DECLARATION

I hereby declare that the work is being presented in the dissertation work entitled "**PERFORMANCE EVALUATION OF WBAN USING CROSS LAYER APPROACH**" towards the partial fulfillment of the requirement for the award of the degree of **Integrated Dual Degree in Electronics and Communication Engineering (with specialization in Wireless Communication)** submitted to the **Department of Electronics and Computer Engineering, Indian Institute of Technology Roorkee, India** is an authentic record of my own work carried out during the period from May, 2009 to June, 2010 under the guidance and provision of **Mr. S. CHAKRAVORTY, Assistant Professor, Department of Electronics and Computer Engineering, IIT Roorkee**.

I have not submitted the matter embodied in this dissertation work for the award of any other degree and diploma.

Date: June, 2010

Place: Roorkee **(SARTHAK GROVER)**

CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge and belief.

Date: June, 2010

Place: Roorkee

Mr. S. CHAKRAVORTY

Assistant professor, E&C Department

IIT Roorkee

Roorkee – 247667 (India)

ACKNOWLEDGEMENT

First of all I would like to thank God for everything, as abstract as that might sound.

I consider it too formal to express thanks to my family and my friend whom I love dearly.

I would like to express my appreciation to all my friends without whom I could not have completed my work. I thank Prince and TJ for Chai Paani with DuDes, the Krows for giving me company when I was hungry, and the Ganga inmates for their numerous phone calls!

Finally, I would like to take this opportunity to extend my heartfelt gratitude to my guide and mentor, Mr. S. Chakravorty, for his precious time and assistance throughout this dissertation work. I thank him for his trust in my work, inspirational support, and critical comments. My experience during the course of this study has helped me improve my outlook in life. I would also like to thank all the faculty members of the Department of Electronics and Computer Engineering for their constant motivation and encouragement, and providing facilities for work.

SARTHAK GROVER

ABSTRACT

Wireless Body Area Network (WBAN) is a new and versatile field with a lot of scope for research and development. The BAN topology consists of two levels of network hierarchy – the intra BAN, or on-body network, and the extra BAN, or off-body network. In this thesis we present a thorough performance evaluation of the complete BAN architecture. This performance can be measured by the throughput and the energy consumption. Both these metrics are impacted immensely by medium access control schemes.

Our work can be divided into two parts based on the network level we are working on. Firstly, the intra BAN is considered and the human body channel is modeled. Then a fixed network topology is simulated and energy consumption as well as throughput efficiency is evaluated with respect to the various MAC schemes. Based on our results, a hybrid network topology is simulated to define the node configuration of intra BAN.

Secondly, the extra BAN is simulated in a Rayleigh fading environment. A cross layer approach is applied to this network integrate the MAC and PHY layers of IEEE 802.11 protocol and to utilize the predictability of Rayleigh channels. Thus unobtrusive transmitter nodes can be employed to monitor mobile users, and the implementation of cross layer modified 802.11 protocol further improves their throughput performance and energy efficiency.

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1 INTRODUCTION

1.1 Body Area Networks

Recent advancements in electronics have enabled the development of small and intelligent (bio-) sensors which can be attached to or implanted into the human body. At the same time, the use and knowledge of wireless networks becomes more and more widespread as a growing number of devices are becoming capable of communicating wirelessly. The combination of these two evolutions, which equip the sensors placed on and inside the body with a wireless interface, paves the way for a new type of network: a Body Area Network or BAN [1]. Wang and Pie define a BAN as a wireless network connecting independent nodes (e.g. data spectacles, medical devices, earphones, microphones, sensors, effectors/actuators) attached to the body surface, implanted into tissues/body, or dispersed in the clothing for applications in home/health care, sports, entertainment, defense, ambient intelligence, pervasive computing and many other fields [2]. When referring to a Wireless Body Area Network (WBAN) where each node comprises of a sensing unit, some researchers use the name Body Area Sensor Network (BASN) or in short Body Sensor Network (BSN) instead of BAN. These networks are very similar to each other and share the same challenges and properties. In the following, we will use the term BAN or WBAN, which is also the one used by the IEEE.

1.1.1 Background and Motivation

Technological progress in low-power integrated circuits, ultra low-power RF (radio frequency) technology, wireless communications, integrated biosensor/microsensor, and energy scavenging and storage have enabled the design of low-cost, miniature, lightweight, intelligent devices, sensors and networking platforms that make the concept of truly pervasive body area networks a reality. These devices communicate by means of a wireless network and interaction with the user or other persons is generally handled by a central node in the network.

Although the technologies as well as the development of BANs can be traced back to several decades, the recent boom of BANs followed years of research and development in wireless sensor networks (WSNs) [3]. The applications of general WSNs can be categorized into: (1)

monitoring environments, (2) monitoring objects, and (3) enabling the interaction of objects with environments. A BAN, in many respects, is a type of wireless sensor network, but specifically tackles the challenges associated with human body monitoring as well as the interaction of human and human body with environments, in addition to dealing with challenges faced by general WSNs. Body Area Networks can be seen as a subclass of WSNs, with specific constraints, in terms of available memory, bandwidth, computational power, and embedded energy. Depending on the application of a BAN, additional requirements may be added. The challenges faced by a BAN are unique due to human body's complicated internal environment and the characteristics of human body that responds to and interacts with the external surroundings.

A basic requirement of any Body Area Network is the need of sensors on the human body connected to a central transmitting device which transmits to a larger network such as the base station at the hospital, or a local computer etc. Each sensor monitoring the body continuously measures parameters of interest and sends the data in short bursts to a central node, which acts as a gateway to the external network [4]. In figure 1.1 (a) a WBAN is depicted on a human body and through a personal digital assistant (PDA), acting as a gateway, the WBAN could communicate for example with an AP of a WLAN. But the WBAN could also be connected to a mobile phone, which is a direct link to a WWAN as in figure 1 (b).

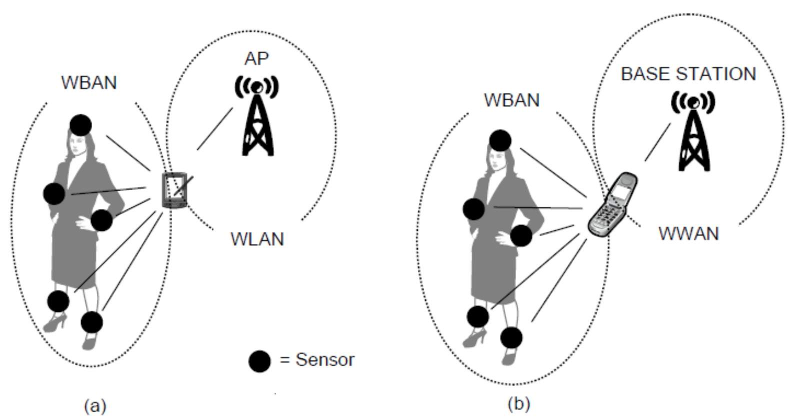


Fig. 1.1: Two different gateways for a WBAN: (a) connected to WLAN, (b) connected to WWAN

Up to date there is no standard specifically intended for WBANs. IEEE chartered a new sub-working group within 802.15 to bring a WBAN standard forward in November 2007 [5]. The IEEE 802.15 Task Group 6 (BAN) is developing a communication standard optimized for low power devices and operation on, in or around the human body (but not limited to humans) to serve a variety of applications including medical, consumer electronics/personal entertainment and others. Many authors suggest the use of low-power consuming MAC protocols, and propose designs based on them for propagation on the human body [6], [7]. As for the external network, works such as [8] propose adjusting transmit power or transmit rate for data packets based on several factors such as wireless channel conditions.

1.1.2 Challenges

BANs have some distinctive characteristics and requirements which make them different from other wireless sensor networks. The following section discusses the major requirements and challenges faced by Body Area Networks:

1. **Wearability**: A majority of existing monitoring devices have large form factors (about the size of a mobile phone) and require to be fitted on people using neoprene pouches and Velcro straps (causing activity restriction or behavior modification). The current requirement is of a device with a small form factor and light weight to be well-suited to unobtrusive monitoring [9]. But an ultra-low power design of the device, operating on a miniature battery, restricts the radio range considerably. Thus either a user must remain near the base station at all times, or data may need to be relayed through other users, which costs precious energy. A communication protocols which balances the requirements of energy efficiency and real-time data delivery is needed.

2. **Minimum Electromagnetic Pollution**: Due to the network's proximity to the human body, electromagnetic pollution should be extremely low. So a BAN requires that every node transmits at an extremely low power for invasive (implanted in body) as well as non-invasive (not implanted in body) networks. The specific absorption rate (SAR) is an important parameter when talking about the exposure of the human body to electromagnetic fields and it measures how much energy that the human body absorbs every second per unit weight (W/kg). The absorption rate decreases when the sending unit is further away from the body. The output power of the sending unit must be regulated so the different SAR values are not exceeded [4].

3. **Power consumption and conservation**: Power management of the low powered monitoring devices with diversity in the range of functionality and computing capabilities used for signal transmission poses a challenge in providing reliable monitoring solutions. The energy resources and consequently the computational power and available memory of such devices will be limited due to their low size [8].

4. **Interference**: The network consists of numerous devices in and on the body which are in each other's vicinity [8]. In order to minimize the heating of the surrounding tissue and the interference between the devices, a low transmit power is required.

5. **Transceiver considerations**: From a power consumption perspective high data rate is often preferable, since involved transceivers should be in active mode for as short time period as possible [6]. There also exists a tradeoff between the range (sensitivity), data rate, and modulation scheme (complexity of the transceiver).

6. **Monitoring and transmission**: Monitoring can be continuous, alert driven (on the detection of an abnormal event) or periodic (at fixed times in a day), depending on the application [4].

7. **Real-time performance**: On-the-fly monitoring requires that the data be available to base-stations in real-time [9]. Existing protocols for real-time delivery in ad-hoc networks are not able to satisfy the constraints of WBAN.

8. **Extreme mobility and rapidly changing topology**: Existing proactive or reactive protocols are not suited for a highly dynamic topology due to the short radio range and the high speeds at which users move [4]. Routing protocols need to handle extreme variability in network topology.

9. **Reasonable time in message delivery**: Any delay in message delivery can have bad consequences, especially in case of medical applications of WBANs. The priority of transmitted message (emergency or routine) can be used to determine the routing of messages by a network to reduce delays to achieve minimum delay in end to end message delivery [6].

10. **Frequency bands and regulations**: All radio transmission is regulated by the government within each country [4]. There exist more non-licensed frequency bands at higher frequencies, but these are of limited practical use at the moment and some of these non-licensed frequencies are assigned to specific applications. All constraints must be met while adhering to the norms.

11. **Scalability**: All networks must scale well in terms of the number of monitored people that can be reliably supported [7].

12. **Heterogeneity**: Finally the devices are often very different and may have very different demands or may require different resources of the network in terms of data rates, power consumption and reliability [7].

1.1.3 Applications

The applications of wireless BANs are enormous including unobtrusive home/health care, drug therapeutic effects study, sports, entertainment, defense, ambient intelligence, pervasive computing and many other areas. The main applications of WBANs have been briefed in this section.

1. **Health Care:** WBAN can be used to offer the automatic medical service through monitoring of living body signal. This requires the exchange of information from sensors on the body, through a gateway to the medical personnel, and then relay of the reply back to the actuators placed on the body. They can be used for diagnostics, drug administration, telemonitoring of human physiological data, etc. Works in the healthcare domain usually consider the human body network to be connected to the hospital network using cell phones and PDAs [10], [11] or wireless broadband [12], thus enabling the patient to be remotely monitored. Major progress has been made in this direction although no protocols have been implemented or developed specifically for health monitoring using WBAN.
2. **Assisted Living:** WBANs can act as an interface for the disabled. Major work is being undertaken to introduce blind people to sensors on the body which collect data and

images of the environment. For example motion sensing by intelligent WBANs may be able to convert hand signals into voice for a person who can't speak [11].

3. **Entertainment and Sports:** Physiological monitoring of athletes during sporting events can maximize player performance while preventing burn-out and injury. Major application of this technology range from providing real-time analysis and referee assist, to streaming AV signals to big screens, sports monitoring [9]. The requirements of such a system are essentially different from those of medical applications as the level of activity is much higher and servers can't be placed such that they interfere with players. From a device perspective the device size, battery capacity and communication range serve as impediments. Whereas the environment under consideration is a rapidly changing topology.
4. **Public Safety:** Apart from the apparent applications of BAN presented previously, more recreational uses include public safety, where it can be used by fire-fighters, policemen, etc. The BAN can monitor the level of toxic substances in the area and warn the fire-fighters if there is threaten for their lives.
5. **Military Uses:** BANs can assist in situational awareness and precision asset location for military, and stress monitoring of fighter pilots in real time during flying missions.
6. Other uses include automation control via body actions, exchange of information by human body contact, entertainment for kids such as learning toys and games and easy control of computer peripherals.

1.1.4 Networking Issue

While BANs can operate stand-alone, their full potential and benefit are realized when the BANs interact with, are interconnected to, and integrated with the external environment. The elements of a BAN collect data from the user, and the data collected by these entities has to be sent to a remote location, where a specialist will view and process them. So this can be considered a distributed system, with on one end the person with the BAN, and in the other end the specialist that receives the collected data (the server) [2]. The complete BAN therefore extends from the human body to the central server as shown in figure 1.2.

The communication process in a BAN can be divided into two simultaneous network levels:

- Intra-BAN Communication (Human Body Network)
- Extra-BAN Communication (Wireless Network between the BANs and the Server)

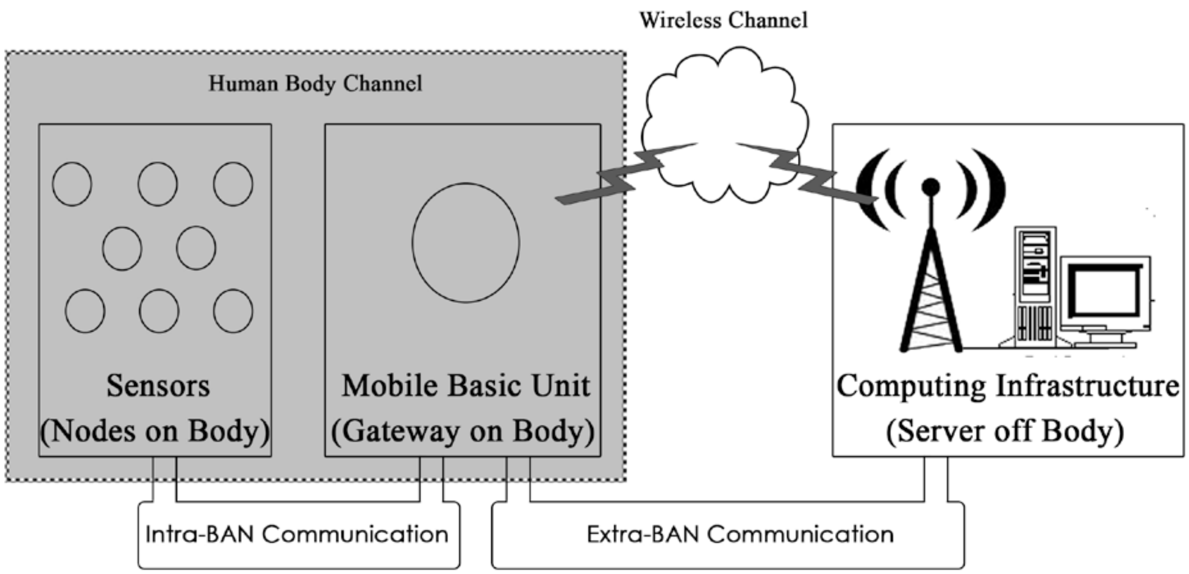


Fig. 1.2: Networking in WBAN

Monitoring of the human body requires communication between entities within a BAN, and is called intra-BAN communication. To use BAN for remote monitoring, external communication with the base station is required which is called extra-BAN communication. The Mobile Basic Unit (MBU) acts as the gateway or server which integrates intra-BAN and extra-BAN services. Many works such as [2], [4], and [10] consider MBUs also have the purpose of making decisions based on the data collected and the communication with the server. In such cases data is collected by sensor nodes, sent to the MBU, and then by the MBU to the server. The server analyzes data and replies to the MBU, which directs actuator nodes to perform a specific task accordingly. The intra-BAN uses the human body channel to communicate whereas the extra-BAN communicates via the wireless channel between users' and the server.

1.1.5 Energy Issue

As mentioned previously, a BAN typically imposes an extremely low transmit power which is necessary to minimize the energy consumption, to minimize the interference and to minimize the heating of the surrounding tissue. The limited available powers in a Wireless BAN make a thorough study of the propagation channel between sensor nodes, both on the human body and between on and off-body nodes, indispensable. Thus new protocols need to be developed which properly take into account the lossy human body, and the environment as well. The study of low-power Medium Access Control (MAC) protocols highlights the most important aspects of developing a novel power-efficient and reliable scheme for a WBAN, which satisfies its stringent requirements.

1.2 Problem Statement

The goal of this thesis is to propose a power efficient scheme that satisfies the stringent requirements imposed by a Body Area Network. Our work is concerned with the communication and networking aspects of BANs at both intra-BAN and extra-BAN levels.

As mentioned previously, the MAC layer plays a very important role with respect to achieving maximum throughput, minimum delay, and to maximizing the network lifetime, by controlling the main sources of energy waste. In order to realize communication between devices forming a non-invasive BAN, techniques from WSNs and ad hoc networks could be used. However, current protocols designed for these networks are not always well suited to support a WBAN. The devices are small, non-redundant, transmit at an extremely low power, and the propagation takes place on the human body. An accurate propagation model is required to characterize the human body channel and a study of the performance of various MAC schemes for a BAN environment is necessary.

Interaction with the user or other persons is usually handled by a gateway or personal device, e.g. a PDA or a smart phone, which acts as a sink for data of the wireless nodes present on the human body. These devices are essentially bulky and obtrusive, and use high power consuming protocols to communicate to the base station via a wireless channel. In order to make this communication more efficient, wireless sensor nodes can be used as a gateway for the user. But under mobile conditions, communication from these nodes undergoes fading, which results in decrease of throughput and waste of energy due to packet drops and subsequent retransmission. A solution to this problem is to predict the channel state before transmission, and pause transmission of data when channel is under fade. This can be achieved using cross layer approach to modify conventional protocols to cater to the energy efficiency and networking issues of BAN with mobile users.

The following studies were undertaken in this dissertation:

- Literature survey of the current developments in BAN and a detailed analysis of the channel and environment associated with on-body and off-body networks.
- Performance evaluation of various MAC protocols for human body network on the basis of throughput and energy efficiency.
- Implementation of cross layer scheme based on the IEEE 802.11 DCF protocol and its performance evaluation under Rayleigh fading environment.

1.3 Thesis Organization

The dissertation thesis comprises of six chapters, including this introduction. The rest of the report is organized into two sections as follows:

Chapter 2 and 3 relate to intra-BAN communication. The former describes the human body channel model and the MAC strategies that could be used for on-body communication. The latter presents the simulation results for intra-BAN and compares the performance of various MAC schemes using NS2 network simulator.

Chapter 4 and 5 relate to extra-BAN communication. Chapter 4 describes introduces the method of cross layer designing and a two state Markov model for Rayleigh fading channel. It examines in detail the cross layer approach based on IEEE 802.11 DCF protocol which could be used to improve the performance of a network under Rayleigh fading. Chapter 5 presents the simulation results, parameters used, and their analysis for the extra-BAN and compares the performance of IEEE 802.11 with and without cross layer design. Finally, chapter 6 summarizes the results of the previous chapters and concludes the thesis with a discussion of future prospects.

2 INTRA BAN COMMUNICATION

A complete body area network consists of two levels: an intra-BAN which involves nodes communicating on the human body, and extra-BAN which refers to the network formed by the gateways of each individual intra-BAN network, and the main server (figure 2.1). This chapter deals with intra-BAN communication for on-body networks.

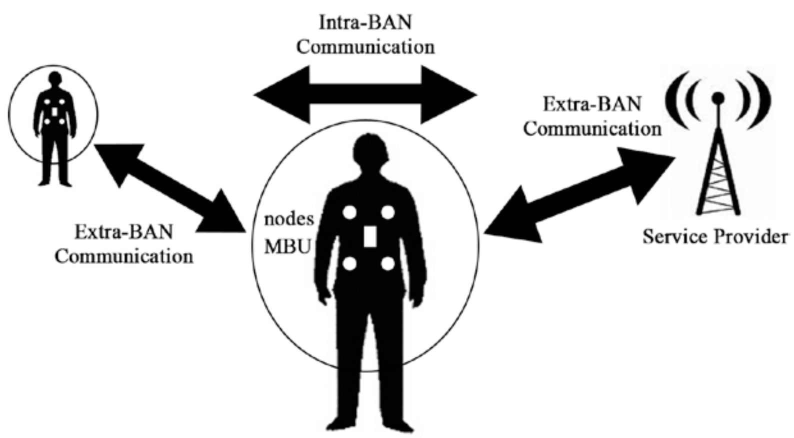


Fig. 2.1: Complete Body Area Network

Intra-BAN communication refers to the internal communication between nodes on a human body. Some applications, such as pacemakers for patients, require that the nodes be implanted within the body under the skin [2]. These are called invasive BANs and require a two-way communication between the implanted medical devices (IMDs) and the central server. Such devices form a very low power system and use the medical implant communication service (MICS) band for transmitting data and supporting diagnostic functions. Transmission in the MICS band lies in the frequency range of 402-405 MHz and it has been observed that propagation characteristics within the human body are conducive at this range. The main issues faced by designers for in-body communication are wireless communication performance, power, low form factor, regulations governing the design of implanted devices, biocompatibility, and so on. Designers can take advantages of the fact that external base stations have fewer restrictions and limitations, and therefore can afford more advanced antennas, electronics, and processing.

A second type of intra-BAN is formed by nodes externally attached directly to the skin surface or clothing [3]. Such networks are called non invasive BANs and are applied to monitor physiological parameters via RF communication between the transmitter worn by the user and a central base station. The sensors are used to measure the temperature, blood pressure, heart rate, ECG, EEG, respiration rate, SpO2-levels etc. Next to sensing devices, a patient may have actuators which act as drug delivery systems. The medicine can be delivered on predetermined moments, triggered by an external source (i.e. a doctor who analyzes the data) or immediately when a sensor notices a problem. One example is the monitoring of the glucose level in the blood of diabetics. If the sensor monitors a sudden drop of glucose, a signal can be sent to the actuator in order to start the injection of insulin. These devices have the advantage of allowing patient movement without tethering the patient to a bedside monitor with a hard-wired connection.

The limited available powers in an intra-BAN make it indispensable to thoroughly study all the possible factors that take part in the communications within a BAN. There are two fields in which research must be carried out to make BANs viable: hardware (HW) components in which need a low cost and low power design, and the network specifications, including the propagation issues of the human body channel and the efficiency of communication protocols, such as Medium Access Control (MAC). In our work, we deal with the networking issues faced in non invasive BANs during communication. This chapter describes first the human body channel observed during communication between nodes, and the propagation models which can be used to best describe it. Then an overview of current advancements at the MAC layer is presented and some suitable strategies are reviewed which can be applied for intra-BAN communication.

2.1 Human Body Channel Model for Intra-BANs

The characteristics of the communication channel are different for a BAN compared to a regular sensor network or an ad-hoc network due to the proximity of the human body. On-body propagation is much different from normal wireless communication. Tests conducted by researchers in the field of medical BANs show a lack of communications between nodes located on the chest and nodes located on the back of the patient [7]. Furthermore, when transmission power is set to minimum for energy saving reasons, link connectivity was observed to be zero. As the devices get smaller and more ubiquitous, a direct connection to the personal device will no longer be possible and more complex network topologies will be needed. But before delving into the study of connectivity on a human body channel, a simple but accurate propagation model is required. In this section, we will discuss the characteristics of the propagation of radio waves in a WBAN and other types of communication.

2.1.1 Propagation in the Human Body Channel

Several researchers have been investigating the path loss along and inside the human body either using narrowband radio signals or Ultra Wide Band (UWB). All of them came to the conclusion that the radio signals experience great losses. Generally in wireless networks, it is known that the transmitted power drops off with d^n where d represents the distance between the sender and the receiver and n the propagation coefficient [13]. In free space n has a value of 2. But propagation of waves on lossy channels such as the human body is affected by other factors such as absorption by tissue, multi path, environment, motion etc [14], [15]. The propagation can be classified according to where it takes place: inside the body or along the body.

The propagation of electromagnetic (EM) waves for invasive BANs has been investigated [7]. The body acts as a communication channel where losses are mainly due to absorption of power in the tissue, which is dissipated as heat. The specific absorption rate (SAR) the parameter used to indicate the loss in power due to heat dissipation. It is concluded that the path loss is very high and that, compared to the free space propagation, an additional 30-35 dB at small distances is noticed. It is argued that considering energy consumption is not enough and that the tissue is sensitive to temperature increase. The radiation pattern is also influenced by the user’s body shape and position.

Most of the devices used in a WBAN however are attached on the body forming a non invasive network. The propagation along the human body can be divided into line of sight (LOS) and non-line of sight (NLOS) situations. In the former, the curvature effects of the body are not taken into account as experiments are done at one side of the body and simulations are performed for a flat topology. In the latter, the effect of propagation from the front of the body to the side or back is evaluated. The channel model for line of sight (LOS) propagation along the human body was studied in [11]. The studies were done for both narrowband and UWB signals. It was found that the path loss exponent n is between 3 and 4, depending on the position of the device. Also the path loss depends on the closeness of the antenna to the body. As the sensors and antennas of a Wireless Body Area Network will be designed to be as small as possible, the antenna will be close to the body which will result in a higher path loss.

In non-line of sight (NLOS) situations, there is no direct view between the sender and receiver. It was observed that EM-waves diffract around the body rather than having a direct path through the body [16]. The study in [17] shows that a higher path loss is observed along the NLOS channel than along the LOS channel, due to diffraction around the human body and absorption of a larger amount of radiation by the body. This is in contrast to previous measurement campaigns in the GHz frequency range where the path loss model was erroneously assumed to be related to the straight-line distance through the body. Authors of [15] performed experiments for UWB signals and found that at higher frequencies the body impermeable by electric field which diffracts around the torso rather than passing through it. The communication along the body was observed to be via creeping waves. Fig 2.2 shows the field view observed around a body.

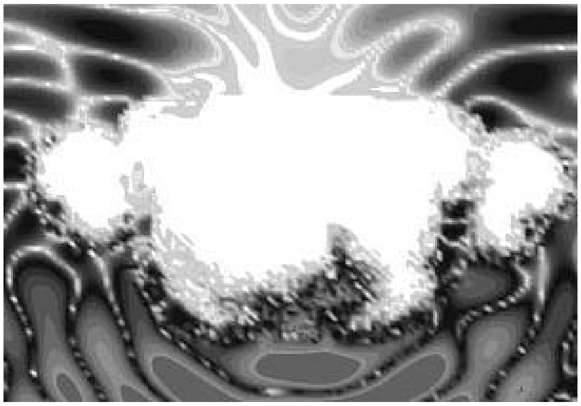


Fig. 2.2: Electric field magnitude around a body slice. The different shades of gray correspond to different field magnitudes: black represents a large magnitude, while lighter colors represent a smaller magnitude. The white area in the center of the diagram is due to the arms and torso. This indicates that very little energy is inside of the body in the GHz range [15]

2.1.2 Channel Models for WBANs

Many channel models have been proposed to accurately model the path loss observed for both invasive and non invasive BANs based on the research done on propagation in a human body channel. A summary of the developed channel models for both intra-BAN and extra-BAN communication is provided in [14], which takes into account losses observed at different positions, environmental factors, motion of limbs, fading etc. In our work we concentrate on non-invasive BANs and briefly summarize the research undertaken in this area.

Unlike traditional wireless communications, the path loss for body area network system (on body applications), is both distance and frequency dependent. The path loss model in dB between the transmitter and the receiver can be on modeled with the following empirical power decay law:

$$PL\ (dB) = PL_0\ (dB) + 10n\ \log(\frac{d}{d_0}) \tag{2.1}$$

where n is the pathloss exponent, d is the distance from the antenna, d_0 is the reference distance, and PL_0 is the path loss at the reference distance. Due to changes in environment surrounding the body or even motion, a shadowing component is added to the total path loss to represent its variation.

$$PL_t(dB) = PL\ (dB) + S, \text{ where } S \sim N(0, \sigma_s) \tag{2.2}$$

Experiments performed for a low frequency range of 13.550 to 13.571 MHz indicated that the body channel exhibits path loss that is nearly similar to free space. Human body can also be used as a communication media over the range of frequencies 5-50MHz. No modulation is needed in this form of communication which is referred to as Human Body Communication (HBC). The channel model for HBC is composed of the frequency response and the noise characteristics. The noise was observed to be Gaussian distributed with a mean and variance values of zero and 2.55×10-5 respectively. Details of the experimentation are provided in [14].

At higher frequency, linear fitting coefficients have been evaluated to model the path loss as $PL\ (dB) = a \log(d) + b + S$, which is similar to eqn. 2.2. Table 2.1 summarizes the parameter values measured at different frequencies. The details of the experiments can be found in [18].

Table 2.1: Parameters for path loss model at different frequencies

	400 MHz	600 MHz	900 MHz	2.4 GHz	3.1-10.6 GHz
a	3	16.7	15.5	8.6	19.2
b	34.6	0.45	5.38	20.3	3.38
σ_s	4.63	5.99	5.35	2.0	4.40

Table 2.2: Channel model parameters for UWB

PDP Model	$h(t) = \sum_{l=0}^{L-1} a_l \exp(j\phi_l)\,\delta(t - t_l)$ $10\log_{10}\lvert a_l\rvert^2 = \begin{cases} 0 & for\ l = 0 \\ \gamma_0 + 10\log_{10}\left(\exp\left(-\frac{t_l}{\Gamma}\right)\right) + S & for\ l \neq 0 \end{cases}$ $p(t_l \mid t_{l-1}) = \lambda \exp\left(-\lambda(t_l - t_{l-1})\right)$ $p(L) = \frac{\bar{L}^L \exp(\bar{L})}{L!}$
a_l	path amplitude for the l-th path
t_l	path arrival time for the l-th path
ϕ_l	phase for the l-th path modeled by uniform distribution over $[0,2\pi)$
L	the number of the arrival paths
$\bar{L}$	the average number of the L
$\delta(t)$	the Dirac function
Γ	an exponential decay with a Rician factor γ_0
S	normal distribution with zero-mean and standard deviation of σ_s
λ	path arrival rate
γ_0	-4.60 dB
Γ	59.7
σ_s	5.02 dB
$1/\lambda$	1.85 ns
$\bar{L}$	38.1

Authors have conducted experiments to extract the parameters of a channel model by measuring the channel transfer function [19]. They report their results for ultra wideband (UWB), the industrial, scientific and medical (ISM) bands, and wireless medical telemetry system (WMTS) bands. In addition a power delay profile (PDP) analysis is also considered for the UWB model. In addition they also consider the effect of node placement by placing nodes on separate parts of the body, such as limbs and torso etc, and measuring the path loss for each situation. Authors of [15] analyze UWB and narrow band communication around the human body by simulating electronic wave propagation model. These results agree with the parameter values presented in [14]. They conclude that the body area channel can be well described by a high path loss exponent and correlated lognormal multipath components. A summary of the derived values for the PDP channel model are provided in table 2.2.

Another factor which affects the strength of the received signal is the movement of the body. It has been shown that arm motions to the front and side of the body can have an impact on the received power [8]. More significant variations are found when the arms are moved so that they block the line of sight between the two antennas. A summary of the path loss parameters derived at different frequencies for user in motion or standing still when nodes are placed on limbs is provided in [14]. In addition, researchers have considered the effect of changes in environment to the packet delivery ratio for nodes on the body [20]. They characterize the link layer behavior of WBANs in real world situations and carry out preliminary evaluation of link estimation metrics used in routing.

2.2 Medium Access Control Layer

2.2.1 Overview

The number of MAC-protocols specifically developed for WBANs is limited. As networking in Wireless Sensor Networks has some points in common with networking in WBANs, it is useful to consider the research in MAC-protocols designed for WSNs. A survey of major MAC schemes is provided in [21]. Two major categories are contention-based and schedule-based. For the former, CSMA/CA is a typical example, while TDMA is a typical scheme for the latter. The advantages of contention-based approaches are the simplicity, its infrastructure-free ad hoc feature and good adaptability to traffic fluctuation, especially for low load. Schedule-based approaches on the other hand are free of idle listening, overhearing and packet collisions because of the lack of medium competition, but require tight time synchronization. The most commonly used technique for reducing energy consumption in contention-based protocols is controlling the power and duty cycle of the radio. Table 2.3 compares TDMA and contention based protocols with respect to their application to BANs.

The most important attribute of a good MAC protocol for a WBAN is energy efficiency. In some applications, the device should support a battery life of months or years without intervention, while others may require a battery life of only tens of hours due to the nature of the applications. Power-efficient and flexible duty cycling techniques are required to minimize the idle listening, overhearing, packet collisions and control packet overhead problems. Furthermore, low duty cycle nodes should not receive frequent synchronization and control information (beacon frames) if they have no data to send or receive.

Table 2.3: Comparison between TDMA and contention-based protocols

Approach	TDMA	Contention-based
Power Consumption	Low Power Consumption. TDMA can easily avoid or reduce energy waste from all major sources (collision, idle listening etc.)	High Power Consumption. Contention protocols needs to work hard in all directions (collision, idle listening, overhearing, over-emitting)
Traffic Level	High	Low
Bandwidth Utilization	Maximum	Low
Scalability	Low –Hard to dynamically change frame size or slot assignment when new nodes join –Restrict direct communication within a cluster	High Contention protocols easily accommodate node changes and support multi-hop communications
Packet Failure	Results in latency	Low effect
Synchronization	Compulsory. Results in overhead	Not required
Application	Good for in-body communication	Good for on/out body communication

In a scheduled-contention mechanism, scheduled and contention based schemes are combined to incur scalability and collision avoidance. In this mechanism, the nodes adapt a common schedule for data communication. The schedules are exchanged periodically during a synchronization period. If two neighboring nodes reside in two different clusters, they keep the schedules of both clusters, which results in extra energy consumption.

The S-MAC [22] protocol is a good example of a power-efficient scheduled-contention mechanism for multi-hop Wireless Sensor Networks (WSNs). In this protocol, the low duty cycle mode is default operation of all nodes. This protocol introduces the concept of coordinated sleeping among neighboring nodes. Furthermore, low duty cycling enables energy efficiency, which is of prime importance to BANs.

Many power control protocols (such as PAMAS, PCM etc.) have been developed based on contention based and scheduled based approaches, but are not designed especially for networks with mobile nodes. There is still no standard currently developed for BANs. Many researchers assume that protocols meant for personal area networks (PANs) such as Bluetooth (802.15.1) and Zigbee (802.15.4) are directly applicable to BANs. But studies in [6] have shown that the connectivity between nodes suffers greatly when these protocols are employed near the human body and also that they not very energy efficient in such scenarios.

Sana et al studied the performance of preamble based TDMA scheme (PB-TDMA), SMAC and beacon enabled IEEE 802.15.4 for priority based medical applications of WBAN [23]. They simulated a 6 node network on the human body in a star based topology and studied the performance of MAC schemes for different transmission powers. It is concluded that throughput and energy efficiency tradeoff is worse using 802.15.4 and SMAC as compared to a protocol based on TDMA scheme.

A scheduled-contention mechanism reduces idle listening using sleep schedules and performs well for multi-hop WSNs. However, considering this mechanism for a WBAN reveals several problems for low-power on-body nodes, which are not required to wake up periodically in order to exchange their schedules with other nodes [6]. Also, in a WBAN, some nodes may have to wake up and listen more often than once per frame. Synchronization issues in such close proximity networks require a more specialized approach.

The BAN traffic requires sophisticated low-power techniques to ensure safe and reliable operations. In a Low-power Listening (LPL) mechanism, nodes wake up for a short duration to check the channel activity without receiving any data. If the channel is idle the nodes go into sleep mode, otherwise they stay on the channel to receive the data. This is also called channel polling. The LPL is performed on regular basis regardless of synchronization among nodes. The sender sends a long preamble before each message in order to detect the polling at the receiving end. The WiseMAC protocol is based on the LPL mechanism and it uses a non-persistent CSMA and a preamble sampling technique to reduce idle listening. It has been shown that for heterogeneous or priority based traffic, existing MAC protocols such as IEEE 802.15.4, and WiseMAC give limited answers [23]. Zhang and Dolmans show that TMAC which was proposed as an extension to SMAC also suffers with synchronization overheads in medical applications [24]. This is because medical data usually needs high priority and reliability than nonmedical data. This motivates the development of MAC protocols which are different on traditional schemes and are meant especially for application to BANs.

2.2.2 MAC Strategies for WBANs

A number of ongoing projects such as CodeBlue, MobiHealth, and iSIM have contributed to establish a proactive and unobtrusive BSN system. A summary of the current research in practically implemented BAN projects is provided in [6]. UbiMon aims to develop a smart and affordable health care system. MITMedia Lab is developing MIThril that gives a complete insight of human-machine interface. HIT focuses on quality interfaces and innovative wearable computers. NASA is developing a wearable physiological monitoring system for astronauts called LifeGuard system. ETRI focuses on the development of a low-power MAC protocol for a BSN. IEEE 802.15.6 is a special task group which aims to provide power-efficient in-body and on-body wireless communication standards for medical and nonmedical applications [5].

Novel protocols like WASP and CICADA are proposed in [25], [26]. These protocols have been developed based on a cross layer approach which uses tree-based mapping to solve MAC and routing issues. Specifically meant to tackle multi-hop topologies in BANs, they are still under development and not practically applicable yet.

Heartbeat Driven MAC protocol (H-MAC) is a TDMA-based protocol originally proposed for a star topology WBAN. The energy efficiency is improved by exploiting heartbeat rhythm information in order to synchronize the nodes. The heartbeat rhythm can be extracted from the sensory data and hence all the rhythms represented by peak sequences are naturally synchronized. The H-MAC protocol assigns dedicated time slots to each node to guarantee collision-free transmission. In addition, this protocol is supported by an active synchronization recovery scheme where two resynchronization schemes are implemented. Although H-MAC offers energy efficiency, it was developed for a star based topology and doesn’t support sporadic events. Also heartbeat rhythm information will depend on patient condition [6].

A Reservation-based Dynamic TDMA Protocol (DTDMA) was originally proposed for normal (periodic) WBAN traffic where slots are allocated to the nodes which have buffered packets and are released to other nodes when the data transmission/reception is completed. It has been shown that for normal (periodic) traffic, the DTDMA protocol provides more dependability in terms of low packet dropping rate and low energy consumption when compared with IEEE 802.15.4 [23]. A similar TDMA based scheme called BodyMAC has been developed with an added advantage that it can accommodate on demand traffic using a downlink subframe. It uses CSMA/CA for contention access whereas DTDMA uses slotted Aloha.

Power-efficient mechanisms play an important role in the performance of a good MAC protocol for BANs. As mentioned, these mechanisms are categorized into Low-power Listening (LPL), Scheduled Contention, and TDMA mechanisms. Table 2.4 compares the applicability of each mechanism to BANs [6].

Table 2.4: Summary of existing MAC Protocols for a WBAN [6]

Power-efficient Mechanisms	Protocols	Channels	Organization and Basic Operation	Advantages and Disadvantages	Ada WBAN
Low-power Listening	WiseMAC	1	Organized randomly and operation is based on listening	Scalable and adaptive to traffic load, Support mobility, low and high power consumption in low and high traffic conditions, and low delay	Good f applications, duty cycle
	BMAC	1	Organized in slots and operation is based on schedules	Flexible, high throughput, tolerable latency, and low-power consumption	Good f ap
	STEM	2	Organized randomly having two sub-channels (control + data channel) and operation is based on wakeup schedules	Suitable for events based applications	Good for especiall applications sporadic eve control sub-c handle spora traffic
Scheduled-contention	SMAC	1	Organized in slots and operation is based on schedules	High transmission latency, loosely synchronized, low throughput	Good f applicati applications not a prima in-body me
	TMAC	1	Organized in slots and operation is based on schedules	Queued packets are sent in a burst thus achieve better delay performance, loosely synchronized	Good f app Early sleep nodes to loc
	PMAC	1	Organized in hybrid mode and operation is based on listening	Adaptation to changes might be slow, loosely synchronized, high throughput under heavy traffic	Good for ap
	DMAC	1	Organized in slots and operation is based on schedules	better delay performance due to Sleep schedules, loosely synchronized, optimized for data forwarding sink	On-bod prioritized application data tree can WBAN co clu
TDMA	FLAMA	1	Organized in frames and operation is based on schedules	Better end-to-end reliability and energy saving, smaller delays, improved energy saving, high reliability	Good f applications traffic
	LEACH	1	Organized in clusters and operations is based on TDMA scheme	Distributed protocol, no global knowledge required, extra overhead for dynamic clustering	TDMA sch created coordinator. not chang minimum energy) as I
	HEED	1	Organized in clusters and operations is based on TDMA scheme	Good for energy efficiency, scalability, prolonged network lifetime, load balancing	The WBAN a cluster hea HEED, the W is often pl

2.3 Model Adopted for Intra-BAN Analysis

In our work we focus on the analysis of MAC strategies for the 2.4 GHz ISM band. Much analysis has been undertaken for on body nodes in this frequency range due to its application to industry and medical healthcare. The propagation model adopted by us is as specified by Takizawa et al in [19]. They have presented stochastic WBAN channel models on path loss and power delay profile for various frequency bands. Furthermore, these parameters were incorporated by [14], which provides a final document of the IEEE802.15.6 channel modeling subcommittee for body area networks. The parameters for 2.4 GHz are provided in table 2.1.

According to Fort et al [15], communication for on body nodes takes place via diffraction. They have provided an in-depth analysis for UWB modeling for communication around the human body. But an average path loss model will be valid only for nodes located at parts of body which suffer similar attenuation. In our work we assume nodes placed on the torso of the user. These nodes will have negligible movement even when the user is in motion, and will also have the same path loss model. We adopt a node topology similar to the one presented in [27]. The human torso is represented by a cylinder with height of 60 cm and circumference of 96 cm. On this surface a topology of 8 nodes is simulated. As these nodes are situated on the torso, there will be negligible movement as a person moves. 4 nodes are employed at the front with 2 on the chest and 2 on the abdomen. 2 nodes are employed at the sides at mid height and 2 nodes are at the back. The details of this configuration are provided in the next chapter where simulation results are presented.

Many studies have been undertaken regarding MAC strategies for WBANs. An overview presented in the previous section shows that development of MAC protocols especially for BANs is a relatively new field. Mainly two types of network topologies have been considered – infrastructure based networks with a star topology to the coordinator node, or multi-hop networks with a mesh based topology. Scheduling based or contention based protocols have been developed to cater to the needs of star topology single hop networks such as BodyMAC, BSN-MAC, HMAC etc. Else completely new approach has been proposed for multi-hop communication in BANs like in WASP and CICADA.

In our work we propose that BANs should be modeled by a hybrid topology. We characterize the link behavior between nodes observed for both star based and mesh based topologies. Three basic protocols which have been studied extensively for wireless sensor node applications have been simulated in our work for BANs: IEEE 802.11, SMAC, and TDMA. The simulation results and specific parameters are presented in the next chapter.

3 SIMULATION RESULTS: INTRA BAN

In the previous chapters we introduced Body Area Networks and then compared some of the MAC strategies which could be applied to them. Channel models to describe the path loss suffered by transmission on the human body were discussed and the parameters which could be used to simulate such a channel were examined. According to the network architecture defined in chapter 1 of this thesis, all nodes of the intra-BAN must communicate to the base station through a gateway. Many authors have suggested intra-BAN be tackled as a pure infrastructure based network, where nodes must communicate directly with the access point [4], [10], [12]. Our aim is to study the network topology applicable to BAN and evaluate a MAC scheme which will perform best in terms of power consumption as well as throughput efficiency. In this chapter we present the results of simulations using the evaluated BAN parameters for three basic MAC strategies: IEEE 802.11, TDMA, and SMAC. First an infrastructure based (single-hop) topology is examined using NS2, and then based on the results obtained, a new topology applicable to intra-BAN is proposed.

Section 1 of this chapter presents the parameters which were used to simulate the intra-BAN environment. Section 2 and 3 examine the performance of predefined topologies. Finally in section 4, the throughput and energy efficiency of a new topology is evaluated and a feasible MAC scheme is proposed.

3.1 System Model

3.1.1 Environment Variables

A static topology as explained in the previous chapter has been used for simulations. 8 nodes are placed on the torso and the access point is placed in the middle of the chest. The coordinates are provided in figure 3.1.

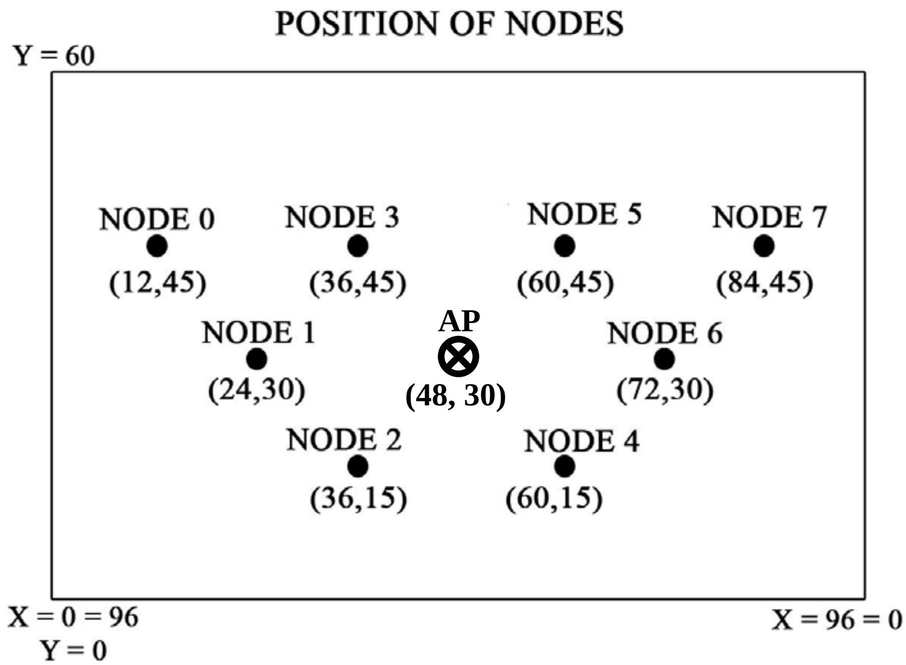


Fig. 3.1: Node configuration for intra-BAN

The wireless physical layer parameters to be used in this BAN environment will be those given in the nRF2401 low power single chip transceiver specifications [28]. This is a commercially available low power transceiver which is being used by IMEC in the Human++ program [29]. It has a very low current consumption and works in the 2.4-2.5 GHz ISM band. The propagation model is as described in [19] for modeling the human body channel in ISM band. The node configuration and simulation parameters are provided in table 3.1 – 3.3.

Table 3.1: Nordic transceiver specifications

Current consumption in transmitting mode	10.5 mA
Current consumption in receiving mode	18 mA
Output power (P_{Tx})	-5 dBm = 0.316 mW = 3.16×10^{-4} W
Receiving sensitivity threshold	-90dBm =1pW=10^{-12} W
Collision avoidance threshold	-95 dBm = 0.3162 pW = 3.162×10^{-13} W
Collision threshold	10 dB
Voltage	1.9 V
Power consumption in transmitting mode	10.5 mA × 1.9 V = 19.95×10^{-3} W
Power consumption in receiving mode	18 mW × 1.9 V = 36.1×10^{-3} W

Table 3.2: Simulation parameters for intra BAN

Topology	96 cm x 60 cm
Deployment	8 nodes and access point (fixed)
Frequency	2.4 GHz (ISM)
Transport Agent	UDP
Packet Size	128 Bytes
Rate	1 Kbps
Antenna Type	Omnidirectional
Initial Energy	30 J

Table 3.3: Propagation model parameters

Path loss model	$PL\ (dB) = \ a \log(d) + b + S(0, \sigma)$
a	*8.6*
b	*20.3*
σ	*2.0 dB*

3.1.2 Performance Metrics

The following performance metrics are used to evaluate the MAC strategies:

- Average power consumption
- Throughput efficiency

The first metric is very important for a Body Area Network, as the energy efficiency of a node provides an insight as to how long can the network be maintained, which is a critical requirement for on body networks. The second metric is important for best-effort traffics, as it measures the ratio between successfully received packets and total sent packets.

The two metrics will be evaluated with changes in transmission power. It is important to observe the effects of varying transmission power on the throughput and the energy efficiency, so that an optimum transmission range can be found which will give the best performance. High power increases the transmission range but results in tissue heating, whereas low transmission power saves energy but may suffer in terms of reliability. A packet will be received correctly at the access point if its power is greater than the receiving threshold of the node i.e. -95 dBm. This packet reception power is calculated by subtracting the path loss from the transmission power.

3.2 Star Based BAN Topology

In this scenario, the BAN indicated in figure 3.1 is simulated. The 8 sensor nodes on the body act as sources and have direct connections to the access point which acts as the sink. The packet size was chosen as 128 bytes and sources transmit at a constant bit rate (CBR) of 1 Kbps. These values are appropriate for data generated in nodes in the case of medical and simple monitoring applications. Figure 3.2 shows the average power consumption of nodes as transmission power is varied for 802.11, TDMA, and SMAC.

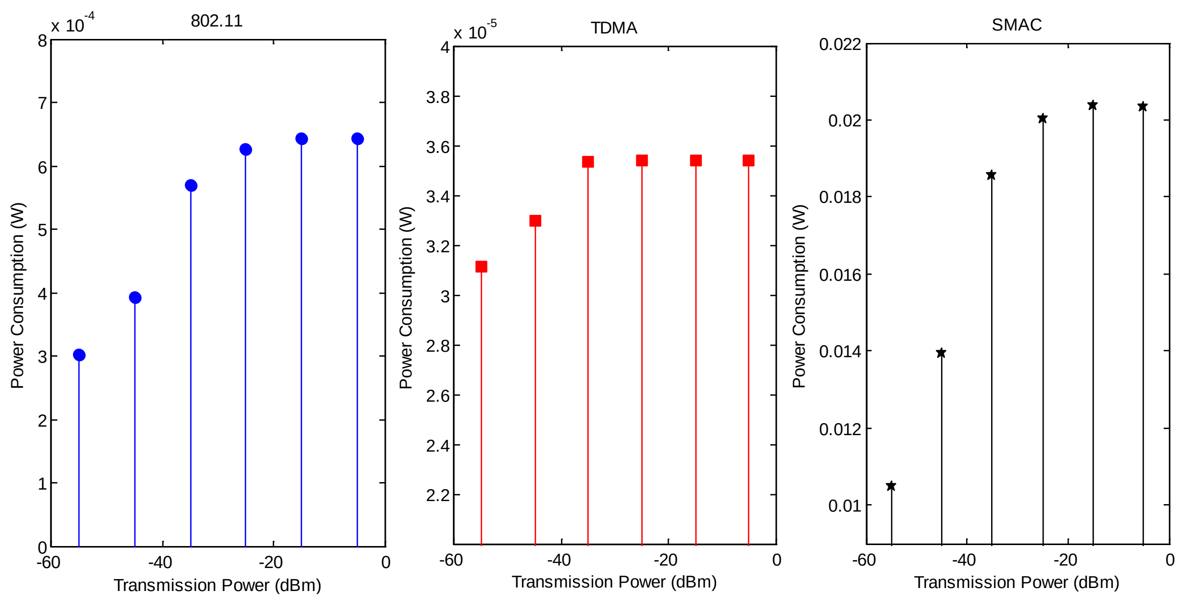


Fig. 3.2: Power consumption for star based network topology

It is observed that the energy loss becomes smaller as the transmission power decreases. As with low transmission power, fewer packets surpass the sensitivity threshold of each node, and so no energy is wasted in receiving packets. But the difference in power consumption at higher transmission powers is very less. The power efficiency for -5 dBm is almost the same as that for -15 dBm, and -25 dBm. To delve further into this issue we plot variation of throughput efficiency with transmission power in Fig 3.3.

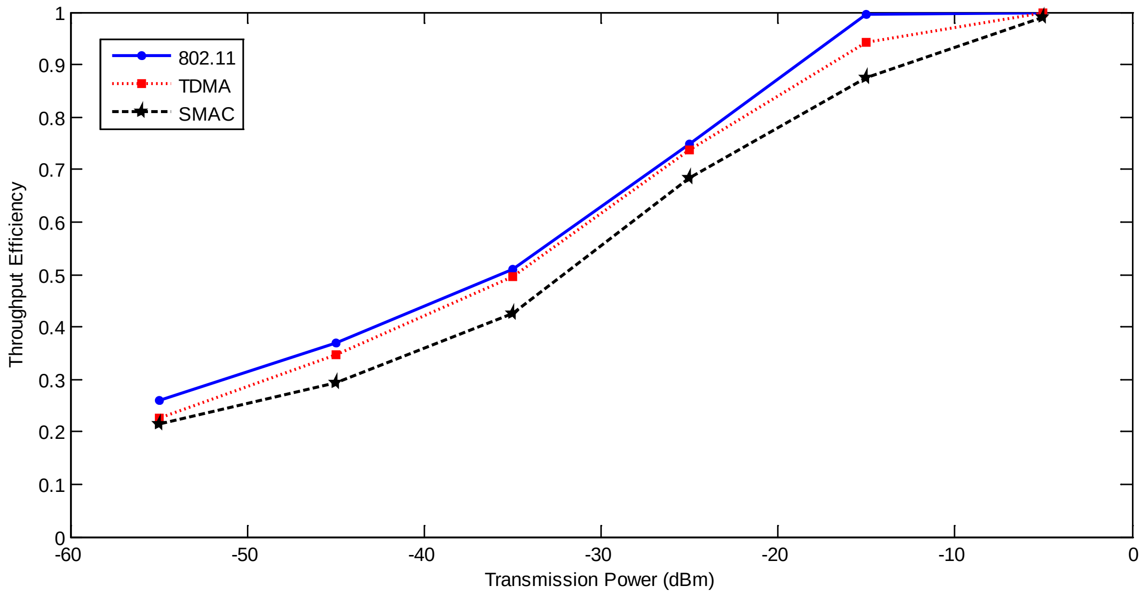


Fig. 3.3: Throughput efficiency for star based network topology

As expected the throughput performance of TDMA was observed to good for infrastructure network. Figure 3.3 also shows that 802.11 and SMAC perform similar to TDMA and at -5 dBm the throughput efficiency is almost 1 for all schemes. As the transmission power decreases, there are collisions and packet drops. Thus energy is wasted and throughput efficiency also decreases.

The throughput performance at low transmission powers suffer because the connection between some of the nodes and the access point cannot be established due to the large path loss. Similar to the average throughput plotted in figure 3.3, we can define a link throughput, between the node and access point. We call this metric the connectivity and measure it as the ratio between the packets successfully received at the destination and the packets sent to it by the source. Table 3.4 (a-c) indicate the connectivity for node to access point links at different transmission power levels. Node positions are as shown in figure 3.1.

Table 3.4(a): Connectivity at different power levels for 802.11

Power\Node	0	1	2	3	4	5	6	7
-5 dBm	1	1	1	1	1	1	1	1
-15 dBm	0.994503	0.995462	1	1	1	1	0.995471	0.989848
-25 dBm	0.126984	0.994482	1	0.994819	1	1	0.990498	0.228572
-35 dBm	0.057592	0.8775	0.994819	0.994949	0.994845	0.994844	0.949447	0.253886
-45 dBm	0	0.506186	0.994624	0.994845	0.995074	0.994764	0.617526	0
-55 dBm	0	0	0.909505	0.990244	0.970244	0.948947	0.030151	0

Table 3.4(b): Connectivity at different power levels for TDMA

Power\Node	0	1	2	3	4	5	6	7
-5 dBm	1	1	1	1	1	1	1	1
-15 dBm	0.928149	1	1	1	1	1	1	1
-25 dBm	0.285352	0.938776	1	1	0.999746	1	0.949582	0.374227
-35 dBm	0.05582	0.855102	0.994845	0.989691	0.994819	1	0.587629	0.041237
-45 dBm	0	0.414286	0.974227	0.967914	0.969072	0.974747	0.475258	0
-55 dBm	0	0.045918	0.896907	0.848877	0.860825	0.898485	0	0

Table 3.4(c): Connectivity at different power levels for SMAC

Power\Node	0	1	2	3	4	5	6	7
-5 dBm	1	1	1	1	1	1	1	1
-15 dBm	1	0.994845	0.994872	1	0.994898	1	0.994764	1
-25 dBm	0.398454	0.998462	0.984615	0.974093	1	0.994949	1	0.295745
-35 dBm	0.053846	0.704712	0.987525	0.989899	0.994924	0.989474	0.828571	0.05641
-45 dBm	0	0.473538	0.88974	0.973958	0.946278	0.989529	0.449524	0
-55 dBm	0	0	0.75	0.889694	0.840206	0.89949	0.025624	0

At high transmission powers all nodes can connect and therefore maximum throughput is observed with minimum energy wastage. As the transmission level is lowered, packets from nodes located at the back of the torso (0 and 7) are not able to reach the access point, which is in the front. At very low transmission levels, even packets from the side of torso (1 and 6) suffer a path loss greater than the power they were transmitted with before reaching their destination. Nodes at the front (2, 3, 4, and 5) remain connected to the AP even at low levels of transmission.

The power consumption in IEEE 802.11 was observed to be almost 25 times that of TDMA, and that of SMAC is around 27 times. It is well known that TDMA is the best usable scheme for infrastructure networks (star based topology). This is because in TDMA, the time slots are well defined from the beginning and nodes just have to wait for their slots to transmit, reducing the energy consumption compared to the other MAC protocols. The only disadvantage is that it assumes connectivity of all nodes to the AP. But on analyzing the traces, no direct connectivity was observed at low powers between the access point and far away nodes.

3.3 Mesh Based BAN Topology

In a single hop connected BAN, the average throughput performance and average energy performance was observed to be very good, but the actual connectivity of individual nodes was not. To overcome the problem of low connectivity with the access point in a star based network, other alternative topologies are needed. One way is to treat BANs as a multi-hop network with all nodes connected to each other. In this section a mesh based topology is simulated and connectivity of links is evaluated on a peer-to-peer basis for different transmission powers.

It is anticipated that the connectivity between nodes will be high at higher levels of transmission power, and as transmission power decreases, the connectivity between some nodes will suffer. The following was observed as transmission power is lowered:

- At -5 dBm maximum throughput efficiency is observed for all MAC schemes. As power level decreases from -15 dBm to -25 dBm the connection between nodes at opposite sides lowers (i.e. between nodes 0 and nodes 4, 5, and nodes 6 and nodes 2, 3). The average link throughput drops to almost 70%.
- At level -35 dBm, none of the back nodes connect fully with front nodes. The total average throughput drops to almost 50% for all three protocols.
- On lowering transmission levels further only immediate neighbor nodes remain connected. Table 3.5 displays the connectivity pattern between peers observed at -45 dBm for 802.11 MAC protocol.

Table 3.5: Peer-to-peer connectivity for 802.11 at -45 dBm

Tx\Rx	0	1	2	3	4	5	6	7
0	-	1	0	0.3442	0	0	0.0314	0.4292
1	1	-	0.9843	1	0	0.0517	0	0
2	0.0282	1	-	0.1524	0.5010	0	0.0084	0
3	0.4243	0.9987	0	-	0.1041	0.5105	0	0
4	0	0	0.4668	0.0348	-	0.2072	1	0.0447
5	0	0	0	0.5396	0.3427	-	0.9989	0.6820
6	0.0426	0	0.0503	0	1	1	-	1
7	0.5861	0	0	0	0	0.5858	0.9946	-

Due to connectivity problems at low powers, some researchers treat on-body communication as a pure multi-hop problem [2], [25], [26]. Such a network will certainly perform well as far as throughput efficiency is concerned, but the energy consumption will be higher. Packets which could be sent directly to the access point will also need to be routed to the destination. Combining the above observations with the analysis of star-based topology for BAN, we propose that a solution lies in a hybrid network topology with direct connectivity of some of the links and indirect connectivity of others. The nearer nodes can use single-hop connections to the access point, and the farther nodes can use indirect connections with a maximum of 3-hops. The analysis of such a proposed topology is provided next.

3.4 Optimum BAN Topology

A hybrid structure for BANs is proposed in this section. From table 3.4 and 3.5 it can be seen that at lower powers nodes at the front can easily connect directly to the access point also located at the front. For nodes at the back and side connectivity to access point can be through other nodes. Packets at node 1 can take two routes: through node 2 or through node 3. Similarly node 6 also has two alternative routes through node 4 or 5. Node 0 and node 7 at the back of the torso are well connected only to nodes 1 and 6 respectively. Thus, node 0 can route its data via node 1 and node 7 can do the same via node 6. Node 0 and 7 may be connected to each other as an alternative route. The proposed topology is presented in figure 3.4 and its performance is evaluated for various MAC schemes.

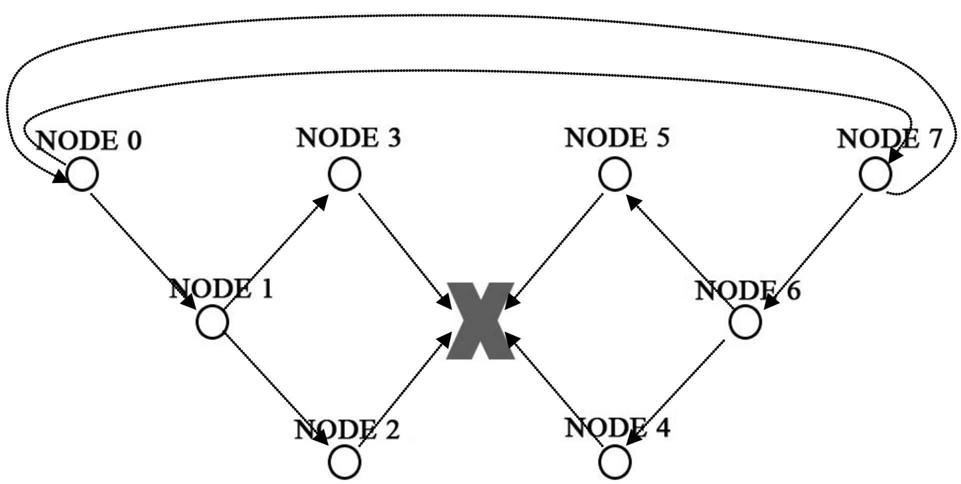


Fig. 3.4: Hybrid topology for considered network

In our simulation we have considered a fixed network topology with a distance dependent path loss model. But in real situations the path loss between nodes will be affected by other factors such as shadowing and mobility of person etc. In such a case, alternative routes can be used in case the connection between two neighborhood nodes suffers. An optimum method will be to simply maintain a table of preferred forwarding nodes, and furthermore this preference may be changed dynamically based on link quality for better congestion control. For simulation purposes we have used AODV protocol as the routing agent. This is a distance vector routing protocol which maintains a dynamic routing table based on neighborhood nodes. Figure 3.5 shows the throughput efficiency at different transmission power levels using 802.11, TDMA and SMAC.

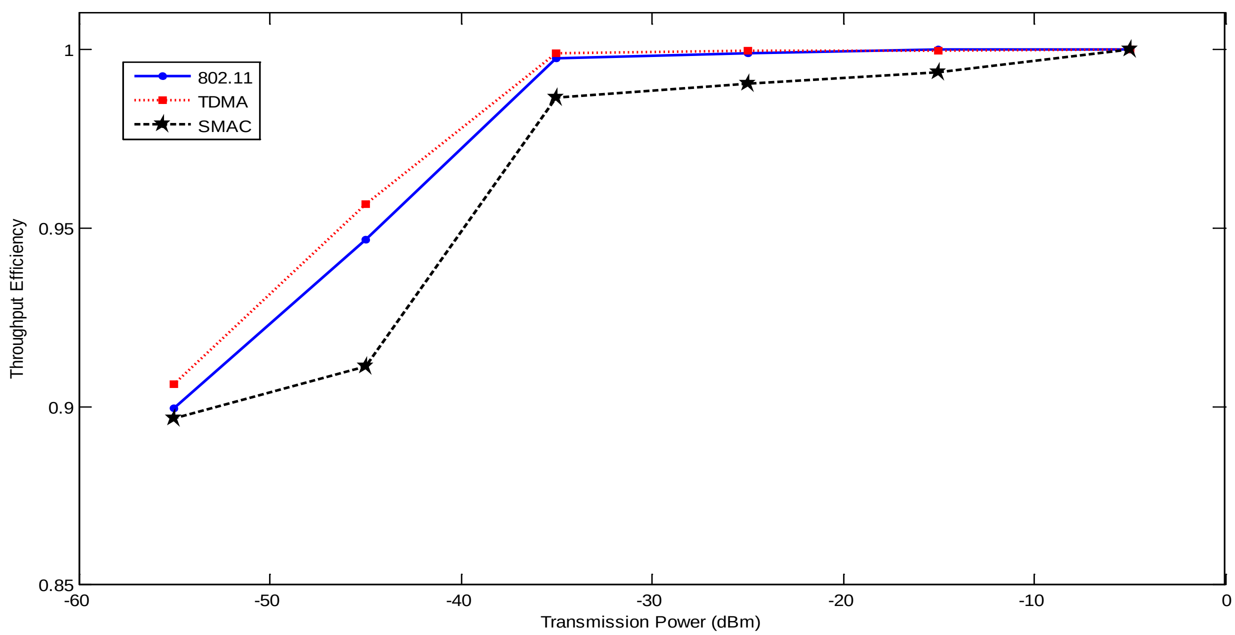


Fig. 3.5: Throughput efficiency for hybrid network topology

It can be observed that the proposed network topology has an extremely good throughput at all power levels. The efficiency remains more than 90% throughout, and all three MAC schemes perform similarly. In comparison, for star based topology throughput efficiency dropped to 30% whereas for mesh topology throughput drops below 50% as transmission power is lowered. As expected, for hybrid topology neighborhood nodes remain connected even at low transmission levels. The power consumption versus transmission power levels for the three protocols is plotted in figure 3.6.

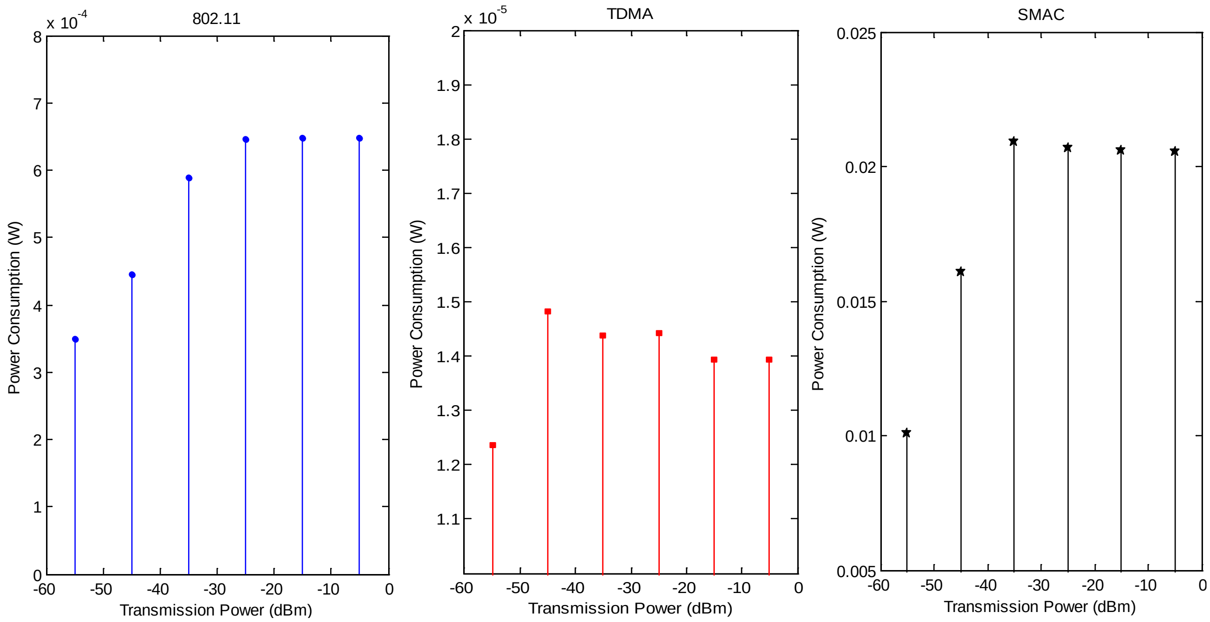


Fig. 3.6: Power consumption for hybrid network topology

Figure 3.6 shows that power consumption value at -5 dBm is slightly lower than that at -15, -25 and even -35 dBm. This is due to high throughput efficiency and minimum energy wastage at -5 dBm. This result agrees with the fact that the transmission power value of - 5 dBm is the recommended value for the Nordic nRF2401 transceiver [28] whose parameters have been applied in the presented simulation, and so the system best behaves in that transmission power range.

In conclusion, a study regarding the existing trade-off of power consumption with the throughput was undertaken, as the energy efficiency is such an important parameter for a BAN. This study aimed to find the optimum MAC scheme in the trade-off between energy and throughput with changes in transmission power level. We simulated a fixed topology and considered a path loss model to characterize the human body channel. But when nodes are placed on limbs, head etc the channel and the path loss may change with change in direction of the on-body nodes. In such a case even if transmission power level for all nodes is same, high path loss will be observed for some connections as compared to others. Thus received power of a packet will vary with node position. Our study shows that an optimum topology is possible which achieves high throughput even at low transmission levels for all MAC schemes. Effectively, even if high path loss is observed the throughput will not suffer in the hybrid topology.

4 EXTRA BAN COMMUNICATION

Protocols developed for WBANs can span from communication between the sensors on the body to communication from a body node to a data center connected to the Internet. We use the term intra-body communication to describe the former, which was detailed in chapter 2 and its simulation results presented in the previous chapter. The latter referred to as extra-body communication will be described here.

The elements of an intra-BAN (sensor nodes) collect data from the user and the data collected by these entities needs to be sent to a remote location, where a specialist will view and process them. These WBAN sensor nodes on the body are interfaced through a gateway or a personal server using predefined protocols such as GPRS, IEEE 802.11, and/or Bluetooth etc connectivity and communicate with services at the main server. A practical mobile healthcare system which uses traditional GPRS/UMTS to enable remote management of health emergencies, without compensating on patient mobility has been described in [12]. Such a system requires bulky PDA devices to always be attached to the user for maintaining a continuous satellite link with the base station.

To date, development has been mainly focused on building the system architecture and service platform for extra-BAN communication. Many of these implementations focus on the repackaging of traditional sensors with existing wireless devices. They consider a very limited WBAN consisting of only a few sensors that are directly and wirelessly connected to a personal device. The connectivity between the personal device and the main base station was not studied until much recently, and was left to mobile service providers. Researchers have established that the link between the personal device (mobile basic unit) and service station will also be characterized according to its application [30]. For example, mobile patient monitoring in a hospital may use IEEE 802.11 to connect to a base station, whereas a BAN in a moving ambulance will need vehicular ad-hoc network (VANET) support or WiMAX connection. But their study also limits itself to body surface to body surface communication without much stress to on body to off body transmission.

Smith et al performed practical experiments with subjects placed in different environments and situation of walking and standing with various orientations of the subject's body with respect to the receiver, and various distances from the receiver. The position of the transmitter node was either on the chest or on the wrist whereas receiver was placed quite near (between 1m to 4m) to the body while performing studies. They observed that this channel is quite stable for test cases with frequencies 900 MHz and 2.36 GHz bands. The details of their experiments and their observations for different situations and varying distance are provided in [16].

Communication to the base station through the wireless interface can be via multi-hop or single-hop connectivity. Whereas single-hop may require high energy to connect directly, multi-hop needs to manage connectivity opportunities effectively considering the mobility, multiple copies and energy too. Figure 4.1 shows the connectivity possible for extra-BAN.

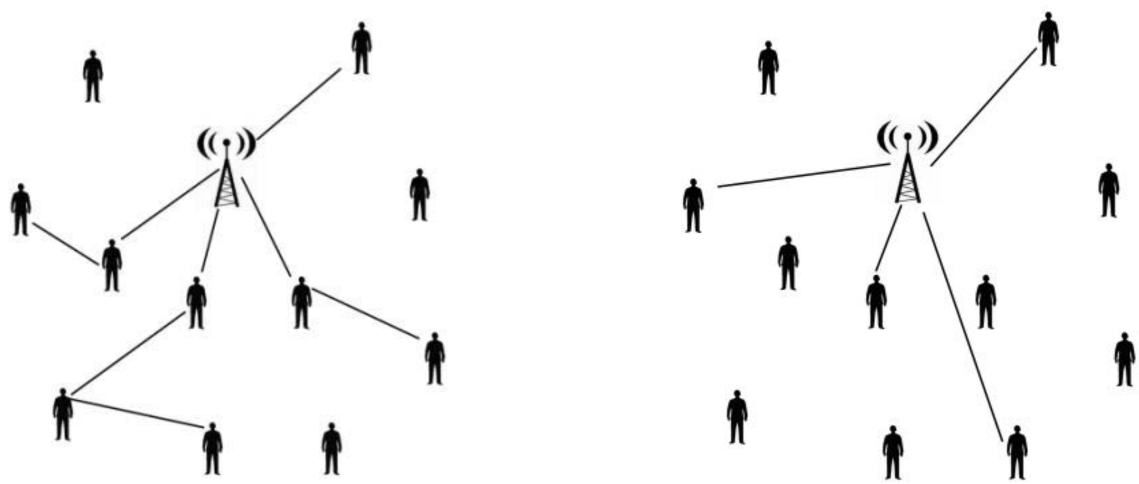


Fig. 4.1: Extra-BAN between many users and one base station for (a) multi-hop and (b) single-hop

Researchers have proposes that multi hop communication be used for athlete monitoring scenarios where service stations cannot be placed near the mobile players [9]. But as of yet no particular channel models are provided for extra-BAN environment with large distances (20 m or more) between source and destination nodes. Therefore for all practical purposes, the extra-BAN environment can be regarded as a wireless sensor network scenario.

The most serious problem in mobile wireless communication systems is the signal distortion due to multipath fading channels. When a moving user is transmitting information to a base station, the signal received will experience severe fluctuations due to multipath propagation. To combat multipath fading on a particular link, the fading channel on that link needs to be estimated at the receive site, and then the transmit site can be informed to adjust accordingly. Indeed, this is an effective way to combat a deep fade, and forms the basis of the cross layer design approach to optimize transmission presented in this chapter.

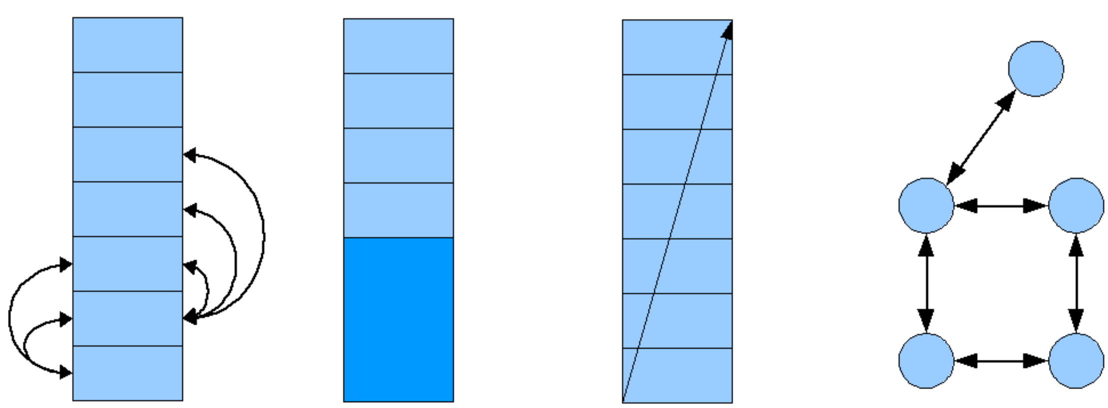
4.1 Cross Layer Approach

The extra-BAN network can be designed by the traditional layered approach, which was developed for wired networks. Major inconvenience of the layered design is that it is highly rigid and does not show any flexibility in dynamic environments [31]. Even though the layering approach was serving the networking designers for a lot of years, with principles widely adopted through various implementations and applications, it could not follow the growth of more demanding applications and the penetration of wireless technologies.

An alternative to using the OSI layered approach is cross-layer design, which is a more suitable and efficient methodology to improve and optimize the performance of a wireless system by exploiting the interactions between the various protocol layers. Cross-layer optimization defines a general concept of communication between layers, considering certain smart interactions between them, and resulting in network performance improvements [31]. The physical layer must adapt to rapid changes in link characteristics. The multiple access control layer needs to minimize collisions and allow fair access and semi-reliable transport of data over the shared wireless links in the presence of rapid changes and hidden or exposed terminals. 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 [32]. Here, adaptation refers to the ability of network protocols and applications to observe and respond to changes in channel conditions. Interactions between layers are based on effective adaptation to the dynamic environment.

In wireless environments, such as WBANs, cross-layer design can compensate for the unpredictable nature of the inherently unreliable wireless channel. Treating the entire communication protocol stack in a holistic manner can help in finding new means to alleviate the harmful performance restraining consequences of common wireless network problems, such as burst errors due to channel distortions, wireless interference problems, multipath propagation or fading effects. Recent research on cross-layer design has concentrated on specific aspects and problems of wireless communication systems. Hurni et al. provide an overview about the current state of the art in cross-layer design techniques and categorize the cross-layer techniques according to the kind of interaction between the layers that are suggested [33]. Illustrations a-d in figure 4.2 point out the major categories of how the traditional layered OSI communication system model is violated in current cross layer design studies. The main ideas behind them can be summarized as follows:

a) Creation of new interfaces: new interfaces between adjacent and non-adjacent layers are introduced to enable information sharing at runtime. This permits to run optimization algorithms and exploit higher and/or lower layer information.
b) Merging of adjacent layers: two or more layers are merged to one inseparable superlayer which runs an optimization algorithm and jointly takes care of all the former layer's tasks.
c) Vertical calibration across all layers: layer-specific parameters are read and manipulated across all layers.
d) Completely new abstractions: as schematically depicted by a graph with bidirectional links instead of layers, some authors suggest to completely renounce the layer paradigm.



(a) (b) (c) (d)

Fig. 4.2: Different kinds of cross-layer design approaches [33]

As an example of cross layer design, a simple illustration in the case of WSNs has been considered, which consists of nodes that communicate with each other using multi-hop. Figure 4.3 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. The packet delay at each link due to low SNR is calculated at the MAC level and this information is provided to network layer. 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.

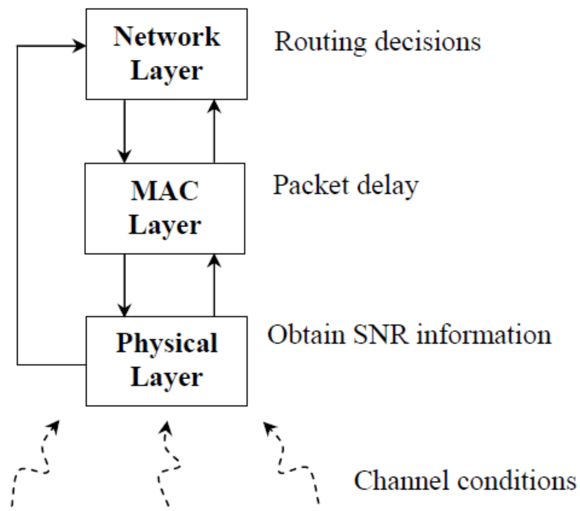


Fig. 4.3: Cross Layer Example

Cross-layer design has been proposed as a promising paradigm to tackle various problems of wireless communication systems. In existing cross-layer approaches, the violation of the OSI architecture typically consists in passing information between different adjacent or non-adjacent layers of one single station's protocol stack to solve an optimization problem and exploiting the dependencies between the layers [33]. Possible applications of lower layer knowledge are manifold: Nodes could detect signs of congestion, interferences, or irregularities in the transmission pattern early and immediately react to it. In our work, we use the SNR of the received packet at the lowermost layer to impact the transmission at MAC level. This approach has been applied to a scenario of a wireless body area network environment and utilize cross layer interaction between PHY and MAC layers at the extra-BAN level.

4.2 Prediction under Rayleigh Fading

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. WBANs are especially vulnerable to multipath due to the adverse environment conditions they may be employed in. In the body area network communications, propagation paths can experience fading due to different reasons, such as energy absorption, reflection, diffraction, shadowing by body, and body posture. The other possible reason for fading is multipath due to the environment around the body. This thesis mainly considers the effect of path loss, shadowing, and fading on the wireless channel of an extra-BAN. These effects are generally dependent on the frequency, location, mobility, and reflection coefficients of the surrounding objects. The surrounding objects influencing propagation can be either static (tables, metal objects) or time varying (moving vehicles, other people) and are considered to be part of the propagation channel. For mobile applications, it is often assumed that the channel varies with time. But when the users move with low speeds, the channel variations can be assumed slow as compared to the transmission rate. The maximum speed a pedestrian achieves (for short intervals) is around 10 kmph. At this speed, slow fading channel can be assumed and prediction can be applied to estimate channel quality.

Any channel can be modeled by the effect of large scale and small scale fading. Considering large-scale fading, the received power can be calculated from the log-distance path loss model as given by eqn. 2.1. On the other hand, small-scale fading describes the rapid changes of the amplitude of radio waves over a short period of time or traveled distance [13]. Fading models with Rayleigh or Ricean distributions are commonly used to describe the wireless environment with mobile users in an indoor propagation environment. The received signal modeled by a Rayleigh distribution can be given by:

$$p(r_0) = \begin{cases} \frac{r_0}{\sigma^2} \exp\left[-\frac{(r_0^2)}{2\sigma^2}\right] & (0 \leq r_0 \leq \infty) \\ 0 & (r_0 \leq 0) \end{cases} \tag{4.1}$$

where σ^2 is the time-average power of the received signal before envelope detection, r_0 is the Rayleigh fading signal envelope, and ${r_0^2}/{2\sigma^2}$ is the instantaneous power.

4.2.1 Correlation of Rayleigh Fading Channel

Rayleigh fading channels with the distribution given by eqn. 4.1 display a correlation property across time. This autocorrelation can be used to estimate prediction coefficients of a filter which may be utilized to predict the channel gain before a node transmits data. The preliminary study of using a channel predictor for applications in power control algorithms is presented in [34]. The idea of prediction filter is that instead of using the present channel strength, the predicted channel strength is used to control transmission at MAC level.

The time-frequency autocorrelation function of a Rayleigh fading channel will be used to compute the predictor coefficients. The following mathematical analysis is based on studies performed in [34] and [35]. The received signal in a multipath channel consists of a series of attenuated, time-delayed, phase shifted replicas of the transmitted signal $s(t)$,

$$r(t) = \left(\sum_{l=1}^{L} C_l s(t-\tau_l). e^{j2\pi[(f_c + f_D \cos\phi_l)t - f_c\tau_l]} \right) \tag{4.2}$$

where

C_l represents amplitude distortion;

τ_l is the l^{th} path delay;

$f_D = \nu/\lambda$ is the Doppler spread;

$\phi_l(t)$ represents the direction of l^{th} scatterer wrt mobile velocity vector ν.

In time domain, for flat Rayleigh fading channel, the time delay is much less than symbol duration. So received signal can be expressed as,

$$r(t) = s(t-\tau_0). \left(\sum_{l=1}^{L} C_l e^{j\phi_l(t)} \right). e^{j2\pi f_c t} \tag{4.3}$$

where $\phi_l(t) = 2\pi f_D \cos\psi_l \, t - f_c\tau_l$ and $\tau_0 \in [\min\tau_l, \max\tau_l]$. The phase $\phi_l(t)$ is an independent and identically distributed (i.i.d.) random variable and uniformly distributed over [0,2π]. The first term of eqn. 4.3 shows that transmitted baseband signal is delayed due to propagation time, and second term reflects the amplitude fluctuation of baseband signal by,

$$\beta(\omega, t) = \sum_{l=1}^{L} C_l e^{j\phi_l(t)} \tag{4.4}$$

Time delay τ_l is assumed to be an i.i.d. variable with probability density function $f_T(\tau)$, where $f_T(\tau)$ is non-zero for $0 \le \tau < \infty$, and zero otherwise. The time frequency correlation of the fading factor $\beta(\omega, t)$ is then,

$$\rho_\beta(\omega_1, \omega_2, t, t+\upsilon) = E[\beta(\omega_1, t)\beta^*(\omega_2, t+\upsilon)]$$
$$= E\left[\sum_{i=1}^{L}\sum_{l=1}^{L} C_i C_l e^{j(\phi_i(\omega_1,t)-\phi_l(\omega_2,t+\upsilon))}\right]$$

(4.5)

Taking $\Delta\omega = \omega_1 - \omega_2$, ρ_β vanishes for $i \neq l$. Thus we have,

$$\rho_\beta(\omega_1, \omega_2, t, t+\upsilon) = \rho_\beta(\Delta\omega, \upsilon) = \sum_i E\left[{C_i}^2\right] e^{j(\omega_D \cos\psi_i \upsilon - \Delta\omega\tau_i)}$$

(4.6)

where $E\ [C_i^2]$ is the average value of the fraction of incoming power in the *i*th path that can be expressed as

$$E\ [C_i^2] = \sigma^2 f_\psi(\psi_\mathrm{i}) f_T(\tau_\mathrm{i}) d\psi_\mathrm{i} d\tau_\mathrm{i} \tag{4.7}$$

where σ^2 is radiated power from mobile and $f_\psi(\psi_\mathrm{i}) f_T(\tau_\mathrm{i}) d\psi_\mathrm{i} d\tau_\mathrm{i}$ represents average fraction of incoming power within $d\psi_\mathrm{i}$ of time τ_i.

For a large number of L, take limit ($L \rightarrow \infty$), eqn. 4.7 can be written as,

$$\rho_\beta(\Delta\omega, \upsilon) = \frac{\sigma^2}{2\pi} \int_0^{2\pi} \int_0^{\infty} e^{j(\omega_D \cos\psi \upsilon - \Delta\omega\tau)} f_T(\tau) d\psi d\tau$$

$$= \sigma^2 J_0(\omega_D \upsilon) F_T(j\Delta\omega) \tag{4.8}$$

where J_0 is the zeroth Bessel function of the first kind, and $F_T(s)$ is the characteristic function of the time delay τ.

For a frequency-nonselective Rayleigh fading channel, only the time correlation is considered and the autocorrelation of the Rayleigh fading is expressed as,

$$\rho_\beta = \sigma^2 J_0(2\pi f_D \upsilon) \tag{4.9}$$

where f_D is the maximum Doppler spread and υ is the time shift.

Eqn. 4.9 can be used to characterize the autocorrelation of Rayleigh channels to calculate prediction coefficients of a channel predictor.

4.2.2 Channel Predictor

The channel predictor considered is a V^{th} order linear predictor which predicts the fading factor at the i^{th} slot, $\beta(i)$, using the past V fading factors between $(i - D)^{th}$ and $(i - D - V + 1)^{th}$ slot. Figure 4.4 shows the predictor that consists of a linear filter with the predictor coefficients or the tap weight vector of dimension V and prediction range D.

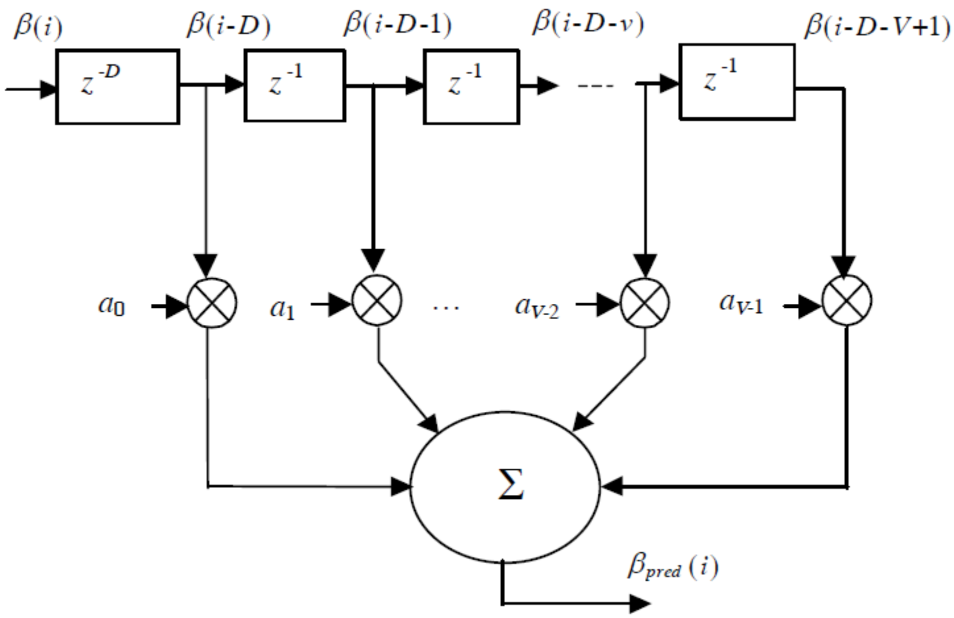


Fig. 4.4: Linear predictor of order V

The predicted fading-factor is expressed as

$$\beta_{pred}(i) = \sum_{v=0}^{V-1} a(i)\beta(i - D - v) \tag{4.10}$$

where $\boldsymbol{a}(i)$ represents the weights of the prediction filter as shown in figure 4.4.

Under the MMSE criterion [36] the vector $\boldsymbol{a}(i)$ can be computed as $\mathbf{a}(i) = \mathbf{R}^{-1}(i)\mathbf{r}(i)$ (4.11)

Here $\mathbf{R}(i)$ is the V x V autocorrelation matrix of the input samples and the vector $\mathbf{r}(i)$ is the cross correlation between the tap-input samples and the desired response.

$$r(i)_v = E[\beta(i)\, \beta^*(i - D - v)], \qquad v = 0, 1, \ldots, V\text{-}1. \tag{4.12}$$

$$R(i)_{v,u} = E[\beta(i - D - v)\, \beta^*(i - D - v)],\ v,u = 0, 1, \ldots, V\text{-}1. \tag{4.13}$$

Thus the autocorrelation function of fading factor can be rewritten as,

$$E[\beta(i)\beta^{*}(i-v)] = \sigma^{2}J_{0}\left(2\pi f_{D}T_{p}v\right) \quad (4.14)$$

The order of predictor V is chosen so that prediction memory exceeds the channel coherence time in order for the prediction too fully exploit the fading correlation. The next section highlights the cross-layer design based on IEEE 802.11 DCF protocol, using the channel predictor.

4.3 IEEE 802.11 DCF Cross Layer Design

Cross-layer design is a way to improve the efficiency of and interaction between the protocols in a wireless network by combining two or more layers from the protocol stack. This research has gained a lot of interest in sensor networks [31], [32], [33]. However, no attempt has been made yet to apply this concept to WBANs. As most of the protocols used for WSN are applicable to extra-BAN communication, a practical approach is to exchange information between layers of predefined protocols. Our work utilizes such a cross-layer energy efficient approach, applicable to the off-body external network, built on IEEE 802.11.

Research on the performance of ad hoc networks under Rayleigh fading channel has attracted lot of interest. This study identifies the causes for performance degradation in fading and proposes a cross-layer approach to: (i) improve the network throughput, (ii) decrease unnecessary packet transmissions, (iii) save power and bandwidth resource, and (iv) reduce packet loss due to channel contention under IEEE 802.11 DCF. In addition, a Markovian model characterizing Rayleigh fading channels has been used to study the performance of the MAC layer under Rayleigh fading channel conditions.

4.3.1 Operation of Design

Using Rayleigh fading assumption, it is possible to predict when the channel is about to undergo a fade, i.e. when the receiver is unable to receive data packets correctly due to low received power. The channel gain for the next transmission can be predicted at the physical layer using eqn 4.10 and then shared with the upper layers. If the upper layers know the channel gain is large enough for a successful transmission, they proceed with the transmission as usual. Else, if the predicted channel gain is low, then the channel is in fade and the upper layers (i.e. in our work, the Medium Access Control) will suspend transmission of packets which otherwise would not be received without significant if not total loss. Transmission of such packets is bound to be lost because of a fade.

In general, it is difficult for the transmitting node to know with certainty whether a packet will be transmitted correctly. Nevertheless, in the case of Rayleigh fading channels, one can predict the value of the channel gain based on the past values of this quantity due to the time based autocorrelation given by eqn. 4.9.

The basic operations involved in the cross-layer design algorithm are illustrated in figure 4.5.

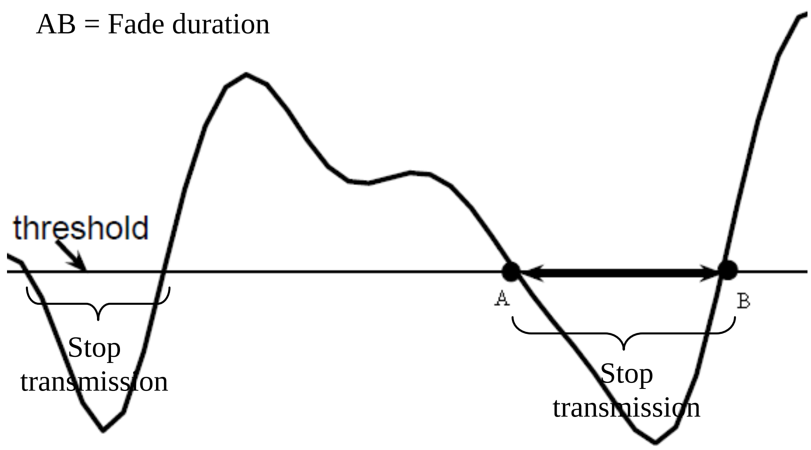


Fig. 4.5: Cross layer design using channel prediction

Using a channel prediction filter, the receiving station can determine whether the packet will be received correctly in the next transmission. If the packet is not to be received correctly, the node performs the following actions:

1. Stops the transmission of any reply packet to the sending node, freeze the Medium Access Control (MAC) until the channel gets out of the current fade.
2. Notifies the sender to stop the transmission and also indicate the expected fade duration of the channel. This notification is achieved by setting a special flag indicating in the header of either the Clear To Send (CTS) packet or Acknowledgment (ACK) packet. The "backward channel" (from the receiver to the sender) is assumed not in fade during the transmission of CTS or ACK as the prediction is done in advance and also because these acknowledgement packets have a small duration as compared to DATA packets.

Upon reception of a CTS or ACK packets containing an activated flag signaling a fade, the transmitting node performs the following actions:

1. Immediately halts the transmission to the destination node in the MAC layer.
2. Obtains the average fade duration (AFD) and schedules the transmission accordingly.

If the neighboring nodes hear a CTS or ACK not meant for them, they automatically set their network allocation vectors (NAVs) accordingly. The channel can then be released to other nodes for transmission during the AFD.

The expected downtime of the channel is the average fade duration which can be derived as [13]:

$$F_a = \frac{e^{\rho^2} - 1}{\sqrt{2\pi}\, f_D \rho} \tag{4.15}$$

where ρ is the ratio between signal threshold power and the Root Mean Square (RMS) of the received signal power, f_D is the maximum Doppler frequency.

4.3.2 Advantages and Implications

In the case of Rayleigh fading channels, the received signal can go into deep fades. If the proposed cross-layer design is not used, the upper layers are not notified when the channel goes into a fade and therefore the transmitting node keeps sending packets which are discarded due to weak received power at the receiver. In turn, the transmitting node stops receiving ACK packets from the destination node and enters the backoff state after a timeout. It then retries to send these packets and eventually discards them if the fade is longer than retry timeout [37].

Therefore, using the proposed cross-layer design approach, the following improvements can be obtained:

1. It prevents the sender from unnecessary packet transmissions, which results in the reduction of power consumption for transmission.
2. It saves bandwidth resources which can be used for other transmissions, leading to an increase in the overall network throughput
3. It avoids retransmissions of packets which ultimately result in permanent packet loss.

The prediction algorithm is entirely dependent on the coefficients of the predictor, the derivation of which is computationally intensive and consumes a significant amount of power which may not be viable during real-time operations. This problem is avoided by pre-computing the coefficients and storing them offline, which can be retrieved based on the Doppler frequency and the data rate. This approach is fast and energy efficient, which suits a WBAN environment.

In the next chapter, the simulation results and performance analysis of the implemented cross layer design is presented to illustrate its benefits.

4.3.3 Markovian Model for Rayleigh Channel

Pham et al have used a Markov model to represent the “good” and “bad” states of a Rayleigh channel, and theoretically derived the probability of the channel being “good” or “bad” for IEEE 802.11 DCF protocol [35]. This model is applicable to the considered scenario and is briefed in this section.

Each state is respectively associated with the probability for the received signal to be below or above a given threshold. As shown in figure 4.6, S_1 represents “good state”, in which transmission continues as usual and S_0 represents “bad state”, in which the PHY layer informs the MAC layer to postpone transmission.

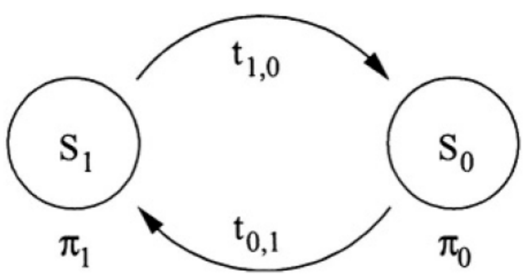


Fig. 4.6: The two state channel model

Under Rayleigh fading, the probability density function (p.d.f.) of received signal P can be expressed as eqn. 4.3. The RMS value of the received signal power is,

$$P_{rms} = \sqrt{E[r^2]} \tag{4.16}$$

$$\rho = \frac{P_{th}}{P_{rms}} \tag{4.17}$$

where P_{th} is the power threshold i.e. the channel is either in state S_1 if $P_{th} < P < \infty$ or S_0 if $0 < P \leq P_{th}$. Then, the number of times per second the received power P crosses the level is [13],

$$N_r = 2\pi f_D \rho e^{\rho^2} \tag{4.18}$$

Using eqn. 4.1, the steady state probabilities π_0 and π_1 of the state S_0 and S_1 can be evaluated as,

$$\pi_1 = \Pr(r > P_{th}) = \int_{P_{th}}^{\infty} \frac{r}{\sigma^2} \exp\left(-\frac{(r^2)}{2\sigma^2}\right) dr = e^{-\rho^2} \tag{4.19}$$

$$\pi_0 = \Pr(0 < r \leq P_{th}) = \int_{0}^{P_{th}} \frac{r}{\sigma^2} \exp\left(-\frac{(r^2)}{2\sigma^2}\right) dr = 1 - e^{-\rho^2} \tag{4.20}$$

The transition probabilities $t_{1,0}$ from state S_0 to S_1 is calculated by dividing fade duration F_a by average duration between each crossing $1/N_r$,

$$t_{1,0} = F_a/\left(1/N_r\right) = e^{-\rho^2}(e^{\rho^2} - 1) = 1 - e^{-\rho^2} \tag{4.21}$$

Similarly, $t_{1,0}$ is given by,

$$t_{0,1} = \frac{(1/N_r - F_a)}{(1/N_r)} = 1 - N_r F_a = 1 - e^{-\rho^2}\left(e^{\rho^2} - 1\right) = e^{-\rho^2} \tag{4.22}$$

It can be seen that state equilibrium equation holds as $\pi_0 t_{0,1} = \pi_1 t_{1,0}$, and hence a Markov process can be used to model the dynamics of a Rayleigh fading channel. The channel is in "good state" S_1 with probability $e^{-\rho^2}$ and expected duration $1/\sqrt{2\pi} f_D \rho$, and "bad state" S_0 with probability $1 - e^{\rho^2}$ and expected duration $(e^{\rho^2} - 1)/\sqrt{2\pi} f_D \rho$ as shown in figure 4.6.

Similarly, a Markovian model of IEEE 802.11 protocol can be derived. Its analysis has been considered comprehensively in [35] and [37].

4.3.4 Implementation on NS2

IEEE 802.11 uses a sequence of RTS/CTS/DATA/ACK to transmit messages between two nodes. The aim of the considered cross layer design is to pass channel state information (CSI) from PHY layer of receiving node, to the MAC layer of both receiving and sending node. This channel state information contains 2 fields: (i) the predicted channel state and (ii) the average fade duration (F_a).

Consider a scenario with a sender node *x* and receiver node *y* as shown in figure 4.7.

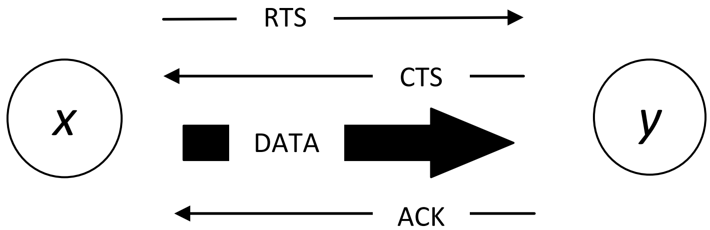


Fig. 4.7: IEEE 802.11 protocol – scenario under consideration

Assume that prediction parameters have been calculated and are stored in a matrix **A**, past values of received powers are stored in a matrix **P**. Also, P_{th} denotes the threshold under which channel is assumed to be in fade. The packet header has been modified to accommodate the average fade duration (AFD), and a flag denoting channel state (S) as denoted in figure 4.8. Note that the AFD can be determined using eqn. 4.16. Instead of introducing this as a calculation overhead, F_a may also be determined offline and stored for a range of P_{rms} values, which is evaluated every time a message is received.

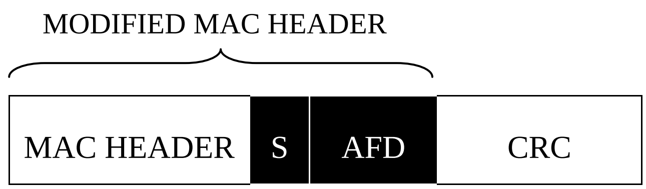


Fig. 4.8: Modified packet headers for CTS and ACK frames

The implemented algorithm for the cross layer protocol is summarized for a two node scenario as follows. Figure 4.9 (a) shows what occurs at node *y* when RTS/DATA packet is received.

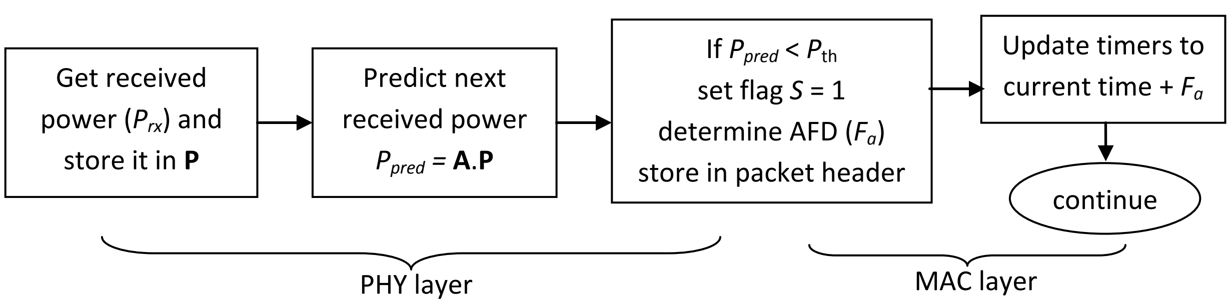


Fig. 4.9 (a): Algorithm at receiver on receiving RTS/DATA

Node *y* continues to reply to the RTS/DATA by CTS/ACK respectively, but the new MAC header contains the channel state information i.e. S and F_a

Figure 4.9 (b) shows what occurs when node *x* receives either a CTS/ACK.

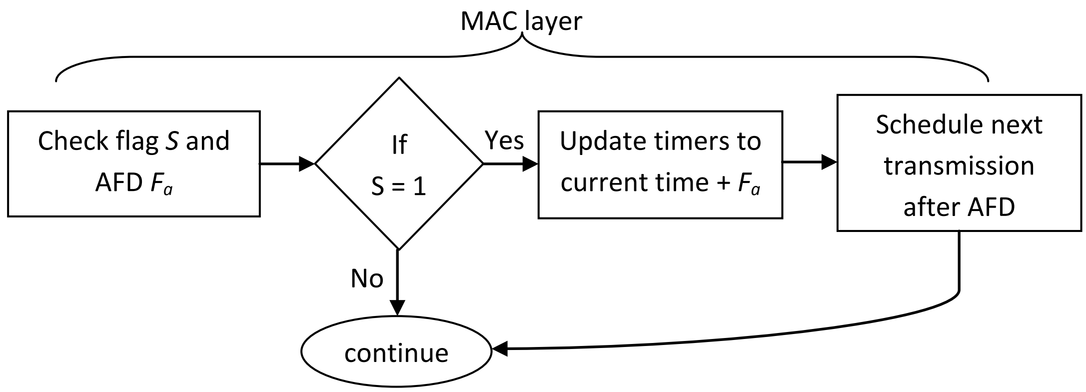


Fig. 4.9 (b): Algorithm at sender on receiving CTS/ACK

In case there is a third node *z* present in the vicinity of node *y*, which hears the CTS or ACK meant for *x*, it also checks the channel state information (S) and sets its Network Allocation Vector (NAV) accordingly. In the original IEEE 802.11 protocol, the node *z* will set its NAV according to the time the channel will remain occupied by *x* and *y*. But in the modified 802.11 protocol, node *z* should understand that the channel between *x* and *y* is in bad state and transmission of further data has been deferred by AFD. Thus, all nodes hearing this CTS or ACK, except for node *x* and *y*, will be free to contend for the channel.

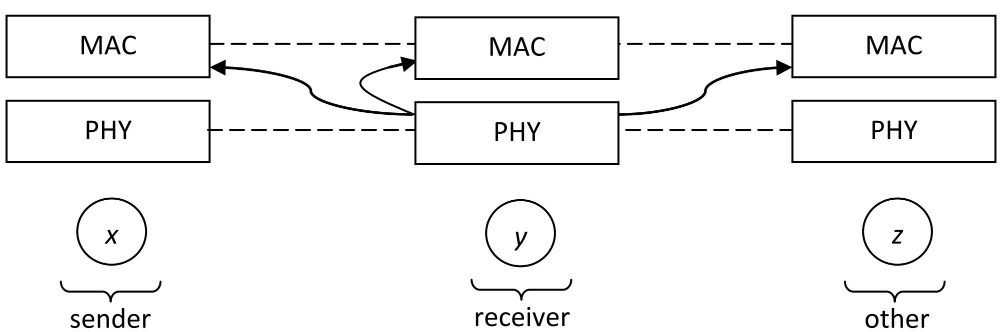


Fig. 4.10: Cross Layer Design based on 802.11 protocol

It can be seen clearly from the previous diagrams that PHY level information determined at node *y* was conveyed to MAC layer at both node *x* and node *y* to defer the transmission. Also, it impacts the NAV timers of node *z* at its MAC layer. Thus, the given approach is a multi-node cross layer design as shown in figure 4.10.

To implement the cross layer design, it is important to calculate the prediction parameters offline. These parameters are different for different speeds of mobile nodes, as f_D changes accordingly. In the next chapter some of these values have been presented, calculated using MATLAB, along with the simulation results of cross layer scheme evaluated using NS2. For the MAC code implementation of IEEE 802.11 protocol on NS2 the reader is referred to [38].

5 SIMULATION RESULTS: EXTRA BAN

In the previous chapter, the cross layer approach based on IEEE 802.11 was examined. In this chapter we use NS2 to compare the network performance of IEEE 802.11 protocol and cross layer 802.11. MATLAB environment is used to evaluate the prediction coefficients, and also confirm the statistical parameters of Rayleigh fading.

This chapter is organized as follows: section 1 presents the system model and steps taken to implement the cross layer scheme. Section 2 examines the prediction parameters, evaluated using NS2 and MATLAB, and their accuracy. The results of implementing the predictive cross layer approach to IEEE 802.11 protocol are evaluated in section 3.

5.1 System Model

A complete WBAN requires that nodes transmit the collected information via an access point, whose purpose is to aggregate all data and send it to the base station. As mentioned previously, authors have proposed the use of large PDA devices communicating to the base station directly via GPRS or Wi-Fi etc [10], [11]. But, apart from being bulky, these solutions are not energy efficient. In this thesis, we use a cross layer design based on IEEE 802.11 for the connectivity between users and base station using energy efficient nodes. The performance of this protocol has been evaluated with changes in number of nodes and their mobility. In the simulations, NS2 is chosen as the simulation tool and standard IEEE 802.11 DCF using RTS/CTS access scheme was adopted as the basic protocol on which cross layer design is applied.

The cross layer protocol was simulated for many different scenarios with varied deployment, topology and connectivity. Throughput and energy efficiency was studied as parameters were varied. The Rayleigh-fading channel simulation model from [39] has been adopted to simulate the propagation environment. The mobile nodes forming the extra-BAN were configured according to the settings of Lucent Wavelan wireless network card which are commonly applied in WSN scenarios. Table 5.1 displays the node configuration settings used in our simulation.

Table 5.1: Node configuration settings

Receiving sensitivity threshold	-91 dB = 3.652 x 10^{-10}
Collision avoidance threshold	-102.5 dB = 1.559 x 10^{-11}
Power consumption in transmitting mode	0.6 W
Power consumption in receiving mode	0.035 W
Transmission power	24.5 dBm = 0.2818 W
Power monitor threshold	-174 dBm = 3.98108 x 10^{-18}

5.2 Evaluation of Prediction Parameters

To apply the cross layer design, the first step is to evaluate the prediction parameters. These parameters are evaluated using the autocorrelation function of a Rayleigh fading channel as shown in the previous chapter. In our simulation V = 10 previous samples have been used in simulations for all cases of fading channels. The fading correlation matrix $\mathbf{R}(i)$ is computed using eqn. 4.15. The AR coefficients $\boldsymbol{a}$(i) are computed using direct inversion technique for simplicity. Furthermore, once estimated, these parameters were confirmed for a two node scenario in NS2 as shown in figure 5.1.

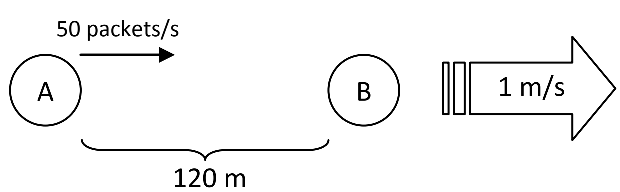


Fig. 5.1: Scenario to calculate channel prediction coefficients

- 2 nodes A and B were placed 120 m apart
- Node A is fixed while node B moves away with a speed of 1 m/s
- Node A transmits to B at a constant rate of 50 packets/s
- Size of packets is 512 Bytes. Therefore CBR with rate 25.6 kbps is used
- Transport agent is TCP and MAC protocol is IEEE 802.11 RTS/CTS
- Rayleigh fading patch by CMU [40] is applied to simulate the channel

Figure 5.2(a) shows the plot of received powers at node B as the distance between A and B increases with time. The channel downtime i.e. the time when channel is in fade, increases as the distance between node A and B increases.

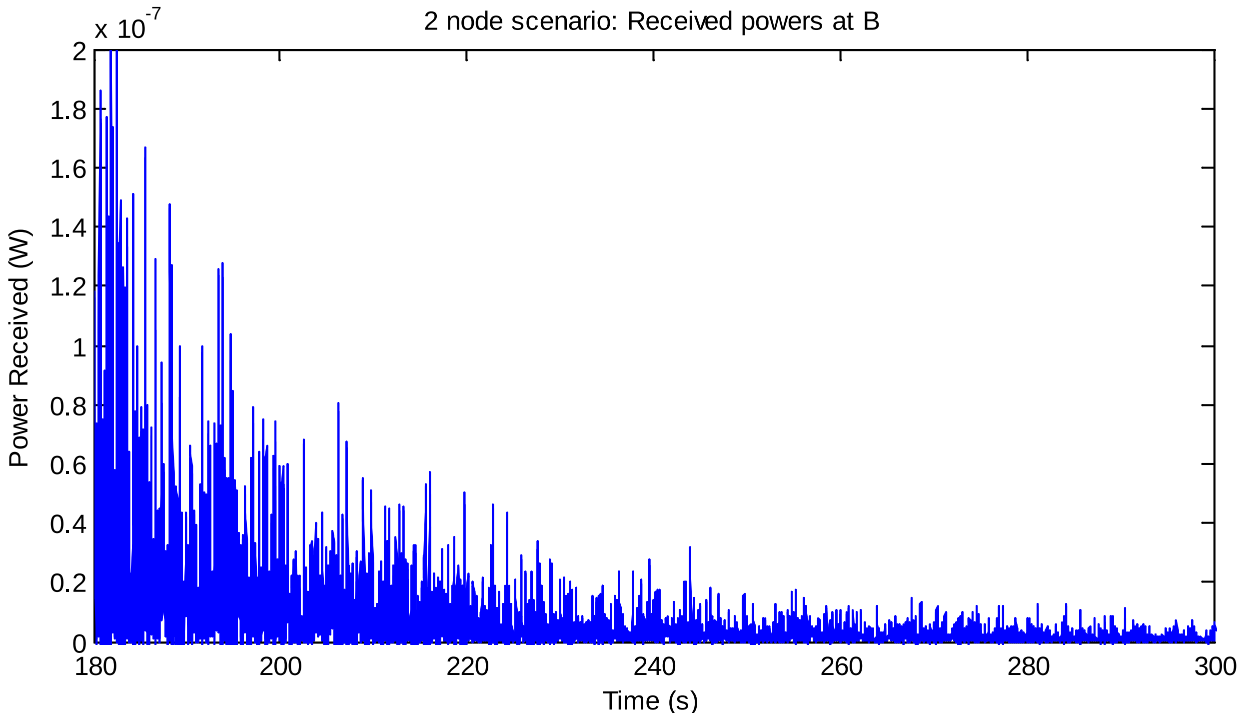


Fig. 5.2 (a): Received powers at node B as distance between nodes increases

The channel prediction parameter accuracy can be confirmed using received powers at node B. As we have assumed a slow Rayleigh fading channel, the prediction accuracy depends on the speed and data rate. This was confirmed by keeping the packet rate constant and increasing the speed of node B and then keeping the speed constant while decreasing the transmission rate. It was observed that above 10 m/s the prediction mechanism is no longer accurate. And at rates below 5 packets/s, the prediction algorithm does not have enough samples to make the prediction. This indicates that using the cross layer design is no longer beneficial a low packet rates and high speeds. For an extra-BAN scenario, our cross layer design will be proficient as pedestrian movement is usually at speeds below 10 kmph.

Figure 5.2 (b) shows a magnified view of the predicted and actual received powers for the scenario described. Power was predicted after evaluating the prediction coefficients (table 5.2).

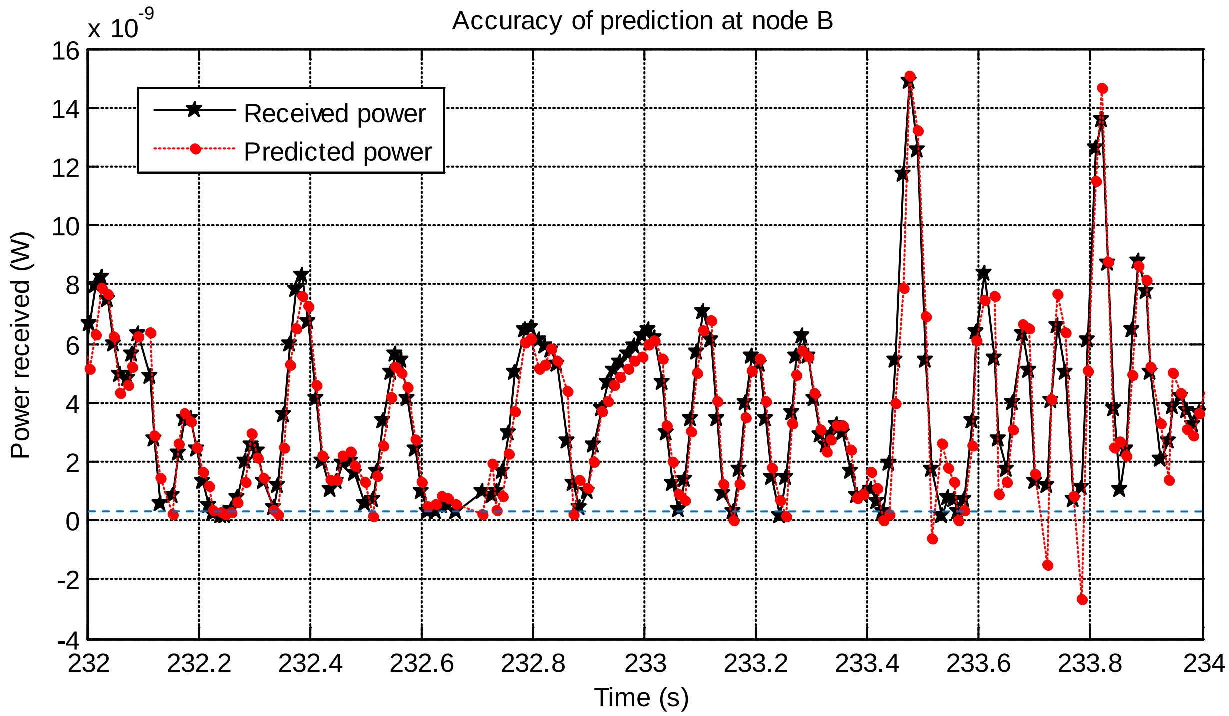


Fig. 5.2 (b): Channel prediction accuracy at 1 m/s and 25.6 kbps, and threshold -98 dBm

It was also found that the average fade duration and level crossing rate evaluated using eqn. 4.16 and eqn. 4.19 confirm with those evaluated by simulation in MATLAB. The prediction parameters for varying speeds ranging from 1 m/s to 10 m/s with 0.5 m/s increments were computed. Some of these coefficients are given in table 5.2.

Table 5.2: Prediction coefficients for different speeds

Speeds	A(0)	A(1)	A(2)	A(3)	A(4)	A(5)	A(6)	A(7)	A(8)	A(9)
1 m/s	1.038	0.837	-0.913	-0.433	0.466	-0.270	0.279	0.104	-0.124	-0.008
2 m/s	1.063	-0.172	0.063	-0.715	0.809	-0.068	-0.044	-0.346	0.419	-0.062
5 m/s	0.892	-0.601	0.589	-0.430	0.430	-0.286	0.297	-0.144	0.159	0.006

As mentioned previously, the cross layer design is applicable mostly for low relative speeds between source and destination nodes. In case the two nodes are mobile and moving in similar directions, it is likely that the link between them will last for a long time. Multipath fading could degrade the performance of such a link, but the cross layer approach tends to counter that.

5.3 Cross Layer Design Performance

Using the predictive parameters evaluated in the previous section, the cross layer design is applied to IEEE 802.11 protocol in NS2 and performance of various scenarios is studied.

5.3.1 Two Node Scenario

This section presents the performance of the cross-layer design as the channel downtime increases. Thus the effect of increasing only the fade durations without the channel contention has been analyzed. This is important to compare the degree of improvement obtained in this scenario with the subsequent ones where the channel contention is considered.

By intuition, the improvement of using the cross-layer design is proportional to the probability of the channel being in fade, i.e., proportional to the channel downtime. The network scenario used is the same as that presented in figure 5.1, except now the throughput performance with normal IEEE protocol versus that with predictive cross layer design implementation is compared.

- 2 nodes A and B are placed *x* m apart. Node B moves away with a speed of 1 m/s.
- MAC protocol is cross layer 802.11 DCF using the prediction parameters for speed 1 m/s.
- The performance is compared for different values of starting distance *x*. Time of simulation is 200 s.

By increasing the distance between node A and node B, the received power at node B decreases, which in turn increases the probability of the channel being in a fade. Therefore, it is anticipated that the cross-layer design improves the network performance as bad channel duration increases. The channel throughput versus the initial distance is shown in figure 5.3 (a). It is observed that the degree of performance improvement is proportional to the initial distance.

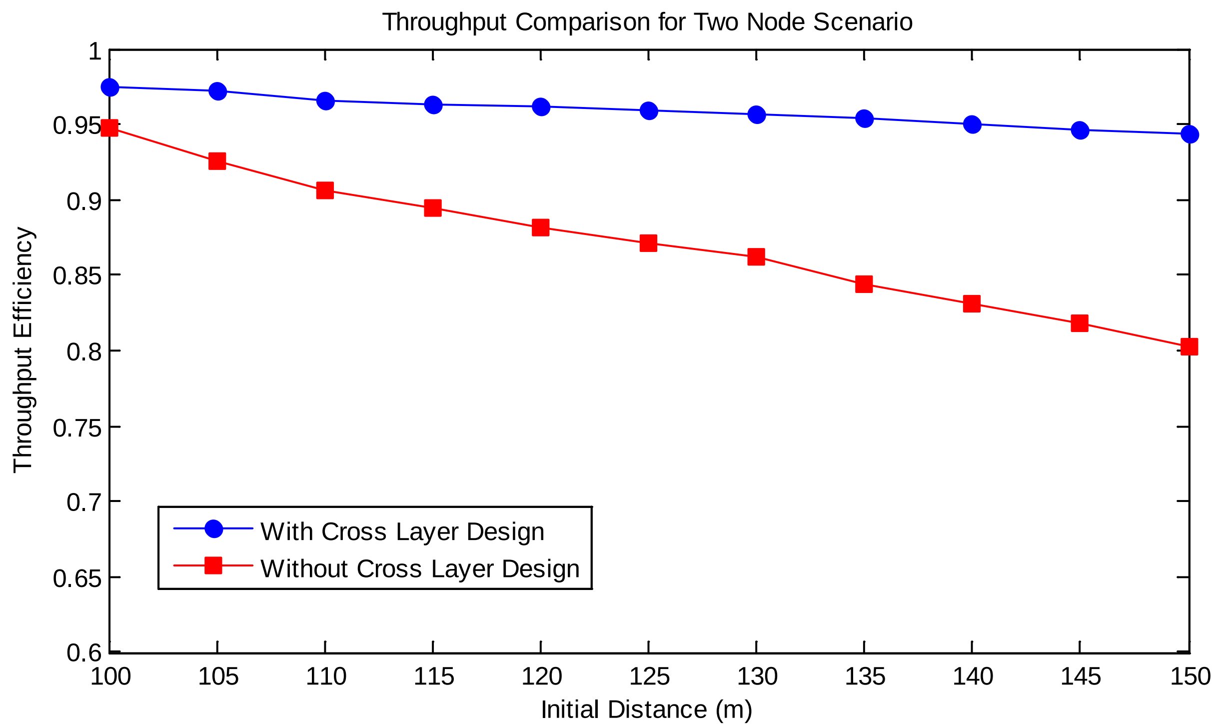


Fig. 5.3 (a): Throughput under different starting positions

Figure 5.3 (b) compares the number of control packets sent using IEEE 802.11 and the cross layer design. The control packets are the RTS, CTS and ACK packets used for handshake purposes in 802.11. It can be seen that the number of control packets are significantly decreased by adopting the cross layer design. This is because the channel state can be predicted and number of total packet drops, due to both retransmission and low received power, is reduced. Finally, the amount of energy consumed using cross layer design is compared with the energy expended without cross layering in figure 5.3 (c).

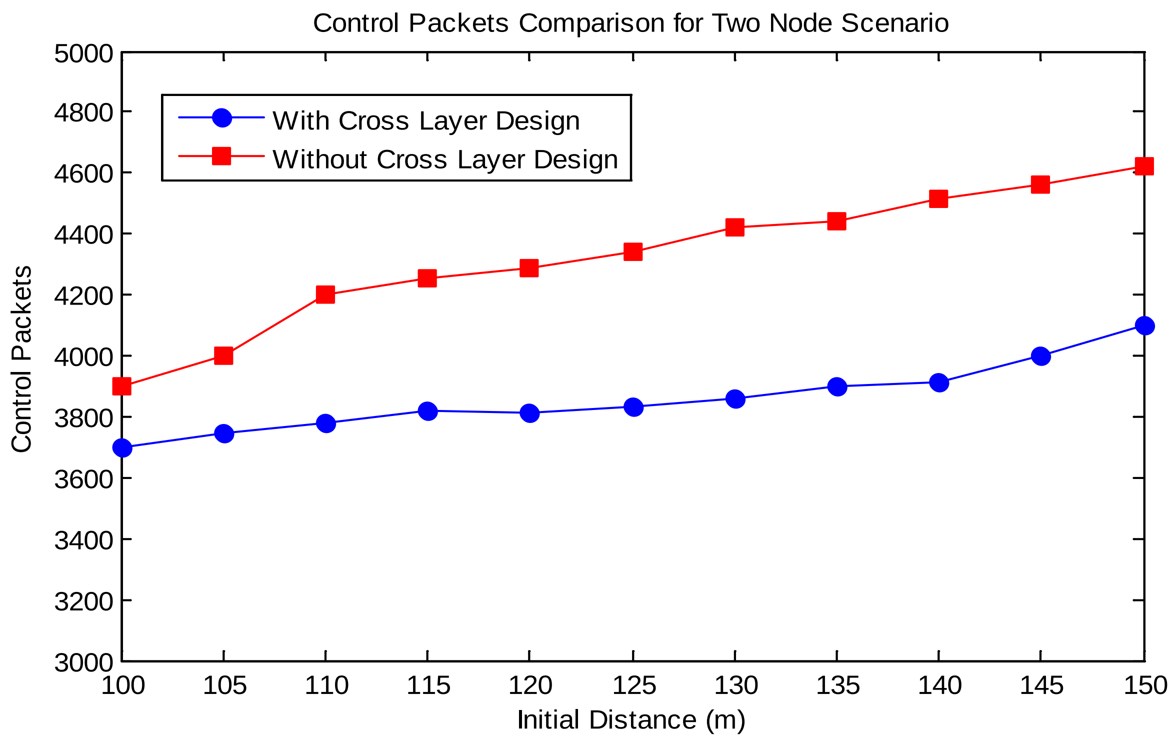


Fig. 5.3 (b): Control packets under different starting positions

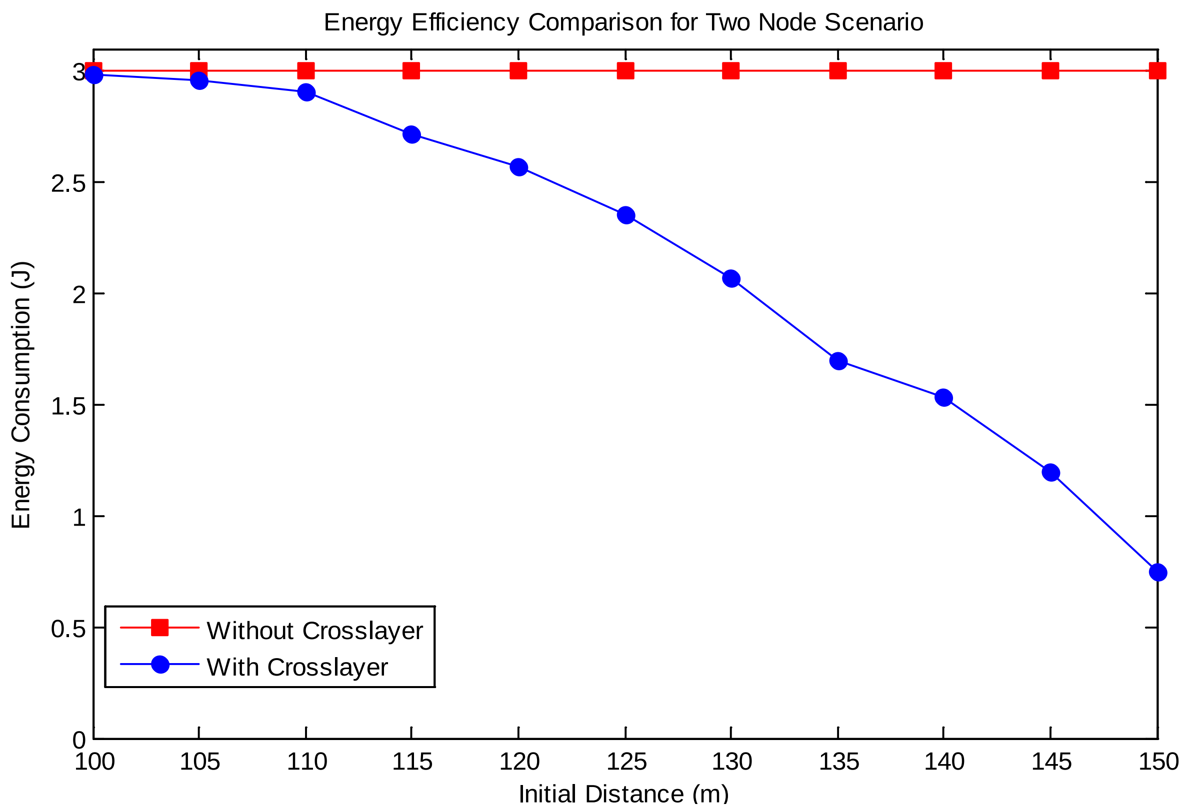


Fig. 5.3 (c): Power efficiency under different starting positions

Thus a significant power saving thanks to the cross-layer design is noticed. The modified protocol also helps reducing the packet losses, and increasing the throughput efficiency. In summary, the results indicate a positive performance gain by adopting the cross-layer approach. However, these results are limited because they are obtained without channel contention. Therefore a more comprehensive simulation with channel contention is presented to judge the performance of the scheme.

5.3.2 General Random Mobility Model Scenario

This scenario studies the performance of cross layer mechanism with the presence of channel contention as well as fades in a more realistic environment. To do that, a topology is chosen which is conventionally adopted by many researchers, as given in table 5.3.

Table 5.3: Simulation parameters for 50 node scenario

Topology	1500 x 1500 m
Deployment	50 mobile nodes
Mobility	Random way point model
Speed	1 m/s
Pause	10 seconds
Packet size	128 Bytes
Packet rate	50 packets/sec
Traffic agent	TCP

As mobile nodes compete for one channel, the probability of packet loss due to contention is higher. The cross layer design minimizes the number of retransmissions, and also releases the channel for other competing nodes when it predicts a fade. Thus an improvement in the average connection throughput is expected.

The impact of changing the traffic load on the network is studied by varying the number of active connections from 1 to 30 in steps of 5. The average network throughput is presented in figure 5.4 (a) and average power consumption of the nodes is plotted in figure 5.4 (b).

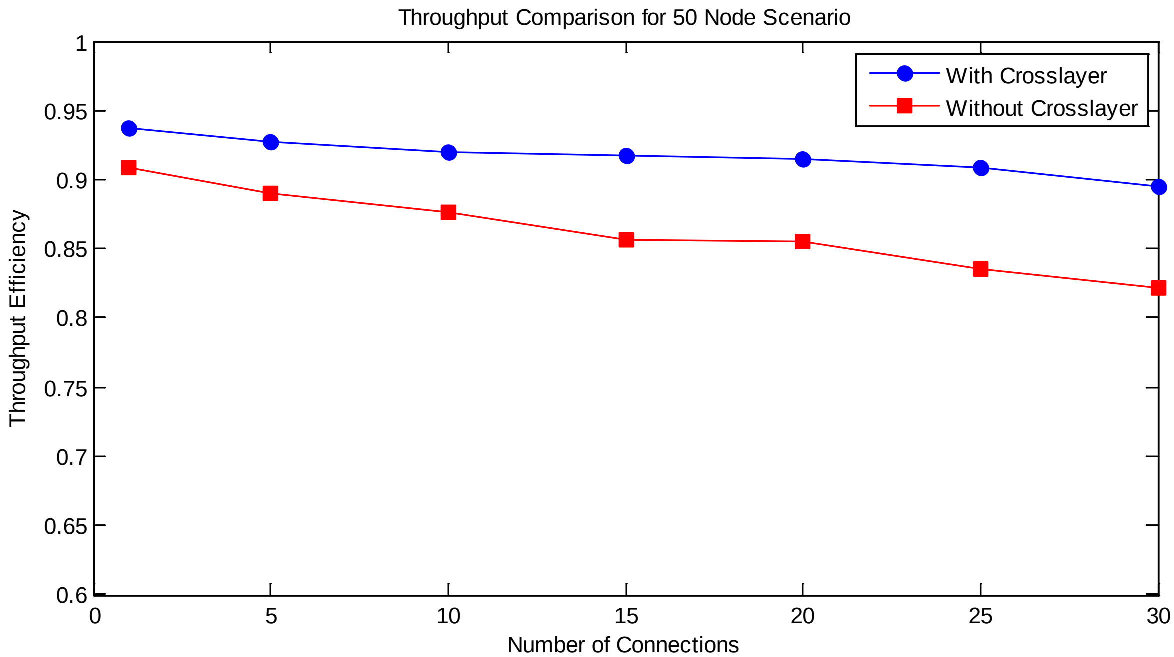


Fig. 5.4 (a): Throughput efficiency as number of connections are varied

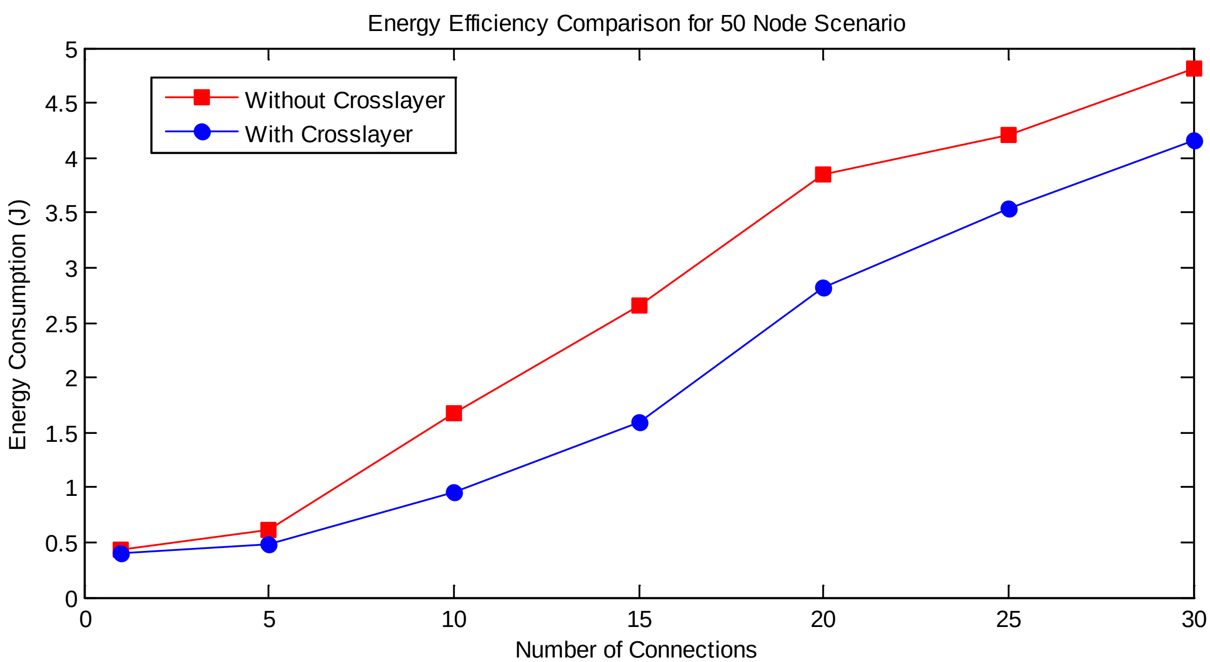


Fig. 5.4 (b): Average power consumption as number of connections are varied

As shown, the cross-layer approach achieves a better network throughput, saves bandwidth resources and reduces power consumption in the considered network scenario. The results obtained by us confirm with those obtained by Pham et al, who compared the performance of

IEEE 802.11 and modified cross layer protocol on the basis of total energy consumption and throughput (kbps) [35].

5.3.3 Nodes and Base Station Scenario

A node density of 50 users in a 1500 x 1500 m environment is not commonly observed for WBAN scenarios. Hence in this section we consider the cross layer approach applied to a scenario with a small number of mobile nodes (taken as 10) and 1 server. It is emphasized that an extra-BAN must be scalable, for example the number of monitored users may increase or decrease by a few. In some applications, the number of nodes remains constant, but the speed may vary. For example in field sports a player may be static at some times and moving with high speeds at others (though this movement is usually in a short burst and not continuous). Thus in the following results, performance of the network has been evaluated for changes in the number of nodes as well as change in speed, using the prediction coefficients evaluated in the previous sections. The simulation parameters are similar to those presented in table 5.3.

Note that in the scenario considered, it has been assumed that nodes move with a constant speed (and random direction) during each simulation. The cross layer algorithm can be extended for scenarios with moving users if speed detection is also possible. This will allow the base station to dynamically select the applicable prediction parameters according to the velocity of the moving node and hence adapt to the channel in a much better way.

Figure 5.5 presents the change in throughput efficiency with change in speed. For analysis purposes, the speed was varied form 1 m/s to 10 m/s and the throughput achieved was studied, when the number of nodes is 10. Similar to the plot presented, throughput was also evaluated as speed was varied from 1 to 10 m/s when the number of nodes was 5, 15, and 20.

It can be clearly noticed that at higher speeds the performance of the protocol degrades. As speed increases, variations in the fading channel change from slow to fast, and the predictor will fail to perform accurately. But at lower speeds the improvement in throughput is substantial.

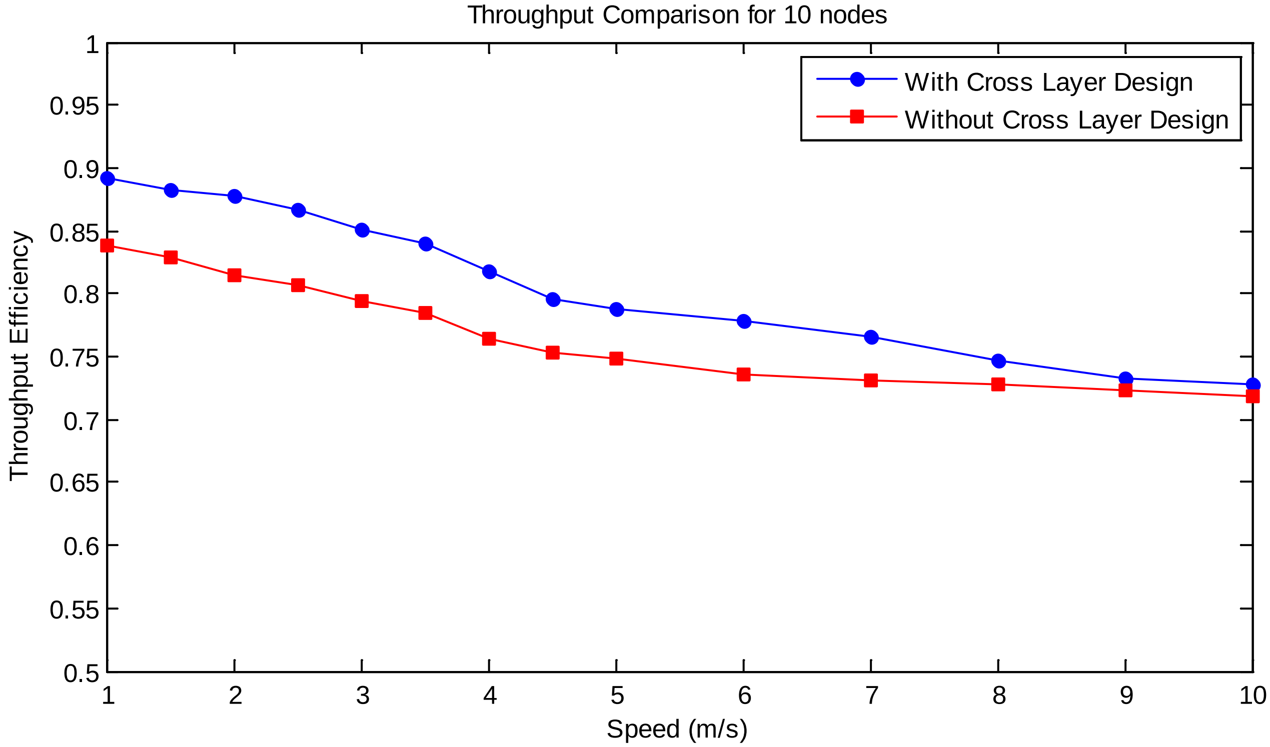


Fig. 5.5: Throughput efficiency as speed of nodes is varied for 10 nodes

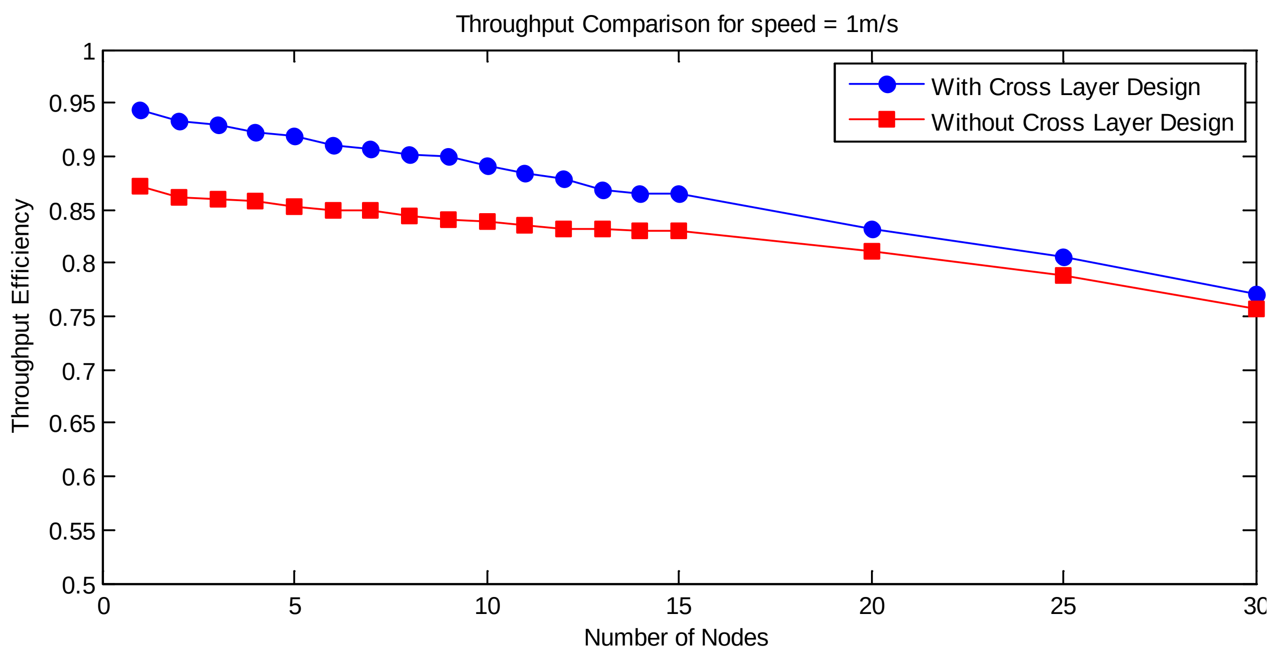


Fig. 5.6 (a): Throughput efficiency as number of nodes are varied

Figure 5.6 (a) presents the change in throughput as the number of nodes change for constant speed of 1 m/s. It can be seen that the performance of cross layer design is better at less node density than at high node density. This is because the modified protocol cannot cope up with increased channel contention when many nodes are present.

Figure 5.6 (b) shows the change in average power consumption as the number of nodes increases. It can be seen that even at high node densities, the modified protocol performs better in terms of energy consumption.

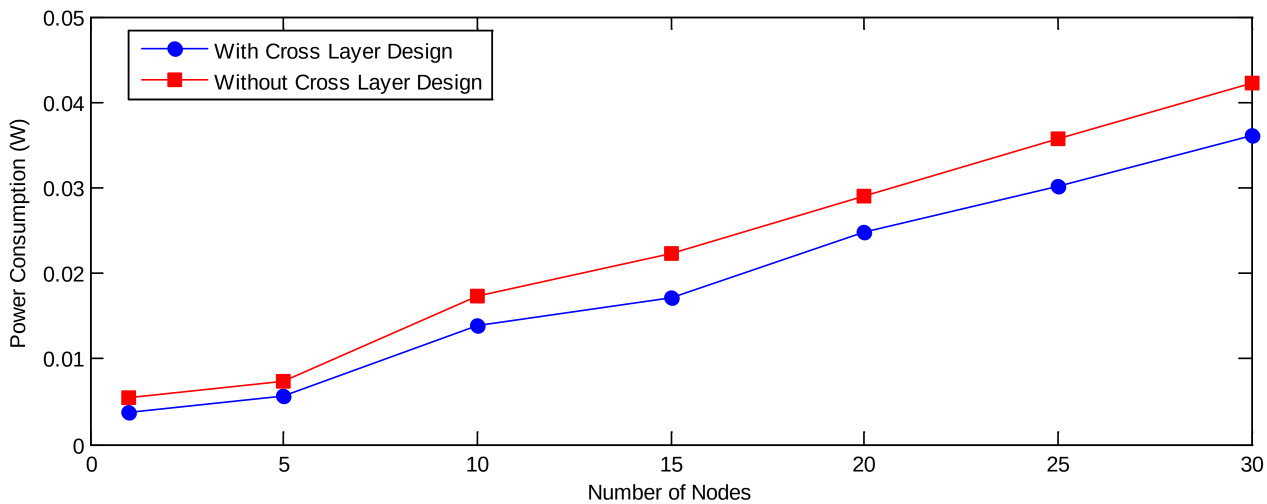


Fig. 5.6 (b): Power consumption as number of nodes are varied

Figure 5.7 summarizes the combined effect of varying both number of nodes and speed.

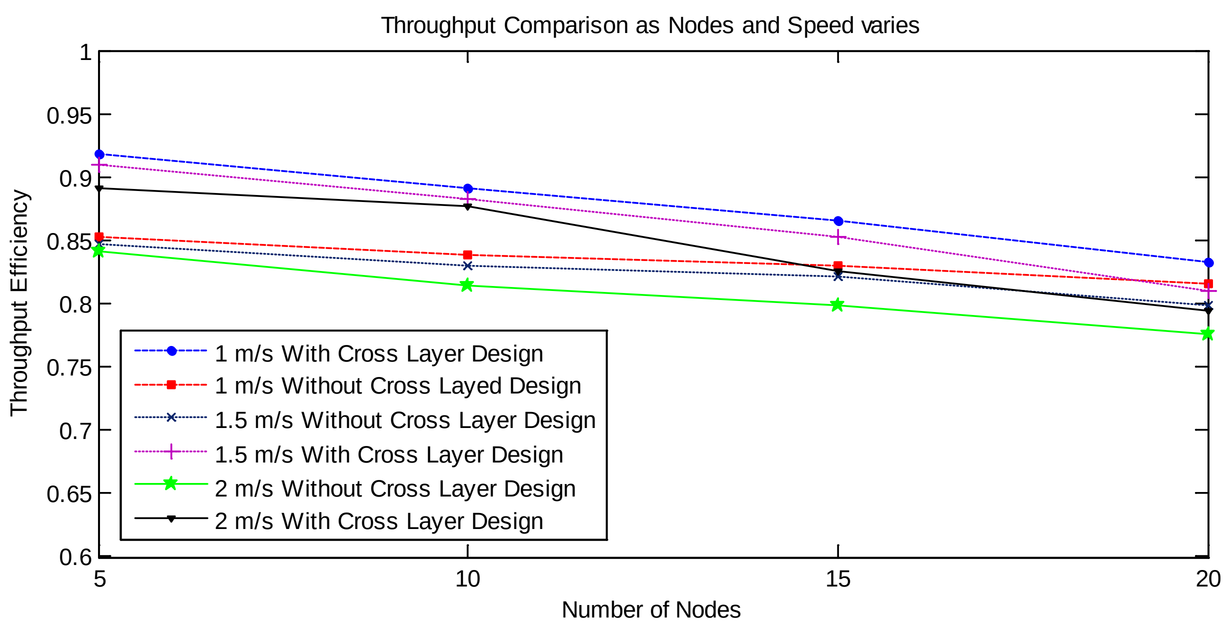


Fig. 5.7: Combined effect on throughput as both speed and number of nodes is varied

5.3.4 Summary of Results

In summary, cross layer 802.11 protocol has been presented as a solution to improving the performance of an extra-BAN under a Rayleigh fading channel. This algorithm has been applied to low mobility body area networks and is shown to enhance their outcome using the predictability of the channel. Small energy efficient nodes with cross layer 802.11 protocol can be used to communicate information from an intra-BAN to the base station rather than the conventional use of bulky PDA devices, or cell phones. This design offers an energy efficient solution to ambulatory monitoring systems where patients need to be monitored without compensating on their mobility.

For applications where the base station connectivity to the users is not strong, the solution will lie in routing data through other mobile nodes. On the other hand for environments where a server can be well connected to all nodes, single hop transmission can be used.

The approach and simulations presented in this chapter can further be extended to other scenarios such as communication to base station through a moving vehicle (VANET), whose speeds are higher. Also, our design can be combined with adaptive modulation at physical layer to model the channel in more than two states. Thus the degradation of the channel can be predicted and both MAC and PHY layer can adapt to it simultaneously.

6 CONCLUSIONS AND FUTURE WORK

This project has allowed the study of a new and promising field of wireless networks: the Body Area Network (BAN). Our work was aimed at evaluating an efficient scheme for the complete Body Area Network. To do this BANs were analyzed separately at two levels of network hierarchy – intra-BAN and extra-BAN. Our research focused on the performance of medium access control schemes for communication on the human body channel. Whereas, communication through the wireless channel was optimized using a cross layer approach. We conclude this thesis by summarizing the results of our analysis, followed by a section on directions for future research.

6.1 Conclusions

BANs have diverse applications such as health care, athlete monitoring, entertainment etc. And each application presents a different challenge to network designers. Researchers have concerned themselves with a study of health care scenarios where only a single user has been considered. No current research has presented a viable scheme which can be applied to multi user applications and also pertains with the requirements of on-body networks. In our work, we have considered a general case and studied the performance of BAN in a mobile environment. The most important parameters to evaluate the performance of a BAN are the energy and throughput efficiency for both on-body nodes and off-body nodes. To study both these metrics, BAN was simulated using NS2 network simulator.

A fixed network topology was considered for BAN on the human body. The on-body channel was modeled for frequency 2.4 GHz ISM band and throughput and energy consumption were analyzed at different transmission powers. Both single hop infrastructure based scenario as well as mesh topology were simulated, and it was proposed that intra-BANs are a hybrid of the two. Based on our analysis, a hybrid topology was proposed and TDMA was suggested as an optimal solution.

It is important that transmission of data from an intra-BAN to the main server does not get affected by the adverse effects caused by mobility of the user. To improve the performance for such situations, it was proposed that a cross layer design be applied to merge the PHY and MAC layers of standard IEEE 802.11 DCF protocol. The effects of increasing the number of nodes or the speed of the terminal were studied and compared using this design. It was found that for extra-BAN with mobile users, such as walking or running persons, the modified protocol has improved performance. This result provides an interesting and efficient alternative to the use of high power consuming devices as PDAs etc, which were considered by many researchers as the optimum solution for health care scenarios. Thus, we propose to replace the gateway agents, which were bulky and obtrusive, by power efficient sensor nodes using a cross layer modification of IEEE 802.11 protocol.

In conclusion, a feasible solution has been provided for the BAN architecture, and the schemes studied in this thesis are practically applicable. Usage of TDMA for on-body networks, and modified cross layer 802.11 for off-body network constitutes an efficient design for scenarios such as health care in hospitals, sports monitoring, indoor office monitoring etc. Furthermore, the approach and simulations presented in this thesis can form a basis for future research on WBANs taking into account mobility of the nodes on human body and other fading environments.

6.2 Suggestions for Future Research

The work presented in this thesis is just the starting point in the field of Body Area Networks. There were many assumptions taken during the course of our work as this was a first attempt at classifying the extra-BAN as well as intra-BAN for a mobile user scenario. As mentioned previously, our work can be extended to take into account different fading environments and applying the predictive cross layer design to them.

A peculiar extension of this work is based on the studies presented in [8]. The authors state that mobility is a predictable process in certain scenarios, such as sports and military. Then for such cases the channel between 2 terminals or a terminal and base station will also be correlated. This means that if autoregressive parameters are evaluated by experimentation, they can be used to calculate prediction coefficients in such cases. Then the design presented in our thesis can be modified according to correlated movement and used to predict the channel.

A further modification to make the extra-BAN simulation more accurate is to consider the direction of user with respect to base station. A connection between source and destination nodes passing through the body may suffer more path loss than a line of sight connection. This excessive path loss can be applied in conjunction with random waypoint model which is commonly used in simulation scenarios. If directional antennas are used, the connectivity may altogether change.

For the intra-BAN network it is suggested that channel models which take into consideration mobility of nodes on the human body as well be used. The absorption near head is more than that of the torso. Similarly, shadowing parameters are different for different parts of the body such as hands and legs etc, and are furthermore affected by mobility. Apart from that, the channel model for implanted nodes can be considered and performance of nodes inside the body can be simulated based on the topology considered in our work.

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