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Master’s Degree Thesis

An Approach to Reduce Reporting Emergency Delay of Emergency Events in IEEE 802.15.4 Networks considering Human Body Monitoring Applications

Graduate School of Chosun University

Department of Computer Engineering

Jay Shree Ranjit

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IEEE802.15.4 기반의 인체 모니터링 어플리케이션에서 긴급 이벤트 전송 지연을 감소하기 위한 기법

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Advisor: Prof. Shin, Seokjoo, Ph.D.

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Department of Computer Engineering

Jay Shree Ranjit

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Acronyms

2G	2nd Generations
3G	3rd Generations
BE	Backoff Exponent
BI	Beacon Interval
CAP	Contention Access Period
CCA	Clean Channel Assessment
CFP	Contention Free Period
CRC	Cyclic Redundancy Check
CSMA/CA	Carrier Sense Multiple access with Collision Avoidance
CW	Contention Window
DRP	Dedicated Transmission Slot Request Packet
DRP	Dedicated Transmission Slot
E2E	End to End
EB	Emergency Beacon
ECG	Concurrent Access MAC
ED	Energy Detection
EEG	Common Control Channel
EMG	Common Channel List
ERP	Emergency Reporting Period
FCFS	First Come First Serve
FFD	Full Function Device
GPRS	General Packet Radio Service
GTS	Guaranteed Transmission Slot
HBM	Human Body Monitoring
IEEE	Institute of Electrical and Electronics Engineers
IFS	Inter-Frame Spacing
IrDA	Infrared Data Association
LOS	Line Of Sight
LQI	Link Quality Index
LR-WPANs	Low Rate Wireless Personal Area Networks

MAC	Medium Access Control
NB	Number of Backoffs
NC	Network Coordinator
OEE	Occasional Emergency Events
P2P	Peer to Peer
PANC	Personal Area Network Coordinator
PANs	Personal Area Networks
PDA	Personal Digital Assistant
PDR	Packet Delivery Ratio
PHY	Physical
QoS	Quality of Service
RFD	Reduced Function Device
ROE	Regular Observatory Event
SD	Superframe Duration
SN	Sensor Node
TCP-IP	Transmission Control Protocol – Internet Protocol
TDMA	Time Division Multiple Access
WLANs	Wireless Local Area Networks
WPAN s	Wireless Personal Area Networks
WSNs	Wireless Sensor Networks

ABSTRACT

An Approach to Reduce Reporting Emergency Delay of Emergency Events in IEEE 802.15.4 Networks considering Human Body Monitoring Applications

Jay Shree Ranjit
Advisor : Prof. Seokjoo Shin, Ph.D.
Department of Computer Engineering,
Graduate School of Chosun University

The recent advancements in wireless communication system and semiconductor technologies are paving the way for new paradigms over wireless sensor area networks. Human body monitoring (HBM) is one of such special purpose sensor application in which diverse sensor devices employed in, or on a human body sense the physiological phenomena of interests and report them to a designated authority (sink device).

Due to the low energy consumption, lower cost, and reliable data transmission features, IEEE 802.15.4 is widely used for HBM application. But, realizing an effective HBM application over the conventional WSN based on IEEE 802.15.4 is challenging, especially when the time critical emergency events are to be reported, because IEEE 802.15.4 doesn't differentiate the time criticality of the monitored events and hence doesn't provide any preferential access opportunity for emergency devices while accessing the shared wireless channel. As a result, the reporting latency of the emergency events may significantly increase.

IEEE 802.15.4 medium access control (MAC) sub-layer defines a superframe structure that contains a beacon period for devices synchronization, the contention access period for command frame exchange, the contention free period for data transmission and inactive period for low duty cycle. During the contention free access period, some sensor devices are allocated with scheduled time slots known as guaranteed time slot (GTSs). There may be a maximum of seven such GTSs exists, but a device can have only one GTS. However, a GTS can expand to more than one transmission slots. So, whenever the maximum of such GTSs is allocated, then the contention free period becomes long and continuous as the GTSs are aligned contiguously. The contention free period is followed by an inactive period where no data transmission takes place. As such, any sensor device with emergency data during the contention free access period is bound to suffer from severe delay because of the contention free period and inactive period. To alleviate this inefficiency of IEEE 802.15.4 MAC, we propose an efficient emergency handling scheme that allows opportunistic transmission of emergency data during the inactive period. The inactive period is modified into three new periods for emergency handling viz. emergency reporting period (ERP) where the emergency devices can request for dedicated data transmission slots (DTSs) for reporting the emergencies to the coordinator, emergency beacon (EB) frame that contains the DTSs schedule for the emergency nodes, and in the emergency transmission period (ETP) which is divided in DTSs for emergency data transmission. These additional new periods are used only for emergency reporting purposes and in case of no emergencies the EB and ETP act as inactive period.

The performance of the proposed scheme is evaluated through the results of computer simulation using Castalia3.2, i.e. a network simulator specifically designed for the sensor and body area networks which is based on OMNeT++ platform. The results showed that the proposed scheme reduces the emergency

event reporting delay up to 28% than in the conventional IEEE 802.15.4 MAC. The normal data transmission delay is also reduced marginally. Similarly, the packet delivery ratio for emergency traffics is observed to be higher than the conventional one.

We believe, the proposed scheme is beneficial in HBM applications due to its ability to handle emergency events with low delay and high packet delivery ratio than the conventional IEEE 802.15.4 MAC. And due to its simplicity, it also can be implemented with the IEEE 802.15.4 MAC for better performance in HBM applications.

한 글 요 약

IEEE 802.15.4 기반의 인체 모니터링 어플리케이션에서 긴급 이벤트 전송 지연을 감소하기 위한 기법

란짓 제이 수리
지도 교수: 신 석주
컴퓨터공학과
대학원, 조선대학교

무선 통신 시스템 및 반도체 기술 분야에 있어서의 최근의 기술 발전은 무선 센서 영역을 넘어서는 무선 통신의 새로운 패러다임을 이끌고 있다. 인체 모니터링(HBM)은 특수 목적용 센서 응용의 하나로써 인체 내부나 외부에 부착된 다양한 센서 노드들이 관찰대상의 생리현상들을 감지하여 지정된 위치(싱크 노드)로 이를 보고하는 어플리케이션을 의미한다.

낮은 에너지 소비, 저비용, 신뢰적 데이터 전송의 특징으로 인하여 IEEE 802.15.4 표준이 HBM 어플리케이션에 대표적으로 사용될 수 있다. 그러나, IEEE 802.15.4 기반의 WSN 시스템에 HBM 어플리케이션을 직접 적용하는 것에는 어려움이 있다. 이는 15.4 표준이 모니터링 이벤트의 지연 특성에 대한 차별 서비스를 제공하지 않기 때문에 긴급 메시지를 공유 접속 채널을 통해 신속히 관찰자에게 전송하기에 부적절한 구조로 되어 있기 때문이다.

IEEE 802.15.4 매체 접근 제어 (MAC) 부계층은 노드 동기화를 위한 비활성 구간, 제어 프레임 교환을 위한 경합 액세스 구간, 데이터 전송을 위한 무경합 구간 그리고 낮은 듀티 사이클을 위한 비활성화 구간을 포함 하는 superframe 구조로 구성된다. 무경합 구간 동안 일부 센서 노드들은 정보 전송을 위해 할당된 보장 시간 슬롯(GTS)으로 패킷 전송을 수행한다. 이러한 GTS 는 최대 7 슬롯까지 할당될 수 있으며 한 노드는 오직 하나의 GTS 만을 가질 수 있다. 그러나 하나의 GTS 는 하나 이상의 전송 슬롯으로 확장 가능하다. 그래서 이러한 GTS 들이 최대로 할당되면 무경합 구간의 비율이 상대적으로 증가하게 된다. 무경합 구간 뒤 데이터 전송이 발생하지 않는 비활성화구간이 이어지게 되고, 이에 따라 긴급 데이터 전송이 필요한 센싱 노드가 무경쟁 구간에서 발생하였다면, 무경쟁 구간 및 비활성 구간을 기다린 후 다음 프레임의 경쟁 구간에 전송시도를 할 수 있기 때문에 심각한 지연을 겪어야 한다.

따라서 본 논문에서는 IEEE 802.15.4 MAC 의 이러한 비효율성을 완화하기 위해서, 비활성화 구간 동안 긴급 데이터의 기회주의적 전송을 허용하는 효율적인 긴급 메시지 처리 기법을 제안한다. 비활성화 구간에서 긴급 메시지 처리를 위한 세 가지 새로운 구간들을 정의하였다. 즉, 긴급 메시지 전송 노드들이 코디네이터에게 긴급 메시지 전송을 하기 위해 예약할 수 있는 전용 데이터 전송 슬롯(DTS)과 이러한 DTS 를 경쟁 기반으로 예약할 수 있는 긴급 보고 구간(ERP), 긴급 노드들의 DTSs 스케줄 정보 등을 포함하는 비상 비컨(EB) 등이 그것이다. 이러한 추가적인 새로운 구간들은 긴급 메시지를 전송하는 목적으로 사용되며 긴급 메시지 전송 노드가 없는 경우에는 이 구간은 기존 표준에서와 같이 비활성화 구간으로 인식된다.

Castalia 3.2 즉, OMNeT++ 플랫폼을 기반으로 센서 및 BAN 네트워크용으로 특별히 설계된 네트워크 시뮬레이터를 사용하여 컴퓨터

시뮬레이션 수행하였으며 시뮬레이션 결과를 통해 제안된 기법의 성능을 평가하였다. 결과로부터 제안된 방식은 긴급 메시지 전송의 지연을 기존의 IEEE 802.15.4 MAC 보다 최대 28%로 감소시킬 수 있을 뿐만 아니라, 긴급 데이터가 아닌 일반 데이터 전송 지연도 소폭 감소됨을 확인하였다. 또한, 긴급 데이터 전송에 대한 패킷 전달율도 기존 표준 방식보다 성능이 우수함을 확인하였다.

결론적으로, 제안된 방식이 기존의 IEEE 802.15.4MAC 과 비교하여 생체 센서 노드의 긴급 데이터 전송에 대해 낮은 지연률과 높은 패킷 전달율을 제공할 수 있음을 확인하였으며, 기존 IEEE 802.15.4MAC 표준 프로토콜을 쉽게 변형하여 이 표준이 HBM 어플리케이션 사용되는 경우 더 좋은 성능을 제공할 수 있음을 증명하였다.

I. Introduction

A. Research Overview

Boundless new possibilities emerged for distributed system applications with the advent of wireless networking system and low power embedded systems. The technological advancements led to successful implementation of wireless sensor networks (WSN) [1] for bridging the physical world and the digital information world through spatially distributed autonomous sensors and actuators. These sensors monitor the physical or environmental conditions such as temperature, sound, pressure etc., and cooperatively pass these data through the network to the main specified location [2]. The rapid advancement in miniaturization of low power and low cost sensor devices has made it possible for wireless personal area network (WPAN) [3] i.e. a short range wireless networking and communication between the devices around an individual's work space. Furthermore, it has been reconnoitered to implement in, or on, or around the human body for personal health care and monitoring purpose. Such the application is called human body 24x7 monitoring (HBM) [4] application that has recently received significant attention as a next generation healthcare service.

According to the World Health Organization statistics, in 2000, there were approximately 600 million people who were aged 60 years and older. Due to the increased life expectancy of the people in industrialized countries, this number is increasing day by day, and is expected to be more than 1.2 billion in 2025 [5]. This accentuates a dire need of futuristic autonomic health monitoring system because the manual health monitoring process for the increasing rate of the elderly people will devour more financial resources and skilled human resource for dedicated care and monitoring.

Another statistic shows that, in 2003, about 17 million people died due to cardiovascular diseases, and about 7.2 million people die every year due to the coronary heart diseases [6]. This exasperating death rate can be minimized by constant monitoring and reporting of vital signs, so that necessary actions can be taken before any intricacies ensue. Because, the impending medical conditions can be warned to the users by intelligent heart monitors [7] or provide information for a specialized service in the case of catastrophic events [8]. That is why, the interest is now sloping on developing remote, autonomous, and ubiquitous health monitoring and reporting system which in fact is the wireless HBM for addressing the existing and the potential health hazards. Besides, the traditional cable connection network based health monitoring system is becoming obsolete now because of its several limitations like it doesn’t support mobility of patients and also needs more installation space. So, HBM application with the wireless transceivers is the major concern at the moment.

The wireless HBM application system demands stringent network requirements (refer Section 2-1-2). Reliably transmission of real-time data and timely reporting of emergency events are such requirements. The real time data if not transmitted timely will be useless when transmitted later. E.g. capsule endoscopy allows the real-time viewing of the digestive tracts for further diagnosis by capturing and transmitting images of the tracts through which it travels [9] and the images when not transmitted in real-time may become useless when received later. In case of emergency events, when not reported on time, may cause the permanent impairment of body organs or even becomes life threatening. E.g. hypertension may cause blurred vision or even blindness, kidney failure, and even heart attack or heart failure too [10] - [12]. Also, human body signals are correlated i.e. one event may trigger another event or series of events. E.g. normally a patient suffering from a fever has a high body temperature, blood pressure, and respiration rate [13]. These changes may also affect the oxygen saturation level (SpO2) in the blood. As such, an emergency event may induce several emergencies simultaneously. An efficient wireless network HBM application system must be able to report all such co-related signals and emergencies within the delay margin. But, in a wireless HBM application system where all radio devices share the same channel, it becomes challenging task in making the channel readily available for emergency devices. That is why, efficient emergency handling schemes are quite essential. Unfortunately, there is not any emergency handling provisions in IEEE 802.15.4 [14] and ZigBee [15] based HBM application system.

B. Research Motivation

In HBM application system, varieties of miniature sensing as well as communicating devices called as sensors, or actuators are deployed inside the human body, or on the surface of the human body as shown in Figure 1-1 [16], which report the sensed events to the center where the corresponding health personals have their access. And, depending on the application types, these sensors can sense different physiological as well as vital signs like respiration rate, blood pressure, humidity, temperature, electrocardiogram (ECG), electromyography (EMG), electroencephalography (EEG), sugar level etc. [17]. These sensed events can be classified into two groups: regular observatory events (ROE) and occasional emergency events (OEE). ROE may include, but not limited to blood pressure, body temperature and oxygen saturation level in the blood , while OEE could be rapid fluctuation in ECG signals, reduced blood level in the brain etc. OEE should be reported urgently within the deadlines in a reliable and real-time manner for the immediate and accurate diagnoses. On the other hand, ROE is required to be delivered within best effort.

Low rate wireless personal area network (LR-WPAN) is widely used for wireless HBM applications due to its features like energy efficiency, scalability, and design flexibility (refer Section 2-2). IEEE 802.15.4 standard defines physical (PHY) layer and MAC layer protocol specifications for LR-WPAN. IEEE 802.15.4 MAC implements a hybrid of carrier sense multiple access with collision avoidance (CSMA/CA) and time division multiple access (TDMA) mechanisms. It provisions the guaranteed time slots (GTSs) on a first-come-first-serve (FCFS) basis to the devices for reliable transmission. Since FCFS, it is not guaranteed that the GTS will be allocated to all the needy devices. Also, there is not any provision for an emergency handling mechanism to report the sensed life-threatening emergency promptly within the specified target delay margin (for example, 125ms for critical medical data [18]). The emergency devices contend for channel assessment as other normal devices. So, there is not any strict QoS support for emergency events. Rather, undesired delay is incurred in reporting those emergency events. Such efficiencies of IEEE 802.15.4 MAC for handling emergency events is discussed in Section 3-3 of chapter II. At this point, our objective is to minimize the delay associated in reporting emergency events. An opportunistic emergency handling scheme in IEEE 802.15.4 MAC can offer better performance in terms of emergency reporting delay of critical data.

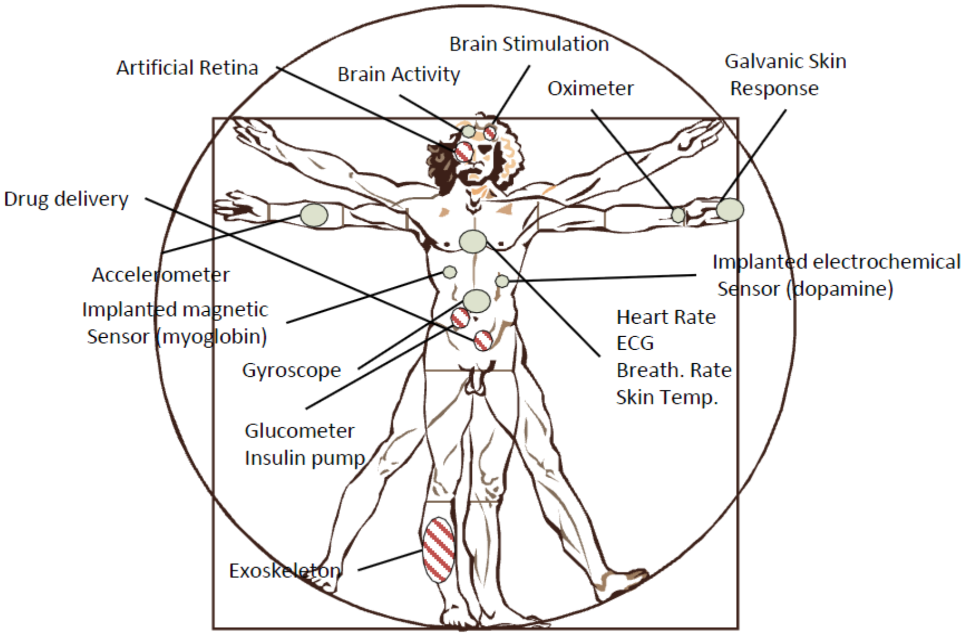

Figure 1-1: Actuators and sensors in HBM application [16].
Vitruvian man from Microsoft clip art: royalty free

C. Thesis Contribution

The characteristic parts of the carried research work are summarized under the title of thesis contribution. They are as follows:

- Research on human body monitoring applications and their requirements.
- Proposition of modified IEEE 802.15.4 superframe structure to incorporate an emergency handling mechanism.
- Achievement of reduced emergency reporting delay in considering HBM applications.
- Achievement of higher packet delivery ratio for emergency traffics than in the conventional IEEE 802.15.4 MAC.
- Achievement of reduced average delay for normal medical traffics.

D. Thesis Organization

The content of this thesis is organized in modular chapters. The first chapter presents a short introduction of research fields, basic terms and fundamental concepts used throughout this thesis, e.g. human body monitoring applications, LR-WPAN, IEEE802.15.4, emergency reporting scheme. With the motivation given and the main terms introduced, chapter II gives more detail about HBM application systems and the IEEE 802.15.4 standard in sections 2.1 and 2.3 respectively. The inefficiencies of IEEE 802.15.4 MAC to handle emergency events in HBM applications are also pointed out in section 2.3. Then after, related works are presented under section 2.4. The proposed scheme as a solution to the inefficiency is explained in chapter III. Detailed information about the simulation environment and the outcomes of the simulations are described on chapter IV. The thesis is concluded in the last chapter with wrapping text for the summary of the carried research and possible future works.

II. Preliminaries

A. HBM Application System

Human body monitoring (HBM) application system is a system for measuring, monitoring and computer analyzing selected physiological variables like lung sound, respiratory rate and rhythm, heart sound, heart rate and rhythm, and body temperature of a patient in real time and transmitting those variables to a remote medical personnel to alert the need for medical treatment or automatically administering such treatment under computer control. The coded signals relating to physiological variables produced are compared with reference values in order to determine the patient's condition. If the evaluation indicates that the medical treatment is needed, then the coordinator device activates a local and/or a remote alarm to alert the medical personnel and/or activates one or more actuators for administering a medical treatment such as injection or infusion of a drug. The transmission of those measured variables is carried out through wireless networks [19]. Hence, the HBM application system is an innovation that merges the trio: biomedicine, technology and wireless communication health for continuous, 24 x 7 monitoring of several crucial bodily functions. The utilization of wireless communication technology in the HBM environment has led to an increased usability and accessibility for both the users and the providers of health care services.

There are many existing terminologies for the health care and monitoring products and systems. The most common ones are e-Health, m-Health, health care, health monitoring etc. e-Health or electronic-health refers to the general healthcare aided by electronic systems, processes and communication technologies like maintaining electronic record of patients or use of internet for medical transcription, whereas m-Health or mobile-Health refers to the personal or general health practices supported by mobile devices like patient monitoring system, data collecting through mobile phones. Similarly, other terminologies like health monitoring are referred often as a passive monitoring of conditions while health care in contrast includes is the active integral part e.g. the active regulation of insulin level [20]. However, through the term human body monitoring system, we cover both the health care and health monitoring along with the patient monitoring system [19].

1. HBM Application System Architecture

The commonly agreed system architecture for the wireless HBM application system contains of three tiers [21, 22] as shown in Figure 2-1.

- *Tier -1:* The tier-1 is the lowest level which includes a set of intelligent physiological sensors like ECG sensor, EMG sensor, EEG sensor, blood pressure sensor etc. These sensors possess the characteristics of minimal weight, miniature form-factor, low-power operation to permit prolonged continuous monitoring, seamless integration into an HBM application system, standard-based interface protocols, and patient-specific calibration, tuning, and customization [21].
- *Tier-2:* The tier-2 level is the personal server (internet enabled PDA, cell phone, or home computer) which connects the tier-1 devices with the upper level tier-3 service. IEEE 802.15.4 [14] or ZigBee [15] or Bluetooth [23] connectivity is used for the communication with tier-1 devices while mobile telephone networks (2G, GPRS, 3G) or WLANs are used for the communication with upper tier-3 level. The tier-2 device acts as a network coordinator for tier-1 devices and can also perform some signal pre-processing and synchronization tasks.

– *Tier-3:* The tier-3 includes the network of remote health care servers and related services (Caregiver, Physician, Clinic, Emergency, and Weather).

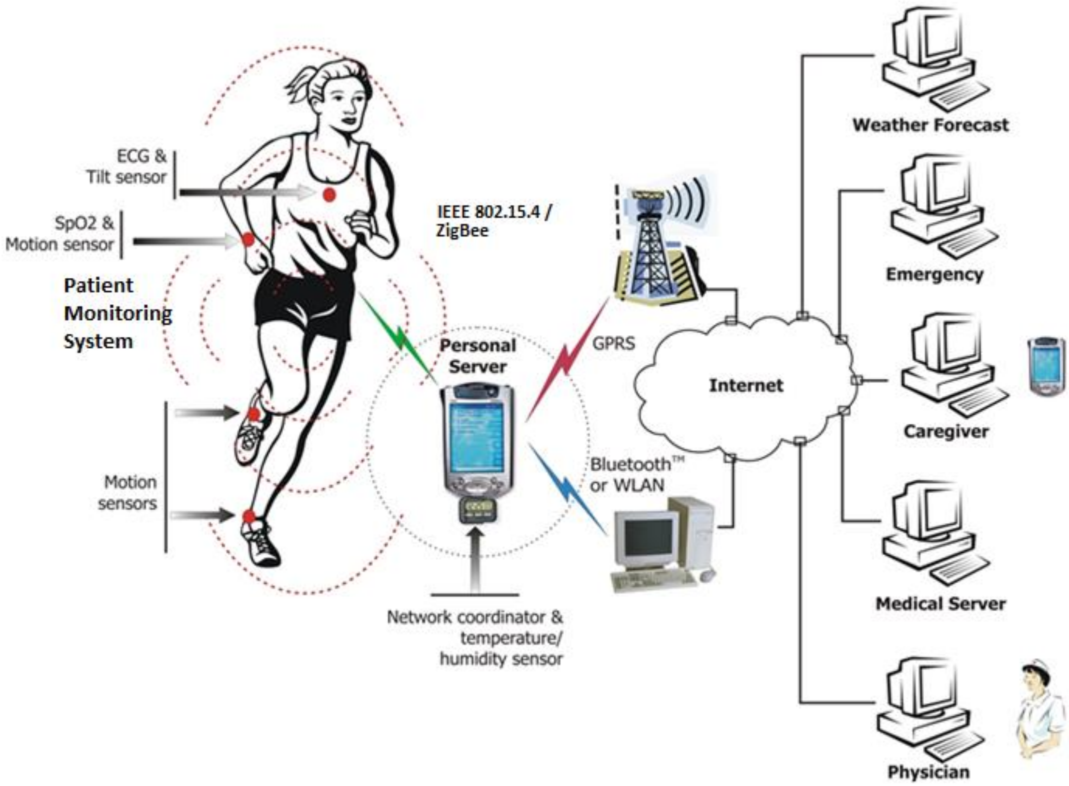

Figure 2-1: Wireless body sensor network of intelligent sensors for patient monitoring [21].

In this thesis work, we are focused only with the communication network between the tier-1 and tier-2 where IEEE 802.15.4 is used as a communication protocol. More specifically, we are more focused into the channel assessment to the emergent devices in tier-1 for reporting emergency events to the tier-2 network coordinator.

2. Issues in HBM Application Systems Network

Wireless networks with HBM application systems have diverse functions and demand strict network requirements, which make it different from other WPANs applications. There are many factors that need to be considered while implementing WPAN based HBM application systems [18] , [24]. Some of them are listed as follows:

- *Power Efficiency:* Since, in HBM applications, sensors are also employed in the body by a minor surgery, frequent replacement of the sensors due to power exhaustion is unbearable. Depending on the application types, the sensors may have different battery life from some hours to months without any intervention. E.g. the swallow-able camera pills like in capsule endoscopy have the power life of tens of hours only while pacemakers and cardiac defibrillators should have the lifetime of more than years. So HBM application system must be power efficient and hence different power efficient technologies by minimizing control packet overheads, network over hearings, packet collisions, idle listening, sleep or hibernate strategy etc. should be implemented in the system.
- *Interoperability:* Depending on the application types, the sensors in HBM application can be wearable on the body surface and also can be implanted inside the body. These sensors hence can operate on different frequency bands and PHY layers. So, the sensors must be interoperable at multiple frequency bands and support multiple physical layers (PHYs). Also, the interoperability refers to the proper data transfer across different network standards such as Bluetooth, LR-WPAN, etc. to facilitate information exchange, plug and play service.
- *Security and Privacy:* The data collected from an HBM application system or during their transmission outside of the wireless HBM must be highly

secured and maintain the highest degree of privacy protection. The sensors devotedly employed for a person only should generate the data for that patient. The data transmission over the networks should be secured and accurate. It requires a high system level and device level security [25].

– *Sensor Validation:* False alarm generations are frequent when the data generated by the sensors are not valid. The reading made by the sensors must be accurate, valid and authentic. However, hardware constraints and inherent communication issues may cause unreliable wired/wireless network links, interference and limited power reserves.
– *Co-existence and Interference Mitigation:* Multiple wireless HBM applications (e.g. one network per patient) may exist in a confined area like a hospital room. These networks must co-exist without any interference between them. And, the wireless link should also increase the coexistence of sensor node devices with other network devices available in the environment.

Besides these, delay guarantee (i.e. low latency), strict QoS for service guarantee, efficient bandwidth utilization, scalability are other requirements. The deployed sensors have heterogeneous functions and mixed data rates depending on the applications. So, the network should scalable enough to support variable data rate from some kbps to Mbps. E.g. the data rate of in-body needs vary, ranging from few kbps in pacemaker to several Mbps in capsule endoscope. The network should be scalable also in terms of the number of devices it supports.

B. Wireless Network Technologies for HBM application systems

Nowadays, wireless communication technologies are widely used in various scenarios for wide ranges of use cases and applications. So, in consideration to human health applications for wireless health care and monitoring solutions, several technologies have been proposed and promoted by different research groups and industrialists. At present, Z-Wave, Infrared according to Infrared Data Association (IrDA) Standard [26], Bluetooth, IEEE 802.15.4 or ZigBee is commonly used. But amongst these standards and technologies, IEEE 802.15.4 is the most prevalent standards in this field.

IEEE 802.15.4 is preferred over other network technologies because of various reasons, such as, proprietary issue in Z-Wave, Line-of-Sight (LOS) connection requirement in Infrared, potential interferences from different devices in Bluetooth etc. Similarly, ZigBee uses IEEE 802.15.4 as an underlying framework. Besides, IEEE 802.15.4 is used extensively also because it only standardizes the basic communication layers like lower layer physical and data link layers and other upper layers like applications, network configuration, routing protocols and other are left upto researchers for the design flexibility to use their own developments. For developers, IEEE 802.15.4 uses worldwide freely accessible 2.45 GHz ISM band. It was designed to support low power usage and low cost transceivers with some small output powers to minimize the inter technology interference. Already available hardware along with small chips and antenna sizes are the other reasons that make IEEE 802.15.4 widely used in HBM applications.

Besides these, the use of IEEE 802.15.4 for HBM application has also been tested by some researchers too. In [27] the authors through their research on the performance of IEEE 802.15.4 WBANS for health care and monitoring solutions showed that the standard is usable when configured properly. Feasibility of IEEE 802.15.4 for HBM applications is also approved in other researches and white papers [28] - [30].

Recently IEEE802.15.6 [31] standard for Wireless Body Area Network is standardized. But in [32] it has been analyzed that that for very small payloads IEEE 802.15.4 performs better in terms of average packet loss ratio and average delay than IEEE 802.15.6 due to the different CSMA strategy [14] [31]. As we are concerned with the emergency handling and emergency packets are also small payload sized data [33], 802.15.4 has advantages in terms of network performances.

C. An Overview of IEEE 802.15.4 - 2006

IEEE 802.15.4 is a uniquely designed standard for low rate wireless personal area networks (LR-WPAN) with low data rate, low power consumption and low hardware cost features. The standard provides only the physical (PHY) layer and the medium access control (MAC) layer specification and the rest of the upper layers (e.g. Application or network layer according to TCP-IP reference model) and enhanced security features are left open for additional frameworks like ZigBee or own developments.

The protocol stack for the standard is given in Figure 2-2. The lowest layer is the PHY layer to be discussed in section 2.3.1. Next to the PHY layer is MAC layer which is discussed in section 2.3.2. The upper layers consist of network layer providing network configuration, message routing, and an application layer providing the intended function of the device an enhanced security features which are out of scope of this standard. An IEEE 802.2 Type 1 logical link control (LLC) can access the MAC sub-layer through the service specific convergence sub-layer (SSCS). The LR-WPAN architecture can be implemented either as embedded devices or as devices requiring the support of an external device such as a PC.

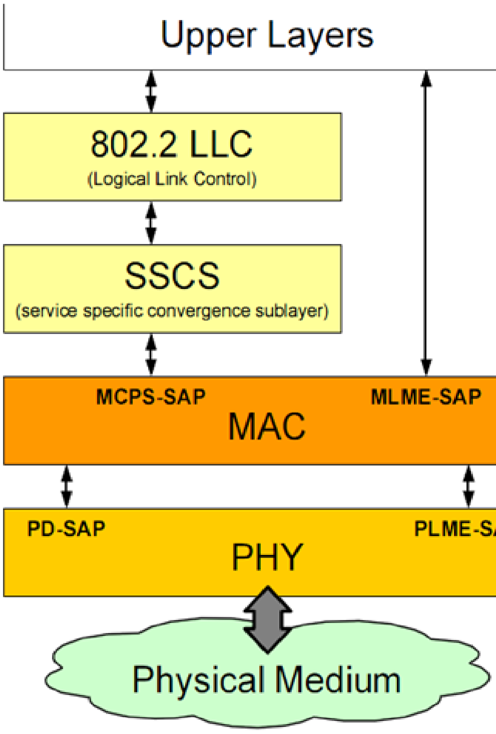

Figure 2-2: IEEE 802.15.4 architecture model [14]

The standard specifies three device kinds (Figure 2-3):

- *Full-Functional Devices (FFDs):* FFDs support the complete standard and are used to build and set up IEEE 802.15.4 networks.
- *Reduced Functional Devices (RFDs):* RFDs are the end devices operating on minimal implementation of IEEE 802.15.4 intended for simple operations like plain sensing and are able to communicate only with the FFDs.
- *Personal Area Network Coordinator (PANC):* The FFD that starts and build up a network is normally selected as PANC which is actually the principal controller of PAN.

The standard defines two basic network topologies:

- *Star Topology:* In the star topology, all messages are transferred over the PANC. It means there is no direct communication between RFDs.
- *Peer-to-Peer (P2P) topology:* In P2P topologies, the PANC still provides management functionalities but the RFDs can communicate with each other directly without the assistance of the PANC or FFDs.

Both topologies and their specific communication flows are shown in the Figure 2-3. With these different topologies, different usage scenarios are therefore possible. An example of IEEE 802.15.4 P2P topology is the cluster tree network (CTN) where several different networks are arranged in a tree topology and combined with a bigger one.

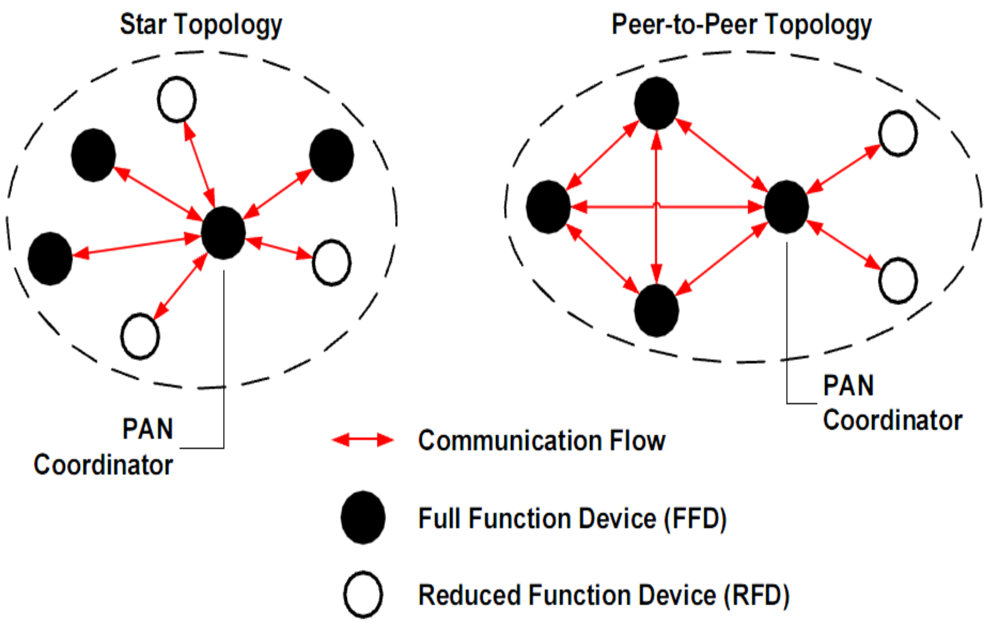

Figure 2-3: IEEE 802.15.4 network topology [14].

1. IEEE 802.15.4 Physical (PHY) layer

The IEEE 802.15.4 physical (PHY) layer defines the radio channel, modulation schemes and spreading technique for data transmission and reception. The standard supports several such PHYs with different data rates and modulation schemes as tabulated in Table 2-1.

Table 2-1 PHY layer specifications of IEEE 802.15.4 [14]

Frequency Band (MHz)	Chip Rate (kchips/s)	Modulation	Bit Rate (kbit/s)	Symbol Rate(ksymbols/s)
868-868.6	300	BPSK	20	20
902-928	600	BPSK	40	40
868-868.6	400	ASK	250	12.5
902-928	1600	ASK	250	50
868-868.6	400	O-QPSK	100	25
902-928	1000	O-QPSK	250	62.5
2400-24835	1600	O-QPSK	250	62.5

All of the frequency bands are supported are based on the Direct Sequence Spread Spectrum (DSSS) spreading technique. Channel assignments are defined through a combination of channel number and channel pages. The channel center frequencies (Fc) are defined as follows:

$$Fc = 868.3\ MHz, \qquad for\ k=0 \tag{1}$$
$$Fc = 906 + 2(k-1)MHz, \qquad for\ k=1,2,\ldots,10 \tag{2}$$
$$Fc = 2405 + 5(k-11)MHz, \qquad for\ k=11,12,\ldots,16 \tag{3}$$

The PHY layer protocol performs following tasks:

- *Activation and deactivation of the radio transceiver:* At an instance, the radio transceiver can either in one of three states: transmitting, receiving or sleeping. Upon request of the MAC sub-layer, the radio is turned ON or OFF. According to the standard, the turnaround time from transmitting to receiving and vice versa should be no more than 12 symbol periods (each symbol corresponds to 4 bits).

– *Energy Detection (ED):* ED estimates the received signal power within the bandwidth of an IEEE 802.15.4 channel. It does not make any signal identification or decoding on the channel. The ED time should be equal to 8 symbol periods. This measurement is typically used by the Network Layer as a part of the channel selection algorithm or for the purpose of Clear Channel Assessment (CCA), to determine if the channel is busy or idle.
– *Link Quality Indication (LQI):* LQI is the measurement of the Strength/Quality of a received packet which may be implemented using receiver ED, a signal to noise estimation or a combination of both techniques to measure the quality of a received signal.
– *Clear Channel Assessment (CCA):* CCA is the evaluation of the medium activity state i.e. busy or idle, and can be performed in three operational modes: (1) Energy Detection mode: the CCA reports a busy medium if the detected energy is above the ED threshold. (2) Carrier Sense mode: the CCA reports a busy medium only is it detects a signal with the modulation and the spreading characteristics of IEEE 802.15.4 and which may be higher or lower than the ED threshold. (3) Carrier Sense with Energy Detection mode: this is a combination of the aforementioned techniques. The CCA report that the medium is busy only if it detects a signal with the modulation and the spreading characteristics of IEEE 802.15.4 and with energy above the ED threshold.
– *Channel Frequency Selection:* IEEE 802.15.4 defines 27 different wireless channels. Each network can support only part of the channel set. Hence, the physical layer should be able to tune its transceiver into a specific channel when requested by a higher layer.

2. IEEE 802.15.4 MAC layer

The MAC sub-layer is the second layer specified in the standard. It mainly provides two services, a data and a management service, both accessible through different interfaces. The MAC layer protocol supports two operational modes (Figure 2-4):

- *The non-beacon-enabled mode:* During this mode, there exiss neither beacons nor superframe and medium is accessed by an un-slotted CSMA/CA mechanism (refer to Section 2.3.2.4).
- *The beacon-enabled mode:* In this mode, beacons are periodically sent by the PANC for synchronization of the nodes associated with it, and to identify the PAN. The beginning of each superframe is delimited by a beacon frame (refer to Section 2.3.2.4) that defines a time interval during which frames are exchanged between different nodes in the PAN. Medium access is basically ruled by the slotted CSMA/CA. However, the beacon-enabled mode also enables the allocation of contention free time slots, called Guaranteed Time Slots (GTSs) for the nodes requiring guaranteed bandwidth.

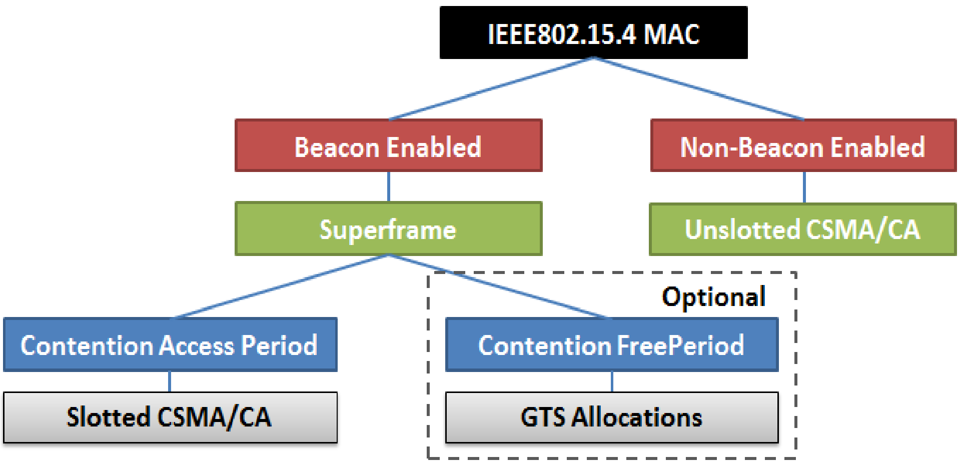

Figure 2-4: IEEE 802.15.4 operational modes [14].

The followings are the different mechanisms, functions and features of the standard worth to be discussed for human body monitoring solutions.

a. Frame Structures

Frame structures are related to the system performance because the efficient message exchange requires slim yet expandable and robust frames. That is why, the complexities of frame structure are lower in IEEE 802.15.4. The frame structure also contains the mechanisms to secure the frames against interference on noisy channels. Each frame type is equipped with a 16-bit frame check sequences where a cyclic redundancy check (CRC) algorithm is used. Four different frame types are defined in the standard:

- MAC command frame
- DATA frame
- BEACON frame
- ACKNOWLEDGE (ACK) frame

The standard follows the OSI principle for layered communication system and in each layer the protocols stack adds the layer specific headers and footers to the structure of these four frame types. The MAC command frame is used for handling the control transmissions while the DATA frame is used for all data transmissions. ACKNOWLEDGEMENT frames are used to confirm a successful reception and BEACON frame is used by the PANC for the beacon distribution. The exact frame type structures are listed in [14].

b. Superframe Structure

In beacon-enabled mode, each coordinator defines a superframe structure as shown Figure 2-4, based on:

– *Beacon Interval (BI),* which defines the time between two consecutive beacon frames;
– *Superframe Duration (SD),* which defines the active portion in the BI, and is divided into 16 equally-sized time slots, during which frame transmissions are allowed.

Optionally, an inactive period is defined if BI > SD. During the inactive period (if it exists), all nodes may enter into a sleep mode (to save energy). BI and SD are determined by two parameters, the Beacon Order (BO) and the Superframe Order (SO), respectively, as follows:

$$BI = aBaseSuperframeDuration*2^{BO} \quad (4)$$

$$SD = aBaseSuperframeDuration*2^{SO} \quad (5)$$

$$Inactive\ Period = BI - SD \quad (6)$$

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

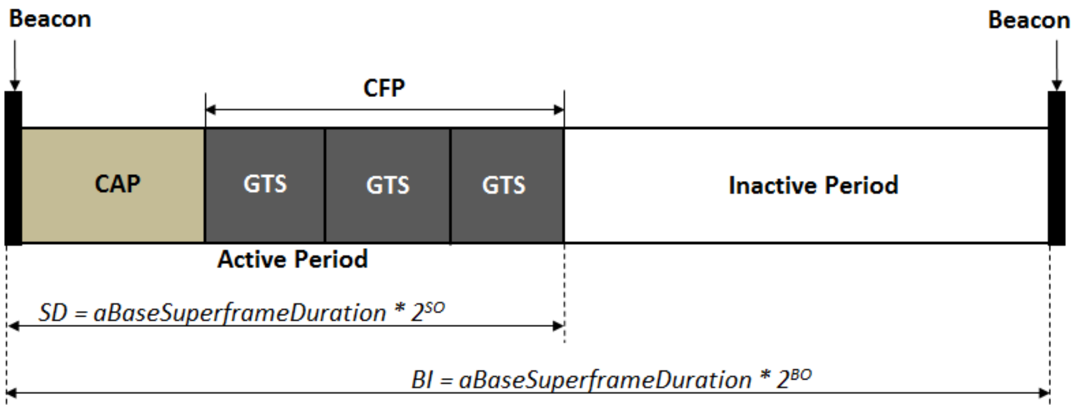

Figure 2-5: IEEE 802.15.4 superframe structure [14]

The active portion of the superframe structure is further divided into following three parts:

- *Beacon:* At the start of every superframe, the PANC broadcasts beacon frame that contains the information of the addressing fields, the superframe specification, the GTS fields, the pending address fields and other PAN related.
- *Contention Access Period (CAP):* CAP starts immediately after the beacon frame and ends before the beginning of the CFP, if it exists. Otherwise, the CAP ends at the end of the active part of the superframe. The length of CAP is variable as it depends on the number and the slots of GTSs allocated but the minimum length of the CAP is fixed at *aMinCAPLength = 440* symbols. And also a temporary violation of this minimum may be allowed if additional space is needed to temporarily accommodate an increase in the beacon frame length like when needed to perform GTS management. The minimum length of CAP ensures the transmission of MAC commands even when maximum GTSs are used. The channel access mechanism during CAP is Slotted CSMA/CA mechanism. But, the acknowledgement frames and any data that immediately follows the acknowledgement of a data request command are transmitted without contention. For a transmission that cannot be completed before the end of the CAP, must be deferred until the next superframe.
- *Contention Free Period (CFP):* CFP starts immediately after the end of the CAP and must complete before the start of the next beacon frame (if no inactive period follows) or the end of the superframe. Transmissions within CFP are contention-free since they use reserved time slots (GTS) that have been previously allocated by the PANC. All GTSs that may be allocated by the Coordinator are located within CFP and must occupy contiguous slots.

The length of CFP may hence grow or shrink depending on the total length of all GTSs.

c. Data Transfer Model and Transmission scenarios

Three different transmission types are defined in IEEE802.15.4.

- Transmissions from a device to the PANC
- Transmissions from the PANC to a device
- Transmissions between any two devices (between FFD or RFD, not PANC)

The Star topology networks only support the first two transaction types while P2P topologies support all three types of transmissions as shown in Figure 2-3.

IEEE 802.15.4 protocol standard enables three different types of transmissions scenarios:

- *Direct transmissions:* Special frames like the frames like the beacon frames, the acknowledgment frames and the frames in the GTS time slots are transmitted to the medium without any channel assessment which is the direct transmissions.
- *Indirect transmissions:* In the indirect transmission, the frames are stored in the Coordinator to which the destination device is associated. Then, the information about the stored frames (or pending transmissions) is included in the pending addresses descriptor fields of the beacon frame. If a device has pending data in the Coordinator it can request it by sending a data request command frame.
- *Normal transmissions:* In normal transmissions, the frames are transmitted to the medium with contention, by applying the CSMA/CA algorithm like the data frames and the command frames transmitted during the CAP.

d. CSMA/CA Mechanism

In IEEE 802.15.4, CSMA/CA mechanism can either be slotted or un-slotted, depending on the network operating mode i.e. beacon-enabled or non-beacon-enabled respectively.

However, the CSMA/CA mechanism is based on backoff periods (with the duration of 20 symbols). Following three variables are used to schedule medium access:

- *Number of Backoffs (NB),* represents the number of failed attempts to access the medium;
- *Contention Window (CW),* representing the number of backoff periods that must be clear before starting transmission;
- *Backoff Exponent (BE),* enabling the computation of the number of wait backoffs before attempting to access the medium again.

Figure 2-6 depicts a flowchart describing the CSMA/CA mechanism. It I divided in to slotted and un-slotted modes. Each modes can be summarized in five steps. The slotted mode is:

- *Step 1:* Initializes algorithm variables i.e. NB equals to 0; CW equals to 2 and BE is set to the minimum value between 2 and a MAC sub-layer constant (macMinBE);
- *Step 2:* Waits for a random defined number of backoff periods before attempting to access the medium after locating a backoff boundary;
- *Step 3:* Performs Clear Channel Assessment (CCA) to verify if the medium is idle or not.
- *Step 4:* If CCA returns busy channel, NB is incremented by 1 and the algorithm must start again in Step 2;

- *Step 5:* If CCA returns an idle channel, CW is decremented by 1 and the message is transmitted when it reaches 0, otherwise the algorithm jumps to Step 3.

In the slotted CSMA/CA, if the battery life extension is set to 0, the CSMA/CA must ensure that, after the random backoff (step 2), the remaining operations can be undertaken and the frame can be transmitted before the end of the CAP. If the number of backoff periods is greater than the remaining in the CAP, the MAC sub-layer pause the backoff countdown at the end of the CAP and defers it to the start of the next superframe. Otherwise, the MAC sub-layer applies the backoff delay and re-evaluate whether it can proceed with the frame transmission. If the MAC sub-layer does not have enough time, it defers until the start of the next superframe, continuing with the two CCA evaluations (step 3). If the battery life extension set to 1, the backoff countdown must only occur during the first six full backoff periods, after the reception of the beacon, as the frame transmission must start in one of these backoff periods.

Figure 2-6 also depicts a flowchart describing the un-slotted version of the CSMA/CA mechanism which is very much similar to the slotted version except few exceptions.

- *Step 1:* The CW variable is not used, since the non-slotted CSMA/CA has no need to iterate the CCA procedure after detecting the idle channel. Hence, in step3, if the channel is assessed to be idle, the MAC protocol immediately starts the transmission of the current frame. Second, the un-slotted CSMA/CA doesn’t support *macBattLifeExt* mode and, hence, BE is always initialized to the *macMinBE* value;

– *Step 2, 3, and 4:* It is similar to slotted CSMA/CA version. The only difference is that the CCA starts immediately after the expiration of the random backoff delay guaranted in step 2;

– *Step 5:* The MAC sub-layer starts immediately transmitting its current frame just after a channel is assessed to be idle by the CCA procedure.

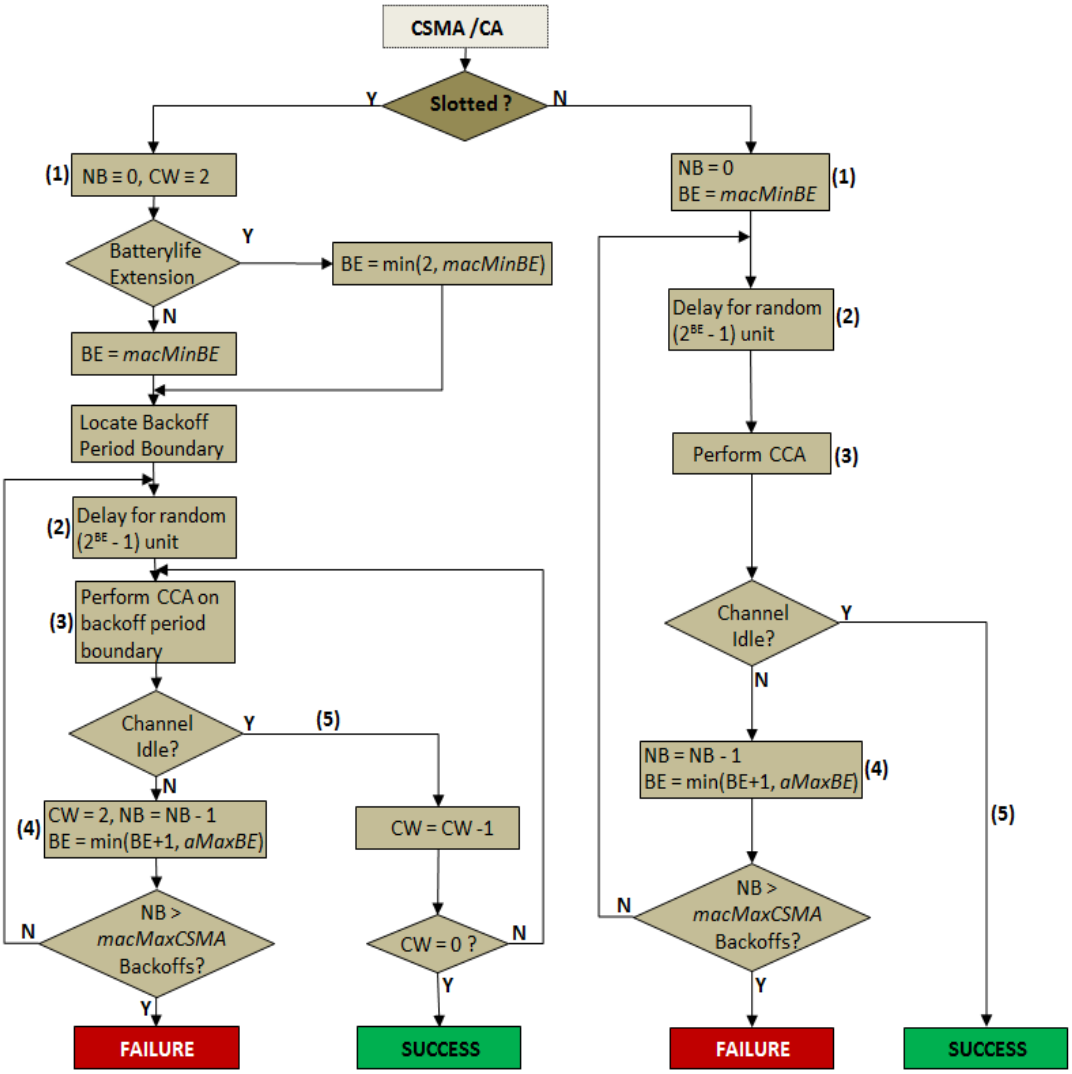

Figure 2-6: The CSMA/CA mechanism [14].

e. Guaranteed Time Slot (GTS) mechanism

In beacon enabled mode, during CFP, the GTS mechanism allows devices to access the medium without contention. But the device to which a GTS has been allocated can also transmit during the CAP. The coordinator allocates the GTSs for communications between the coordinator and a device. The maximum number of GTSs is limited to seven in the same superframe and a single GTS may contain one or more time slots provided that there is sufficient capacity in the superframe. GTS has only one direction: from the device to the Coordinator (transmit) or from the Coordinator to the device (receive).

The GTS can be de-allocated at any time at only if the de-allocation is initiated by Coordinator or the device that originally requested the GTS allocation. The GTSs are managed by Coordinator only. For each GTS, it stores the starting slot, length, direction, and associated device address in the GTS request command. Only one transmit and/or one receive GTS are allowed for each device. Upon the reception of the deallocation request the Coordinator updates the GTS descriptor list by removing the previous allocated slot and rearranging the remaining allocation starting slots. The arrangement of the CFP consists in shifting right the allocated GTS descriptors with starting slot before the recent deallocated GTS descriptor and consequently the final CAP slot variable is updated.

The Coordinators monitor GTS activity and if there are no transmissions during a defined number of time slots the GTS allocation expires. The expiration occurs if no data or no acknowledgement frames are received by the device or by the Coordinator, on every $2 * n$ superframes, where n is defined as:

$$\begin{cases} n=2^{(8-BO)}, & \text{if } 0 \leq BO \leq 8 \\ n=1, & \text{if } 9 \leq BO \leq 14 \end{cases} \quad (7)$$

f. Inter-Frame Spacing (IFS)

MAC sub-layer needs some time to process data received by the physical layer, for which an idle IFS period is placed after all transmitted frames. If the transmission requires an acknowledgment, the IFS will follow the acknowledgement frame. The length of the IFS period depends on the size of the transmitted frame: a long inter-frame spacing (LIFS) or short inter-frame spacing (SIFS). The selection of the IFS is based on the IEEE 802.15.4 *aMaxSIFSFrameSize* parameter, defining the maximum allowed frame size to use the SIFS. The CSMA/CA algorithm takes the IFS value into account for transmissions in the CAP. These concepts are illustrated in Figure 2-7.

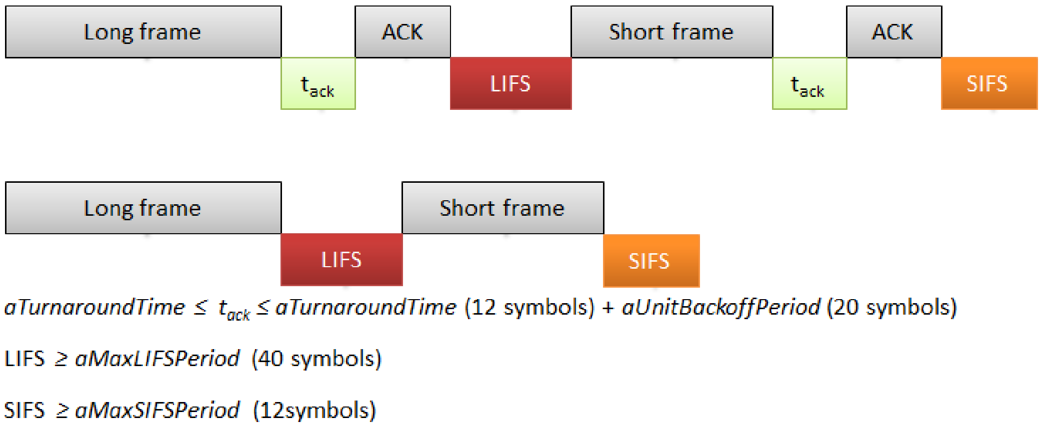

Figure 2-7: Inter-frame spacing [14].

3. Inefficiency of IEEE 802.15.4 MAC

IEEE 802.15.4 is widely used for HBM applications due to its several benefits over other wireless technologies. But still, it exhibits some inefficiency while considering the strict QoS requirement in term of delay for reporting the emergency events.

First and foremost, there is no traffic differentiation mechanism in IEEE 802.15.4. All data are treated as same, so there is no way that critical or medical data gets higher priority during channel access.

Secondly, there is no priority based mechanism for GTSs allocation; instead GTSs are served in first-come-first-serve (FCFS) manner. So, it is not guaranteed that emergency nodes always get GTS for guaranteed data transmission.

The GTS request in a frame is addressed only by beacon in the subsequent frame if it is available. So an undesired waiting delay is incurred prior to the actual transmission in the GTS.

The delay exceeds the minimum delay requirement for reporting emergency when the emergency events happen during CFP. For example, if an emergency event occurs at the beginning of CFP, it will be reported only in the subsequent CAP (in the next frame) or else the emergency event demands GTS then it first has to first contend for GTS in the subsequent CAP and will be scheduled with GTS in the next's next frame if only the GTS is available. As an trivial example, if we consider the CFP of a superframe with BO 4 and SO 3 (length of superframe as such is 256.76 ms) consists of the 7 GTS with each GTS expanding to a slot, then as such the emergency events occurring at the beginning of CFP will be considered for access at least only after 176.76 ms in the subsequent CAP (considering the summation of CFP and inactive period only) which is higher than the target delay limit for reporting emergency events, 125 ms [18].

D. Related Works

A number of MAC protocols based IEEE 802.15.4 on have been proposed for wireless HBM application to satisfy QoS requirement of delay.

A traffic adaptive MAC for handling emergency and on-demand traffics has been proposed in [34] which maintains table to store the traffic pattern of the nodes. It also consists of configurable contention access period (CCAP) but rest of the superframe parts resembles the conventional IEEE 802.15.4 MAC. So this MAC is bound to incur undesired delay on reporting emergency as described in previous Section 2.3.3.

Lee et al. has proposed enhanced MAC protocol of IEEE 802.15.4 [35] for WBAN with enhanced superframe structure containing emergency slot (ES) for emergency handling. ES is a quite short period where data transmission is described by success or fail. The protocol contains a long CFP and inactive period follows the CFP. So emergency occurred in CFP incurs an unnecessary delay due to inactive period.

Zhang et al. [36] has differentiated the traffics into two classes: periodic and bursty, and proposed diversified CFPs for these two classes are allocated based upon the traffic arrivals in the previous superframe. CAP is also divided into two control channels: Access Channel1 (AC1) and Access Channel2 (AC2). But the protocol is bound to suffer a long delay due to the long CFPs. Since traffics of class1 are not allowed the CFP of class2 and vice-versa, delay bound is higher when different traffics occur at different CFPs.

Khaled et al. [37] has classified traffic based on critical and non-critical issues. However, their work mainly concentrated on determining the number of retransmissions based on traffic criticality and avoided the other QoS issues.

Otgonchimeg et al. [38] has proposed emergency handling MAC protocol for human body communication using emergency GTS (EGTS) in CFP. Emergency events are treated as regular events and the number of EGTS required to handle possible emergencies are calculated. The channel access mechanism in EGTS is slotted ALOHA. This protocol is bound to fail when the multiple emergencies occur. Also emergency events are the unpredictable occasional events and allocating resources solely for those events decreases the bandwidth utilization.

Apart from the state-of-the-art emergency handling capability, we introduce an opportunistic emergency handling MAC scheme that strengthens the IEEE 802.15.4 MAC for reducing the emergency reporting delay in HBM applications thereby providing the reliable data transmission method for emergency events.

III. Proposed Scheme

A. System Model and Assumptions

The proposed scheme is based on IEEE 820.15.4 MAC standard, operating in 2.4 GHz RF band with a point-to-multipoint (star) network topology as shown in Figure 3-1, that consists a central coordinating FFD called network coordinator (NC) and many other RFDs known as sensing nodes (SNs). Being a FFD device, NC can perform some enhanced functions like synchronization with other surrounding SNs, slot allocation to SNs, exchanging control packets etc. whereas SNs only the sense and transmit the sensed data to NC. SNs can directly communicate with NC following single hop communication architecture.

SNs can be wearable or implanted devices and NC also be attached with the body or detached to some location but within the communication range of the SNs. The SNs are energy-constrained since they are battery powered. But, NC is assumed to have an external power supply.

As described in Section 1-2, SNs can transmit two types of messages: ROE and OEE. Besides these, SNs can transmit the control frames like association request, GTS request, DTS request etc.

The NC can process data received from SNs and then sends it to the monitoring station or server through other networks (i.e., cellular, WLAN, or wired); this communication paradigm is beyond the scope of this thesis. There may exist multiple NCs with different independent HBM-WPANs connected to the monitoring station. However, in this thesis, our concern is to design a MAC framework within a single WPAN with HBM application.

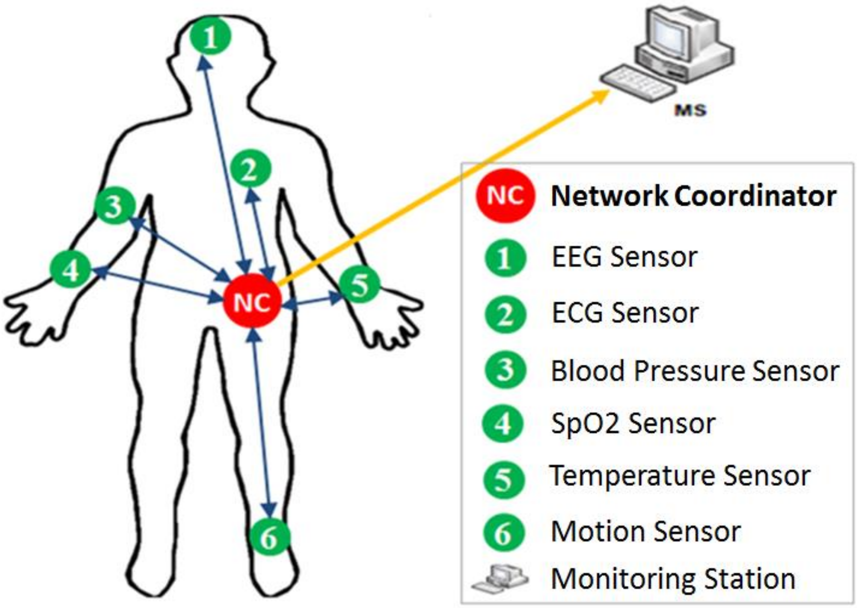

Figure 3-1: Network model.

B. Proposed Scheme Approach

In IEEE 802.15.4 MAC, there is a provision of GTS allocation in the contention free period that allows dedicated bandwidth to a device ensuring low latency. Any SN can transmit its data in CAP or in GTS if allocated. So any emergency events can be reported in CAP or in GTS depending on the instance of the occurrence.

We consider a scenario where two emergency events (OEE1 in SN1 and OEE2 in SN2) occur during CFP in any i^{th} superframe as shown in Figure 3-2. If neither of these SNs has following GTS schedule in that i^{th} superframe, they have to wait for next frame $i+1^{th}$ superframe to transmit their data. If SN1 doesn't need GTS to report its emergency event, then it can report the emergency in CAP of $i+1^{th}$ superframe But if SN2 requires GTS for its data transmission, it will first send a GTS request to NC. The request is granted if it is successfully received by NC and if there is any GTS resource available in the system. For the successful GTS request granted, the GTS schedule will be broadcasted by NC through beacon in i+2th superframe. Otherwise, it has to contend once again for GTS allocation in the next superframe.

Each nodes SN1 and SN2 suffer waiting time inorder to transmit the emergency data to NC. In case of SN1, it has to wait until the inactive period of the ith superframe and the beacon period of i+1th superframe so as to transmit its data in the CAP, whereas the SN2 has to at least wait complete i+1th superframe to report the emergency only in i+2th superframe. This is the inflexibility of IEEE 802.15.4 MAC to handle emergency.

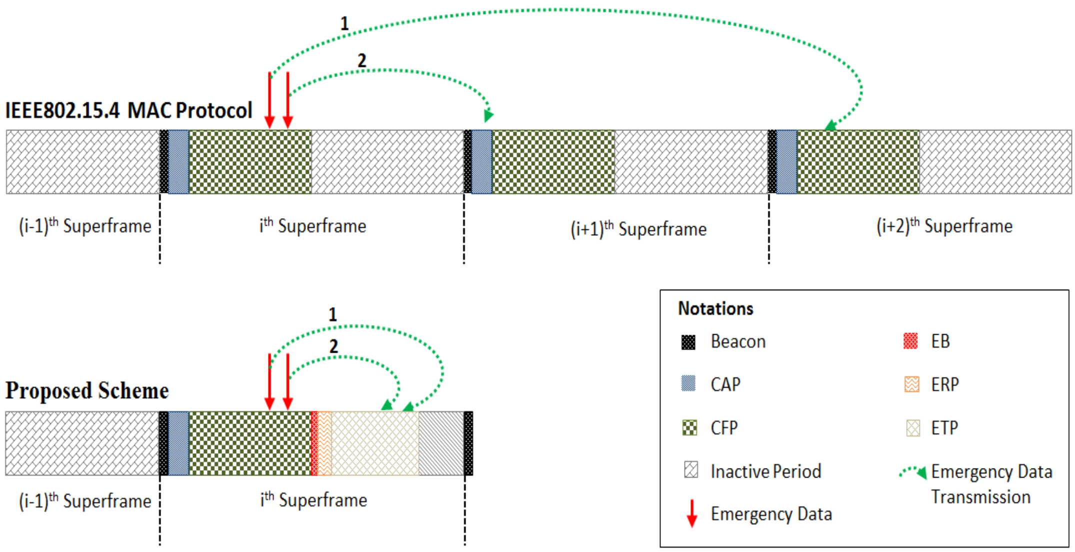

Figure 3-2: Proposed protocol approach.

But in the proposed scheme, SN1 and SN2 wait until CFP ith superframe finishes. A special time slot is allocated after CFP for requesting dedicated transmission slot to report the OEE1 and OEE2. SN1 and SN2, thereby, are allocated with the dedicated transmission slots for the assured data transmission. The emergency is handled in the same ith superframe for which the inactive period is opportunistically used. A fraction of inactive period is used for reporting emergency and transmitting the data. This is how the delay for reporting emergency events is minimized in the proposed scheme. The detailed flow diagram of the proposed scheme is presented in section 2.

1. Modified Superframe Structure

In the conventional beacon enabled IEEE 802.15.4 MAC, after the CFP ends, SNs and NC go to sleep mode in inactive period. As described in section 3-3, the inactive period is the one that causes undesired delay in reporting emergency events. That is why, in the proposed scheme, the inactive period is modified and opportunistically used for reporting those emergencies. Figure 3-3 shows the modified superframe format.

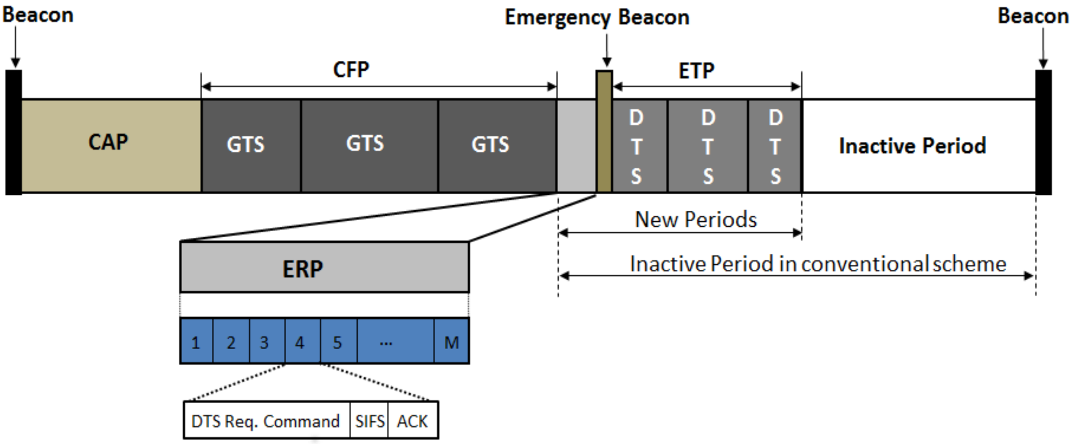

Figure 3-3: Modified superframe structure in the proposed scheme.

As shown in Figure3-3, the proposed scheme keeps the previous periods described section 2-3 intact both in structurally and functionally. The inactive period is modified to three new periods which are as follows:

- *Emergency Reporting Period (ERP):* ERP is a mandatory period in the modified IEEE 802.15.4 scheme. It starts immediately after the CFP and ends before the beginning of emergency beacon if exists. Otherwise the

ERP ends at the beginning of the inactive period of the superframe. In order to notify this ERP information to all SNs, the conventional beacon is modified to incorporate the ERP start slot and ERP length as shown in Figure 3-4. A single slot length is allocated for the ERP. Only the dedicated transmit Slot (DTS) request frames are transmitted during the ERP from the emergency SNs to the NC random backoff based random access method. A DTS request command frame is shown in Figure 3-5. However, the acknowledgement frames are transmitted without random backoff. If a transmission cannot be completed before the end of the ERP, it must be deferred until the next superframe.

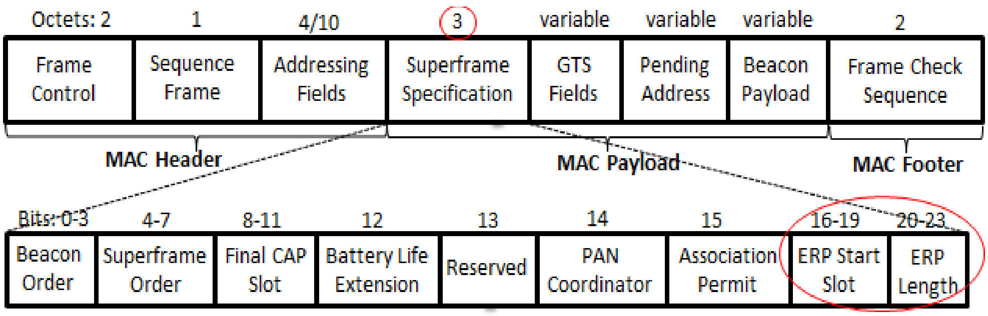

Figure 3-4: Modified beacon frame structure in the proposed scheme.

Octets: 7	1	1
MHR Fields	Command Frame Identifier	No. of Slots Request

Figure 3-5: DTS request command frame format.

– *Emergency Beacon (EB):* EB starts straightaway after the ERP. But EB is broadcasted by the BNC, only if any emergency is reported during ERP, otherwise EB period is used as inactive period. EB contains the transmission schedules (i.e. allocated Dedicated Transmission Slots (DTS)) as shown in Figure 3-6, in the following ETP. All the SNs who have reported emergency in ERP should listen to EB to check whether their reporting in ERP are acknowledged by NC and are allocated with DTS schedule.

Octets: 2	1	4	variable	2
Frame Control	Sequence Frame	Addressing Fields	DTS Fields	Frame Check Sequence

Figure 3-6: Emergency beacon frame structure.

– *Emergency Transmission Period (ETP):* ETP starts just after the EB. ETP is divided into a number of slots called as dedicated time slots (DTSs). Data transmissions in ETP follow contention-free method. Since they use dedicated time slots (DTS) that must be previously allocated by the NC. All the DTSs that may be allocated by the NC are located in the ETP and must occupy contiguous slots. The ETP may therefore grow or shrink depending on the total length of all DTSs. The number of such DTSs is limited to seven. The length of a DTS is so determined to accommodate at least an emergency data and an ACK message.

2. Channel Access in ERP

In the proposed scheme, collision does not occur during the OEE traffics transmission because OEE traffics are transmitted within the scheduled dedicated transmission slot in ETS, but collision may occur in the ERP slot during the transmission of DTS Request Packet (DRP). To reduce the collision probability in the ERP slot, the transmission of DRP is controlled by random backoff based contention access method. The ERP slot is divided into M virtual mini-slots as shown in Figure 3-3. Each of these mini-slots have Z time duration which is sufficient enough to send one DTS Request Packet (DRP) to NC and receive DRP ACK from NC. Thus, ERP duration should be $M * Z$. For example, if we consider DRP and DRP ACK are of the same size as GTS Request Frame (GRF) and GRF

ACK in IEEE 802.15.4 standard (i.e. 17 Bytes and 11 Bytes, respectively) with short inter frame space (T_{SIFS}) between a DRP and DRP ACK is 192μs and the raw data rate of the network is 250 kbps, the minimum duration of a backoff period within ERP is 1.088ms. So the length of ERP is M * 1.088ms. The value of *M* is adjusted according to the applications' need.

3. Proposed Scheme Flow

Figure 3-7 below gives the basic flow of the proposed scheme.

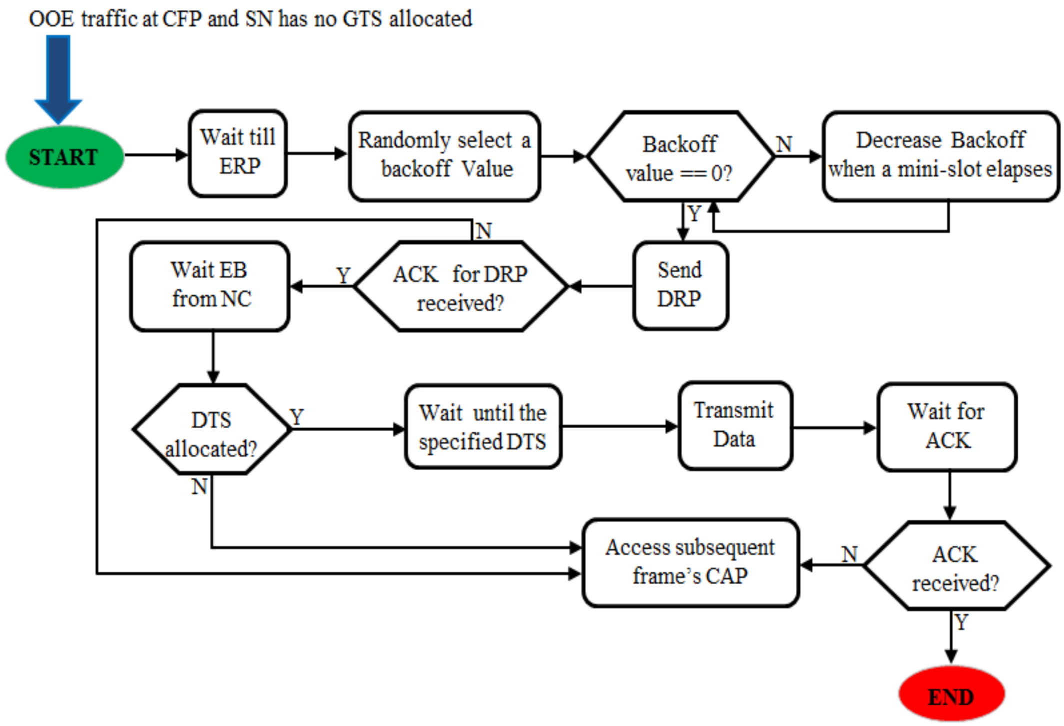

Figure 3-7: Proposed scheme flow diagram.

If a SN detects an emergency event during CFP, it waits until the start of ERP and randomly selects a backoff value within [*0, M*]. At the elapse of a backoff duration, the SN decreases its backoff counter by 1. Once the backoff counter value reaches 0, the SN sends a DTS Request Frame (DRF) and waits for ACK. If it receives

ACK for the sent DRF and DTS allocation information (regarding which DTS has been assigned to it) in the EB message, it will transmit its emergency data in the DTS allocated to it. On the other hand, if it does not receive ACK for DRF or DTS is not allocated in the EB message, the SN wait till the next CAP for data transmission by contention.

IV. Performance Evaluation

A. Simulation Environment

In order to evaluate protocol performance, we conducted the simulation of the proposed scheme on Castalia-3.2 [39], a network simulator specifically designed for sensor and body area networks based on OMNeT++ platform [40]. The simulation was carried out with star topology as shown in Figure 3-1, with the single hop communication between the NC and SNs. The numbers of SNs vary from 4, 8, 16 and 32.

The traffics are generated using Poisson distribution with varying mean inter-arrival time (T_{mean}). The generated packet lengths are fixed to 40 bytes. The generated traffics are classified as ROE and OEE. Out of the total traffics generated, random x% are OEE traffic and the rest are ROE traffics. The value of x is varied from 1 to 5. Figure 3-5 shows the traffic generation scenario for varying number of SNs when mean packet inter-arrival time is 500ms for the total simulation time of the 50s and the number of seeds is 75.

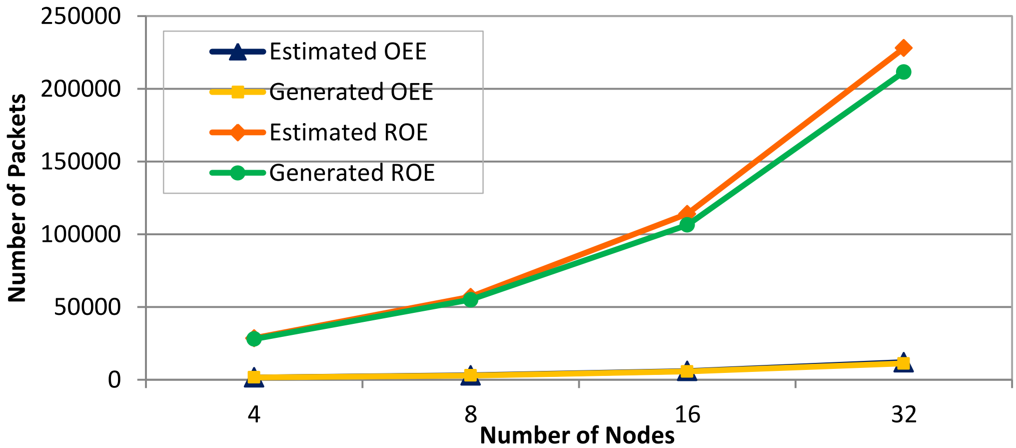

Figure 4-1: Traffic generation by Poisson distribution with T_{mean} = 0.5s and x =5%.

The detailed simulation parameters and their values for IEEE 802.14 MAC from Castalia [4] are summarized in Table 4-1.

Table 4-1 Simulation parameters

Simulation time	50 seconds		
Frequency band	2.4GHz		
Data rate	250 kbps		
MAC Buffer Size	60 packets		
Frame Parameters	**Command frames Information**	Association request	8 bytes
		GTS request	
		DTS request	
	ACK packet Size	6 bytes	
	Inter-frame Spacing	SIFS	12 symbols
		LIFS	40 symbols
	Turnaround Time	12 symbols	
Superframe Parameters	**Beacon Order (BO)**	4	
	Superframe Order (SO)	3	
	aNumSuperframeSlots	16	
	aBaseSlotDuration	60 symbols	
	Beacon Information	Base Beacon Packet Size	12 bytes
		GTS Descriptor Size	3 bytes
	CAP Parameters	aMinCAPLength	440 symbols
		unitBackoffPeriod	20 symbols
		macMinBE	5
		macMaxBE	7
		macMaxCSMABackoffs	4
	CFP Parameters	Max. No. of GTS	7
		1 GTS length	2 superframe slots
	ERP Parameters	ERP length	1 superframe slot
		No. of minislots (M)	4
	Emergency Beacon (EB) Information	Base EB Packet Size	9 bytes
		DTS Descriptor Size	3 bytes
	ETS Parameters	Max. No. of DTS	7
		1 DTS length	1 superframe slot

B. Performance Metrics

The performance of a system or a technology is usually characterized with the help of several metrics. The followings are the selected metrics which are suitable for evaluation of the IEEE 802.15.4 under the given reference scenario, to verify the need and usefulness of the proposed solution approach.

1. Delay

Delay is defined by the time required to transmit a packet of data from source to destination and is relevant only to the successfully transmitted packets. Similarly, in this thesis, delay is calculated by measuring the time interval from the instant a packet is available in the buffer for transmission until the ACK is received for that packet. The OOE or ROE delay is the average delay, where all delays of the successfully transmitted OEE or ROE packets are accumulated and divided by the total number of received OEE or ROE packets. Similarly, overall delay is another average delay where all delays (OOE and ROE) are summed and divided by the sum of total successfully transmitted OEE and ROE packets.

2. Packet Delivery ratio (PDR)

Packet delivery ratio (PDR) is calculated by accumulating the total number of successfully received packets by the coordinator and the total number of packets generated at each node. It is an important characterization of wireless systems because it indicates the congested network (e.g. data packets are lost refers low delivery ratio). The number of dropped packets and retransmissions influence the PDR directly.

$$PDR = \frac{Total\ number\ of\ successfully\ transmitted\ packets\ to\ coordinator}{Total\ number\ of\ generated\ packets} \quad (9)$$

C. Simulations Results and Discussion

In this section, we compare the simulated results of the proposed scheme with the conventional IEEE 802.15.4 MAC. The comparisons are made on the basis of the metrics defined at Section 4-2.

1. Delay Analysis

Figures 4-2 - 4-5 show the comparison between proposed scheme and conventional IEEE802.15.4 in terms of packet delay. In general, packet delay increases as the number of nodes increases for both schemes. But the proposed scheme has a lower packet delay than the conventional one.

Figures 4-2 (a) and (b) compare the OEE traffic delays for the proposed and the conventional schemes when packet inter-arrival rate is 1 second and OEE traffics percentage is varied (1% and 5%) respectively. In both the cases, it is noted that the OEE traffic delay is significantly reduced in the proposed scheme than the conventional MAC. An average of 28% delay is minimized in the proposed scheme. In the graphs, when the number of nodes is 16 and 32, the delay is reduced drastically for the proposed scheme but delay is reduced marginally for number of nodes equal to 4 and 8. For low number of nodes, there are sufficient number of GTSs and also more resources in the CAP, so the effect of the proposed scheme is similar to the conventional scheme. But still, OEE traffic delays are reduced marginally in this case too.

The ROE delay is also reduced in the proposed scheme to some extent as seen in Figures 4-2 (c) and (d). Because the impromptu transmission of the OEE traffics increases the opportunity for the ROE traffics to be transmitted proposed scheme.

Also, the if there is any sufficient DTS length available after the transmission of the OEE traffics, the ROE traffics are allowed to be transmitted in that residue.

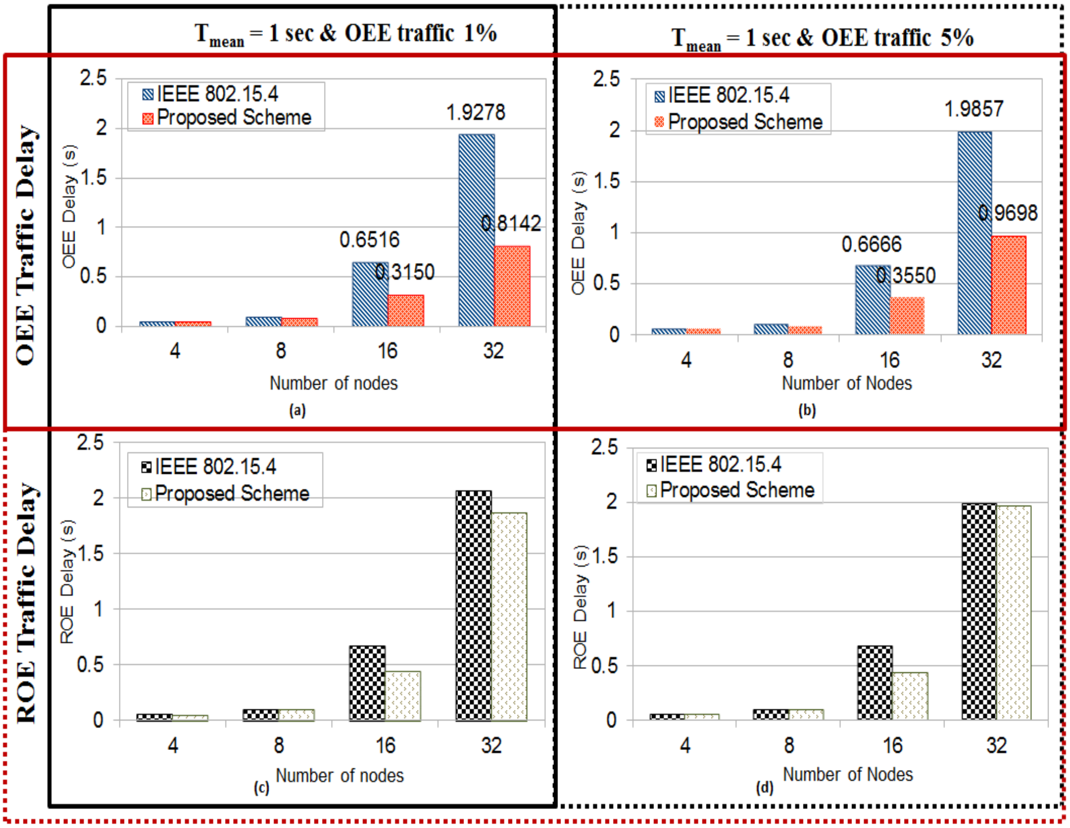

Figure 4-2: OEE and ROE traffic delay comparison of proposed and conventional schemes when T_{mean} = 1s and x =1% and 5%.

Similarly, Figure 4-3 compares the overall traffic delay where individual delays of both the OEE and ROE traffics are summed up and divided by the sum of total number of successful OEE and ROE traffics. It is obvious that due to the combined effects of minimized OEE and ROE delays in the proposed scheme, the overall delay is also lower in the proposed scheme than in the conventional MAC.

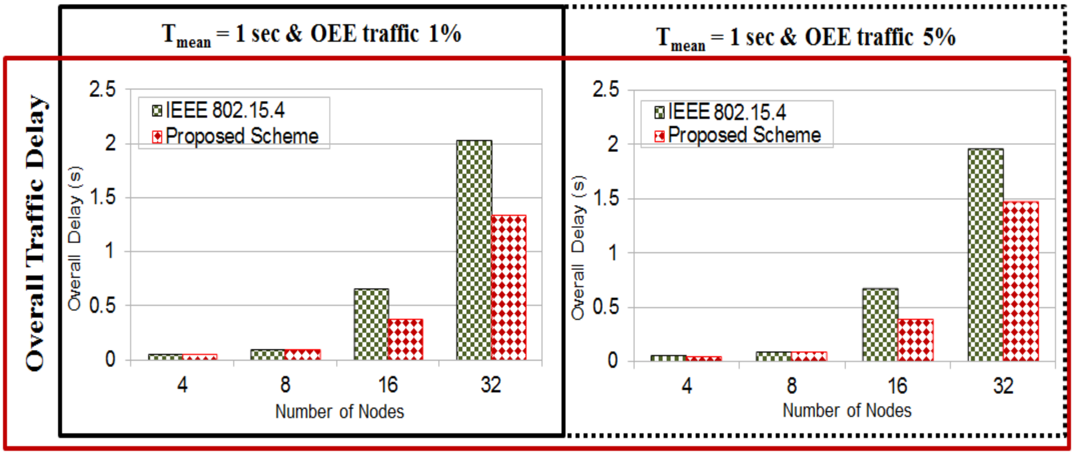

Figure 4-3: Overall traffic delay comparison of proposed and conventional schemes when T_{mean} = 1s and x =1% and 5%.

Figure 4-4 compares the OEE traffic delay and ROE traffic delay when the packet inter-arrival rate is halved (0.5s) than the previous plot. As in the previous plot, in this plot also the OEE delays are reduced sharply ans ROE delays are also reduced in marginal value. But, the delay increases in both the proposed and conventional schemes when the packet inter-arrival shortens. Because, shorten traffic inter-arrival time means more rapidness in the incoming of packets from the upper layer and more traffics at a time means more congestion in the network, so the delay is observed to be more. However, the proposed scheme yields 25% minimum OEE traffic delay than the conventional scheme.

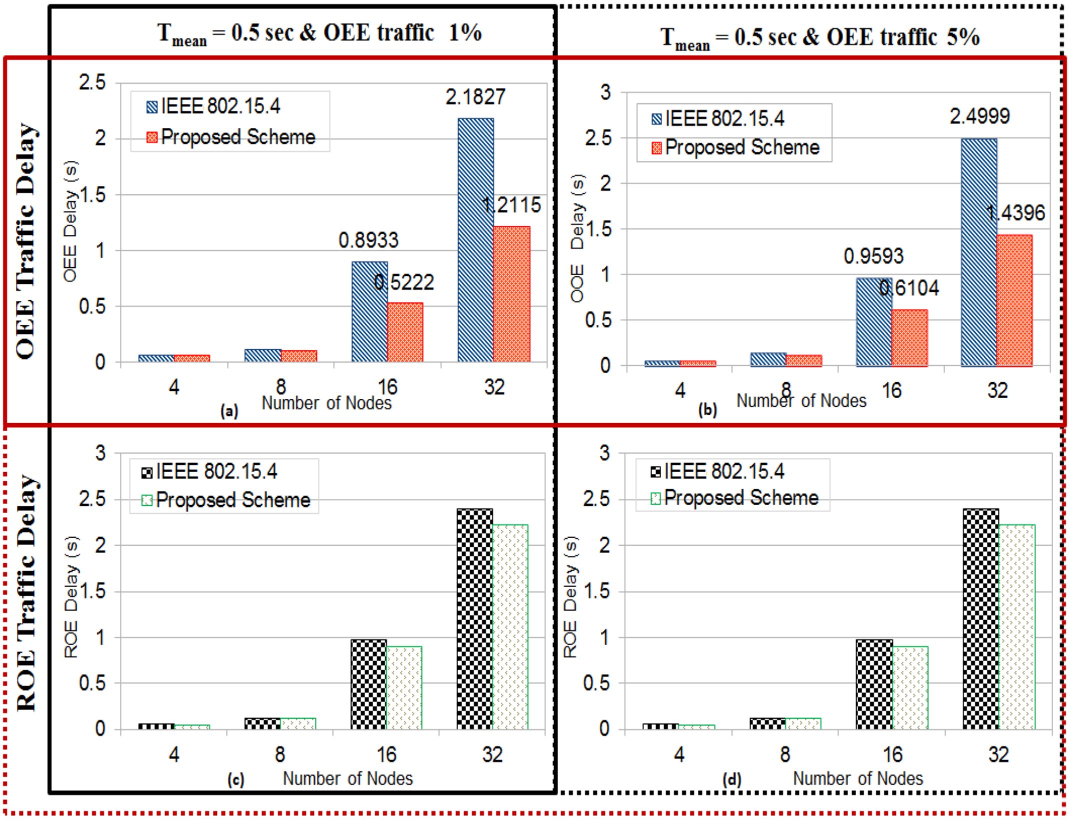

Figure 4-4: OEE and ROE traffic delay comparison of proposed and conventional schemes when T_{mean} = 0.5s and x =1% and 5%.

As in Figure 4-3, the overall delay in Figure 45 is also lower in the proposed scheme than in the conventional MAC.

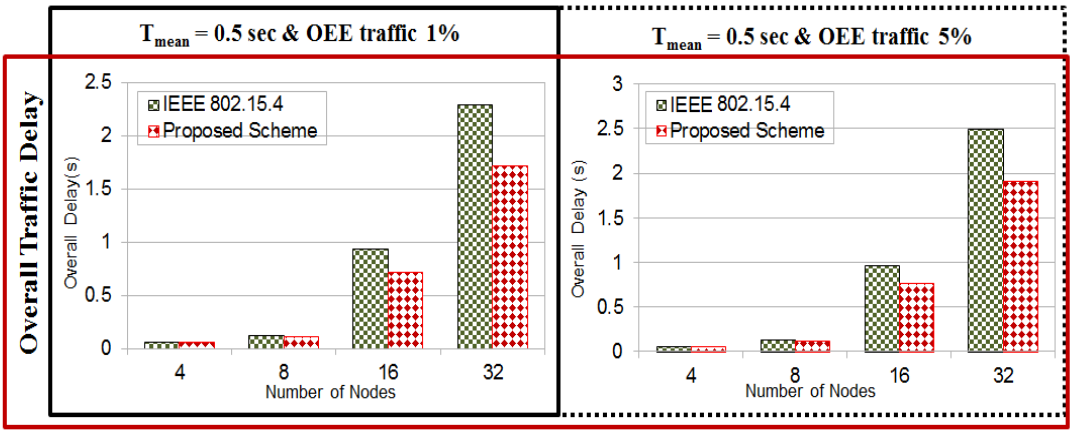

Figure 4-5: Overall traffic delay comparison of proposed and conventional schemes when T_{mean} = 0.5s and x =1% and 5%.

Table 4-1, shows the standard deviation of the delay for the traffics originated from the occasional emergency events.

Table 4-1 Standard deviation of OEE delays in the proposed scheme

Traffic Scenarios	Number of Nodes			
	4	**8**	**16**	**32**
OEE delay SD when T_{mean}=1s & x= 1%	0.01268	0.004361	0.061	0.243
OEE delay SD when T_{mean}=1s & x= 5%	0.00243	0.00183	0.0203	0.3077
OEE delay SD when T_{mean}=0.5s & x= 1%	0.00437	0.01064	0.0355	0.250
OEE delay SD when T_{mean}=0.5s & x= 5%	0.00142	0.00312	0.0733	0.2799

2. PDR Analysis

Figure 4-4, shows the comparison of the PDR of the OEE traffics when the packet inter-arrival is set to 1s and the OEE traffic percentage varies from 1% and 5%. In general, PDR decreases as the number of nodes increases in the both conventional and proposed schemes. However, the decrement is very sharp in the conventional scheme whereas it is gradual in the proposed scheme. Around 80% of the total generated OEE traffics are successfully transmitted in the proposed scheme. This signifies that the proposed scheme has highly reliable than the conventional scheme for handling the emergency traffics. There is some packets loss in the system for both schemes which is due to the events like limited number of MAC buffer size and the limited number of allowed retransmissions. In the simulation these values are set to 60 packets and 2 respectively.

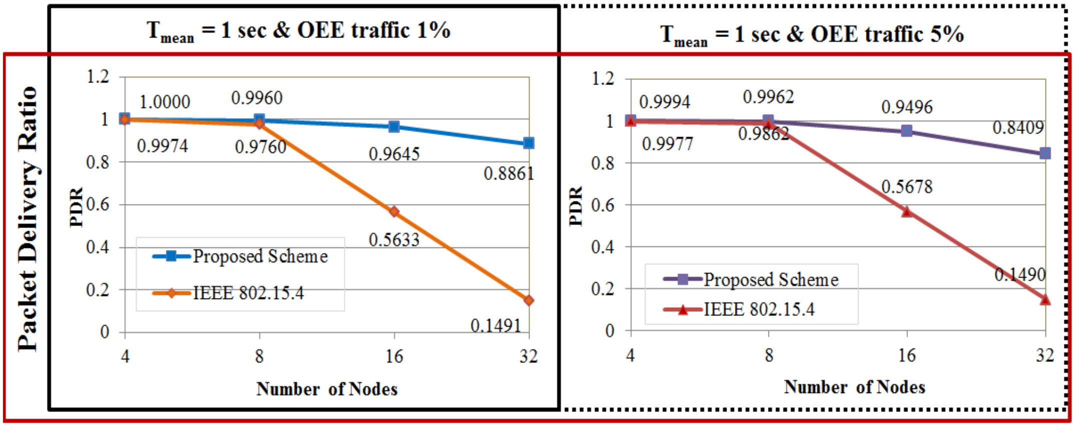

Figure 4-4: PDR comparison of OEE traffic of proposed and conventional schemes with T_{mean} = 1s and x =1% and 5%.

V. Conclusions and Future Works

An efficient emergency handling scheme to enhance IEEE 802.15.4 in consideration to HBM application was researched and developed in the context of this thesis. For the development of the scheme, existing HBM application system and the underlying wireless communication technology (IEEE 802.15.4) were investigated to identify the problematic condition regarding emergency event handling. The scheme involved a modified IEEE 802.15.4 frame structure that opportunistically uses the inactive period for handling emergency events. About 28% performance improvement over conventional IEEE 802.15.4 MAC regarding the reporting delay for emergency events is achieved through the proposed scheme. Similarly, a higher packet delivery ratio (more than 80%) for emergency traffics is also obtained in the proposed scheme. A marginal decrement in delay for transmitting the normal medical traffics is also achieved in the proposed scheme. Despite, some energy issues due additional emergency beacon, the proposed scheme is best suitable for HBM applications due to its increasing emergency handling capability and packet delivery ratio. And because of its simplicity, the proposed scheme can easily be adopted in IEEE 802.15.4 MAC for efficient handling of emergency events.

Since this work is primarily focused on minimizing the emergency reporting delay, other network issues are not addressed in detail. Energy efficiency and security are such issues which seek more attention. So in the future, this scheme can be evaluated and researched on the basis of these issues. At the same time, the proposed scheme can be enhanced by applying priority based access mechanisms in the previously existing periods in the conventional MAC .

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