UNIVERSITY OF OULU

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MASTER'S THESIS

PERFORMANCE EVALUATION OF WAKE-UP RADIO BASED WIRELESS BODY AREA NETWORK

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ABSTRACT

The last decade has been really ambitious in new research and development techniques to reduce energy consumption especially in wireless sensor networks (WSNs). Sensor nodes are usually battery-powered and thus have very limited lifetime. Energy efficiency has been the most important aspect to discuss when talking about wireless body area network (WBAN) in particular, since it is the bottleneck of these networks. Medium access control (MAC) protocols hold the vital position to determine the energy efficiency of a WBAN, which is a key design issue for battery operated sensor nodes. The wake-up radio (WUR) based MAC and physical layer (PHY) have been evaluated in this research work in order to contribute to the energy efficient solutions development.

WUR is an on-demand approach in which the node is woken up by the wake-up signal (WUS). A WUS switches a node from sleep mode to wake up mode to start signal transmission and reception. The WUS is transmitted or received by a secondary radio transceiver, which operates on very low power. The energy benefit of using WUR is compared with conventional duty-cycling approach. As the protocol defines the nodes in WUR based network do not waste energy on idle listening and are only awakened when there is a request for communication, therefore, energy consumption is extremely low. The performance of WUR based MAC protocol has been evaluated for both physical layer (PHY) and MAC for transmission of WUS and data. The probabilities of miss detection, false alarm and detection error rates are calculated for PHY and the probabilities of collision and successful data transmission for channel access method Aloha is evaluated. The results are obtained to compute and compare the total energy consumption of WUR based network with duty cycling. The results prove that the WUR based networks have significant potential to improve energy efficiency, in comparison to conventional duty cycling approach especially, in the case of low data-reporting rate applications. The duty cycle approach is better than WUR approach when sufficiently low duty cycle is combined with highly frequent communication between the network nodes.

Keywords: WSN, WBAN, MAC protocol, energy efficiency, false alarm, miss detection, Aloha.

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PREFACE

This master's thesis has been conducted in partial fulfilment for the degree towards Master's Degree Programme in Wireless Communication Engineering at the Centre for Wireless Communications, University of Oulu, Finland.

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My heartiest gratitude goes to my parents and sisters for their love, encouragement and support.

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LIST OF SYMBOLS AND ABBREVIATIONS

α	wake-up activity rate
α_i	sample of noise
b_i	sample of signal
β	normalization factor
BW	bandwidth
λ	energy threshold
v	sensitivity
C_i	channel in kasami sequence
Cp	contention probability
CW	contention window
CW_{max}	maximum contention window
CW_{min}	minimum contention window
DC	duty cycle
E_b/N_o	energy per bit to noise ratio
f	frequency
G	offered load
H_0	hypothesis when no signal transmitted
H_1	hypothesis when signal transmitted
h	channel
N_o	noise power spectrum density
NF	noise figure
$n(t)$	noise waveform
P_f	probability of false alarm
P_m	probability of miss detection
P_d	packet duration
SNR_{min}	minimum signal to noise ratio
$s(t)$	signal waveform
T	integration time
T_1	wake-up time
T_2	sleep time
$T_{Packet\_duration}$	packet duration time
T_{tran_on}	sleep to idle mode transition time
T_{tran_off}	idle to sleep mode transition time
T_{wake_Tx}	wake-up signal transmission time
x_0	input for hypothesis H_0
x_1	input for hypothesis H_1
$y(t)$	detected signal
ACK	acknowledgement
AP	access point
BAN	body area network
BC	back-off counter
BW	bandwidth
CAP	contention access phase
CDF	cumulative distribution function
CP	contention probability

CRC	cyclic redundancy check
CSMA/CA	carrier sense multiple access/ collision avoidance
CSA	clear channel assessment
CW	contention window
DBPSK	differential binary phase shift keying
DCM	duty cycle based MAC
DER	detection error rate
DQPSK	differential quadrature phase shift keying
D8PSK	differential 8 phase shift keying
EAP	exclusive access phase
ECG	electrocardiogram
EFC	electrostatic field communication
FBAR	film bulk acoustic resonator
FCS	frame check sequence
FM	frequency modulation
FSC	frequency shift code
GMSK	Gaussian minimum shift keying
GSM	global system for mobile communication
GTK	group temporal key
GWR	generic wake-up radio
HBC	human body communication
IF	intermediate frequency
IoT	internet of things
IR	impulse radio
LPL	low power listening
MAC	medium access control
MCU	microcontroller unit
MICS	medical implant communication service
MK	master key
NB	narrowband
PDA	personal digital assistant
PHR	physical header
PHY	physical layer
PLCP	physical layer convergence protocol
PPDU	physical layer protocol data unit
PS	personal server
PSDU	physical layer service data unit
PTK	pairwise temporal key
QoS	quality of service
RAP	random access phase
RF	radio frequency
SCM	subcarrier modulation
SFD	start frame delimiter
SMS	short message service
SNR	signal to noise ratio
SPI	serial peripheral interface
TDMA	time division multiple access
UP	user priority
UWB	ultra wideband

WBAN	wireless body area network
WLAN	wireless local area network
WPAN	wireless personal area network
WSN	wireless sensor network
WUC	wake-up call
WUR	wake-up radio
WURx	wake-up receivers
WUS	wake-up signal
WUTx	wake-up transmitters

1. INTRODUCTION

Recent technological advances in wireless communications, mobile computation, and sensor technologies have enabled the development of low-cost, miniature, ultra-low power, lightweight and intelligent wireless sensor devices. A collection of these devices can be placed strategically on the key positions of the human body to perform sensing of certain physiological parameters, and connected by means of a wireless communication to form a Wireless Body Area Network (WBAN).

WBAN has recently attracted a great deal of attention from researchers both in academia as well as industry. This is generally due to its unique capabilities and promising applications in areas like healthcare, sports, fitness, military and security [1]. In the healthcare domain, WBAN promises to revolutionize healthcare system through allowing inexpensive, unobtrusive, non-invasive, ambulatory monitoring of human's health-status anytime, anywhere. WBANs are supposed to operate properly for long duration of time without any battery recharge or replacement, especially in the in-body (implanted) sensors case. Therefore, energy management is one of the major concerns for WBAN protocols so that recharging and replacement of batteries is as infrequent as possible and network is responsive for long period of time (network lifetime).

Medium access control (MAC) layer is considered appropriate to discuss energy and power issues. Several MAC protocols have been developed in this regard. Performance of MAC protocol is enhanced through utilization of low power mechanisms. The simple technique to enhance energy efficiency is to minimize the energy waste. Most of the energy is wasted during communication process because of the collision of packets, idle listening, over hearing, over-emitting, control packet overhead and traffic fluctuations [2]. Idle listening can be reduced through duty cycling. To reduce energy waste in order to increase network's life time and to enhance the performance of MAC protocol, different mechanisms are used. Some of these mechanisms are low power listening (LPL), scheduled contention, and time division multiple access (TDMA) [2]. In LPL, node awakes for a very short period to check activity of channel. If the channel is not idle, then the node remains in active state to receive data. In the scenario of highly varying traffic rates the performance of LPL is degraded. Scheduled contention is the combination of the scheduling and contention based mechanisms to effectively cope with the scalability and collision problems [2]. In contention based protocols, contending nodes try to access the channel for data transmission, therefore, probability of packet collision is increased as compare to LPL. In TDMA, a super frame comprised of a fixed number of time slots is used. Time slots are allocated to the sensor nodes by a central node. This scheme is highly sensitive to clock drift, which may result in limited throughput. The scheme is power efficient because a node gets time slot for transmission of data and remains in sleep mode for rest of the time. However, the synchronization requirements may degrade performance in terms of power consumption. These all schemes, along their benefits, have some downsides as well which are briefly discussed in this chapter. [2]

Duty cycling based methods have timer based wake-ups in which main radio is turned off, its microcontroller unit (MCU) is set into sleep mode and a timer is used to turn the node active periodically. Duty cycling has been widely used in WSN. However, it suffers an energy-latency trade-off issue. By setting the duty cycle accordingly, the trade-off between energy consumption and data latency can be managed.

With a higher duty cycle the packet delay is shortened because even if packet was generated when the receive node is asleep, it does not take too long until the next active period [3]. Though, in this case, energy consumption is high since the node is turned to active more frequently which leads to more idle listening. On the other hand, with a lower duty cycle, the node will consume less energy at the cost of higher latency for data delivery since sleeping period in each cycle is now longer. There is no way to improve the energy and latency performance at the same time by the duty cycling approach. The best way is to try to synchronize the whole system so that receiver is exactly in its active mode when the packet is generated at the transmitter side [3]. But there are two major disadvantages of synchronization. First, usually system events are not so periodical or predictable. This makes the synchronization process more difficult. Second, the synchronization process itself introduces overhead and complexities to the MAC protocol.

To break this energy and latency trade-off, wake-up radio (WUR) [4] provides a solution, as this is an on-demand approach where the node is woken up by the wake-up signal (WUS). A WUS triggers a node to wake up from the sleep mode to start reception/transmission activities. The WUS is received or sent by a secondary radio transceiver, which consumes extremely low power. The energy benefit of using radio wake-up in comparison with duty-cycling is that nodes do not waste energy on idle listening of the main radio, since they are only awakened when there is a request for communication. The latency benefit is that since wake-up radio is a purely on-demand approach, the only delay is the one introduced by the wake-up process itself.

The aim of this thesis is to evaluate the performance of WUR, based WBAN with focus on PHY and MAC layers and to calculate the total energy consumption of network utilizing the results. The performance metrics considered in this research work are false alarm probability, signal detection probability, miss detection probability and successful data transmission probability. The generic wake-up radio based MAC protocol (GWR-MAC) is evaluated regarding both physical layer (PHY) and medium access layer (MAC). The PHY includes WUS transmission and its effects in terms of false alarm, miss detection while MAC contains channel access and data transmission and its effects in terms of packet collision and successful transmission. These probabilities are then exploited to calculate the energy consumption of this approach of WUR and compare it with the conventional duty cycle management (DCM) based network.

This thesis is structured as follows. Chapter 2 gives a detailed description of WBANs and IEEE standard 802.15.6. The chapter also includes literature review of two layers of WBAN communication protocol stack, PHY and MAC. Chapter 3, gives an overview on wake up radios and discusses the existing protocols. This chapter also emphasis on the performance of generic wake up radio based MAC protocol. In Chapter 4, the simulation model for WUR based MAC protocol is derived for PHY and MAC layers. These results are evaluated and the performance of the very protocol regarding energy efficiency for the network is also evaluated. Chapter 5 provides a comprehensive discussion of these results and Chapter 6 gives the summary of this research work.

2. WIRELESS BODY AREA NETWORKS

With the rapid development of technology and wireless communications the expanse of sensor networks has grown significantly, supporting a range of applications including healthcare and medical systems. The healthcare sector is gradually eyeing for advanced information and communications systems to efficiently manage the healthcare progression for a range of services. Well advanced information and communication systems will be capable enough to offer healthcare not only for patients in hospitals and healthcare centers, but also in their workplaces and homes, thus offering cost savings and improving the quality of life of patients. There are already many prevailing medical monitoring systems which are using some very specialized equipment to communicate information using either standard telephone lines or specially designed networks for medical applications. However, these systems are location dependent and in most cases they are inept in nature due to use of wired sensors. Use of wireless body area networks can introduce location independent monitoring systems. WBAN can also be applied to sports and gaming areas where athletes can be supervised to improve their skills and find their deficiencies. [5]

2.1. Introduction

Body area network (BAN) is a short range wireless network that can potentially support a variety of medical applications from monitoring the functioning of implants to tracking vital signs and executing state of the art endoscopic exams. A WBAN comes up with many promising new applications in the area of medical care, remote health monitoring, home health care, sports, games and multimedia, all of these produce advantage of freedom of movement the WBAN offers. In the field of healthcare, a patient can be equipped with a network which consists of sensors that continuously measure particular biological functions, like, blood pressure, heart rate, temperature, sugar level, electrocardiogram (ECG) and respiration rate etc. There are a lot of advantages of this network, the patient does not need to be there in the hospital or to stay in the bed, but can easily move around. It reduces the hospital's costs and improves the quality of life. The evident advantage is that the data collected in natural environment of the patient and over a longer period, offers very beneficial information, complying for a more precise and even faster diagnosis. As discussed in [6], sensor nodes are greatly power constrained and power budget for communication is limited. This is the reason that energy efficiency is an important aspect in WBAN because with limited power, long duration of operation is expected. For low power consumption, the basic idea is to minimize the energy consumption in sensing, data processing, and communication. In the communication process most of the energy is wasted because of the idle listening, collision of packets, over hearing, control packet overhead and traffic fluctuations. In [7], writers provide relatively comprehensive study of energy minimization techniques in MAC protocol. The most appropriate layer for discussing power and energy issues is MAC layer. To save energy in order to increase network's life span and to enhance performance of MAC protocol, different mechanism have been developed. One common mechanism, as discussed in [8], is duty cycling. In duty cycling, each node switches between active and sleep state, and the active/ sleep schedule can vary from node to node. Duty cycle is measured as the ratio of listening period length to total period length. If the duty cycle is small, it means that the node is asleep most of the time in order to avoid idle listening and overhearing. Duty cycling is easy in implementation and is an effective way for energy preservation. Further, the concept of low duty cycle comes up, with the basic idea of reducing the time a node is idle or spends overhearing an unnecessary activity by putting the node in sleep state. For low duty cycle, the most ideal condition is when a node is asleep most of the time and wakes up only to transmit or receive data. But duty cycling has several drawbacks including energy wastage and data latency. To save energy a low duty cycle can be used so that the nodes can sleep longer, whereas fewer nodes are available to participate in data routing at any given time. This approach can save energy but it will decrease throughput and increase the transmission latency. So there is a trade-off between energy efficiency, transmission latency, and throughput, determined by the nodes' duty cycles. According to the literature, the low duty cycle is characterized as a periodic wake-up mechanism. [9]

A WBAN consists of small intelligent devices, i.e., sensors, as in Fig. 1 [10], that are placed on the body, in the body or close to the surface of the body. These arrangements allow for the continuous monitoring of a patient's condition regardless of the patient's location. The WBAN generally expands over the whole human body and the nodes are linked through a wireless communication channel. As per implementation, these nodes are situated in multihop or star topology. Speaking of the two mentioned devices, sensors are used to measure certain human body parameters internally or externally such as body temperature, recording a prolonged ECG or heartbeat. Actuators are used for some specific actions according to some predefined schedule or information they receive through interaction with the user or sensors. Usually interaction with the user or other person is handled by a personal device, e.g., a Personal Digital Assistant (PDA) or a smart phone which acts as a sink for the data of wireless devices. [7] [11]

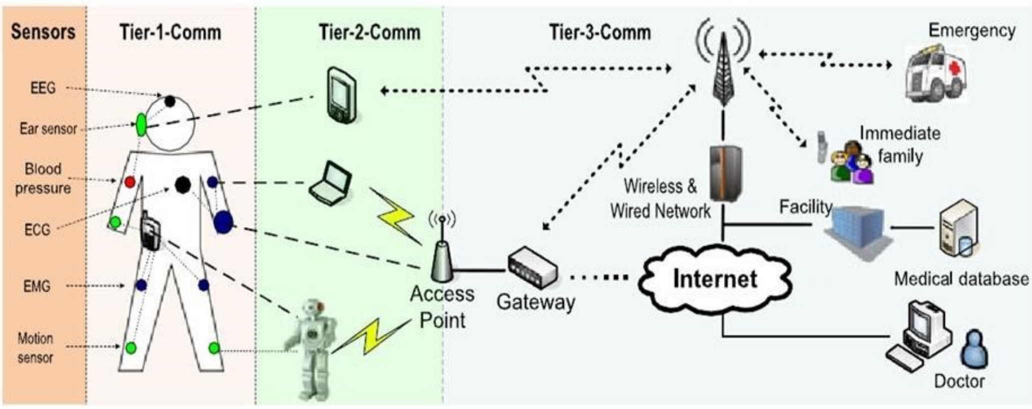

Figure 1. A three-tier architecture based on BAN.

The communication architecture of WBAN is divided into three different tiers, mentioned in Fig. 1 [6], as follows:

- Tier-1: Intra-WBAN communication
- Tier-2: Inter-WBAN communication
- Tier-3: Beyond-WBAN communication

Tier-1: Intra-WBAN communication: Tier-1, which is the actual WBAN, is defined as the radio communication between two sensors or between a sensor and a portable device, e.g., a cellular phone or a personal server (PS) [12]. A PS is a device which collect data from sensors and process to get some meaningful results. PS is quite a complex multipurpose device which should be equipped with radios to communicate with body sensor networks. In architecture, coordinator or gateways are similar as sensor nodes from which they collect data, forward it to APs and then APs route the data on internet to remote database/sever. The typical intra-WBAN designs proposes multiple sensors forwarding body signals to a PS that in turn forwards the processed physiological data to an AP. [13]

Tier-2: Inter-WBAN communication: Inter-WBAN communication is between PS and APs. In Tier-2, WBAN can be interconnected with various networks which can be accessed in cellular networks and internet as well as in daily life [13]. Tier-2 is further sub-categorized in two parts, *infrastructure based architecture*, which assumes limited space environment such as home, office or waiting room. Centralized management and security control through the APs are significant features of infrastructure based networks. The other is *ad hoc based architecture*, which uses multiple APs to cover a larger network area. The APs in ad hoc network form a mesh structure, allowing flexible wireless deployment that can be rapidly installed. [12]

Tier-3: Beyond-WBAN communications: A gateway, e.g. a PDA, is used to bridge the connection between Tier-2 and Tier-3. A database, in a medical environment, is one of the most essential components of Tier-3, as it contains the profile of the user and his/ her medical history. Hence, the patients or doctors can be alerted of an emergency status through either a Short Message Service (SMS) or internet. Furthermore, Tier-3 restores information of a patient which can be helpful in further treatment. [13]

The complete system diagram of a WBAN transceiver is shown in Fig. 2. In the transmitter block, the PSDU from the MAC layer is processed to generate a PPDU packet. In the transmitter baseband processor module, signal processing and channel coding are performed on the PPDU. First, the baseband raw data is modulated and then directly converted to a RF signal. In the receiver block, first the RF signal is down-converted to Intermediate Frequency (IF) signal and then demodulated by a low power demodulator, which is dependent on PHY and its mode. After the demodulation, the received signal is processed by the receiver baseband processor module and then the received PSDU is transferred to MAC layer. [13]

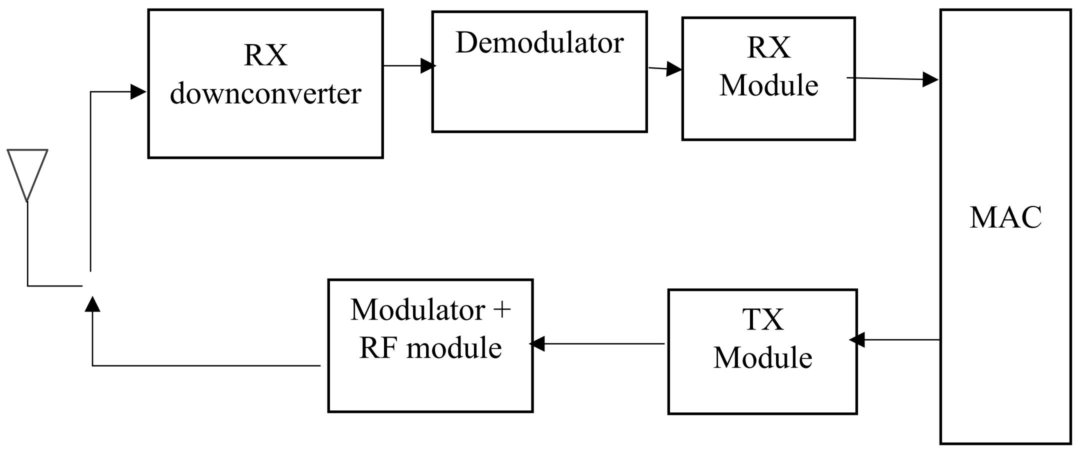

Figure 2. Block diagram of WBAN radio transceiver.

2.2. IEEE Std. 802.15.6

With exponential proliferation in the demands of wireless communication and reckoning the great potential to revolutionize the prospect of healthcare technology, several wireless technologies have been developed. Wireless Sensors Networks (WSN) have been studied extensively and are considered intelligent sensor nodes which are capable of collecting, processing and sending information to the base stations. WBAN is considered a type of WSN. Recently, WBAN have been studied in the literature and is generally focused on technical issues of WBAN. The IEEE has defined numerous protocols to support different access networks e.g. WiMax (IEEE Std. 802.16), Wireless Local Area Network (WLAN) (IEEE Std. 802.11) and Wireless Personal Area Network (WPAN) (IEEE Std. 802.15). IEEE 802.15 Task Group 6 (BAN) has developed a communication standard optimized for low power devices and maneuver on, in or around the human body but not restricted to medical usage, providing variety of applications including personal entertainment, consumer electronics and sports. [14] [15] [16]

In IEEE Std. 802.15.6, nodes are classified based on the way they are implemented within the body, as follows:

Sensor: sensors are used to measure certain parameters in a body either externally or internally. They collect data, process data, respond to data on physical stimuli, and provides wireless response to information. Sensors are of numerous types like, ambient sensors, physiological sensors, and biokinetics. [13]

Personal Device (PD): It is responsible of collecting all the information from actuators and sensors and managing communication with other users. PD notifies the user about different information via an external gateway, a display/LED on the actuators or other devices. [13]

Actuator: On the reception of data from sensors, the actuator interacts with the user. It has the responsibility of providing feedback in the network by acting on sensor data. [12]

External Node: it is not in contact with the human body, somewhat a few centimeters to 5 meters away from the body.

Body Surface Node: this node is either placed on the surface of the human body or 2 centimeters away from the body.

Implant Node: this node is planted in the human body, either inside the body tissue or immediately under the skin.

End Nodes: These nodes are classified to performing their embedded applications. Though, they are not adept of relaying messages from other nodes.

Relay: The intermediate nodes are called relays. They have a parent node, own a child node and relay messages. If a node is at extremity e.g. a foot, any data sent is essential to be relayed by other nodes before reaching the PDA. Also these nodes are capable of sensing data.

Coordinator – This node is like a gateway to the outer world, another WBAN, a trust center or an access coordinator. The coordinator of a WBAN can be the PDA, through which all other nodes communicate. [13]

The WBAN operates in a one-hop or two hop star topology with the node in the center of the star being positioned, for example, in the waist. Data transmission in onehop star topology is of two types: transmission from device to coordinator and transmission from coordinator to device.

In the star topology the communication methods that exists are *beacon mode* and *non-beacon mode*. Talking about former, the beacon mode, the network coordinator which is the node in the center of the star topology controls the communication. It transmits periodic beacon to define the start and end of a superframe to enable network association control and device synchronization. The user, during the configuration of the device, can specify the duty cycle of the system, which is the length of the beacon period. In the later, the non-beacon mode, a node in the network is capable of sending data to the coordinator and can use, for example, Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) when essential. The nodes need to wake up the coordinator to receive data. The coordinator, however, cannot communicate with the nodes all the times and the nodes must wait till they are requested to participate in a communication. The network is considered to have a one-hop star topology, when all the nodes in the network have a direct connection with the sink. The coordinator, in the WBAN, is known as the sink node to which all the nodes communicate. While in the multihop communication in the WBAN, all the nodes are connected to Access Points (APs) through other nodes. [13] [16]

The hub or the coordinator allocates the time axis/ channel, for time referenced resource allocation, into a series of superframes (in case of superframes boundaries) or the coordinator provides unscheduled Type II polled allocations (in case of without superframe boundaries) [15]. These superframes are further bounded by beacon periods of equal length.

To ensure high level security, standard entitles three levels, [17]

- Level 0: Unsecured Communication
- Level 1: Authentication Only
- Level 2: Authentication and Encryption

Level 0: Unsecured Communication: There is no mechanism for data authentication, confidentiality, privacy protection and integrity as data is transmitted in unsecured frames. It is pondered as the lowest security level. [15]

Level 1: Authentication Only: This is the medium security level where transmission data is authenticated but not encrypted. At this level confidentiality and privacy is not supported. [15]

Level 2: Authentication and Encryption: The highest security level where data is transmitted in secured authentication and encryption frames, hence providing measures for authenticity, privacy protection, replay defense, confidentiality and integrity validation. Level 2 furnish solutions to all of the problems which were not covered by level 0 and 1. [15]

The vital security level is selected in the course of association process. In unicast communication, a new key (generated through unauthenticated association) or a preshared Master Key (MK) is activated. Auxiliary, a Pairwise Temporal Key (PTK) is generated that is used once per session. In multicast communication a Group Temporal Key (GTK) is generated and shared with its corresponding group. In WBAN, before data exchange, all nodes and coordinators have to go through certain stages at the MAC layer. By this, frames are required or allowed to exchange between a node and a hub at each stage. [13]

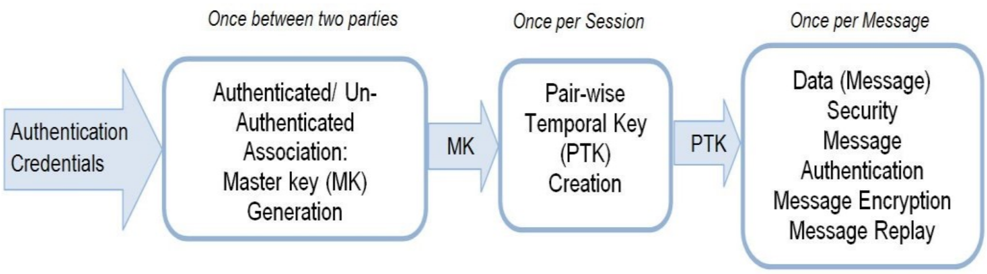

Figure 3. Security paradigm of IEEE Std. 802.15.6.

To complete or achieve the security process the nodes have to go through various states, the first is the *Orphan* state, where nodes does not have any relationship with the coordinator for secured communication. Then the *Associated* state, where the node contains a shared MK with the coordinator for their Pairwise Temporal Key (PTK) creation, stating that the node is associated. After association comes the *Secured* state, where the node is secured because it contains a PTK with the coordinator for secure frame exchanges. The last state is *Connected* state. At this state, the node is connected and holds an assigned *Connected_NID,* a wakeup arrangement and schedule allocation(s) with the coordinator, anticipated wakeup and optionally scheduled and unscheduled access. [13]

As discussed in [16], the aim of IEEE Std. 802.15.6 standard is to support in fulfilling the requirements of WBAN through low cost, low power, low complexity and reliable transmission. The standard defines a Physical layer (PHY), which has three different options such as Narrowband (NB), Ultra-Wideband (UWB) and Human Body Communication (HBC). On top of PHY, standard defines a MAC to control access to the channel. [15] [18]

Fig. 4 [18] illustrates the low power transceiver protocol stack layer. In IEEE Std. 802.15.6 PHY and MAC layers are considered only. At the physical layer, protocols need to take account of how the body reacts to Radio Frequency (RF) communications and the complications therein. The characteristics of RF signals at the physical layer can be separated into signal propagation effects in and along the human body and how body movement has an impact on the transmission of RF signals. The transmission of RF signals is a major overhead for the energy efficiency of a WBAN. The MAC layer controls the channel access, packet encoding, addressing and as such must achieve maximum energy efficiency and data throughput by the efficient management of these functions. [18]

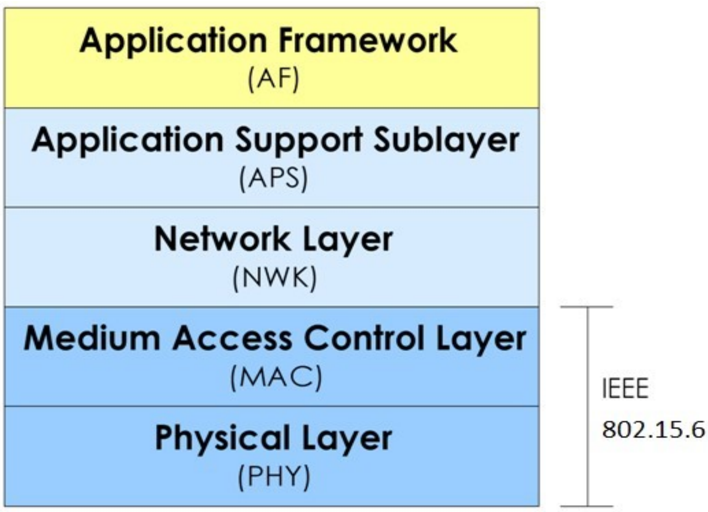

Figure 4. Low power transceiver protocol stack layer.

2.2.1. *Physical Layer*

The PHY is generally responsible for establishing a link, reliable and physical, to transmit binary data. The selection of PHY depends on the intended application: in, on or off body, medical or non-medical. The PHY compromises a procedure for transforming a Physical layer Service Data Unit (PSDU) into a Physical layer Protocol Data Unit (PPDU). [13] [19]

IEEE Std. 802.15.6 define three different physical layers: NB, UWB and HBC, which are introduced below.

Narrowband: Narrowband PHY is targeted at communication with the wearable nodes on body and implanted nodes in body. It is responsible for activation or deactivation of the radio transceiver, data transmission and reception and Clear Channel Assessment (CSA) within the current channel. According to the specifications, in order to construct PPDU, PSDU has to be pre-appended with the Physical Layer Preamble (PLCP) and a Physical layer Header as shown in Fig. 5 [9]. The PLCP preamble supports the receiver in time synchronization, packet detection and carrier offset recovery. After the PLCP preamble, the PLCP Header is sent by using the data rates specified in its operating frequency band. It transfers the required information needed to successfully decode a packet to its receiver. Each PLCP preamble is built by concatenating a length-63 m-sequence with an extension sequence. Therefore, the length of the preamble is 90 bits. The m-sequence is used for coarse-timing synchronization, packet detection, and carrier offset recovery while the extension sequence is used to implement fine-timing synchronization. The PHY header contains information of the length of MAC frame body, data rate of MAC frame body and whether the next packet is being sent in a Burst Mode. This information is vital to decode the PSDU at the receiver. The PSDU which is the last element of PPDU, comprises of a MAC Header, a MAC Frame Body and a Frame Check Sequence (FCS). In NB PHY, standard uses Differential 8 Phase Shift Keying (D8PSK), Differential Quadrature Phase Shift Keying (DQPSK), Differential Binary Phase Shift Keying (DBPSK) modulation methods except 420-450 MHZ band which uses Gaussian Minimum Shift Keying (GMSK) method. [13] [19]

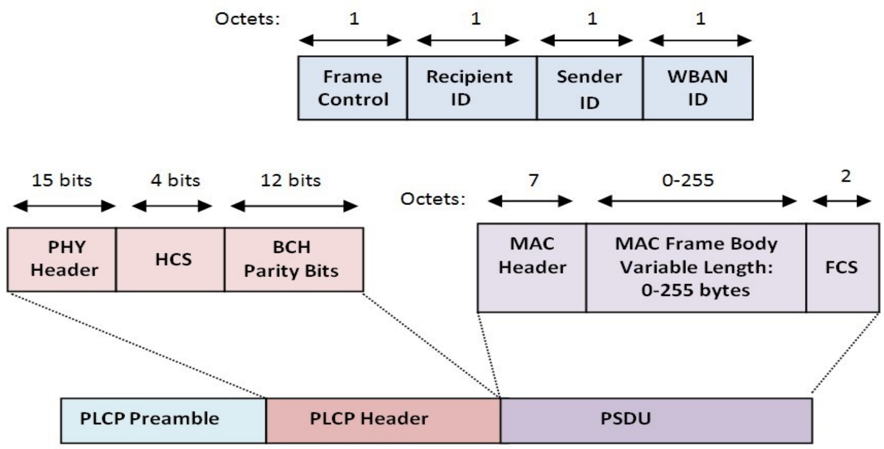

Figure 5. NB PPDU structure.

Ultra-Wideband: The UWB PHY improves robustness of WBAN, provides prospects for implementation of high performance, low complexity and low power consumption operation. UWB PHY comprises of two different types of UWB technologies, namely, Impulse Radio (IR-UWB) and wideband Frequency Modulation (FM-UWB). The specification contains two modes of operations; default mode and high Quality of Service (QoS) mode.

The default mode is used for medical and non-medical applications. In the default mode IR-UWB is mandatory PHY and FM-UWB is optional PHY. As discussed in [22], high Quality of Service mode is used for high priority medical applications and it supports only IR-UWB.

The UWB PHY is used in communication between on body devices and for on body and off body devices. In UWB PHY transceivers produce similar power level as in MICS band and also allow low complexity implementation. The standard outlines 11 channels, 0 to 10, each has a bandwidth of 499.2 MHz. The channels are further divided into two groups, low band and high band. Low band holds three channels, 0 to 2, whereas High band contains eight channels, 3 to 10, all are mandatory except channel 6. The central frequencies, bandwidths, and channel attributes are mentioned in Table 1 [16].

Table 1. UWB operating frequency bands

Band group	Channel no	Central-frequency (MHz)	Bandwidth (MHz)	Channel-attribute
Low band	0	3494.4	499.2	Optional
	1	3993.6	499.2	Mandatory
	2	4492.8	499.2	Optional
High band	3	6489.6	499.2	Optional
	4	6988.8	499.2	Optional
	5	7488.0	499.2	Optional
	6	7987.2	499.2	Mandatory
	7	8486.4	499.2	Optional
	8	8985.6	499.2	Optional
	9	9484.8	499.2	Optional
	10	9984.0	499.2	Optional

As per design specifications, the PPDU bits are transformed into RF signals for transmission in the wireless channel. UWB PHY comprises of a Synchronization Header (SHR), Physical Header (PHR) and a PSDU. SHR consists of recurrences of Kasami Intervals of length 63. [13] [19]

Kasami sequence of length 63 is used to construct preamble. There are eight Kasami sequences, each is indexed by C_i, for $i = 1, \ldots, 8$. The set of sequences is divided into 2 pools, where each pool contains four preamble sequences. The first pool, C_1 to C_4 is used for odd number of physical channels, whereas C_5 to C_8 for even number of physical channels. So, for every physical channel, four logical channels are available. The coordinator uses the preamble sequence with minimum received power level by scanning all the logical channels. By using preamble sequences coexistence of BANs and interference mitigation improves as different BANs use different preamble sequences. [16]

SHR is made up of two subfields: the first is a preamble, aimed for packet detection, frequency offset recovery and timing synchronization; and the second is Start Frame Delimiter (SFD), shown in Fig 6. [13] [19]

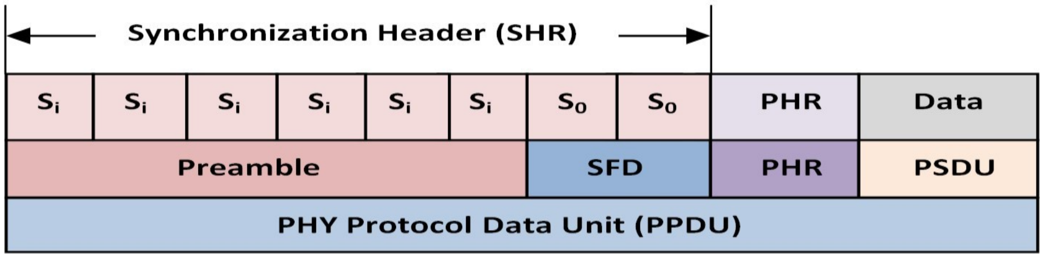

Figure 6. UWB PPDU Structure.

The PHR carries information about length of the payload, data rate of the PSDU and information about the scrambler seed. The receiver uses this information in the PHR to decode the PSDU. [13]

UWB frequencies provides higher data rates and throughput while lowest frequencies face less shadowing and attenuation from the body. [13]

Human Body Communication: Human body communication PHY uses Electrostatic Field Communication (EFC), which entails modulation, SFD and packet structure. Its transmitter, instead of antenna, needs one electrode and implemented with only digital circuits. No RF modules required during the realization of the receiver which makes equipment easy to carry and power consumption very low. PLCP Preamble, Start Frame Delimiter (SFD), PLCP Header, and PHY Payload (PSDU) constitutes the entire HBC PHY layer, as shown in Fig. 7 [13]. The Preamble and SFD are defined data patterns. They are pre-generated and sent afore the payload and packet header. The preamble sequence is transmitted four times to assure packet synchronization while the SFD is only transmitted once. The primary PLCP Preamble is composed of 64 bit gold code sequence which is repeated four times and spread using Frequency Shift Code (FSC). The SFD sequence is also composed of 64 bit gold code generator and is spread using FSC. On reception of a packet the receiver uses a preamble sequence to detect the initiation of the packet. Afterwards, it detects the start of the frame by using SFD. The PHY Header holds following fields: Data Rate, Pilot Information, Synchronization, WBAN ID, Payload length and a CRC calculated over the PHY Header. [13] [19]

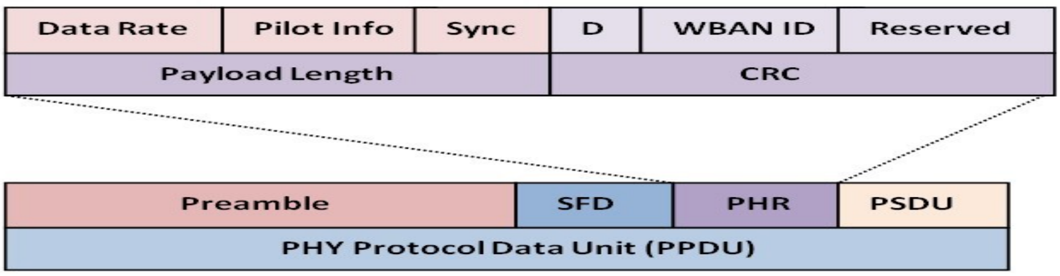

Figure 7. HBC PPDU structure.

The HBC PHY has a bandwidth of 4 MHz, operates in two different frequencies centered at 16 MHz and 27 MHz. The center frequency for the transmission is selected by using the specific frequency selective spreading code of the data transmitted. The data rate distributed in 164.1kbps, 328.1kbps, 656.3kbps, or 1312.5kbps respectively. The frequencies and bandwidths of the above mentioned three physical layers are given in Table 2. [13] [19] [23]

Table 2. Frequency and bandwidth of different PHY layers of IEEE Std. 802.15.6

Frequency	Bandwidth
Narrowband communication	
402–405 MHz	300 KHz
420-450 MHz	300 KHz
863–870 MHz	400 KHz
902–928 MHz	500 KHz
956–956 MHz	400 KHz
2360–2400 MHz	1 MHz
2400–2438.5 MHz	1 MHz
Ultra-Wideband communication	
3.2-4.7 GHz	499 MHz
6.2-10.3 GHz	499 MHz
Human body communication	
16 MHz	4 MHz
27 MHz	4 MHz

2.2.2. ***MAC Layer***

The IEEE Std. 802.15 Task Group 6 delineates a MAC layer on top of the PHY layer in order to control channel access. The MAC layer works under three different access modes: beacon mode with beacon period superframe boundaries, non-beacon mode with superframe boundaries, and non-beacon mode without superframe boundaries. Before going into detail of various modes, below is the general idea about the terms used to describe the mechanism. [13] [23]

The channel access in WBAN is organized using superframe structures. The superframe is composed of beacons and each beacon is of the same size. The hub divides the entire channel/ time axis into a chain of superframes for time referenced resources. The hub selects boundaries of beacon periods and transmits a beacon frame at every superframe beacon period. The hub also shifts the Offsets of the beacon periods. The beacons are generally transmitted in each beacon period unless prohibited by regulations in MICS band or inactive superframe. [13] [23]

Beacon is a signal transmitted along the initial slot of any superframe, as shown in Fig. 8 [23]. It is transmitted by a hub to facilitate network management, such as the coordination of medium access and power management of the nodes, and to facilitate clock synchronization in the body area network.

In case of emergency traffic, Exclusive Access Phases (EAP) are used. These access phases are used if the data to be transmitted is of high priority than its preceding data. These access phases are of two types, EAP1 and EAP2. Besides these, there are Random Access Phase (RAP) and Contention Access Phase (CAP), which are used for the normal traffic when there is no critical emergency traffic. Moreover, RAP is of two types, RAP1 and RAP2. For uplink, downlink and bi-link allocation, type1 access phase is used. It improvises, polled and posts, both allocations outside the certain scheduled allocations as well as bi-link scheduled allocations. Type1 allocation is defined in terms of its time duration while Type2 is for frame count. The latter is generally used for bi-link and delayed bi-link allocation intervals. [23]

Beacon Mode with Beacon Period Superframe Boundaries: In this channel access mode, the hub sends a beacon frame in every beacon period during the issue of each superframe unless prohibited by restrictions in the MICS band or inactive superframes. In IEEE 802.15.6, superframe structure comprises of Beacon, EAP1 and EAP2, RAP1 and RAP2, Type I/II phase and CAP, as shown in Fig. 8. [23]

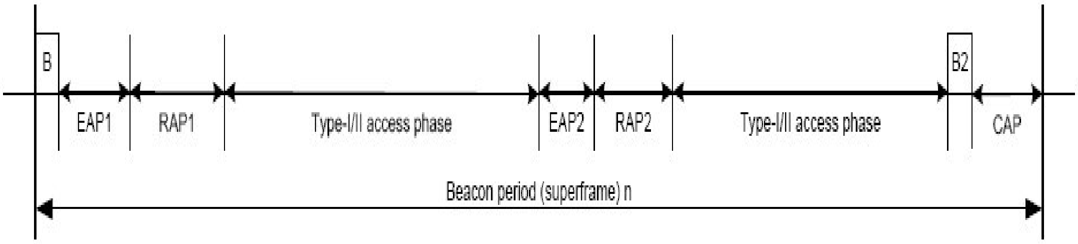

Figure 8. Beacon mode with beacon period superframe boundaries.

The hub manages the communication of superframe structure by using Beacon frames or Timed frames (T-Polls). According to the given structure, in EAPs, RAPs and CAP, nodes contend for resource allocation by either slotted Aloha access procedure or CSMA/CA. For high priority traffic, EAPs are applied while RAPs and CAP are utilized for normal traffic. Type Phase I/II are used for bi-link allocation intervals, downlink allocation intervals, uplink allocation intervals, and delay bi-link allocation intervals. For resource allocation in Type I/II, polling is used. On the basis of application requirements, any of these periods can be deactivated by setting the duration length to zero [13] [23]. According to IEEE standard [12] and as Flavia Martelli, *et al.* stated in [20], only Type-I/II access phases are used for scheduled allocation, whereas EAPs, RAPs and CAP use CSMA/CA or Slotted Aloha for allocations, which takes place by contention between different nodes.

Non-Beacon Mode with Superframe boundaries: This access mode is not adept of transmitting beacons, so used the Timed frames (T-poll) of the superframe structure. The hub/ coordinator, as shown in Fig. 9 [23], can have superframe only one in Type I or Type II access phase, but not both. The transmission time is relative to the beginning of recent superframes, as given by the Timed frames (T-Polls). T-Poll is analogous to the Poll frame containing a transmit timestamp for superframe boundary synchronization. [13] [23]

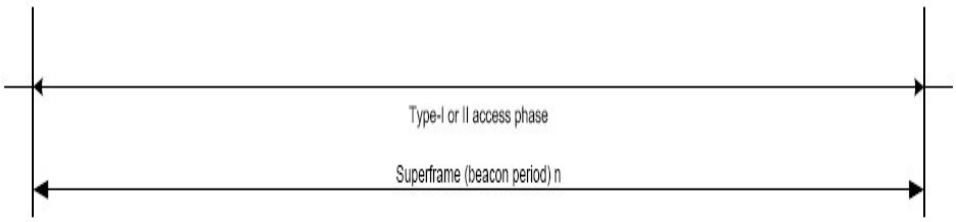

Figure 9. Non-beacon mode with superframe boundaries.

Non-Beacon Mode without Superframe Boundaries: In this access mode, there are no superframe boundaries. As illustrated in the Fig. 10 [23], the hub or the coordinator only provides Unscheduled Type II polled allocation, which means that every node has to fix its own time scheduled independently. [13] [23]

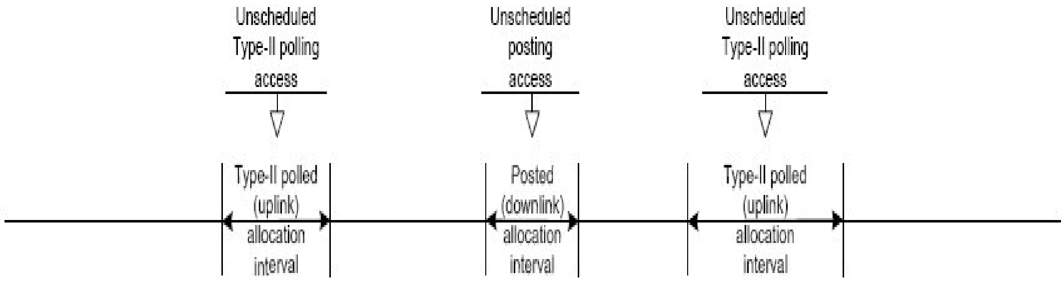

Figure 10. Non-beacon mode without superframe boundaries.

Access Mechanism

The allocations in EAPs, RAPs and CAP are confined and the access methods for allocations are CSMA/CA and Slotted Aloha access. When the hub or a node sends data type frames in an emergency access phase with a high priority, the hub can obtain contended allocation, and this procedure is performed without affecting the slotted Aloha access mechanism or CSMA/CA. However, when the hub needs to send data either in RAP or CAP, the allocation is reserved and does not have preemptive privilege of an EAP. [23]

CSMA/CA: It uses a back off counter and a contention window to attain a new allocation. A node holds the privilege to initiate, use, adapt, halt or terminate a contended allocation. As Fig. 11 [16] shows that the node initializes its counter to a random integer value between one and a contention window (*CW*). According to the user priority, *CW* varies from *CWmax* to *CWmin*. Afterwards, the counter constantly decremented till a CSMA slot is equivalent to the pCSMASlotLength. As the counter stretches to zero the data is transmitted.

When the counter reaches *CWmax*, i.e., high priority, the *CW* will be doubled and the channel will be busy. [23]

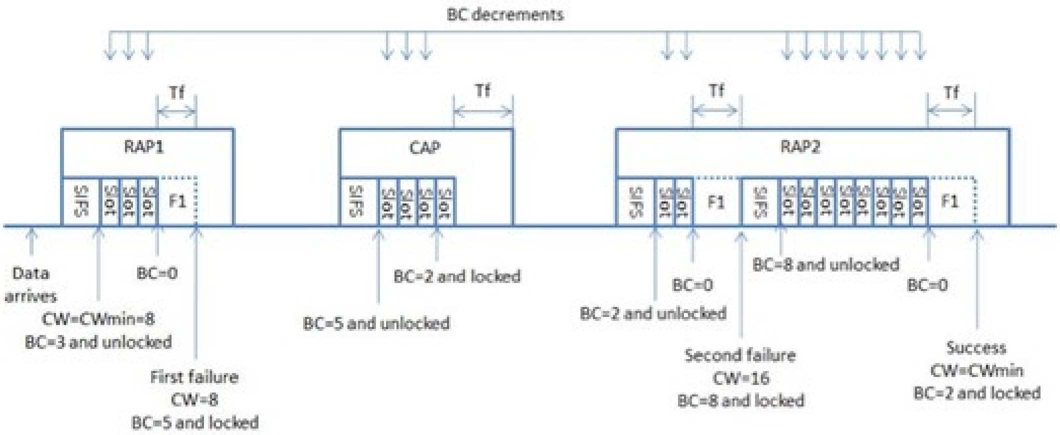

Figure 11. CSMA/CA illustration.

As described comprehensively in IEEE 802.15.6 standard [16], a node shall set its back-off counter to a sample of an integer random variable uniformly distributed over the interval [1, *CW*], to obtain a new contended allocation, when its back-off counter (BC) has a value of zero and the node has at least one frame of user priority (UP) or higher to transmit or retransmit, where *CW* configuration is described in the below following sections. [16]

If the node did not get any allocation slot or if the frame transmission was successful, node shall set CW to CWmin. The CW will not be changed, if the transmitter node does not require an acknowledgment (ACK) frame or if this is its m^{th} time where the node has failed consecutively, where m is an odd number. If the node has failed consecutively n^{th} time, while n is an even number, the CW is doubled. The CW is set to CWmin, if after doubling it exceeds CWmax. [16]

If the channel is busy, BC is locked by the node until the end of the current frame transmission. It will also remain locked, if the current time is outside of RAP and CAP for regular traffic or if the current time is outside of EAP, RAP, and CAP for emergency traffic. If there is not enough time to complete the current transmission, the BC is also locked. Whereas, the BC is unlocked when there is enough time to finish the current transmission and when the channel is idle for the pSIFS period within a CAP or RAP for regular traffic. [16]

The node shall decrement its BC by one for each idle CSMA slot that follows, upon unlocking its BC counter. The node considers a CSMA slot to be idle if it determines that the channel has been idle between the start of the CSMA slot and pCCATime, where pCCATime, as defined in [25], is the time required by the PHY to detect a transmission (or an idle period) and indicate the detection to the MAC decrementing the BC effectively. Each CSMA slot shall have a fixed duration of pCSMASlotLength. [16]

Slotted Aloha Access: Contention probability, as discussed in [26], is used in this access mechanism. In an Aloha slot, as shown in Fig. 12, a node gets a new contended allocation based on the probability. A node has the analogous privileges as a CSMA/CA mechanism. [23]

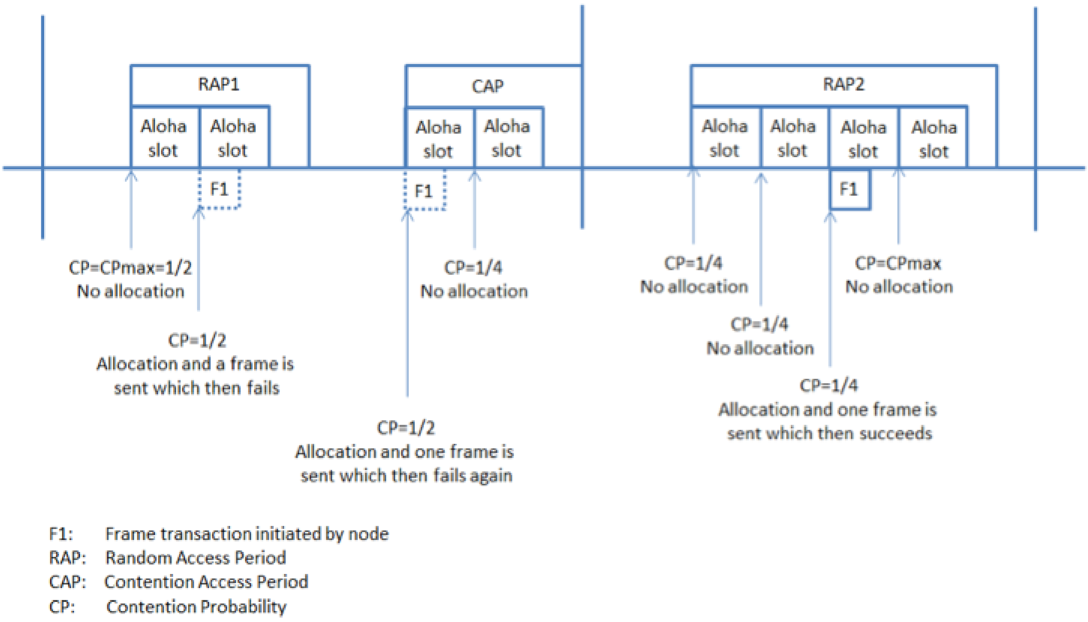

Figure 12. Slotted Aloha Access illustration.

The contention probability, *CP*, is randomly selected from the interval [0, 1] and shall be configured in a way that if the node does not get any contended allocation or if a node receives an expected acknowledgement, the *CP* is set to *CPmax*. If the transmission did not require an ACK or if this is the m^{th} consecutive failed transmission, where *m* is an odd number, the *CP* shall not be changed. Whereas, it will be halved, if this is the n^{th} consecutive failed transmission, where *n* is an even number. After being halved, if the *CP* value is smaller than *CPmin*, it shall be set to *CPmin*. [16]

Unscheduled access: A hub, in this access mechanism, employs unscheduled polling/posting access to send polls or posts at any time across the frame. The active bit of the node will be set to 1 and the node will remain active keeping itself available for polled or posted allocations which may be unscheduled. [23]

Improvised Access: A hub may utilize unscheduled posting or polling access and has the privilege of a RAP in both polling and posting allocations. [23]

3. WAKE-UP RADIO COMMUNICATIONS

In WBANs, as mentioned earlier, energy efficiency is one of the important aspects and a lot of efforts have been undertaken at different levels to reduce energy consumption. According to [27], several efforts have been made to propose energy efficient waveforms and optimized RF frontends. At MAC layer several methods are used to overcome the energy waste problem, for example, dynamically adapting active/sleep duty cycle. However, wireless communication still suffers from three key problems which affect the power consumption: idle listening, overhearing and packet collision [28]. To resolve these orthodox MAC problems to some extent, a novel approach of wake up radio is being used. WUR offers a solution to break the energy-latency tradeoff. In [29], first introduced the idea of using a WUR beside the main radio in sensor networks. It ensures that the main radio's energy consumption is significantly reduced, by keeping the main radio in sleep mode [28]. WUR is an on demand approach in which the sleeping node is woken up by triggering a radio signal, named as Wake-Up Signal, which can either be multicast to all nodes within range or targeted to wake up a specific node depending on the design and routing protocol used [30]. The WUS triggers a node to wake up from the sleep mode and initiate transmission/reception procedures. The secondary radio transceiver which consumes very low power transmit and receive wake up signal. Comparing WUR with duty cycling, the former offers very low energy consumption as the nodes do not waste energy on idle listening, since they are only awakened when the communication in requested [3].

In WUR, multiple radios will be implemented and there will be no extra burden of sleep/awake synchronization and schedule between the nodes. It is possible that a WSN utilizing WURs could passively perceive specific events for several weeks or months without even needing to wake up a sleeping node(s). Finally, with the occurrence of an event, a threshold on the sensor is reached and the node decides to relay information to the network gateway. The sensor node wakes up nearby nodes, which in turn wake up their adjacent nodes, until the entire network is awake. [30]

WUS can be multicast to wake up all the nodes or unicast for a specific node. These signals can be used for event driven or query based applications. As the discussion suggests, concept of WUR is highly applicable to event driven applications, however, it can also be applied to periodic applications, for example to send temperature data to the gateway. A query-based example would be when a gateway, when externally queried by a user, wakes up the entire temperature monitoring network to check temperatures on demand. Many network applications instead of waking up the entire network, would be better utilized by targeting to wake up only those nodes which are essential to get the required information and are in the path to relay packets from source to destination. [30] [3]

The fundamental components of WUR which are discussed already are illustrated in Fig. 13 [28]. Main radio is used for data communication while for data acquisition and processing tasks Micro-Controller Unit is used. MCU also controls the main radio. The WUR on reception of a WUS, generates a wake up through the MCU to its main radio. As discussed in [32], main radio will broadcast a signal/ message to initiate the transmission period for the sensor nodes as per the channel access procedure [28] [31]. To better understand the process, we will discuss these components in more detail in Section 3.3.

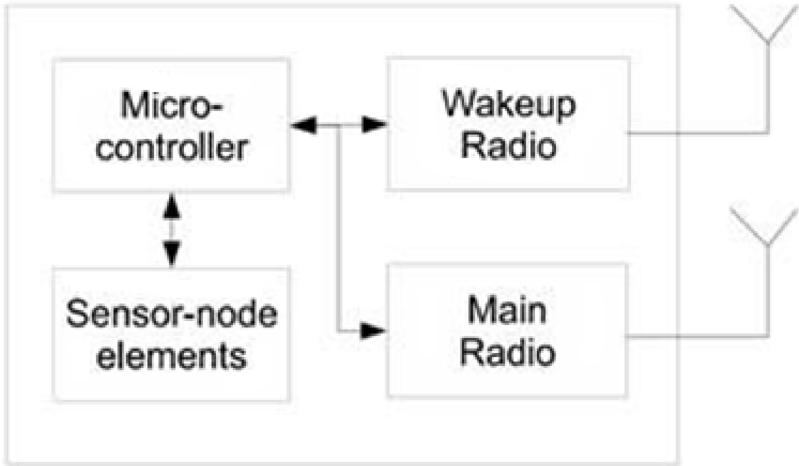

Figure 13. Common architecture of a node with WUR.

3.1. Wake-up Radios: Related Work

With the advancement in technology, our world is evolving into a networking society where more and more wireless devices communicate with each other. Gartner, a research and technology advisory firm estimated in 2014 [33] that by the end of 2020 there will be 25 billion Internet of Things (IoT) devices. Same kind of estimates has been presented by a technology market intelligence firm, ABI Research, showing that the number of devices will be 30 billion and as per Cisco it will be 50 billion by 2020. With these estimates we can safely say that IoT market is potentially huge and expanding. Because of the IoT based devices we can assume that most of them will be wireless so the number of radios can be even higher as each device may be equipped with multiple radios. With the increase in number of wireless devices new ways will be exploited to find techniques for the energy efficiency of sensors, as energy is already a scarce resource. A lot of research is going on in this prospect to save as much energy as possible. Some of them is discussed below. [34]

WURs can be divided into two types: Active WUR and Passive WUR. Active WUR sensor nodes have longer wake up range and need continuous power supply. Whereas, passive WURs operate in a relatively smaller range and harvest energy to power themselves from the wake up radio signal transmitted by the sender. [35]

Sensor networks are composed of low power devices with the capabilities of sensing and computing. In most of the sensor networks, the power to the nodes comes from batteries which is a depletable source. To increase the lifetime of these sensor networks, a number of approaches have been introduced to design low power WUR technologies. In [36], the authors have introduced a radio triggered power management. In their approach, a special hardware component, i.e., a radio triggered circuit, is connected to one of the interrupt inputs of the processor. The circuit does not contain any power supply. As they have discussed, a node can enter sleep mode without periodic wake up. When one node sends a power management signal/message to another within a certain distance, the radio triggered circuit gathers enough energy to trigger the interrupt to wake up the network node. As it is obvious that a radio transceiver needs to listen the messages, for which it requires help from a radio sub-controller or processor to conduct message parsing and channel monitoring. This whole listening process consumes energy of the node. On the other hand, radio triggered circuit is powered by radio signals themselves. It will remain power off until a suitable radio signal arrives. The radio triggered circuit is independent of any other components on the node except that it needs to activate the wake up interrupt. As shown in their simulations and calculations, the power management schemes based on radio triggered hardware can improve energy efficiency significantly. It saves 98% energy used in a system without power management and for a system with typical existing power management schemes it saves over 70% energy. This wake up mechanism is somewhat simple and energy efficient. [36]

As discussed earlier, to increase the lifespan of the sensors, reduction in their power consumption is important. The radio transceiver is one of the highest power consumers in WSN. Optimizing its power consumption can make the sensor life longer as it decreases the overall power consumption of complete sensor network. To reduce the power consumption of communication several ideas have been floated and one of them is proposed in [37], where the researchers presented the design of a WUR receiver which uses a comparator and an ultra-low power microcontroller as active components. They designed a wake up receiver with high sensitivity, low power, fast reactivity, and with addressing capability on board. To test the functionality, they set up a testbed which had a transmitter, an attenuator to emulate the attenuation of the distance and reduce the received power from WUR receiver. In their simulations and results they have presented the implementation of a nanowatt WUR which generates interrupts and receives data in a way to achieve low power and high sensitivity. As various applications require addressing capabilities this proposed method has a nanowatt microcontroller on board to read the demodulated data and check the address before waking up the main node and radio. For this reason, the proposed WUR receiver can reduce power consumption of power constrain devices significantly using a radio transceiver. The results of the experiments they conducted illustrate that the proposed WUR receiver significantly increases the sensitivity and reduces power consumption. Their results indicate that the proposed WUR receiver can consume less than 200 nW and achieve sensitivity up to -55 dBm in the higher power consumption version. [37]

To save energy of the sensors, one way is to reduce the transceiver's duty cycle. If there is a case when asynchronous events initiated by the network coordinator, a lot of energy is wasted by each sensor on idle listening. To avoid the idle listening, WBAN need an ultra-low power wireless receiver which takes over the task of listening for asynchronous signals, letting the main transceiver to be shut down. Several approaches were proposed for this type of WUR receiver. Among those proposals, one important development was the idea of a Nano WUR [38]. In this design, a charged pump, i.e. two stage voltage double-multiplier, detects the received signal envelope. Then by using a comparator, a correct bit sequence of a received packet is formed. In the design the comparator threshold is adaptive instead of constant and is determined by the WUS strength. Then a preamble detector, detects the wake up preamble if it is generated in the data rate range of expected On-Off Keying (OOK). By this, unnecessary wake ups from common interference sources will be excluded. As it is in our knowledge that several devices are used by a person wearing WBAN, for example, global system for mobile communication (GSM) phones, Bluetooth devices, WiFi devices etc. The authors have suggested that passive filtering is not an appropriate option to filter a signal from a mobile phone when the phone is in immediate vicinity of a sensor. In this case active filtering is helpful but it will significantly increase power consumption. Then the second comparator generates the WUS on the reception of correct preamble sequence. But it's an optional stage and mostly would not be used in order to conserve energy, instead a microcontroller can generate an interrupt. The authors have tested the WUR on a frequency of 433MHz and the data rate of 9600bps. According to the measurements the static power consumption of their WUR is 470nW at low voltage (2V). Dynamic power consumption when receiving an OOK packet is 440nW at 2V. The total power consumption will rise to 910nW while receiving a packet. Based on the ultra-low power microcontroller the consumption will be much lower than any other method for false wake up filtering or preamble detection. [38]

To address the challenge of energy consumption, a 98 nW WUR with an active area of 0.03 mm^2, the radio sensitivity of -41 dBm and a data rate of 100 kbps is used in [35]. In this design 2 off-chip passive components are required which must be smaller than the size of a typical 915 MHz chip antenna. Along this there is needed a single external 1.2 V power supply. The low power WUR operates under a single 1.2V power supply and is fabricated in 0.13µm CMOS. The WUR's active period is 156 x 190 μm^2. A 915 MHz signal with -41dBm sensitivity was connected directly to the receiver input and the signal output was monitored on an oscilloscope. At a data rate of 100Kbps the signal is OOK modulated. With patch antennas, communication was verified at a distance of 1.22 meter using 0 dBm transmit power. Their measurements show that the entire radio consumed a total of 98nW with a sleep power of 11 pW. With their results it is obvious that reducing the sensitivity allows much low power radio design along more energy efficient communication. They have concluded that by avoiding the need to generate transconductance at RF, WUR power can be reduced beyond the surveyed 50 µW power floor. [39]

In order to be acceptable for different kind of applications, a good WUR design should offer long operational ranges, need very low power, and present a low cost hardware design. Subcarrier Modulation (SCM) WUR system as discussed in [40], covers all these aspects to a certain level. This SCM WUR is based on a reconfigurable way of operation in which the node's radio is used as main radio as well as WUR, i.e. an in-band WUR. The radio settings, in this design, are different in two operation modes. In wake up mode, SCM-WUR transmitter and receiver set the radio to transmit and detect respectively, the wake up RF signal i.e. the wake-up call.

Wake up receivers (WURx), upon reception of a wake-up signal (WUS), triggers the MCU of the receiving node which was in sleep state, to switch to an active state. After that the nodes turn their radio transceivers to data communication mode for the communication. SCM WUR comprises of off the shelf low frequency AS3932 WURx integrated circuit, a low power wake up Amplitude Shift Keying (ASK) receiver which generates a wake up interruption as it detects a 110–150 kHz signal. A channel selector in the AS3932, on reception of the amplitude-modulated WUC, routes the RF input of the antenna with the best reception to the 125 kHz envelope detector. This detector than extracts the complete shape of the signal. Then a data slicer which is operating at a specific bit rate computes the amplitude values as 0 or 1. In the last phase, a correlator verifies that the values (bit pattern) extracted from the WUC matches the WURx address. These address can be assigned to the AS3932 through its Serial Peripheral Interface (SPI). If the incoming address and correlator's values match, the chip triggers an interrupt to switch the sensor node's MCU from sleep mode to active mode. Their measurements show that the total wake up delay is 13.08ms, because of the additional factors like RF settling time i.e. 250 µs, and the time a bit takes to completely enter to the data slicer i.e. 366 µs for a bit-rate of 2,730 bps. For energy consumption measurements, they have evaluated 3 different transmit power levels, -10 dBm, 0 dBm, +10 dBm for which the corresponding current consumption values are 13 mA, 14.4 mA and 19.1 mA, respectively. The results show that half of the bits of a WUC are silent on average so the Texas Instruments CC1101 868 MHz transceiver needs less power to generate them. A wake up transmitter (WUTx) is calculated to require 5.5 mJ to send a WUC. SCM WUR systems keep sensor nodes in a very energy-efficient mode until their intervention is not required, which offers drastic energy savings. [40]

Another significant development, to improve energy efficiency and avoid idle listening, was the concept of generic WUR based MAC protocol [32]. They used two tier WBAN topology, the lower tier sensor nodes which are continuously sensing and the higher tier sink nodes which are in sleep mode. Sink nodes are more advanced and complex so they consume more energy. Therefore, they should be kept in sleep mode as much as possible to increase their lifespan. The sensor nodes will continuously monitor human vital functions and will wake up the sink nodes when needed. The higher tier node will collect data from lower tier node and triggers actions according to the situation. All the nodes are equipped with two radios, WUR and main radio. They have defined two modes for GWR-MAC, sink initiated mode and source initiated mode. In source initiated mode sensor nodes wake up sink nodes by sending a WUS. Then the WUR of the sink node will generate a wake up via the MCU to its main radio. Then this main radio will broadcast a Beacon message (BC) to initiate the transmission period for the sensor nodes. Upon the reception of the BC, the sensor node will transmit data to the sink node using channel access method specified in the BC. In the sink initiated mode, the sink node will generate a WUS using either broadcast, unicast or multicast signal to wake up sensor nodes. On the reception of a WUS, the sensor nodes will send an ACK message to sink. When the sink node receives an ACK it sends the BC containing information about the following transmission period. Different channel access methods can be used for transmission period management in both modes. The simulation and results show that their proposed GWR-MAC has significantly lower energy consumption for the lower number of events per hour and it is also less than conventional duty cycling approach even with ultra-low duty cycle ($\lambda = 0.03$ %). This very approach outperforms the 5% duty cycle approach almost by three orders of magnitude when the number of events are low. Once the number of events starts increasing the duty cycle approach starts outperforming GWR-MAC. The GWR-MAC is energy efficient until the number of events is larger than 5000 per year. Comparing GWR-MAC with duty cycle approach with a more realistic 1% duty cycle, the GWR-MAC is more energy efficient until the number of events increases to around 150000 events per year (approximately. 17 / h). GWR-MAC improves energy efficiency and low latency communication with the help of wake up radios by activating the target nodes only when seen necessary. [32]

WUR sensitivity varies from -40 dBm to -90 dBm in design having active power consumption not more than 50 µW. A typical short range transceiver has a sensitivity of -95dBm, so a lot of work needs to be done to bridge this gap between WUR and data transceivers. In a case where range of a WUR is less than the range of data radio, a higher transmit power or a higher density node in the network will be needed for wake up signaling. This gap would become more vital aspect when WURs are equipped with a wide area IoT sensor nodes. The WURs found in different proposed ideas have much higher data rate, i.e., from 100 to 350kbps. So for future WUR design one aspect could be sensitivity improvement at the cost of data rate. Since the wake up packet's length is usually in order of a few bytes, so the WUS can be transmitted sufficiently fast even with low data rate, maintain energy efficiency as well [30]. Since most of the devices in a WBAN have very low energy consumption requirements, but still need to have high flexibility and low latency, WUR can be seen as one of the devices that will find its use in this type of sensors. The methodology used here can be also adapted to other short range Wireless Sensor Networks topologies where power consumption is the most important. [41]

The comparison of the approaches discussed above is given in the Table 3.

Table 3. Comparison of different approaches of WUR

Techniques	Power Consumption	Bandwidth	Data Rate	Sensitivity
Radio-Triggered [36]	1mW	433MHz	NA	NA
Ultra-low power Rx [37]	196nW	868MHz	10Kbps	-55dBm
Nano power WUR [38]	470nW	433MHz	9.6Kbps	NA
98nW WUR [39]	98nW	915MHz	100Kbps	-41dBm
SCM-WUR [40]	0.1mW, 1mW, 10mW	868MHz	2730bps	-53dBm

3.2. MAC Protocol

To address energy efficiency medium access control layer is the most appropriate level. It is used to coordinate node access to the shared wireless medium. In any wireless network, MAC is the core of a communication protocol stack whose performance provides the base to achieve Quality of Service. A versatile MAC must support diverse applications and distinct types of data such as periodic, non-periodic, continuous, and burst along with high level of QoS. MAC produces a key decisive impact on improving overall network performance. It's the basic task of MAC protocol to avoid collisions and to keep check on simultaneous transmissions while preserving minimum latency, maximum throughput, maximum energy efficiency, and communication reliability. While designing MAC, things to focus on are that the nodes must be prone to failure, constrained capabilities, and limited energy resources. [42]

Several MAC protocols have been proposed to overcome the energy challenge. One of them is [43] where authors presented a topology design where all sensors are within range of each other. They used 2 radios, the main radio and an extra radio which uses very low power. Two channels are used: primary and wake up. The primary channel is used for controlling packets and sending data while the wake up is used to wake up neighbors. The second radio will transmit a busy tone instead of actual data and a node will listen it on the wake up channel for T_1 time, then sleep for T_2 time ($T_1 << T_2$). The sender must transmit a wake up signal for T_{wake_TX} time to make sure that all the neighbors listen the wake up signal, where $T_{wake\_TX} = 2T_1 + T_2 + T_{tran\_on} + T_{tran\_off}$. The duty cycle is defined as

$$DC = \frac{T_{tran\_on} + T_1 + T_{tran\_off}}{T_{tran\_on} + T_1 + T_{tran\_off} + T_2} \quad (3.1)$$

where T_{tran_on} and T_{tran_off} are the times for sleep to idle mode transition and idle to sleep mode transition respectively. So a low duty cycle increases the delay to wake a node's neighbor but reduces idle listening. They have specified a queue threshold L, which can be used to limit the storage usage on a sensor and control the delay. When transmission time, T, is too small, both the sender and receiver waste a lot of energy on wake up while the queue is empty. Such events result in idle listening as the main radio stays on long enough. To achieve results close to the static optimal, protocol uses rate estimation. It seems to behave well in multiple hop and multiple flow scenarios. [43]

Among several MAC protocols to save energy, one was a very low power MAC where the researchers used low power wake up receiver/ transmitter [44]. They presented a stored energy radio triggered circuit with a filter. It first collects and save energy gathered from the radio signals and then triggers the enough output voltage to interrupt MCU. According to the proposed architecture the antenna of this circuit will collect the energy from electromagnetic waves. The incoming RF activates the antenna and the electrical energy powers the circuit to generate an output voltage. The band filters (composed of resistors and capacitors) will be used to increases the selecting power of the circuit to differentiate between wake up signals and false alarms. Comparing with the basic radio triggered circuit this technique needs some extra time, i.e., about 2.8 ms, to gather energy for producing sufficient voltage to generate the interrupt. The capacitor is used to store energy, when the antenna receives radio signals, the energy is stored on capacitors. The wake up receiver continuously monitors the channel for activity and keeps main radio and MCU in sleep state. Wake up receiver will interrupt MCU when an event of interest happens which then activates the main radio to initiate communication. This protocol helps to improve energy efficiency and reduce idle listening. [44]

Different MAC protocols for WBAN have been discussed above. Here GWR-MAC protocol [32], is discussed in detail. The general architecture of a WBAN node is given in Fig. 14 [32]. The nodes as already defined in earlier section are equipped with two radios, and it comprises of a two tier WBAN topology. The lower tier sensor nodes which are continuously sensing and the higher tier sink nodes which are in sleep mode. Sink nodes are more advanced and complex so they consume more energy. Therefore, they should be kept in sleep mode as much as possible to increase their lifespan. The sensor nodes will continuously monitor human vital functions and will wake up the sink nodes when needed. The higher tier node will collect data from lower tier node and triggers actions according to the situation. Higher tier node is used for performing different calculations, combining collected data, triggering complex sensing actions and also sending an alarm to a remote location, for example, to a doctor at the hospital. Though the lower tier node will continuously perform monitoring and will trigger the higher tier node on the occurrence of some specific event, but it is also possible for the higher tier node to wake up the lower tier node and poll required data. One example of this kind of polling is when lower tier nodes are placed in a place where there is no need of continuous sensing, so whenever there is a need from application point of view, the higher tier nodes will wake them up. Installation of lower tier nodes on medical equipment is one scenario for this polling, so that the application can poll data from sensors to verify that everything is in expected condition and are where they are supposed to be. Nodes like these should have a long lifetime in order to save costs which would be caused by frequent battery or sensor node replacements. [32]

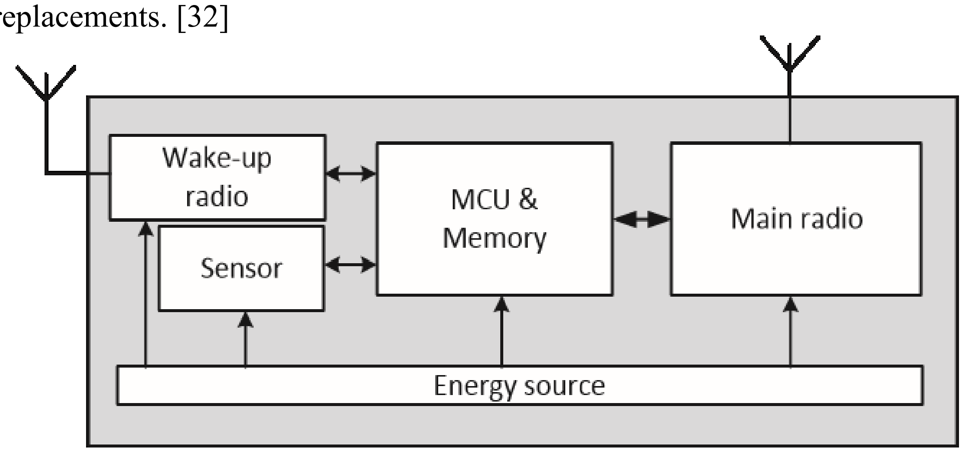

Figure 14. Node architecture.

Wake up procedure for GWR-MAC comprises of two different modes: source initiated mode and sink initiated mode. In the source initiated mode, the lower tier sensor nodes transmit a WUS to wake up higher tier sink node from sleep mode, as illustrated in Fig. 15 [32]. Upon reception of a WUS, WUR of the sink node will trigger a wake up through the MCU to its main radio. Then the main radio of the sink node will broadcast a BC to initiate the transmission period for sensor node as per the channel access procedure. Channel access procedures vary depending on the different scenarios. When the sink has received WUS it will send a BC signal as an acknowledgement to the sensor node. If the sensor node does not receive a BC it will retransmit the WUS after a random back-off period. The transmission procedure of WUS is similar to an Aloha channel access with random delay for the first transmission. Upon the reception of the BC, the sensor node will transmit data to the sink node using channel access method specified in the BC. So we can say that this mode of GWR-MAC is a combination of channel access control method and source initiated wake up procedure for the transmission period. [32]

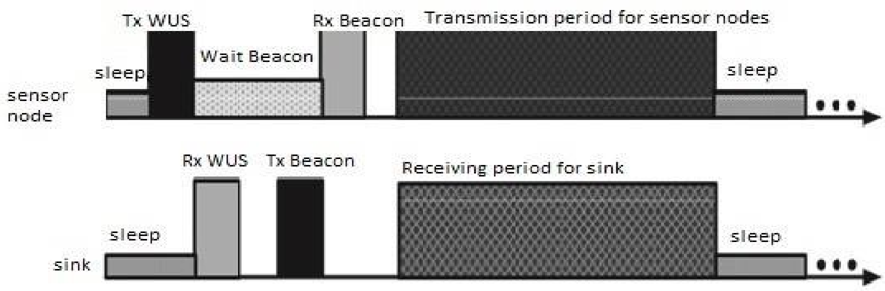

Figure 15. GWR-MAC source-initiated mode.

Contrary to the above, in the sink initiated mode, as shown in Fig. 16 [28], the sink node will generate a WUS using either broadcast, unicast or multicast signal to wake up sensor nodes. On the reception of a WUS, the sensor node will send an ACK message to the sink. When the sink node receives an ACK it sends the BC containing information about the following transmission period. Usually the data flow is from sensor nodes towards sink node but the transmission period can also be other way around to transmit data, for example, a wireless software update or reconfiguration of the sensor nodes. The sink node, in the BC, can specify information about the next transmission period like channel access mechanism, timing and scheduling information. The transmission period in this mode can be dedicated, as shown in the Fig. 16, for the sensor node or sink node for packet transmission. [32]

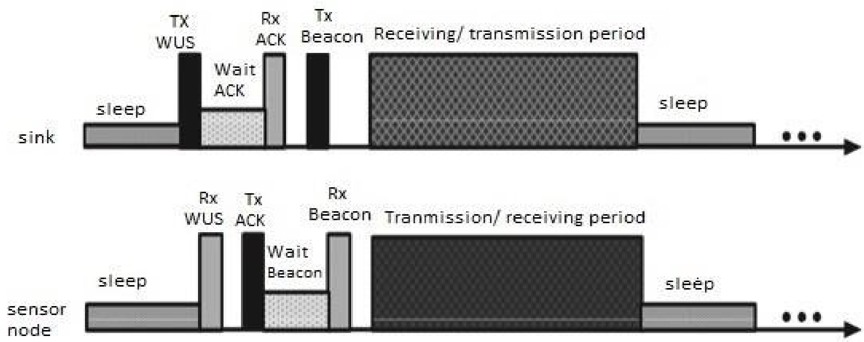

Figure 16. GWR-MAC sink initiated mode.

For the management of transmission period, different channel access methods are used in both above discussed modes. Once the transmission period is finished all the nodes enter the sleep mode and next transmission will take place after the next wake up procedure. There are couple of options for the transmission period channel access, one of them is contention based MAC where the nodes compete for channel access. In a case when packet is not successfully received, the retransmission policy considers either that packet is discarded or retransmitted. Usually, if the corresponding ACK is not received during certain time period, the unsuccessful packet will be retransmitted in a randomly selected slot. Another option is the use of contention free methods, where the sink node assigns dedicated time slots for each sensor node. The GWRMAC message exchange provides information to the sink node about the nodes that have data to send. The sink node, in the source-initiated mode, wait for some specified time before sending a BC, to collect the WUS signals from the sensor nodes. After that it will schedule the time slot for the sensor node that have transmitted WUS. On the other hand, in the sink-initiated mode, the sink will schedule transmission slots for those sensor nodes that sent ACK after receiving a WUS. The sink node should have information about the nodes which have packets to transmit, otherwise channel resources would be wasted. The collision will never occur, in an ideal contention free case, if the noes follow schedule and are perfectly synchronized. [32]

3.3. Discussion

In WSN, sensors are typically constrained by low cost and small sizes, which affect the design of power supplies, computational speeds, and memory. Sensor nodes particularly rely on portable power sources which are required for power supply, for example batteries. So energy efficiency is considered most critical aspect of WSN. If the sensors remain active continuously, the lifetime of these batteries will be short and energy will be wasted during idle listening without being used properly. Therefore, in WSN for energy efficiency, idle listening is a key factor. To solve this issue different approaches are introduced and duty cycling is supposed to be the conventional one, where the radios activate as per their schedule (or sometime randomly) and then enter the sleep mode. If we further look at the duty cycling, there is a slotted listening mode, where a node is active in selected slots and asleep in the remaining. Another way is low power listening mode, where a node will be fractionally active in each slot and then enters the sleep state. Though the duty cycle based MAC performs well for different scenarios but not in the cases when there is no fixed pattern or schedule of the occurrence of events. Besides this, slotted listening mode and low power listening have their own drawbacks, for example, they will not be appropriate in the applications where emergency communication is needed. So in those scenarios when communication occurs rarely, using DCM is not a better approach.

GWR and DCM characterize two very different approaches to improve the overall performance of WSN, scheduled, and on-demand approach. The two major aspects to consider while comparing them are energy efficiency and low latency. By comparing different proposed approaches, which are already described in the above section, the GWR is a much better model to use in the applications where energy efficiency has the vital impact and latency cannot be tolerated at all. GWR is supposed to have a better performance, in terms of energy consumption, as it completely avoids idle listening which consumes more energy in DCM. But, this is not always the case. Theoretically, if the packet rate increases, too frequent wake-ups may lead to more energy consumption than DCM. About latency, it is quite obvious that the lower the duty cycling is the longer the packet delay will be, as there will be longer sleeping periods in each cycle. The GWR in fact, can outperform DCM, in the latency performance. As the GWR has capability of detecting a signal even in low power idle mode, it assures the high latency not take place in the communication. Wake-up devices also signify a quick response time, lowering the latency of multihop communication and improving the overall responsiveness of asynchronous network.

GWR-MAC is a general level framework suitable for short range communication which take the advantage of the WUR. Which mode to use among the source-initiated and sink-initiated, depends on the application. In some scenarios, there might be only need of source-initiated usage, then the sink need will be equipped with a WUR. Contrary, in only sink-initiated case, the sensor nodes will be equipped with WUR. If in some application scenarios there is need of both the modes, then they both should be accompanied by the WUR and main radio.

This GWR-MAC as described in [32], having a bidirectional wake-up procedure between sink and sensor nodes, is well suited for different types of applications. It also allows different channel access methods usage in the transmission period and can be used for different WSN and WBAN applications, while enabling energy efficiency and low latency communication by utilizing the proposed wake-up procedure which activates the targeted nodes only when needed. Because GWR-MAC is not limited to a specific data radio technology or WUR technology, so it is well suited for a variety of WSN and WBAN. With an efficient WUR realization, it is possible that we can catch extensive benefits in terms of power and latency for many applications like medical, health, and sports.

4. SIMULATION MODEL

This chapter explains the simulation model developed in this research work and results of the relevant concepts described in the previous sections. The simulations are performed to evaluate performance of GWR based MAC and physical layers. Probability of miss detection, probability of false alarm, detection error rate and probability of collision during channel access using Aloha method have been derived from the simulation results. For the receiver design, probability of false alarm and miss detection are metrics of interest and have been focused in this research work. A typical star-topology WBAN with *N* sensor nodes and a hub is considered in this work, where sensor nodes are sensing continuously. When a threshold value is sensed a wake-up signal is generated and sent to the hub node which can depending on the application, take actions based on the information or forward it to a remote monitoring or control unit. To determine the behavior of wake-up signal transmission and reception the PHY and MAC layers are evaluated. For physical layer evaluation three different metrics are considered which includes the probability of false alarm, probability of miss detection and detection error rate. Probability of false alarm means that there was no event occurred or no decision threshold has met but the wake-up is generated considering noise as the signal. Contrary to false alarm, probability of miss detection depicts that in actual the event has occurred or decision threshold value has met but the main radio could not detect it. To verify the channel access method and probability of successful transmission MAC is evaluated while taken into account the Aloha method. This scenario describes the probability of collision while accessing the channel. The scenario used here is that upon sensing a threshold value node(s) try to transmit WUS to hub. If several nodes sense at the same time and transmit the signal to hub and hub receive signal from one of the nodes the wake-up process is considered successful. As many nodes are being used in this network so the probability of nodes to sense some event at the same time is significant. After detecting the event, the nodes try to access channel to start communication which may ends up in the collision. These scenarios are discussed and evaluated in detail in the subsequent sections.

4.1. Description

A low power wake up receiver is used in this architecture. The wake-up receiver architecture studied in this research work as shown in Fig. 17 is based on the ultra-low power wake-up receiver from [45]. The architecture uses a high quality film bulk acoustic resonator (FBAR) for matching the network and filtering from antenna. The input signal is first filtered by the matching network. The matching network has two purposes. First it supplies a stable impedance match to the input source and second it provides the narrow RF filter as per the architecture requirement. After that a passive mixer using a low power ring oscillator down-converts the signal to a wideband intermediate frequency (IF). Then the gain of the IF amplifiers takes the signal to a certain level that is easier to detect. To bring the IF signal further down to the baseband an energy detector is used.

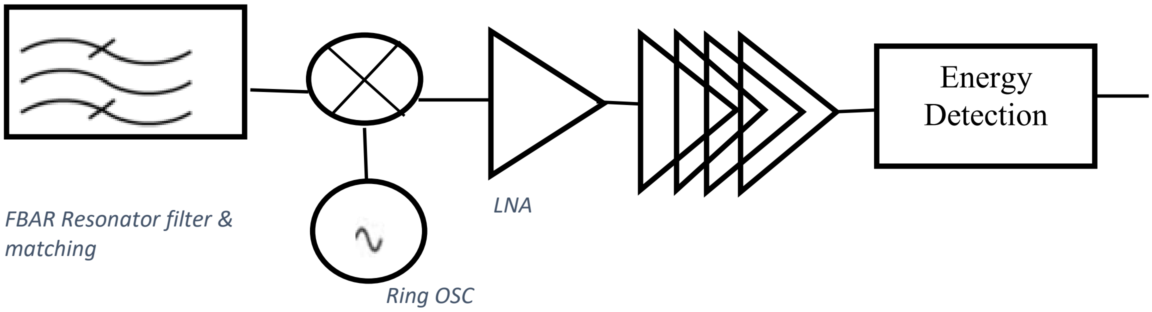

Figure 17. Receiver architecture.

The frequency planning/ allocation of the discussed receiver architecture is shown in Fig. 18 [45], and its sensitivity, v, can be calculated as

$$v = -174\text{dBm} + 10\log\text{BW} + \text{NF} + SNR_{min}\ , \tag{4.1}$$

where SNR_{min} is the required minimum SNR to detect the signal, NF is the receiver's noise figure which is proportional to the bias current and cannot be reduced without increasing power considerably, and BW is the noise bandwidth of the front-end in Hz. The "Uncertain-IF" architecture has a consequence that the effective noise bandwidth of the receiver becomes the wide bandwidth of the IF. The IF bandwidth is designed to be much larger than the data bandwidth because of the low precision and low accuracy of the ring oscillator. While performing envelop detection, noise will be folded into baseband and the receiver sensitivity will be damaged.

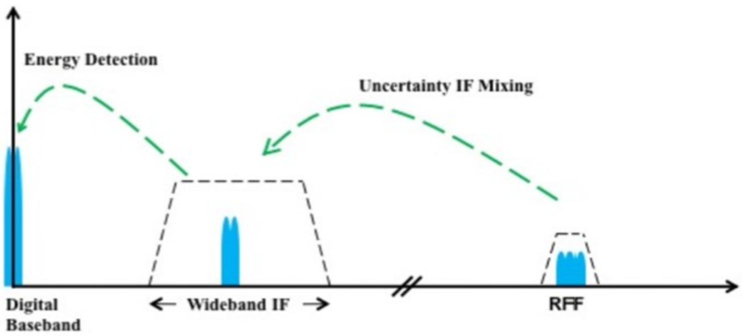

Figure 18. Frequency Planning.

One efficient way to detect energy and address the above discussed problem is to add an integrator and a comparator following the envelop detector. The data from envelop detector will be integrated and compared at the receiver side. As the IF bandwidth is wider than the desired signal so it contains a significant amount of excess noise. So the integrator illustrated in Fig. 19, will reduce that excess noise and increase the sensitivity performance.

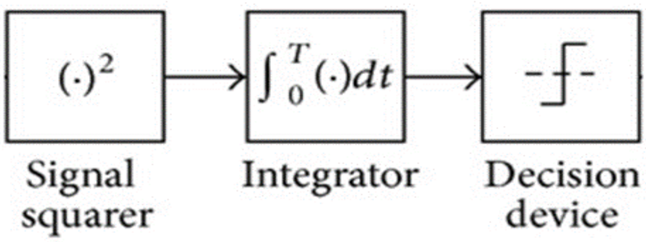

Figure 19. Energy Detector.

4.1.1. Physical Layer

In signal detection theory [46], a threshold decision is the correct technique to separate signal from noise. The outcome of the signal detection can be done in four possible ways as explained in Table 4. For any threshold λ, four types of events can occur. Given below, $y(t)$ is the detected signal at time t.

Table 4. Signal detection outcomes

Comparator Decision	Signal present	Signal absent
Yes	Correct detection: Signal present; $y(t) > \lambda$	False alarm: Signal not present; $y(t) > \lambda$
No	Miss detection: Signal present; $y(t) < \lambda$	correct rejection/no action: Signal not present; $y(t) < \lambda$

The probability of false alarm, P_f, is the probability for an output sample at receiver to be larger than the threshold value in the presence of noise only. In a sensor network, false alarm is one of the reason of energy wastage. Every time a false alarm occurs the network must consume resources imagining that a signal is received. It can be explained in another way as, every time the output of the sample exceeds the threshold, a detection is recorded. The envelop detector does not know, a priori, whether the detection is a target detection or the result of noise (i.e., a false alarm). In order to minimize wasted resources, the objective is to minimize the possibility of a false alarm. In calculation, P_f is considered to provide an acceptable number of false alarms within a given time period. The P_f, can be calculated by using cumulative distribution function, cdf, of normalized chi-square distribution with n degrees of freedom. The number of degrees of freedom in probability distribution is the number of parameters which may be independently varied.

Similarly, according to the signal detection theory [46], the presence or absence of a signal can be determined by comparing the output sample and the threshold value. The probability of miss detection, P_m, is the probability that the output sample, be less than the threshold value while the signal to be detected, is present. The P_m, can be derived as non-central chi-square distribution with n degrees of freedom and a non-centrality parameter. In case of miss detection, the transmitter has to retransmit the wake up signal, which results in the increase of latency and power consumption. Similarly, in false alarm case, power is wasted as the main receiver is active. The two performance metrics P_f and P_m cannot be minimized simultaneously [45]. There is a tradeoff between P_f and P_m.

To discuss the above mentioned probabilities and their simulations in detail, following is the list of notations in Table 5, which are used for designing semi-analytical model using the receiver architecture described in the above section [45].

Table 5. Symbols and descriptions

Symbol	Description
B	bandwidth
N_0	Noise power spectrum density
$s(t)$	signal waveform
$n(t)$	noise waveform
λ	decision threshold

T	integration time
f	frequency
H_0	Hypothesis when no signal transmitted
H_1	Hypothesis when signal transmitted
$F_n(x)$	cdf of normalized chi-square distribution with n degrees of freedom
$F_{n,s}(x)$	cdf of non-central chi-square distribution with n degrees of freedom and a non-centrality parameter s.
P_f	probability of false alarm
P_m	probability of miss detection.

Below is given the analytical model derived from [45]. By using the above notations, an input signal takes the form

$$x(t) = h * s(t) + n(t) \tag{4.2}$$

where $h = 0$ for hypothesis H_0 and $h = 1$ for hypothesis H_1. The output signal y will be used to test the two hypothesis. The y will be represented as

For hypothesis H_0
$$x_0(t) = n(t) \tag{4.3}$$

$$y_0 = \int_0^T x_0^2(t)dt = \int_0^T n^2(t)dt \tag{4.4}$$

For hypothesis H_1
$$x_1(t) = s(t) + n(t) \tag{4.5}$$

$$y_1 = \int_0^T x_1^2(t)dt = \int_0^T (s(t) + n(t))^2 dt \tag{4.6}$$

The input $x(t)$ in (4.3) is noise alone while in (4.5) the input is signal plus noise. The integrator's output is expressed as $y(t)$ and the integration time is T. As per sampling theorem [38], the signal and noise can be expressed as

$$s(t) = \sum_{i=-\infty}^{\infty} b_i sinc(2BT - i) \tag{4.7}$$

$$n(t) = \sum_{i=-\infty}^{\infty} a_i sinc(2BT - i) \tag{4.8}$$

In the above equations $sinc = \frac{sin\pi x}{\pi x}$, $b_i = s\left(\frac{i}{2B}\right)$ and $a_i = n\left(\frac{i}{2B}\right)$ where b_i and a_i are the samples of signal and noise respectively. y_0 and y_1 from the (4.7) and (4.8) can be derived as

$$y_0 = \int_0^T x_0^2(t)dt = \frac{1}{2B}\sum_{i=0}^{2BT} a_i^2 \tag{4.9}$$

$$y_1 = \int_0^T x_1^2(t)dt = \frac{1}{2B}\sum_{i=0}^{2BT} (a_i + b_i)^2 \tag{4.10}$$

The noise sample, a_i, is the sample of zero mean white Gaussian random process and y_0 and y_1 can be calculated from (4.9) and (4.10) as

$$y_0 = \frac{N_0}{2} \sum_{i=i}^{2BT} (\frac{a_i}{\sqrt{N_0 B}})^2 \quad (4.11)$$

$$y_1 = \frac{N_0}{2} \sum_{i=i}^{2BT} (\frac{a_i + b_i}{\sqrt{N_0 B}})^2 \quad (4.12)$$

$$\sum_{i=i}^{2BT} (\frac{b_i}{\sqrt{N_0 B}})^2 = \frac{2BT \frac{1}{T} \int_0^T s^2(t) dt}{N_0 B} = 2BT \cdot SNR \quad (4.13)$$

In (4.13) each sample is taken, integrated and summed from 0 to T. It is derived to calculate SNR which is being used in calculation of false alarm and miss detection probabilities.

Using a central chi-square distribution with $2BT$ degrees of freedom, $\frac{2y_0}{N_0}$ is expressed as sum of squares of $2BT$ Gaussian variables with zero mean and unit variance and $\frac{2y_1}{N_0}$ has non-central chi-square distribution with the same degree of freedom and $2BT \cdot SNR$ as non-centrality parameter. By using the above derived equations, probability of false alarm and probability of miss detection can be calculated as follows

$$P_f = P(y > \lambda | H_0) = P\left(\frac{2y_0}{N_0} > \frac{2\lambda}{N_0}\right) \Leftrightarrow y_0 > \lambda \quad (4.14)$$

$$P_m = P(y > \lambda | H_1) = P\left(\frac{2y_1}{N_0} > \frac{2\lambda}{N_0}\right) \Leftrightarrow y_1 > \lambda \quad (4.15)$$

In the probability of false alarm, for a given threshold value, the right hand side shows a chi-square variable with $2BT$ degree of freedom. Similarly, in the probability of miss detection, $2BT$ shows a non-centrality chi-square distribution with the non-centrality parameter $2BT \cdot SNR$. In P_f case it is central chi-square distribution as there is only noise while in P_m case it is non centrality as there is SNR which varies.
The decision threshold value λ is expressed as

$$\lambda = \beta \cdot BN_0 \cdot T \quad (4.16)$$

where β is the normalization factor. Using value of λ in (4.14) and (4.15) gives

$$P_f = P\left(\frac{2y_0}{N_0} > \frac{2\beta \cdot BN_0 \cdot T}{N_0}\right) \quad (4.17)$$

$$P_m = P\left(\frac{2y_1}{N_0} > \frac{2\beta \cdot BN_0 \cdot T}{N_0}\right) \quad (4.18)$$

$$P_f = 1 - F_{2BT}(2BT \cdot \beta) \quad (4.19)$$

$$P_m = F_{2BT, 2BT \cdot SNR}(2BT \cdot \beta) \quad (4.20)$$

and the cumulative distribution function is defined as [47]

$$F_x(x) = P(X \leq x), \quad (4.21)$$

where subscript X indicates that this is the CDF of the random variable X and all $x \in$ R.
The formula for the cumulative distribution function of the chi-square distribution is

$$F(x) = \frac{\gamma\left(\frac{\nu}{2}, \frac{x}{2}\right)}{\Gamma\left(\frac{\nu}{2}\right)} = P\left(\frac{\nu}{2}, \frac{x}{2}\right), \quad \text{for } x \geq 0 \tag{4.22}$$

where $P\left(\frac{\nu}{2}, \frac{x}{2}\right)$ is the cdf for Gamma random variables. [47]

After calculating the probabilities of false alarm and miss detection, the energy detection error rate (*DER*) can be defined as

$$DER = \alpha * P_m + (1-\alpha)\ P_f \tag{4.23}$$

where α is the wake-up activity rate.

Energy detection is the energy associated with the received signal over a specified time duration and bandwidth. The detected energy is then compared with an appropriately selected threshold to determine the presence or the absence of the primary signal. From the above equations and analysis it is understandable that false alarm and miss detection probabilities are determined by two elements: decision threshold (λ) and signal to noise ratio.

4.1.2. MAC layer

Aloha is a MAC protocol, which is the simplest of all mechanisms and provides access to a common communication channel from multiple independent transmitters [17]. The idea is that each transmitter (station) sends data irrespective of the other communications going on. However, since there is only one channel for one frequency to share, there is the possibility of collision between frames from different stations. If the frame successfully reaches the receiver (destination), it means that no collision occurred during the transmission, so the next frame, if there is one, is sent. It is worth mentioning that theoretically, even if one bit of a frame coexists on the channel with one bit from another frame, there is a collision and both will be destroyed. But the recent receivers in use are efficient enough to reconstruct that collided bit. It is obvious that in case of collision frames should be transmitted again. If the acknowledgment does not arrive after a time-out period, the station assumes that the frame (or the acknowledgment) has been destroyed and resends the frame.

A collision involves two or more stations. If the stations try to resend their frames after the same time-out, the frames will collide again. Pure Aloha dictates that when the time-out period passes, each station waits a random amount of time before resending its frame. The randomness will help avoid collisions and the random waiting time is called the back-off time.

To simulate, basic assumptions for Aloha for this simulation have been made as

- N number of nodes
- Packet duration $T_{packet\_duration}$
- All frames have same length
- Each node transmits with probability p

To calculate the throughput, the primary aspect is time period of length $T_{packet\_duration}$. The most efficient approach is to transmit one packet within this time period. In Aloha system, there are total $N \cdot p$ transmission attempts each with the probability of e^{-2Np}. Hence, the average number of packets that can successfully go through or the throughput is

$$S = N \cdot p \cdot e^{-2N \cdot p} \tag{4.24}$$

According to the theoretical calculation [17], the maximum throughput occurs at *Np* = 0.5 and is 0.184 (approximately), i.e., 18.4 % of frames are only transmitted successfully while 81.6 % end up in collisions and are therefore lost.

4.2. Results

Simulations have been performed using the above analysis for the different parametric values to evaluate the performance of false alarm probability and miss detection probability along with simple Aloha signal transmission scheme. For false alarm and miss detection probabilities the noise bandwidth used is -174 dB per hertz. The IF frequency is 30 MHz and integration time is set to 10 micro-second. The utilized noise bandwidth is 30 MHz and a sinusoidal waveform is generated to represent a signal. The simulations have been performed with 4 different decision threshold, λ , values i.e. 1.1, 1.2, 1.3, and 1.4. These values of decision threshold are obtained from [45].

Physical Layer

Fig. 20 shows the generated sine wave. This probability of false alarm and miss detection are calculated for different amplitude values. The signals are generated with these different amplitudes which vary between 0.1-0.6 in order to set the SNR at the desired level. (4.13) is used to derive the SNR. Below is shown a signal with amplitude 0.6 and symbol duration 10^{-6} s. Used BW is 30 MHz and integration time is 10 micro-second. The noise power spectrum density is -174 dB per hertz. This sine wave is simulated as the wake-up signal a sensor node transmits.

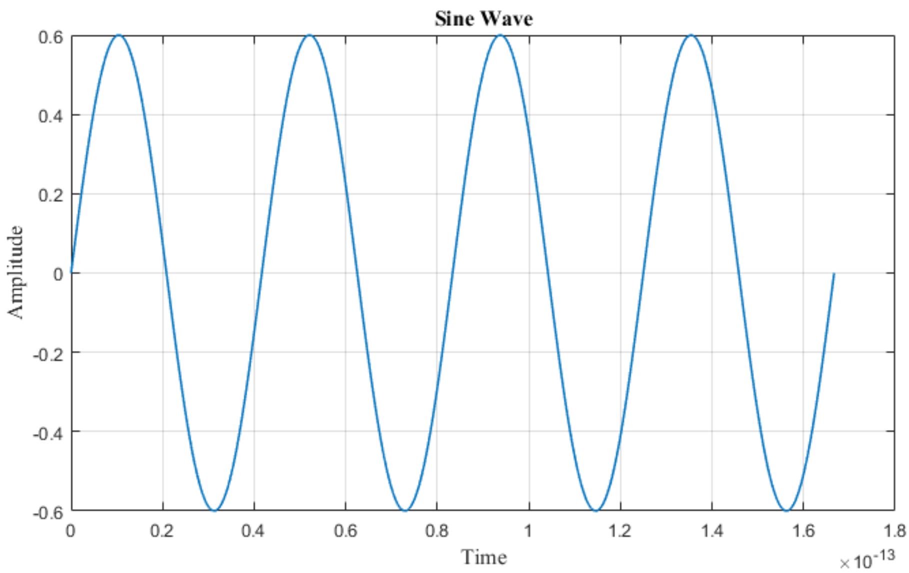

Figure 20. Sine wave.

Probability of false alarm is calculated using (4.19) and shown in Fig. 21. It can be seen from the results that as the decision threshold value is increasing, the probability of false alarm is decreasing. When λ is 1.1, the P_f is around 0.1, but as the threshold value increases to 1.2 the P_f decreases to a little more than 0.001. Similarly, for the threshold values 1.3 the P_f goes down to 10^{-6} and for threshold value 1.4 it touches close to 10^{-9} as in [45].

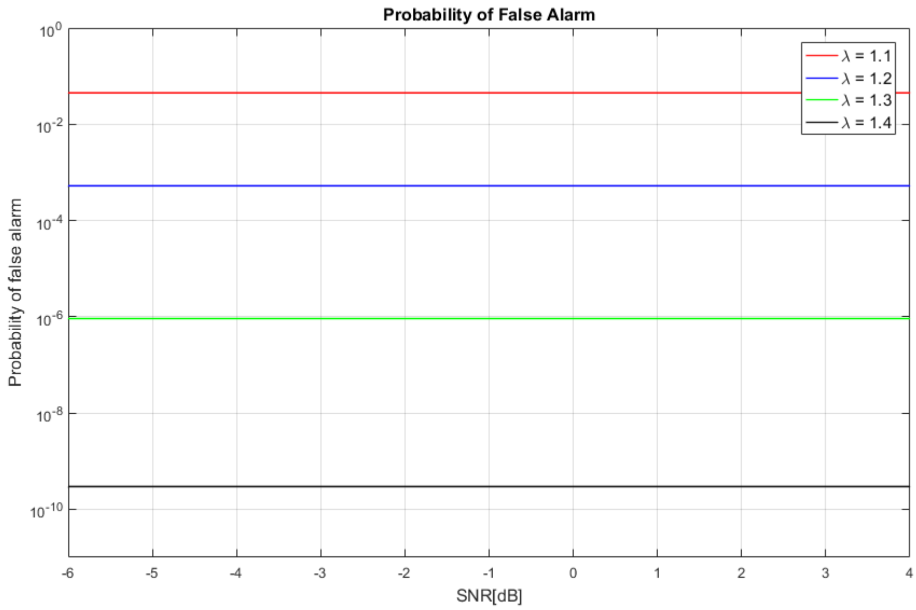

Figure 21. Probability of false alarm.

Probability of miss detection is calculated with the same parameters and the results are shown in Fig. 22. Contrary to false alarm, in miss detection as the threshold value increases the probability of miss detection also increases. It can be seen from the result that when the threshold value for SNR -6 dB is 1.1, the P_m is 0.01. For the threshold value 1.2 and the SNR -6 dB, the P_m, is 0.1. As the threshold value increases from 1.2 to 1.4 the P_m also increases to approximately 1. Also, it can be seen that the increase in SNR can also help reducing the miss detection. Higher the SNR, lower the probability of miss detection.

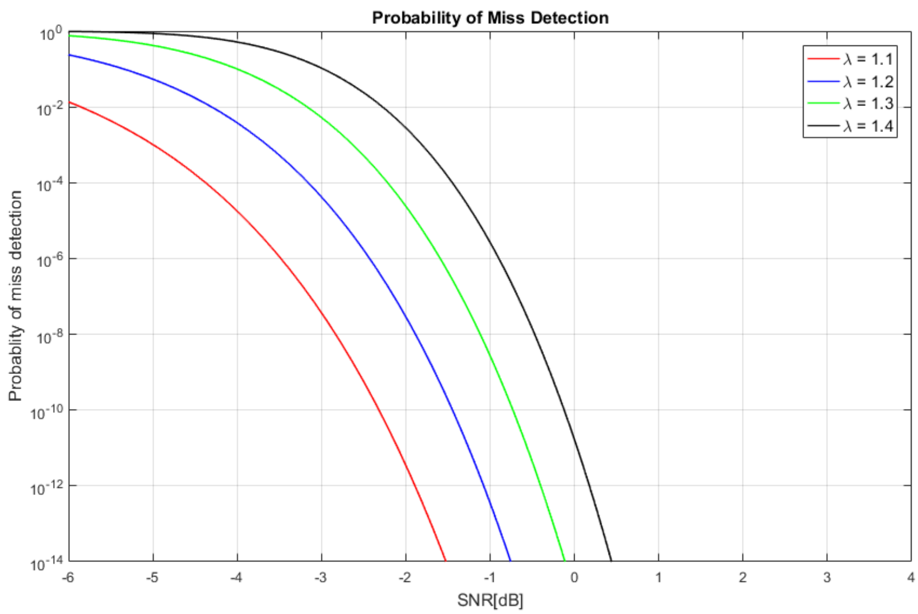

Figure 22. Probability of miss detection.

So there is a tradeoff between false alarm and miss detection probabilities with respect to threshold values. Increase in threshold value can decrease the false alarm but also increases the miss detection probability. So the selection of threshold value is an adjustment between miss detection and false alarm.

Now the values of both the probabilities P_m and P_f can be used to find out detection error rate according to the (4.21). The result is shown in Fig. 23.

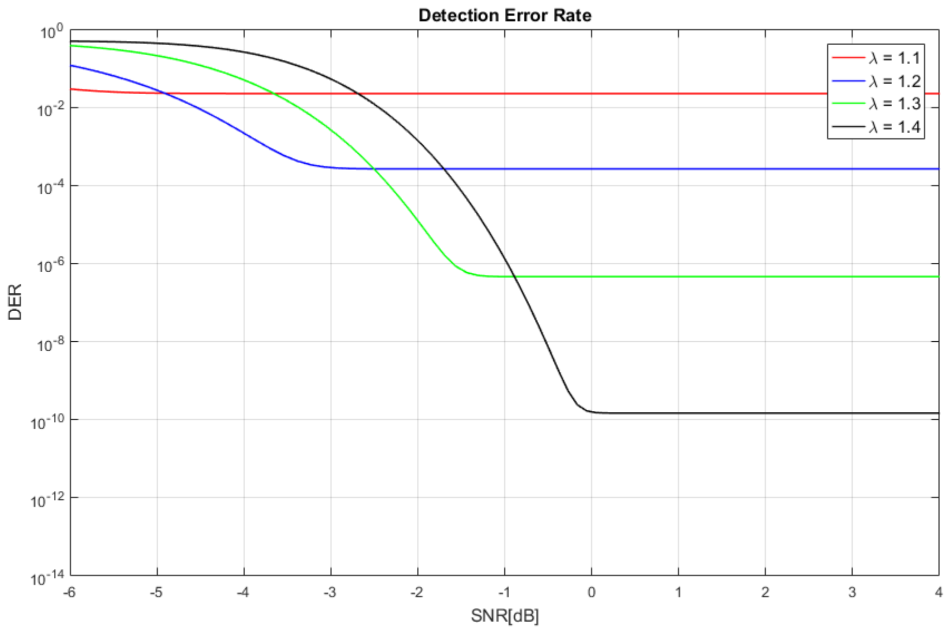

Figure 23. Detection error rate.

The above result shows that the DER is high for λ 1.4 when the SNR is at -6dB. As the SNR increases the DER decreases and as the SNR reaches 0 dB the DER stays constant after that. Similarly, for threshold 1.3 DER is high at SNR -6 dB but it changes with the increase in SNR and when the SNR touches -1.5 dB it stays constant. So is the result of threshold value 1.2. With the increase in SNR the DER decreases but λ 1.1 does not show any drastic change. The above result states that to keep DER low either threshold values should be kept low or a high SNR is required for high threshold value to keep DER low.

The miss detection and false alarm along detection error rate has been calculated for wake-up signal. These results will be used to calculate the energy consumption of the network. These results are used in the next section to calculate energy consumption of the network.

Medium Access Control Layer

After simulating the PHY for wake-up signal transmission, MAC simulations are performed to calculate data transmission probabilities i.e. failed wake-up probability and successful wake-up probability. To measure the performance of channel access method, pure Aloha, simulations have been performed for different nodes.

All the nodes are in sleep mode at the beginning. The arrival times of the frames are randomly distributed, using probability as the arrival time between 0 and 1 second. All the nodes start transmitting the frames as soon as they arrive to them. If all the nodes are in a collision state, the signal has to be transmitted again. If one node successfully transmits the signal the wake-up process is successful. This cycle will continue until one of the node successfully transmits the signal to receiver. Packet duration is set to be between 0 and 1 second. The traffic load, *G*, will vary as per the packet duration. Since three different scenarios are simulated here with 2 nodes, 5 nodes and 10 nodes so the traffic load will be between 0-2, 0-5 and 0-10 respectively.

When the nodes detect an event, they will start transmitting wake-up signal immediately. For these simulations maximum 20 attempts are specified for the transmitter to transmit successfully. Total 10 signals are generated and all the nodes detected those signals at random times. After successful transmission of all the signals, successful transmission attempts are calculated for each signal i.e. each signal may take any number of attempts between 1 and 20, to successfully transmit. Then probability of successful transmission is calculated on the basis of the results. This cycle is executed 10 times to find out the mean of that probability of successful transmission. Now 10 signals are transmitted 10000 times and a mean value is calculated. To find out statistically reliable results, this whole cycle is executed 20 times and successful transmission probability and collision probability have been calculated. Overall 2 million signals are transmitted and their success probability and failed probability are calculated.

Probability of failed wake-up process as a function of packet duration is shown in Fig. 24.

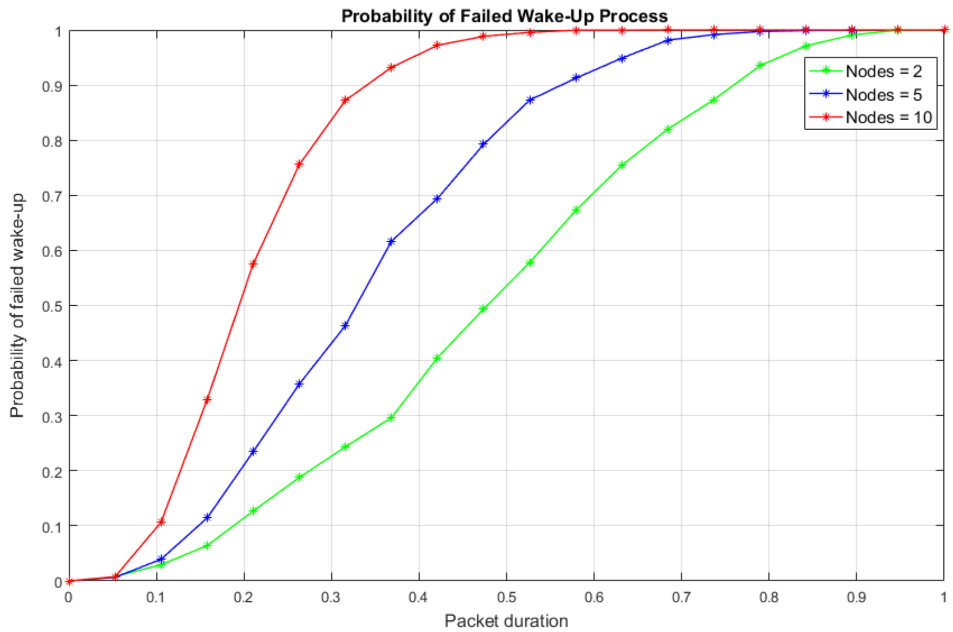

Figure 24. Failed wake-up probability.

It can be seen from the graph, that as the packet duration increases, the probability of failed wake-up gets higher because the packet duration affects the offered traffic load. The simulations are performed for 3 different number of nodes. The result shows that when there are 2 nodes in the network the failed wake-up process probability is lower than other two cases. Only in the case when packet duration is 1 the successful wake-up transmission is not possible. But when the nodes are increased from 2 to 5, failed wake-up probability increases significantly. For packet duration 0.1 to 0.6 there is a possibility for successful transmission but when the packet duration increases from 0.6 the successful transmission is not possible as it ends up every time in collision. The last scenario is generated with 10 nodes and the simulated result illustrates that until packet duration is 0.4 the successful transmission is possible. Once the packet duration increases from 0.4 in the case of 10 nodes in the network the successful transmission is not possible.

Therefore, the network needs a compromise between the packet duration and number of nodes. With the higher nodes in the network successful wake-up transmission probability is low. To increase the probability of successful wake-up transmission, traffic load must be kept low.

Probability of successful wake-up signal with the same number of nodes is calculated and shown in the Fig. 25. The result illustrates that with the increase in the packet duration time, the probability of successful wake-up decreases.

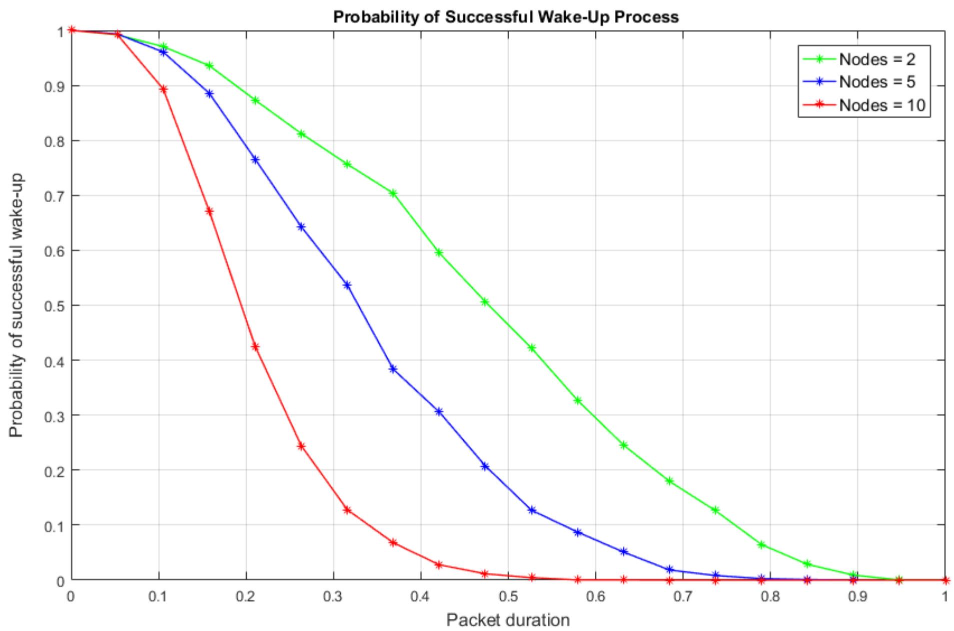

Figure 25. Successful wake-up probability.

Another main aspect of evaluation of Aloha is to calculate the throughput. Before calculating the throughput, offered load is calculated and represented as G. It is the product of total nodes and packet duration time. According to the literature the maximum throughput of simple Aloha is 0.184 frames per frame time which can be achieved when $G = 0.5$. Fig. 26 shows the throughput against offered load, for the three different scenarios with 2, 5 and 10 nodes. It can be seen that the maximum throughput is when offered load is 0.5. The maximum throughput is achieved when $G = 0.5$ for all the cases. The result shows that only 18.4% of the frames are transmitted successfully while the remaining 81.6% of the frames end up in collision. The throughput of the simulated Aloha scheme matches with the literature in all the 3 different cases.

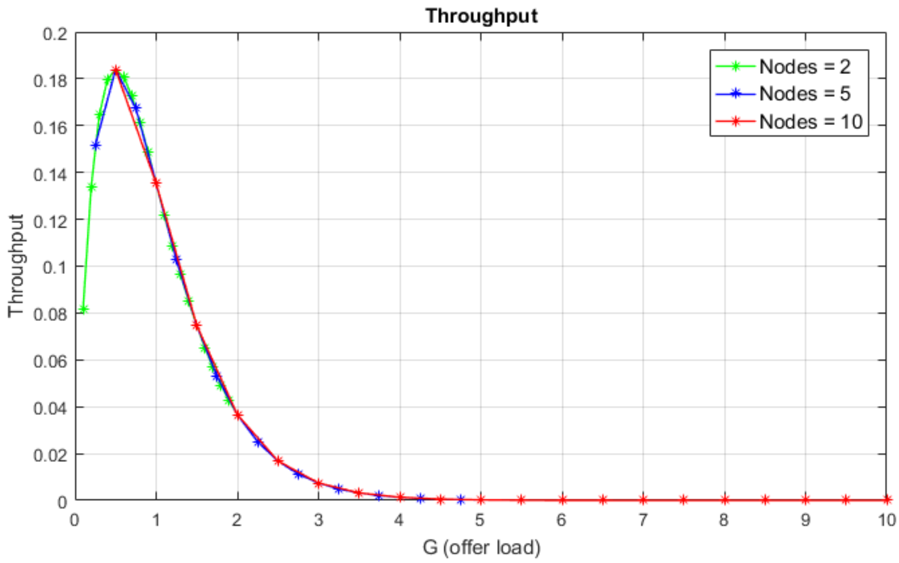

Figure 26. Throughput of Aloha.

Energy Consumption

Now as the results of wake-up signal transmission are calculated, they can be used in the calculation of energy consumption of the network as the energy consumption of the network is dependent on the transmission of wake-up signals, false alarms, miss detection and retransmission of the signals in case of collisions. So the derived results are used in the energy consumption model proposed in [48]. This model compares the GWR-MAC and conventional DCM approach. It takes into account the energy consumption of sensing, processing and communications of both networks. The main energy consumption factors, of each transceiver's component, are taken into account: wake-up signaling, data transmission and reception, and MCU and sensor active mode current consumption. The total energy consumption during the network operation time, *t*, as a function of number of events and bit error probability for GWR-MAC based network and DCM has been calculated. Table 6 gives parameters along their values. For this research work these parameters are taken into account as they affect the calculation of total energy consumption. Some other parameter values such as transmitter mode current consumption, receiver mode current consumption, WUR idle mode current consumption, number of events per year, length of wake-up signal and operating voltage etc. are used from [48].

Table 6: Parameters for total energy consumption calculation

Parameter	Description	Value
N	number of nodes	10
λ	Decision threshold	1.1, 1.2, 1.4 [45]
E_b/N_o	energy per bit to noise ratio for data transmission	18.0604 dB, 16.442 dB
SNR	signal to noise ratio for wake-up signal transmission	-6 dB to 4 dB

By using the results of PHY and MAC layers simulated in this research work, total energy consumption of the network has been calculated and is presented in Fig. 27. The result shows total energy consumption of both DCM and GWR-MAC network against occurrence of events per hour. The energy per bit to noise ratio (E_b/N_o), i.e., 18.06 dB, is used here for data transmission. The SNR is -6 dB for WUS transmission and the decision threshold is 1.2. It is illustrated in the result that when the occurrence of events is low in an hour the GWR-MAC consumes less energy but as the events occurrence increases GWR-MAC starts consuming significantly more energy because of the energy usage in transmission of wake-up signals towards main radio. The DCM consumes less energy as compared to the GWR-MAC as it has already specified a duty cycle to switch between sleep and active mode so, no extra energy required to send a wake-up signal towards main radio especially in the case when event occurrence is high.

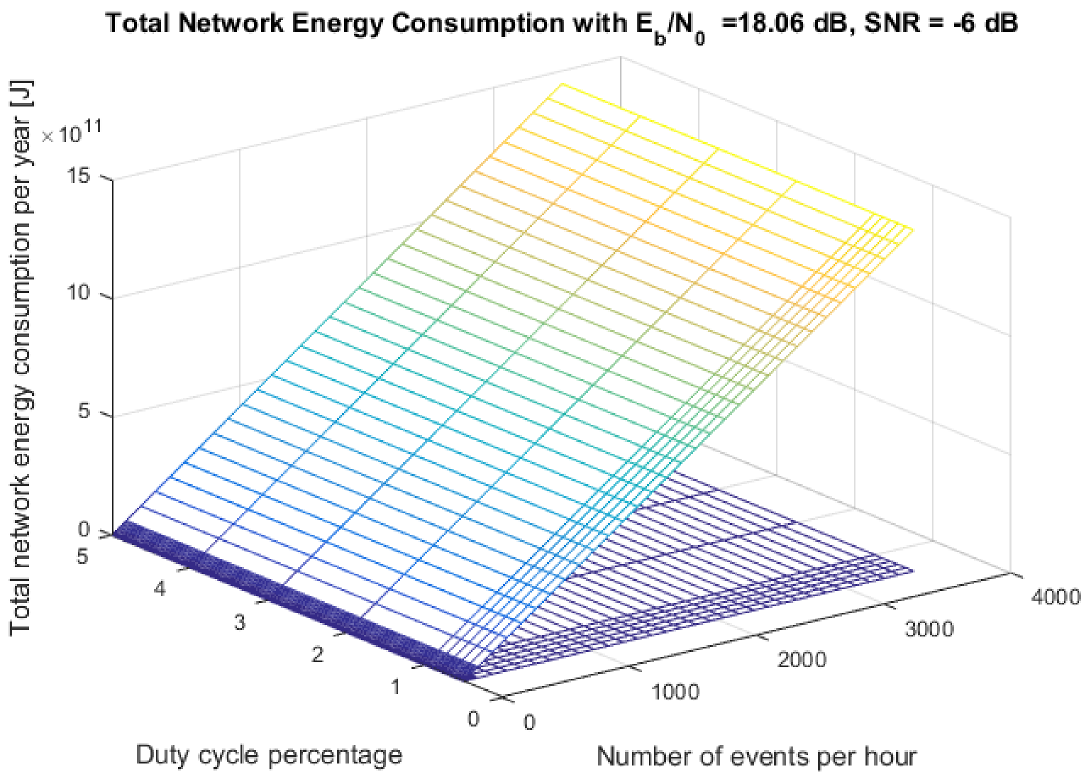

Figure 27. Total energy consumption of network with E_b/N_o = 18.06 dB & SNR = -6 dB.

Another simulation is executed with the same parametric values except energy per bit to noise ratio, which is 16.44 dB. The objective was to compare and verify the effects of E_b/N_o on the total energy consumption of the network. Fig. 28 shows that with the decrease in E_b/N_o the energy consumption of both network increased. This hypothesis proves that when the E_b/N_o is low more energy is consumed because the probability of data packet retransmission gets higher and it significantly increases total energy consumption of the network.

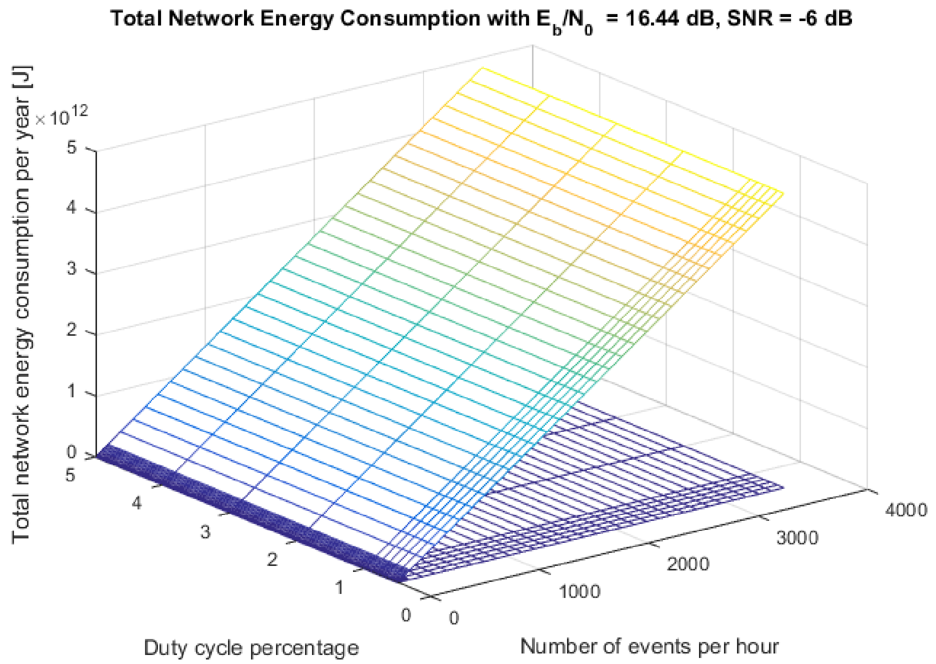

Figure 28. Total energy consumption of network with E_b/N_o = 16.44 dB & SNR = -6 dB.

After comparing the effects of energy per bit to noise ratio, another simulation is executed to see the effects of SNR on total energy consumption of the network. Now the E_b/N_o is 18.06 dB as in Fig. 27. For this simulation the decision threshold remains same i.e. 1.2 but the SNR is -2 dB. Fig. 29 shows that with the increase in SNR the total energy consumption of the network decreased significantly. By comparing both the results i.e. Fig. 27 and Fig. 29 it can be seen that with the same decision threshold, same E_b/N_o but with a higher SNR the energy consumption of the WUR based network decreased remarkably. This decrease in energy consumption is because less WUS transmission are required, as feasible SNR is used here.

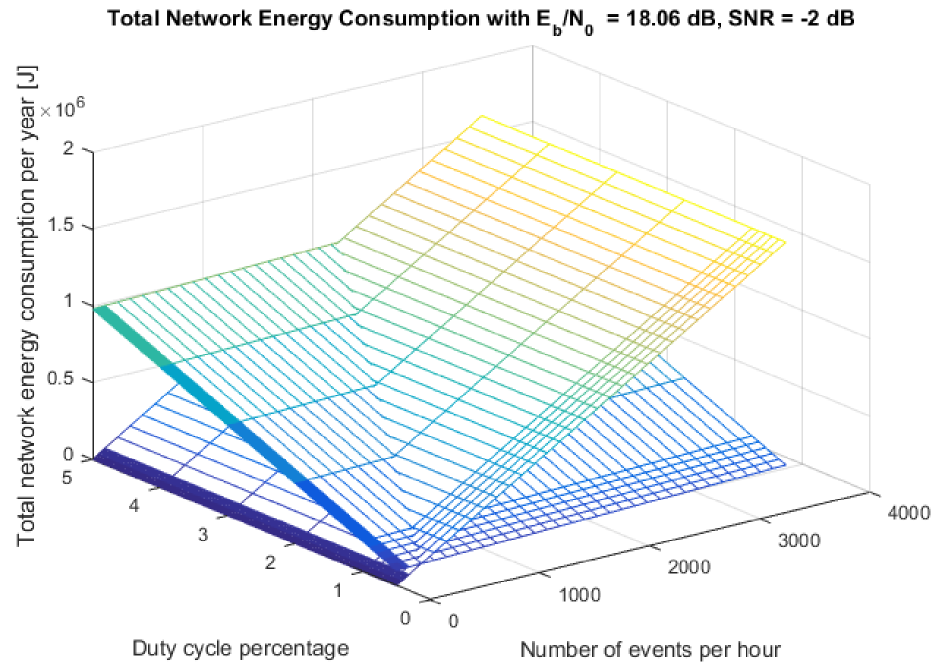

Figure 29. Total energy consumption of network with E_b/N_o = 18.06 dB & SNR = -2 dB.

The effects of E_b/N_o and SNR on total network energy consumption have been verified in the above simulations. To study the impact of decision threshold value two simulations have been performed with λ 1.1 and 1.4. Fig. 30 illustrates the total network energy consumption when the decision threshold is 1.1, E_b/N_o is 18.06 dB and SNR is -2 dB.

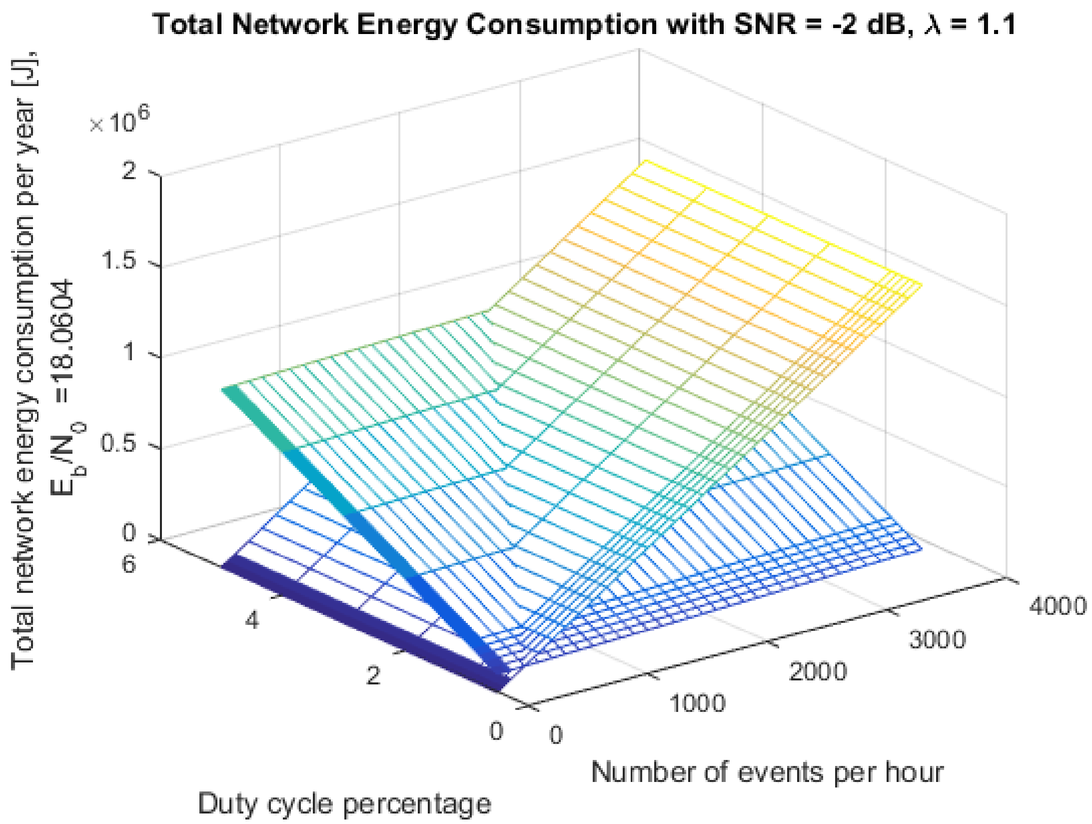

Figure 30. Total energy consumption of network with λ = 1.1 & SNR = -2 dB.

Fig. 31 shows the total network energy consumption when the decision threshold is 1.4, E_b/N_o is 18.06 dB and SNR is -2 dB. The result explains that as the decision threshold value is increased from 1.1 to 1.4 the total energy consumption of the network also increased in WUR case. It is because for higher decision threshold value the probability of miss detection is high which can also be seen in Fig. 22. So the high P_m causes more energy consumption. This clearly states that among the number of nodes, offered load, wake-up signaling and successful transmission, the decision threshold has a vital impact on the total energy consumption of the network in the WUR case.

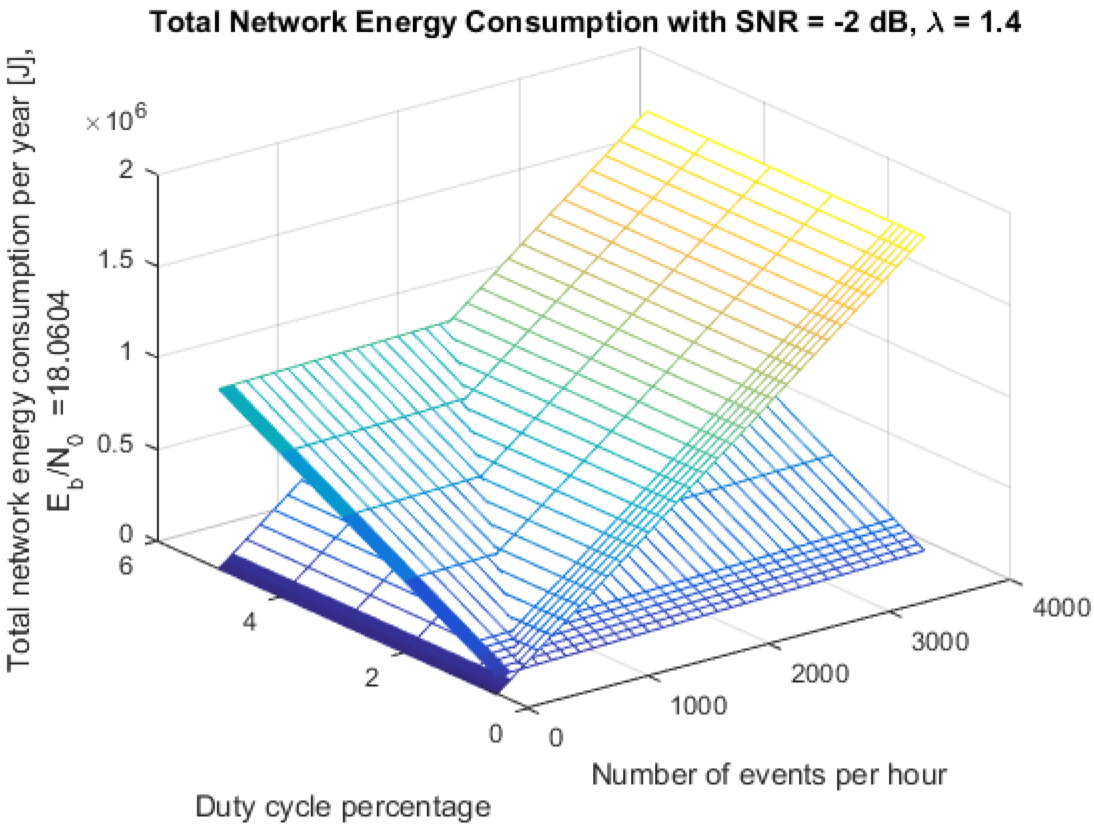

Figure 31. Total energy consumption of network with λ = 1.4 & SNR = -2 dB.

Another simulation has been performed to study the impact of probability of successful wake-up signal transmission taking into account MAC layer. In the above simulations the successful WUS channel access probability was 1 but in this simulation it is changed from 1 to 0.5, while all other parameters remain same. Fig. 32 illustrates that with the decrease in successful WUS transmission probability the total energy consumption of the WUR based network increased exceptionally. To verify the effect of channel access probability on DCM based network, Fig. 32 is compared with Fig. 29. In both cases other parameters, such as E_b/N_o, SNR and decision threshold remain same. It can be seen from the results that with the decrease in channel access probability total energy consumption of the DCM based network increased significantly. Fig 29. illustrates that with channel access probability 1 energy consumption of DCM based network for 2000 number of events per hour is same as in case when channel access probability is 0.5 and number of events per hour is 1000, as shown in Fig. 32. With the decrease in channel access probability the energy consumption of DCM based network is doubled. The exceptional increase in energy consumption of WUR based network is because as the channel access probability decreases, the retransmission of WUS increases which will cause more energy consumption.

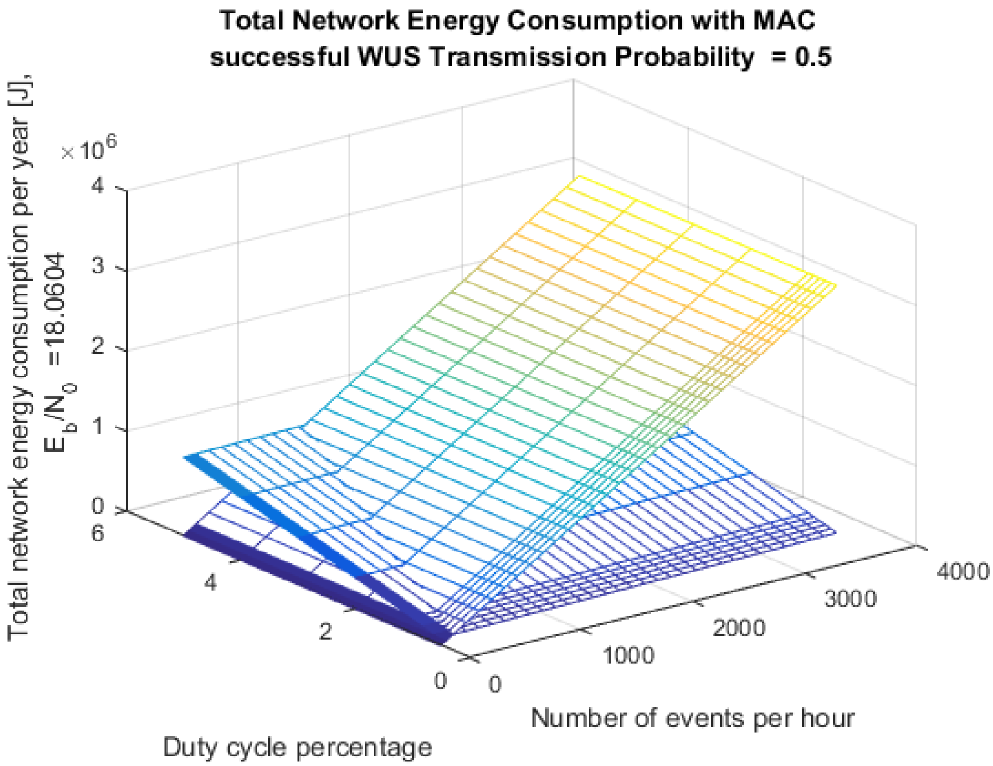

Figure 32. Total energy consumption of network with MAC probability = 0.5.

4.3. Conclusion

The simulations and the calculations derived above express the performance of wake-up radios in MAC and PHY layers. The detection of a signal is a significant factor working with the wake-up radios. The probability of miss detection is calculated with different parameters. Simulations have been performed for 4 different threshold values. Fig. 22 stated that as the amplitude increases P_m decreases, but the relation of P_m with λ is directly proportional. As the λ increases from 1.1 to 1.4 P_m also increases. Higher the decision threshold value higher the miss detection probability. But to decrease the probability of miss detection, a higher amplitude or higher total samples are required. The simulation illustrates that the probability of miss detection relies on the threshold value. The results show that the smaller threshold value has a positive robustness to uncertainty of probability of miss detection. What decision threshold value to choose is entirely up to the requirement of robustness. Obviously zero robustness is not acceptable so as per the results the minimum miss detection occurs with the minimum threshold value i.e. 1.1. It is convenient if a receiver dynamically determines the decision threshold value. One can get the value of P_m very low, when decision threshold is 1.1 as compare to other decision threshold values. As long as the threshold value is low or amplitude and total sample are high the probability of miss detection is in a decreasing order. To achieve a very low level in miss detection a high SNR is required. False alarm is calculated according to the equations derived in Section 4.2, with four different decision threshold values and the results have been compared. The P_f diverges with every decision threshold value. As λ increases, the P_f decreases. For these simulations all other parameters were remained same except λ. By changing λ in every simulation, P_f keeps changing. As the λ keeps on increasing the P_f keeps on decreasing. P_f, as can be seen in the graph is constant for one threshold value against all the SNRs even if the background noise level changes. Having a constant probability of false alarm is useful because the network's performance can be easily controlled by design. So false alarm is reliant on decision threshold value. Higher the decision threshold value, lower the false alarm probability is. Selecting a decision threshold value is a difficult task because of its complex and diverse uncertainties. One way is to find a threshold value for which the P_m and P_f are small. However, it is not possible to find the optimal value for decision threshold because neither the accurate information for the variables exist nor the previous values indicate the future events as it is completely a random process.

The WUS transmission and channel access is verified, taking into account MAC layer. To access the channel, a contention based, simple Aloha is used. In simple Aloha, source transmits the wake-up as it detects a decision threshold or sense an event. If the number of sources are large, they will compete to access channel, so the collision chances will be high. Also, if the packet duration is large the collision probability is high. The simulations have been performed and evaluated for different packet duration times. Fig. 24 shows that as the packet durations is increasing the failed wake-up probability is increasing. Offered load is a measure of traffic in the channel. Fig. 25 shows that as the offered load increases the throughput decreases. Fig. 24 and 25 proves that higher the packet duration time higher the collision probability. The calculated throughput is precisely matching the theoretical throughput. The successful transmission probability and collision probability are dependent on the traffic load and number of nodes. If the packet duration time varies, both the probabilities vary with it. In the above simulations maximum packet duration time is set to be 1 at which the collision probability is maximum or the successful transmission probability is at its lowest. Similarly, with the nodes having a different data need and link quality, there are many limiting aspects to keep things functioning. A lower data rate implies longer packet duration time for every frame. This limits the maximum packet size, to ensure other end-devices get time to use the network as well. So with the 2 nodes as used in the performed simulations, the probability of failed wake-up process is less than as compare to 5 or 10 nodes case. With the increase in number of nodes, probability of collision for each frame gets increasing. To access channel and transmit frames from source node to sink node the packet duration time should be kept smaller if the number of nodes are supposed to be higher. Another hypothesis can be generated that higher the number of nodes higher the collision probability.

Total energy consumption of network has been calculated with different parameters. The results show that with low E_b/N_o the energy consumption of the network is high. Similarly, with lower SNR the total energy consumption of network gets higher in WUR case. To decrease the energy consumption a high SNR or high E_b/N_o is required. Decision threshold also affect the total energy consumption. To decrease network's total energy consumption a low decision threshold is need. A high successful wake-up transmission probability is vital to keep the total energy consumption of the network low. Total energy consumption of the network varies with the number of event occurrence. If in a network event occurrence is low, it is better to use GWR-MAC to save energy. In the case when events occur very frequently the good approach is to use DCM as it will use less energy. In this case GWR-MAC utilizes more energy in transmission of wake-up signals.

5. DISCUSSION

The wake-up radio based wireless body area network is studied in this research work. The scope was to study and evaluate PHY and MAC layers for wake-up signal transmission and successful transmission. The purpose of this research was to derive mathematical representation of miss detection probability, false alarm probability and detection error rate for PHY, and evaluate the performance of Aloha channel access method for MAC layer. The results of both layers are used then to find out the energy consumption of the network. An analytical method is adapted to calculate the false alarm and miss detection probabilities. In case of false alarm high threshold value gives better results but in miss detection case a low threshold value performs better. Finding out a threshold value where both miss detection and false alarm rates are adequate is a difficult task as both are contrary to each other. For this thesis work the threshold values 1.1, 1.2, 1.3 and 1.4 are used to calculate energy consumption, where both the probabilities were reasonable. To get the probability of miss detection as less as possible either a high SNR is required or smaller threshold value is needed. A signal with high amplitude can also help in reducing the probability of miss detection. Probability of false alarm is calculated and it can be seen from the results that it is dependent on the decision threshold value. To get a low probability of false alarm a higher threshold value is needed. Which threshold value should be used where both probabilities can be at a suitable level, is entirely dependent on the requirement and objective of the network. With the results of P_m and P_f, the detection error rate is calculated with a wake-up activity rate of 0.5. The result explains that the threshold value should be kept low when SNR is low so that the DER can be at a certain level, but in case of high SNR threshold value can be high. The efficient way to reduce DER is to set threshold at the point where P_m and P_f equal to each other.

In MAC layer, for wake-up transmission, Aloha is used. For channel access, Aloha works well with the wake-up radios. The performance or throughput derived in this research work is not different from the theoretical method. To increase the probability of successful transmission a small packet duration time is required. Number of nodes that are being used is a key factor to analyze the performance of channel access method. How many nodes there should be in a network is entirely according to the requirement of that network. Though, lower the number of nodes higher the successful transmission probability. Higher number of nodes has shown increase in the collision probability.

The throughput of Aloha is 18.4 % for wake-up radios. The throughput can be improved by using slotted Aloha but then, its behavior is against the spirit of WUR. The concept of WUR is to transmit a wake-up signal immediately after detecting an event. Carrier sense multiple access with collision avoidance CSMA/CA can be used instead of slotted Aloha to improve the throughput but the concept of WUR rather suits the behavior of simple Aloha.

After calculating the results of PHY and MAC for wake-up signal transmission and data transmission, the results are used to calculate the energy consumption of the network, which was the primary objective of this research work. The results of wake-up signal transmission which includes the probabilities of miss detection and correct detection are used here. The successful WUS transmission probability from MAC layer is also calculated to be used in this energy consumption model. The joint success probability of PHY and MAC layers is calculated and used in finding out the total energy consumption for the WUR. The WUR and DCM are compared as a function of duty cycle percentage and number of events. Until occurrence of events is low, WUR outperforms the DCM in consumption of energy. With the duty cycle percentage increases the energy consumption of DCM based network also increases while the WUR's energy consumption stays constant for the fixed number of events. With the increase in event occurrence the result illustrates that WUR starts consuming more energy whereas DCM consumes less energy. This is one of the drawbacks of WUR. Another limitation of WUR is in terms of wake-up range. The DCM approach, in practical applications generally use a fixed duty cycle. With the increase in events occurrence, the duty cycle should be changed dynamically. Also, in case the duty cycle is low, it needs a strict synchronization to transmit exactly in right time. But the drawback of strict synchronization is that it requires message exchange between nodes, which will eventually consume more energy. So, a proposition can be made that for a network where the event occurrence ratio is low, use of WUR can be a good approach as it will save significant energy and the maximum life span of the sensors can be achieved. The wake up radio research field is still not fully explored so it needs to be defined in more detail and implemented to evaluate the performance and verify the functionalities in real time applications.

6. SUMMARY

Wake up radios are the basic circuits for the on-demand communications technique. The WUR manages the transmission and reception of wake up messages that switch on the main processing unit or the main radio. Low power consumption is required for the WUR receiver. WURs can be compared with duty cycling approaches, where nodes are periodically set into the sleep mode. The nodes can manage the trade-off between energy consumption and data latency, by setting the duty cycle value accordingly. With lower duty cycles, the nodes will consume less energy at the cost of higher latency for data delivery. Once a node wakes up during the active part of its duty cycle, it must listen to the channel for a period of time to determine whether other nodes or the sink are available for communication. This introduces complexities and adds overhead to the medium access control protocol. By using WUR techniques, such overhead can be reduced. A wake-up signal triggers a node to wake up from the sleep mode and start reception activities. Generally, the wake-up signal is sent or received by a secondary radio transceiver. In order to improve energy efficiency, the energy consumption of this extra wake-up radio transceiver should be extremely low. The energy benefit of using WUR in comparison with duty-cycling is that nodes do not waste energy on idle listening of the main radio, since they are only awakened by neighboring nodes when there is a request for communication. In addition, using a wakeup signal reduces the overhead in control traffic since a node woken up through a wake-up radio knows that another node is ready to receive data.

The PHY and MAC are evaluated with the WUR to calculate the wake-up signals transmission and successful transmission. The results are also derived for false alarm, detections error rate and correct detection to calculate the total energy consumption of the network. These results are compared with DCM approach for both high and low traffic rates. The total energy consumption of the network is calculated for different scenarios varying decision threshold values and energy per bit to noise ratios. WUR works better in case of low traffic rate in comparison to DCM which is effective when the traffic rate is high.

An efficient WUR realization can bring extensive advantages in terms of power and energy efficiency for many applications in both medical and non-medical fields. Depending on the application, such savings can result in a significantly prolonged battery life. The use of the above discussed techniques depends on several aspects such as number of events, channel conditions and duty cycle percentage. From the simulated results it is obvious that WUR based network has significantly lower energy consumption than DCM based network specially when the events occurrence is low.

The thesis work was documented in different chapters. First scope and aim of this research work was introduced. Then in Chapter 2 WBANs, IEEE Std. 802.15.6, physical layer and MAC layer are studied in detail. In Chapter 3, wake-up radios and already existing protocols are discussed. This chapter also emphasis on the performance of generic wake up radio based MAC protocol. In Chapter 4, the simulation model for WUR based MAC protocol is derived for PHY and MAC layers. These results are studied and the performance of the WUR based MAC protocol regarding energy efficiency for the network is also evaluated. Chapter 5 provides a comprehensive discussion of the results and Chapter 6 gives the summary of this research work.

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