left(f \pm 0.7 f_d\right), \qquad -f_d \le f \le f_d \quad (4.2)$$

The multipath intensity profile for a wireless radio channel is dependent on the type of terrain. Two of the commonly used terrain types to model the multipath delay profile are the urban/suburban and the rural mountainous terrains. In the urban and suburban areas, the typical values of the multipath spread ranges from 1 to 10 µs whereas in the rural mountainous areas, the multipath delay spread are much greater ranging from 10 to 30 µs [36]. The power delay profile for the urban and suburban areas can be modeled as:

$$P_m(\tau) = \begin{cases} \exp(-\tau) & \text{for } 0<\tau<7\mu\text{sec} \\ 0 & \text{otherwise} \end{cases} \quad (4.3)$$

In rural mountainous areas, the power delay profile can be modeled as:

$$P_m(\tau) = \begin{cases} \exp(-\tau) & \text{for } 0<\tau<7\mu\text{sec} \\ 0.1\exp(15-\tau) & \text{for } 15<\tau<20\mu\text{sec} \\ 0 & \text{otherwise} \end{cases} \quad (4.4)$$

where $P_m(\tau)$ is the received signal power as a function of the delay time, τ.

In addition to the two-tap TDL model, a 12-tap TDL model using GSM Rec. 05.05 channel model was also used in the simulation to verify the results. The multipath channel is modeled by the 12-tap TDL with delays and average gains as stated in GSM Rec. 05.05 recommendation for radio transmission and reception [37].

2. Simulation Results and Analysis

The simulations were performed by assuming an urban environment with a carrier frequency of 2.4 GHz. The plot of the doppler power spectrum at a velocity of 20 mph (doppler frequency, f_d of 72 Hz) using the Jakes model is shown in Figure 11. The equivalent power spectral density (PSD) at the filter output using the Jakes spectrum is shown in Figure 12. The exponential power delay profile described in Equation 4.3 was also used in the simulation and the corresponding plot is shown in Figure 13. The power delay profile used in the GSM Rec. 05.05 recommendation to simulate the 12-tap TDL channel model is also shown in Figure 14.

Simulation results of the bit error rate (BER) performance for the two-tap and 12-tap TDL channel models are shown in Figure 15 and 16. In both plots, we observed that the BER performance starts to degrade under increasing velocity and the performance will worsen as the velocity gets higher. For both models, we noticed that there is a rapid increase in BER when the velocity is increased from 10 to 20 mph and in the case of the two-tap TDL model, the BER performance will start to deteriorate gradually at velocities from 20 mph and above. For the 12-tap TDL model, the BER performance will start deteriorating to a constant level of about $10^{-0.3}$ at velocities from 30 mph onwards.

A similar result was also observed in [38] where the authors investigated the performance of a communication system as a function of mobile velocity and it has been shown that the correlation of the wireless channel has a large influence on the performance of the overall system. Intuitively, we would expect the performance of a system to degrade under the influence of mobility and impairments caused by the wireless channel. It was observed that the BER increases at high velocities as compared to a lower velocity and this is because at low velocities the transmitted and received symbols are still highly correlated in the channel, whereas at high velocities there is virtually no correlation between successive received symbols due to the increased fading and mobility changes.

In our simulation, we did not consider the use of adaptive modulation or coding techniques. Adaptive modulation and coding techniques can help to provide a more robust and spectrally efficient transmission scheme over time varying channels. The basic principle is to provide an estimation of the channel status at the receiver and feedback this information to the transmitter, so that the transmission scheme can be adapted to the instantaneous channel characteristics. Techniques that do not adapt to the channel conditions will often require a fixed link margin to maintain an acceptable performance when the channel quality is poor and wireless systems that use this technique are often designed to operate effectively under the worst-case channel conditions [39].

By adapting to the channel conditions, it is possible to increase the average throughput and to reduce the average BER of a wireless system by taking advantage of favorable channel conditions to send data at a suitable data rate or coding rate, or by either reducing or increasing the required transmission power. However, there are several constraints that determine when adaptive modulation and coding techniques should be used. Firstly, the technique requires a feedback path between the transmitter and receiver, which may not be feasible in the case of WSNs given the frequent link and topological changes in the sensor network environment. Moreover, if the channel is changing faster than it can be reliably estimated and feedback to the transmitter, the adaptive modulation technique will perform poorly. Hardware constraints may dictate how often the transmitter can change its data rate and transmit power, and this may be a major limitation in WSNs given its small size and limited power requirements.

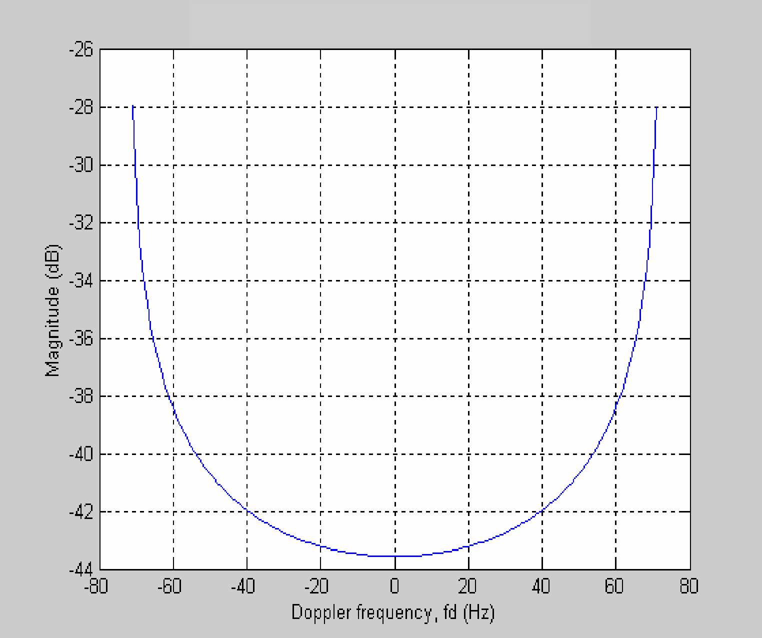

Figure 11. Doppler power spectrum using Jakes model at velocity of 20 mph (f_d of 72 Hz) and frequency of 2.4 GHz.

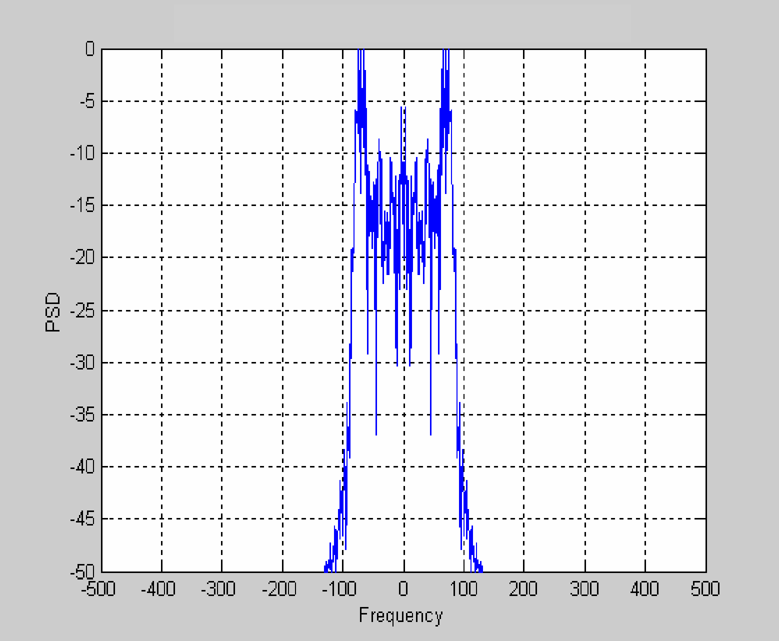

Figure 12. PSD of doppler filter using Jakes model at velocity of 20 mph (f_d of 72 Hz) and frequency of 2.4 GHz.

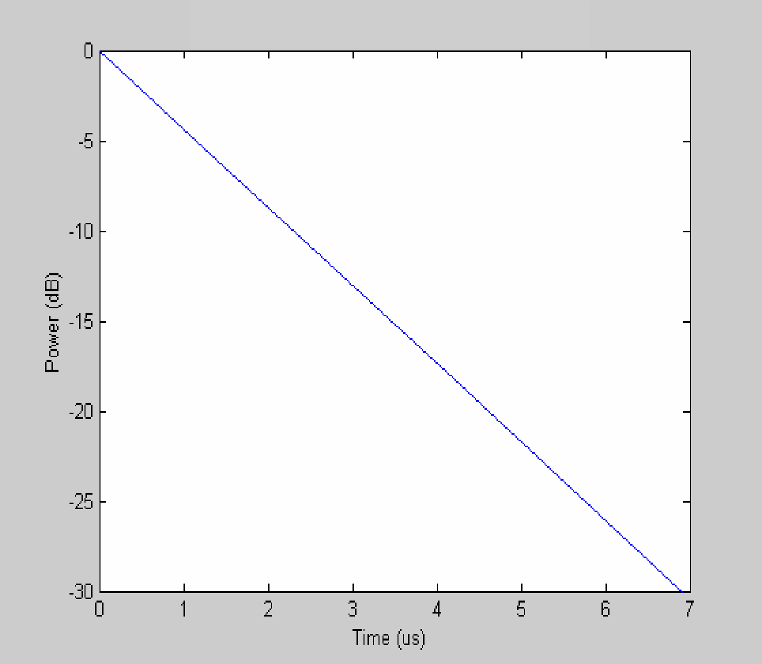

Figure 13. Exponential power delay profile.

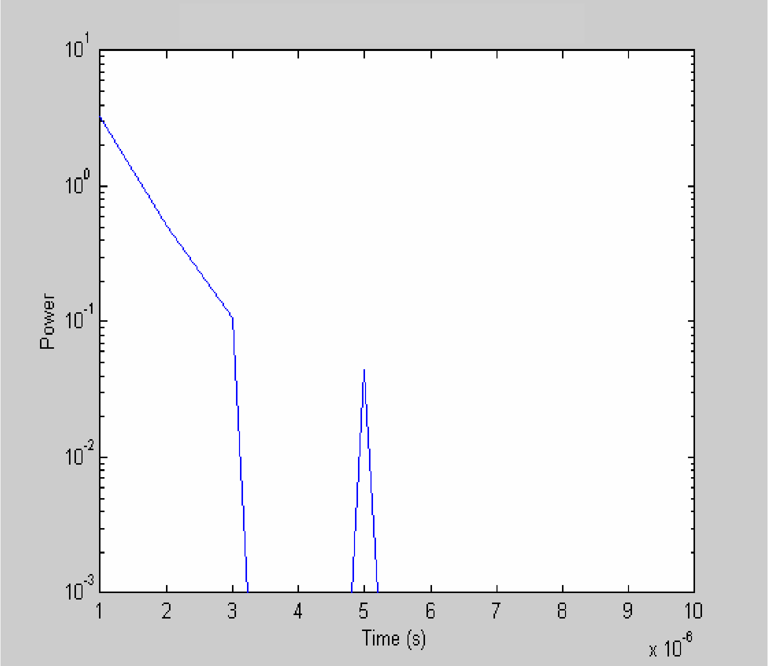

Figure 14. Power delay profile used in GSM Rec. 05.05.

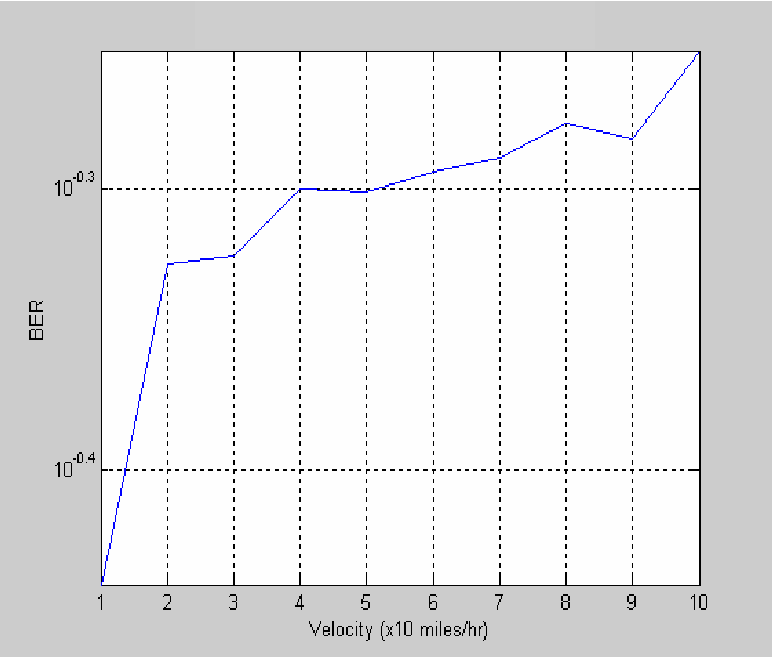

Figure 15. BER of two-tap TDL channel model under increasing velocity.

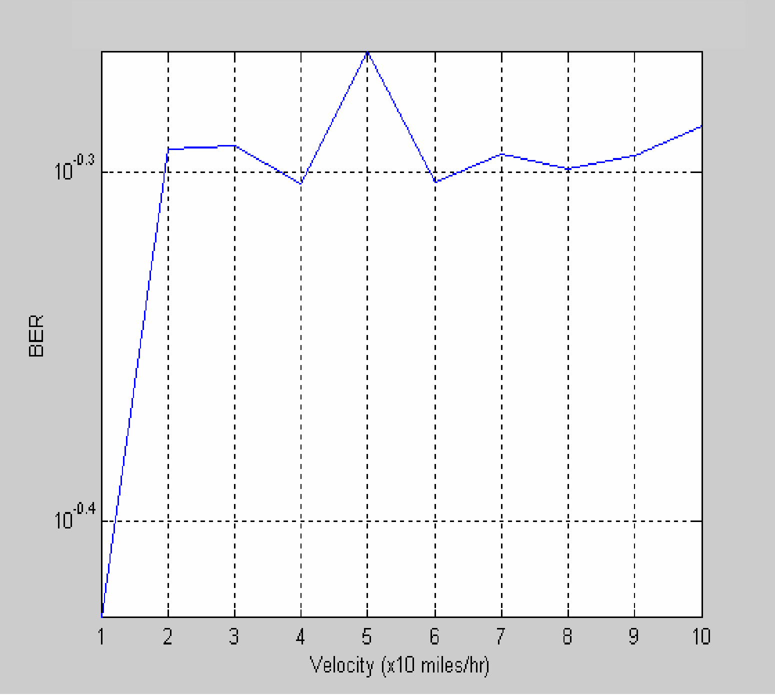

Figure 16. BER of 12-tap TDL channel model using GSM Rec. 05.05 under increasing velocity.

B. PERFORMANCE MEASUREMENTS WITH MICAZ MOTES

Performance measurements were conducted for a group of Micaz motes to study and investigate the effects of interference and co-existence between IEEE 802.15.4 ZigBee and IEEE 802.11 WLAN networks operating within the 2.4-GHz ISM band. The transmission range profiles for the Micaz motes were also measured and characterized when they were configured to three different power transmission levels.

1. Experimental Setup and Approach

The experimental setup for the interference study consists of two networks; IEEE 802.11b and IEEE 802.15.4 networks that have been setup in close operating proximity. The IEEE 802.11b network consists of two laptops (equipped with IEEE 802.11b WLAN cards) that are connected together wirelessly via the ad-hoc connection mode and it was being used as the interference source in the experiment. The two laptops were positioned at a distance of five meters apart.

The IEEE 802.15.4 network consists of a group of four Micaz motes that had been configured to form a small scale wireless sensor network. The Micaz motes were configured to the maximum transmit power of 0 dBm and one of the Micaz motes (Node 0) was configured as the central base station (sink) to log sensor data from the network. Two of the Micaz motes (Nodes 1 and 2) were positioned less than 10 meters away while one of the Micaz mote (Node 3) was deliberately positioned further away at 10 meters. The rationale for positioning these Micaz motes at different distances from the base station is to study the effects of interference on the hop or link distance between the wireless sensors.

Each of these Micaz motes was placed on a plastic chair at about 0.5 meters above the ground and they were positioned at three different locations as shown in Figure 17. There was line of sight between the four Micaz motes and the two laptops, and all the measurements were taken in a residential outdoor urban environment where there are no huge obstacles (e.g., tall buildings or trees) within the paths of the two networks. The distance of the interference source (Laptops 1 and 2) to the nearest Micaz mote (Node 2) is about three meters and the distance to the furthest Micaz mote (Node 3) is about 15 meters. Figure 17 shows the experimental setup of the IEEE 802.11b WLAN and IEEE 802.15.4 Micaz networks with the representative distances between the various devices.

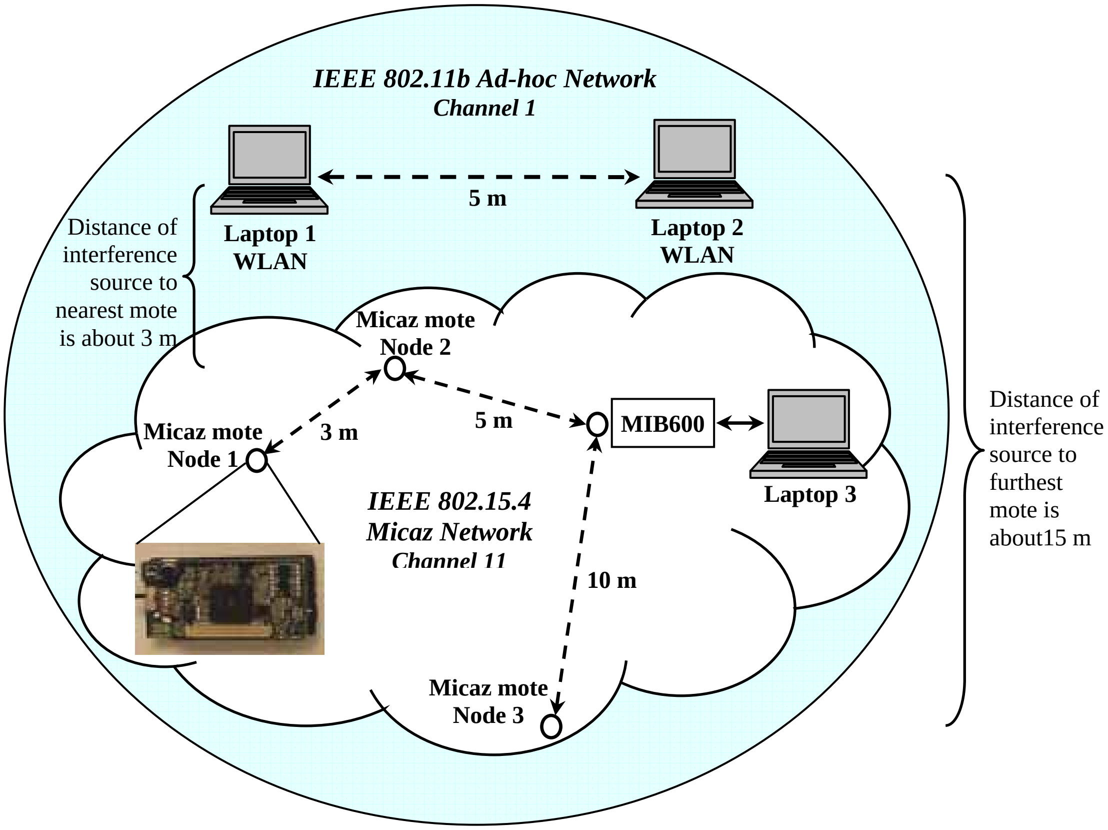

Figure 17. Experimental setup of IEEE 802.11b WLAN and IEEE 802.15.4 Micaz networks.

The Micaz mote that was used in the experiment is a 2.4-GHz, IEEE 802.15.4 ZigBee compliant module that is used for enabling low-power, wireless sensor networks and it is part of Crossbow’s MICA family of wireless sensor networking products. The Micaz mote is equipped with an IEEE 802.15.4 ZigBee compliant RF transceiver (Chipcon CC2420), operates on TinyOS software, supports a data rate of up to 250 kbps, and it uses direct sequence spread spectrum radio communications [40].

The Micaz mote can be powered in two ways, either by battery or by an external power supply (via an external connector). The Micaz mote that was used in the experiment is powered by two AA alkaline batteries and any battery combination (e.g., AAA, C, D, cells, etc) can be used provided that the output voltage falls within the recommended operating range of between 2.7 VDC to 3.6 VDC. The Micaz mote (Node 0) that had been designated as the central base station (sink) is connected to an Ethernet interface card via the Crossbow's MIB600 card, which in turn is connected to a laptop (Laptop 3) where the sensor topology and data statistics are logged.

The operating frequencies for the two networks were chosen such that they fall within the same ISM band. In the case of the IEEE 802.11b network, the two laptops were configured using channel 1 (2.401-2.423 GHz) and the IEEE 802.15.4 Micaz network was configured using channel 11 (2.405 GHz). Table 4 shows the channel assignments for both the IEEE 802.11b and IEEE 802.15.4 in the 2.4 GHz ISM band. There are a total of 11 channels in the IEEE 802.11b standard and each channel occupies a bandwidth of 22 MHz and for the IEEE 802.15.4 standard, there are a total of 16 channels and each channel occupies a bandwidth of 2 MHz. The frequency range for one IEEE 802.11b channel overlaps with four channels in the IEEE 802.15.4 standard. For example, channel 1 of IEEE 802.11b has the frequency range from 2.401 MHz to 2.423 MHz, which overlaps with channels 11, 12, 13 and 14 of IEEE 802.15.4 standard.

2.4 GHz ISM Band				**Remarks**
IEEE 802.11b		**IEEE 802.15.4**		
Channel (22 MHz)	**Frequency (GHz)**	**Channel (2 MHz)**	**Frequency (GHz)**	
1	2.401-2.423	11	2.405	Overlapping
2	2.404-2.428	12	2.410	
3	2.411-2.433	13	2.415	
4	2.416-2.438	14	2.420	
5	2.421-2.443	15	2.425	
6	2.426-2.448	16	2.430	
7	2.431-2.453	17	2.435	
8	2.436-2.458	18	2.440	
9	2.441-2.463	19	2.445	
10	2.446-2.468	20	2.450	
11	2.451-2.473	21	2.455	
		22	2.460	
		23	2.465	
		24	2.470	
		25	2.475	Ch.25 non-overlapping
		26	2.480	Ch.26 non-overlapping

Table 4. IEEE 802.15.4 and IEEE 802.11b channel assignments within the 2.4 GHz ISM frequency band.

Measurement readings of the packet received rate for the IEEE 802.15.4 Micaz network were taken over a period of 60 minutes. The Micaz network was established for the first 20 minutes and during that period there is no interference source within the vicinity of the Micaz motes. For the next 20 minutes, a file transfer operation was being performed between the two laptops to emulate as an active interferer within the vicinity of the Micaz network. Finally, for the last 20 minutes, the ad-hoc connection between the two laptops was disconnected and the Micaz motes were allowed to operate normally without any interference from the surrounding.

The transmission range of a wireless sensor is influenced by several factors, such as transmit power, receiver sensitivity, data rate, antenna gains and efficiency. To increase the effective range and coverage of a wireless sensor, one of the commonly used method is to simply increase the transmit power level. To characterize and measure the maximum allowable distance that the Micaz motes are able to operate, the motes were configured to three different power transmission levels at 0 dBm, -5 dBm, and -25 dBm and the corresponding achieved distance and link quality were measured. The Micaz motes can be configured to operate in six different power transmission levels. Table 5 shows the six different power levels and the corresponding current consumption. The maximum allowable transmit power that can be configured is 0 dBm and the lowest possible transmit power is at -25 dBm.

Levels	Power Level Rating	Current Consumption	Remarks
1	0 dBm	17.4 mA	Maximum (1 mW)
2	-3 dBm	16 mA	
3	-5 dBm	14 mA	
4	-10 dBm	11 mA	
5	-15 dBm	9.9 mA	
6	-25 dBm	8.5 mA	Minimum

Table 5. Transmit power ratings and current consumption for Micaz motes.

2. Experimental Results and Analysis

Figures 18 and 19 shows two captured snap-shoots of the Micaz network topology when the interference source is being switched on (ad-hoc link connected) and off for a period of 20 minutes. The two figures show the relative positions of the Micaz motes on the IEEE 802.15.4 network and the interference source (Laptops 1 and 2) is not shown in the figures. Statistics of the link quality, packet received rates and prediction levels for the Micaz motes can be seen next to the displayed nodes. Figure 20 shows the compiled result of the packet received rate for the three Micaz motes over a period of 60 minutes. It was observed that there is a reduction of about 23% in the packet received rate (i.e. packets lost) when the interference source is switched on for node 3 whereas nodes 1 and 2 remains unaffected by the interference. As nodes 1 and 2 are positioned much closer (< 10 meters) to the base station and were configured to the maximum transmit power, the effect of interference from the IEEE 802.11b laptops does not affect much on the measured link quality between the two Micaz motes and the base station. However, this is not true for node 3 as it is located further away (at 10 meters) from the base station and even though it was also configured with the same maximum transmit power setting.

Hence, we can deduce that for WSNs that have long hop links between any two sensors, the effect of interference will degrade the link quality and substantially reduce the success rate of packets received much more than shorter hop links and it would be more desirable to have shorter hop links between sensor nodes (e.g., in a multi-hop manner) to establish a connection back to the base station. Similarly, we would also expect the effect of loss packets and poorer link quality to be more serious and will degrade the performance of WSNs that are under the influence of interference if the Micaz motes were configured to operate with a lower transmit power setting.

The operational range profiles when the Micaz motes were configured to three different power transmission levels was also investigated. As expected, the transmission range increases with a higher transmit power. At the maximum transmit power of 0 dBm, the achievable transmission range is approximately about 60 to 65 meters. While at the minimum transmit power, the maximum achievable distance is approximately about 30 meters. Figure 21 shows the transmission ranges for the three different transmit power level ratings for the Micaz motes configured at 0 dBm, -5 dBm and -25 dBm. The experiments for the transmission range profiles were conducted in the same environmental setting as the interference measurements.

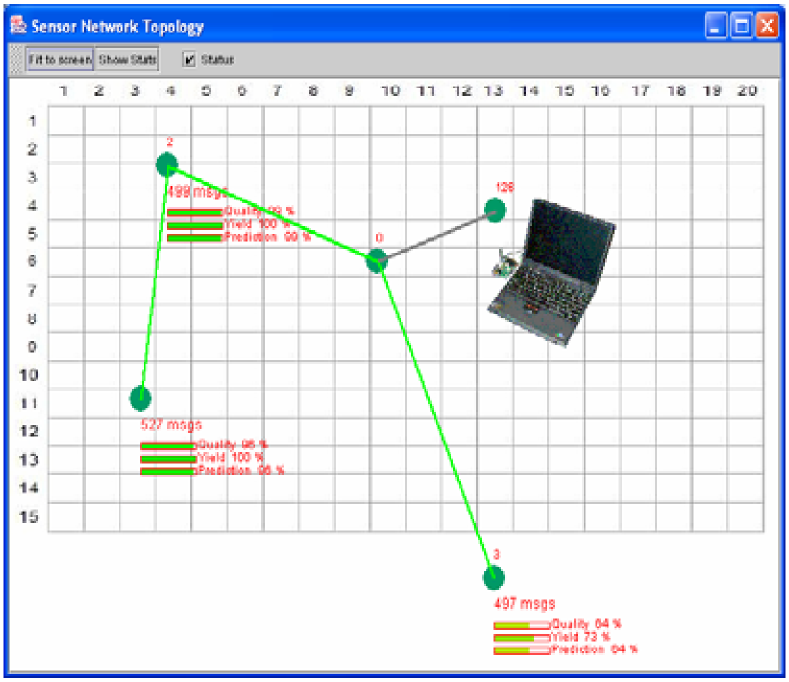

Figure 18. Micaz network topology (with interference switched on).

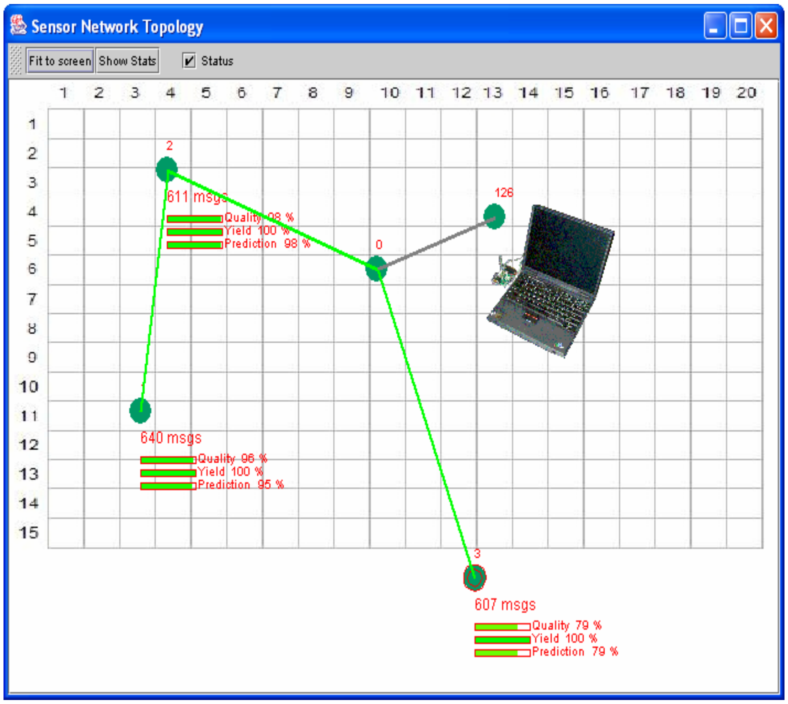

Figure 19. Micaz network topology (with interference switched off).

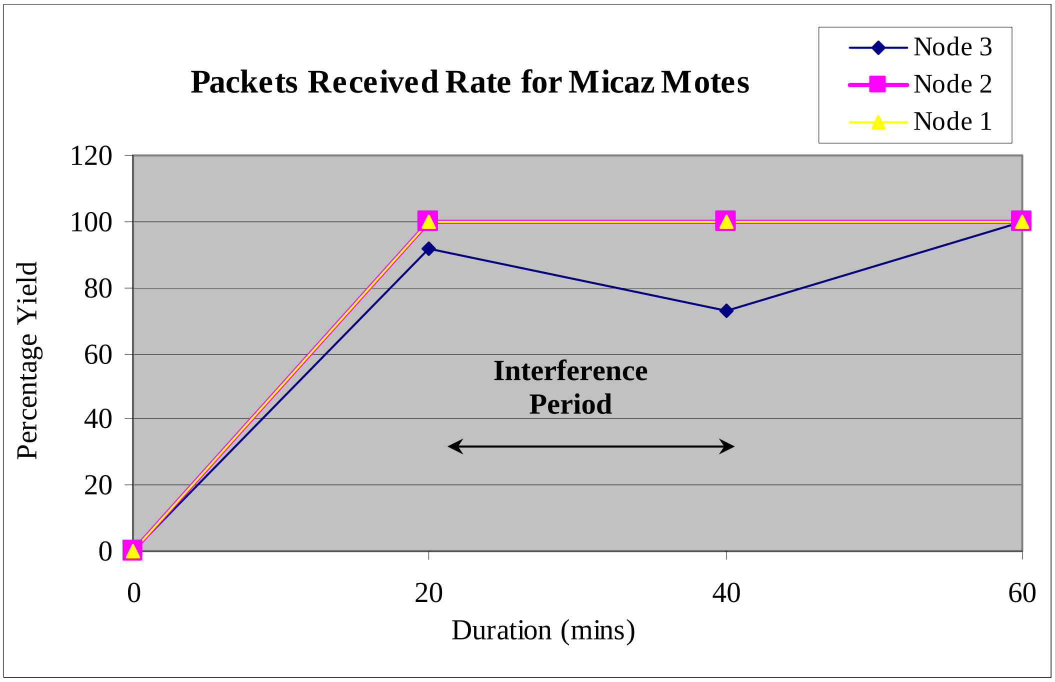

Figure 20. Packets received rate for the IEEE 802.15.4 Micaz network.

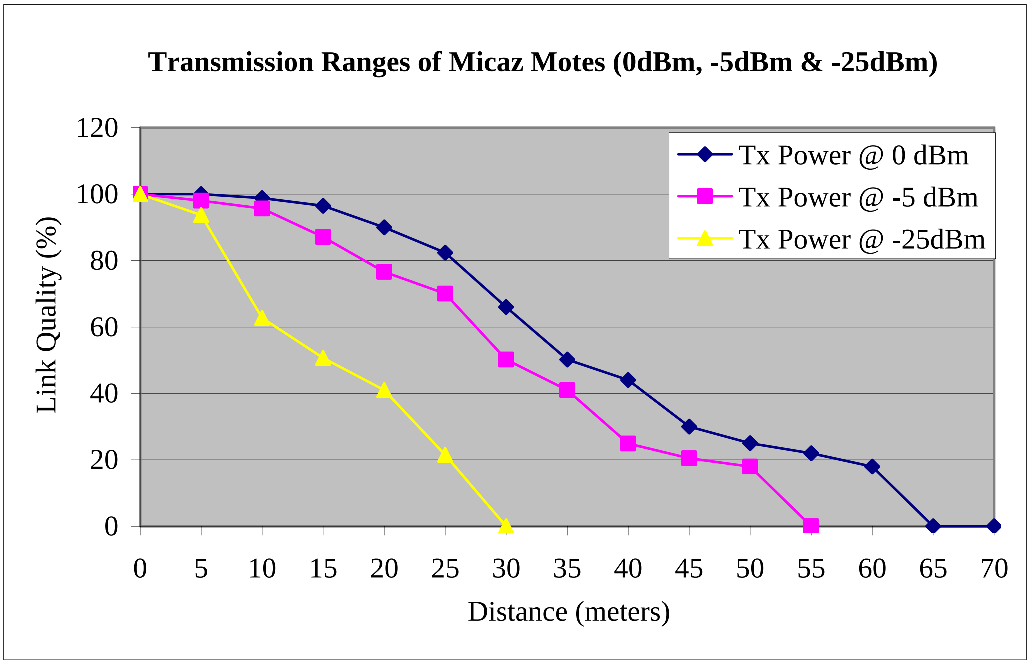

Figure 21. Transmission ranges of Micaz motes at 0 dBm, -5 dBm and -25 dBm.

In order to provide a satisfactory level of performance for the Micaz network, a shorter operating range is recommended based on the measured results of the transmission range for the three different power transmission levels. This is because the link quality and packets received rate for the Micaz motes may fluctuate and can be affected by the movement of scatterers (e.g., people walking, moving vehicles, etc) within the transmission radius, and there may also be potential interferences from IEEE 802.11 devices. These external disturbances will more likely degrade the link quality and cause transmitted packets to be lost for the Micaz network and the recommended operating range is provided in order to maintain a minimum level of network and link connectivity.

The recommended operating range for the Micaz motes when configured to the maximum power transmit level of 0 dBm is about 40 meters, for the -5 dBm transmit power level setting, the recommended range of operation is about 30 meters, and for the minimum transmit power level setting at -25 dBm, the recommended range of operation would be less than 15 meters in order to achieve a link quality of at least 50%.

From the measurement results, it clearly evident that there are possible interferences while operating within the 2.4 GHz ISM band. In the co-existence of IEEE 802.15.4 and IEEE 802.11b, the main concern is the performance degradation of IEEE 802.1.5.4 devices caused by the interference from IEEE 802.11b devices. A measurement study reported that over 92% of the IEEE 802.15.4 frames were lost due to the interference caused by IEEE 802.11b [41]. It would be expected that the interference from IEEE 802.11b devices to affect IEEE 802.15.4 devices more than it would be for the IEEE 802.15.4 device to affect the IEEE 802.11b systems. As the bandwidth of the IEEE 802.15.4 channel is much smaller as compared to IEEE 802.11b, the RF signals from the IEEE 802.15.4 channels would appear as narrow band interference, which can be sufficiently suppressed by IEEE 802.11b system that uses spread spectrum technology.

It is possible to configure and operate the Micaz motes at the maximum transmit power level in order to mitigate some of the potential interference effects but there would be a trade-off in terms of the energy efficiency and lifetime operations of the wireless sensors. The lifetime operations of the Micaz motes is determined by many factors such as the current consumption of its subsystems such as the micro-controller unit (ATMega128L), radio unit (Chipcon CC2420) logger memory (Atmel AT45DB041), sensor boards (e.g., MTS300CA), and also the various mode of operations (e.g., full, sleep or receive modes).

In the case of the radio unit requirements, the different transmit powers will draw different amount of current from the batteries, for example, if the Micaz motes are configured to operate at the maximum transmit power of 0 dBm (i.e., current consumption of 17.4 mA), it will consume twice the current consumption when it is configured to operate at the lowest transmit power of -25 dBm (i.e., current consumption of 8.5 mA). It is obvious that with operations at a higher transmit power, it is possible to achieve a longer transmission range and gain better performance (to mitigate against the interference effects) but we will get a reduced operational lifespan for the Micaz motes. In some cases where the battery voltage drops below the recommended level of 2.7 VDC, the Micaz motes may not function and operate well to support its operations as the capacity and lifespan of the batteries are reduced. As there are many different types of batteries with different capacities, careful planning and selection of the batteries should be taken in consideration in order to match the energy requirements of the Micaz motes and their required operational lifespan.

In environment in which frequent interferences from IEEE 802.11b networks are expected, it will not be possible to remove all the potential interferences caused by the IEEE 802.11b devices, the best alternative solution would be to shift and reconfigure the wireless sensors to operate in the two unaffected channels (channels 25 and 26) that are non-overlapping with the IEEE 802.11b frequency spectrum to avoid any potential interferences.

The interference problem may also manifest itself as a tool that can be exploited for use as a jamming application if it is used in the military context. For example, a denial of service (DOS) attack could be triggered by means of a transmitting a strong radio interference jamming tone at the central frequencies of all the IEEE 802.15.4 channels.

C. CROSS-LAYER OPTIMIZATION APPROACHES USING OA

The insights gained from the simulations of the TDL model and performance measurements of the Micaz motes can help to facilitate the design and development of the OA. For example, mobility issues in WSNs can cause serious degradation in BER performance for a wireless sensor. By incorporating the use of the OA as a core repository for the exchange of essential information across the protocol layers, the OA can be used to trigger an increase in transmit power to overcome the effects of mobility or channel impairments due to fading when it detects a degradation in BER. Alternatively, it can also reduce the transmit power to conserve energy to prolong its lifetime operations in the absence of mobility or channel fading.

In a similar manner, the OA can also be used to provide the feedback mechanism required in adaptive modulation and coding techniques to improve the performance in WSNs by adapting the transmit power, coding rate or data rate transmissions to suit a specific application. For example, for low bandwidth applications such as the transmission of regular temperature updates from a remote monitoring site, the data rate transmissions can be configured for the lowest data rate (i.e. update only when required or when there are changes) such that the lifetime of the sensor nodes could also be prolonged. On the other hand for applications that may require a higher data rate such as live streaming, motion detection, video broadcast, the data rate can be adjusted to provide the maximum throughput for the network.

The interference problem within the 2.4-GHz ISM band prevents IEEE 802.15.4 networks from operating at its maximal performance level and the network performance is often degraded under the influence of interference. The OA can be used to provide a means of measuring or updating the link quality and received packet success rates for the network by extracting the key information from the physical layer such that provisions can be made to reconfigure the wireless sensors to either one of the two unaffected channels (channels 25 and 26) when it senses that there are potential interference within its operating vicinity. However, such a technique might require a change in the existing physical layer modulation scheme of the IEEE 802.15.4 from DSSS to support FHSS instead or to use UWB modulation techniques.

The OA can also be used to provide QoS provisioning for different types of traffic. This can be done by tagging different priority traffic with different transmit power levels, for example, a high priority traffic (e.g., urgent control messages) that needs to be transmitted can be tagged with the maximum transmit power while a normal traffic of lower priority can be tagged to be transmitted with a lower transmit power level. This can help to ensure that critical information and different priority traffic gets transmitted across the network as and when required.

Hence, the insights gained from our study can be used to design and develop the OA and by suitably incorporating performance related inputs from the study of WSNs, it is possible to design and create a flexible and adaptive framework which can be employed in any design methodology that brings about potential benefits to improve and optimize the performance not just in the area of WSNs but also across other domains as well.

D. SUMMARY

This chapter summarizes the results of the TDL models that were used to simulate the effects of the wireless channel impairments due to mobility and multipath fading. Performance measurements for the study of interference between IEEE 802.15.4 and IEEE 802.11b networks and the transmission ranges for a Micaz mote were also conducted. From the TDL simulation results, we observed that there is a general trend in the degradation of BER performance under fading and mobility. Potential interference exists within the 2.4-GHz ISM band and the interference impact will affect IEEE 802.15.4 networks more than it would affect IEEE 802.11b networks. The maximum transmission ranges for the Micaz motes were also determined when the Micaz motes were configured to three different transmit power levels.

V. CONCLUSIONS

Cross-layer design is strongly recommended as a new methodology for designing and optimizing the performance for future wireless networks because of the many possible benefits it could bring. The goal of this thesis was to develop a framework for the study of cross-layer design and optimization. Such a framework not only can be used in the context of WSNs, but it can also be adapted and applied across different domains of wireless networks. To meet this goal, a generic cross-layer framework and the concept of utilizing the OA to improve and optimize the performance of a wireless system was proposed.

Before designing the OA and developing the cross-layer framework, it would be necessary to understand the characteristics and performance at each protocol layer and how they react with each other. In this thesis, to provide insights and guidelines that could be used in the design and development of the OA, we proceed to investigate the performance at the physical layer and how the effects wireless channel could affect the performance of a WSN. It is of fundamental importance to understand the performance at the lower layers (i.e., wireless channel and physical layer) as the resulting responses are cascaded up and will affect the performance of the higher layers.

A tap delay line (TDL) model was developed and the simulation was performed in MATLAB to study the performance of a system (e.g., a wireless sensor) under the influence of multipath fading and mobility. Performance measurements were conducted for a group of Micaz motes to study and investigate the effects of interference and co-existence between IEEE 802.15.4 ZigBee and IEEE 802.11b WLAN networks operating within the 2.4 GHz ISM band. The transmission range profiles for the Micaz motes were also measured and characterized when they were configured to three different power transmission levels.

A. SUMMARY OF RESULTS

Simulations of the BER performance for the two-tap TDL channel model and 12-tap TDL channel model using GSM Rec. 05.05 were performed and it was observed that there was a degradation in BER performance as the velocity increased and the performance of the system started to deteriorate rapidly when the velocity was increased from 10 mph and above due to the effects of mobility and impairments caused by the wireless channel. In the performance measurement study, the effects of interference were observed as there was a reduction of about 23% in the packet received rate (i.e., packets lost) for the Micaz mote that is positioned at 10 meters away from the base station when there is a nearby interfering source (e.g., IEEE 802.11b device).

The transmission range profiles for three different transmit power levels were also measured to determine the effective operating distance that the Micaz motes could support. At the maximum transmit power of 0 dBm, the achievable transmission range was approximately about 60 to 65 meters. To achieve a link quality of at least 50%, the recommended operating range for the Micaz motes configured to the maximum power transmit level of 0 dBm is about 40 meters; for the -5 dBm transmit power level setting, the recommended range of operation is about 30 meters; and for the minimum transmit power level setting at -25 dBm, the recommended range of operation would be less than 15 meters.

Several useful insights were developed and envisioned on how the optimization agent could be used, designed and further developed to fit into the proposed cross-layer optimization framework to improve and maximize the performance in a WSN.

B. RECOMMENDATIONS FOR FUTURE WORK

The investigations, performance measurements, and analysis work considered so far in this thesis mainly focused on issues at the physical layer and there are still many possible research areas that can be explored in the domain of WSNs. One possible area is to study the performance at the MAC and network layers by looking at the interactions between MAC protocols and network routing issues in WSNs. For example, simulations can be performed using TOSSIM, which is a simulator for TinyOS wireless sensor networks to investigate the MAC interactions, routing protocols, and reconfiguration issues in WSNs. Insights gained from the proposed study can also be used to design and develop a more robust OA to enhance the overall performance in a WSN.

Another possible area for future work is to develop and implement the OA in software. For example, the OA can be written in NesC programming language and implemented on TinyOS platform. As the Micaz motes are supported on TinyOS, performance analysis and the benefits from the implementation of our proposed cross-layer framework can be validated by configuring and implementing the OA onto the Micaz motes.

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