

# **Delay and Energy Efficient TDMA Based MAC Protocols in Wireless Sensor Networks**



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CIIT/SP12-PEE-007/ISB

PhD Thesis  
In  
Electrical Engineering

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**COMSATS Institute of Information Technology**

# **Delay and Energy Efficient TDMA Based MAC Protocols in Wireless Sensor Networks**

A Thesis Presented to

**COMSATS Institute of Information Technology**

In partial fulfillment  
of the requirement for the degree of

**PhD (Electrical Engineering)**

By  
**Ahmad Naseem Alvi**  
**CIIT/SP12-PEE-007/ISB**

**Fall 2015**

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A Post Graduate Thesis submitted to the Department of Electrical Engineering as partial fulfillment of the requirement for the award of Degree of Ph.D (Electrical Engineering).

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Protocols in Wireless Sensor Networks**

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## Declaration

I Ahmad Naseem Alvi (Registration No. CIIT/SP12-PEE-007/ISB) hereby declare that I have produced the work presented in this thesis, during the scheduled period of study. I also declare that I have not taken any material from any source except referred to wherever due that amount of plagiarism is within acceptable range. If a violation of HEC rules on research has occurred in this thesis, I shall be liable to punishable action under the plagiarism rules of the HEC.

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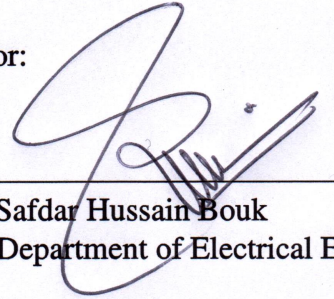
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It is certified that Ahmad Naseem Alvi (Registration No. CIIT/SP12-PEE- 007/ISB) has carried out all the work related to this thesis under my supervision at the Department of Electrical Engineering, COMSATS Institute of Information Technology, Islamabad and the work fulfills the requirement for award of PhD degree.

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## DEDICATION

Dedicated to my mother who left me for her eternal home, but her prayers are always with me, to my father for his all kind of support and encouragement, to my beloved wife and my children; Faareh, Izzah, and Azfar, whose smiles kept me going.

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# **ABSTRACT**

## **Delay and Energy Efficient TDMA Based MAC Protocols in Wireless Sensor Networks**

Efficient energy consumption in wireless sensors is one of the major constraints in Wireless Sensor Networks (WSNs). Multiple contentions based and contention free Medium Access Control (MAC) protocols are designed to make them energy efficient. Sensor nodes are generally deployed in large number where contention based MAC protocols do not perform well due to increased chances of collision. In such scenario, contention free MAC protocols are preferred over contention based MAC protocols. Performance in terms of energy, delay and throughput are not adequate in most of the WSN applications. In this work, we introduced couple of bit map assisted TDMA based MAC protocols for hierarchical wireless networks named as *BS – MAC* and *BEST – MAC*. In addition to this, we have suggested some modification in IEEE 802.15.4 standard which enhances its performance without compromising on existing parameters.

Both BS-MAC and BEST-MAC are designed for adaptive traffic flow and the main contribution of both of these protocols is that: (a) it uses small size time slots. (b) the number of those time slots is more than the number of member nodes. (c) Short node address (1 Byte) to identify member nodes. These contributions help to handle adaptive traffic loads of all network members in an efficient manner. In BS-MAC, Shortest Job First algorithm is applied to minimize network delay and to enhance the link utilization. However in BEST-MAC, Knapsack algorithm is used to schedule time slots in an efficient manner minimize the network's delay and better link utilization. In addition to this, scalability is included to adjust new nodes in the mid of a TDMA round. Simulation results show that both BS-MAC and BEST-MAC perform better as of the existing TDMA based MAC protocols.

An efficient superframe structure for IEEE 802.15.4 Medium Access Control (MAC) layer is also proposed in this work. In this superframe structure, Contention Free Period (CFP) precedes the Contention Access Period (CAP) and more number of slots are used in the same CFP period as of original 802.15.4 standard. The standard operates in three different frequency bands as 868MHz, 915MHz and 2400Mhz. As CFP precedes the CAP, the communication delay for the CFP traffic is exceptionally reduced. The Beacon frame is fine-tuned to achieve the above said superframe structure and makes it backward com-

patible with the original standard. Due to large number of small slots in CFP, more small amount of data requesting nodes can be assigned CFP space for communication. The analytical results show that our proposed superframe structure has nearly 50% less delay, accommodate almost double the number of nodes in CFP and has better link utilization compared to the original 802.15.4 standard during all three frequency bands.

# List of Publications

1. **Ahmad Naseem Alvi**, Safdar H. Bouk, S. H. Ahmed, M. A. Yaqub, N. Javaid, and Dongkyun Kim, “Enhanced TDMA based MAC Protocol for Adaptive Data Control in Wireless Sensor Networks,” *International Journal of communications and networks*, JCN’13.
2. **Ahmad Naseem Alvi**, M. A. Yaqub, N. Javaid, Syed Hassan Ahmed, Safdar. H. Bouk and Dongkyun Kim, “An Improved IEEE 802.15.4 Superframe Structure with Minimum Delay and Maximum CFP Link Utilization,” *Ad Hoc & Sensor Wireless Networks (AHSWN)*, 2015.
3. **A. N. Alvi**, S. S. Naqvi, S. H. Bouk, N. Javaid, U. Qasim, Z.A. Khan, “Evaluation of Slotted CSMA/CA of IEEE 802.15. 4,” *Broadband, Wireless Computing, Communication and Applications (BWCCA)*, 2012 Seventh International Conference, 01/2012.

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# Introduction

## 1.1 Wireless Sensor Networks

Wireless Sensor Networks (WSNs) are used in wide variety of applications such as temperature, humidity, acoustic detection, seismic detection and observation of such areas where human approach is almost impossible. Military organizations are also very much interested in huge deployment of wireless networks for surveillance and many tactical military applications [1]. WSNs are also used to monitor the pets movements and for inventory tracking. In Wireless Body Area Sensor Networks (WBASN) multiple wireless sensors are applied to observe the patient's vital signs for emergency treatments.

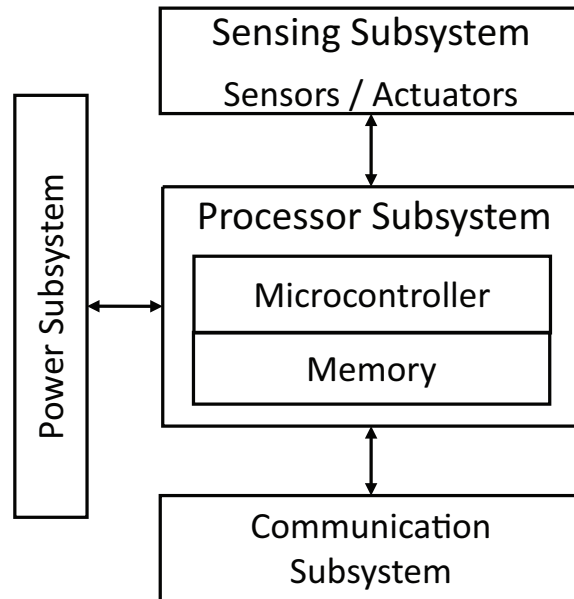
## 1.2 Wireless Node Architecture

A wireless sensor network consists of a number of wireless sensors and one or more base stations. Each sensor node is required to transmit its data periodically or immediately on receiving a priority based response directly or indirectly to its base station. A wireless sensor node comprise of following subsystems.

1. Sensing subsystem
2. Processor subsystem
3. Communication subsystem
4. Power subsystem

### 1.2.1. Sensing Subsystem:

---



**Figure 1.1:** Node overview

### 1.2.1 Sensing Subsystem:

It consists of sensors and actuators which provide actual interface with the physical environment. This subsystem is responsible to observe the parameters of the environment. Mostly the sensed information is in analog form and processor only requires digital information for processing. That's why the information is converted in to digital form by using Analog to digital converter (ADC). Sensors are designed in order to fulfill the demands of different applications. Sensors are mainly classified in 5 different fields.

1. Environmental
2. Biometric
3. Optical
4. Physical
5. Gas

## **1.2.1. Sensing Subsystem:**

---

### **1.2.1.1 Environmental Sensors**

Environmental sensors consists of temperature, humidity, soil moisture, wind, pressure, leaf, Redox and Ph sensors. One of its highly demand application is agriculture field, where these are precisely used to monitor the environmental conditions such as temperature, Humidity along with speed and direction of the wind.

### **1.2.1.2 Biometric Sensors**

Biometric sensors comprise of Electrocardiogram (ECG), Pulse, Oximetry, Fall and sweat sensors. These are used to continuously monitor the patient's conditions in order to prevent a possible attack by monitoring his heart pulse rate, Electrocardiogram (ECG), sweat and fall of the patient. A real time and redundant response of all these sensors is communicated to the medical clinic/hospital for necessary response.

### **1.2.1.3 Optical Sensors**

Optical sensors such as Sunlight, Ultraviolet, Radiation and color are used in agricultural application to observe and measure the energy absorbed my the plants. Most commonly used optical sensors are Infrared sensors and are mainly used to detect the presence of the human and pets body.

### **1.2.1.4 Physical Sensors**

Physical sensors such as accelerometer, vibration, ultrasound, water, sound, bend, flex, strain, stress are used to detect any kind of motion of the object and to interact an object with the world to monitor its state.

### **1.2.1.5 Gas Sensors**

Gas sensors are basically used to detect the organic (carbone) and toxic gases. Organic gases sensors such as ( $CO_2$ ) and  $CO$  are most required sensors and used for respiration in humans and burning forest respectively. Toxic gases such as  $NH_3$  and  $SH_2$  can be found in animal farms whereas ( $NO_2$ ) gas sensors are used to measure the air pollution by vehicles.

## 1.2.2 Processor subsystem:

The processor subsystem interacts with all the other subsystems of a sensor node and some supplementary peripheral interfaces. Main purpose of this subsystem is process/execute instructions relating to sensing, communication, and self-organization. It comprises of processing and memory units along with internal clock. Main purpose of processing unit is to process all the related data. It comprises of a processor chip in the form of micro-controller, microprocessor, field programmable gate arrays (FPGAs) and application-specific integrated circuit (ASIC). Memory unit consists of a nonvolatile memory (internal flash memory) and active memory. Nonvolatile memory is to store the program instructions and active memory is used for temporary storage of the sensed data before processing.

## 1.2.3 Communication Subsystem:

Purpose of communication subsystem is to exchange information between different subsystems within a sensor node along with exchanging information with other nodes in a network. Within a node, fast and energy efficient data transfer is required. Serial and parallel buses are used to carry data between different subsystems. Parallel communication is faster than serial communication but it requires more space which increases the size of sensor node. That's why serial communication is preferred instead of parallel communication. However, in order to attain the same throughput as of parallel buses, it requires a high clock speed. Some serial buses such as  $I^2C$  can not scale well with the high processor's speed. Serial peripheral interface (SPI) buses are used with high data rate for short distance communication and are preferred over  $I^2C$ , where high data rate is required.

Wireless sensors use unguided transmission medium while exchanging information with other nodes of the network. In some specific cases, medium is optical, ultrasound and magnetic induction. However, most of the WSN applications follow radio frequency (RF)-based communication as it does not require line of sight and also covers a longer distance with high data rate and acceptable error rates.

### 1.2.4 Power Subsystem:

Power subsystem is a crucial part of a wireless sensor node as it provides power to a sensor node. It basically consists of two parts. One is to store the power and second is to refill the consumed energy by scavenging it from some external sources. Power saving is conventionally done by using batteries of different designs. A lot of research is taking place in energy scavenging techniques such as obtaining energy from the environment in the form of solar energy.

*Energy Consumption:* Energy is one of the major constraints of a wireless sensor node. As wireless nodes are mainly deployed in remote areas and are required to observe the data for longer life cycle. Earlier depletion of node disrupts the nodes communication and required information is not reached up to the gateway or sink. Different pattern and protocols are designed in order to minimize node's energy consumption. A wireless sensor node consumes energy in different states. Transmitting and receiving cause maximum amount of energy consumption. If during transmitting or receiving of a packet collision occurs then a node has to resend its data which causes un-necessary energy. Different protocols are designed to avoid such collisions. A significant amount of energy is consumed during over hearing state where node receives information which is destined for some other nodes. It is avoided by using control messages such as request to send and clear to send (RTS/CTS). Some amount of energy is also wasted during idle listening mode; in which node keep its radios ON but neither receiving nor transmitting any packet. Node can conserve this energy by keeping itself in sleep mode i.e by turning off its transceiver, when there is no data to send or receive.

## 1.3 Applications of Wireless Sensor Networks

WSNs have attracted many useful and diverse applications. Few of them are Ground traffic management, health care, environmental monitoring, precision agriculture, Ground traffic management, supply chain management, active volcano monitoring, transportation, human activity monitoring and underground mining.



## 1.3.1 Ground traffic Control

Smooth and un-interruptible ground traffic control is very important as it is closely attached with our routine life matters. Road congestion along with interruption in traffic flow in addition to socio-economic disturbance may cause severe loss of human lives.

Constructing new roads is not always possible as in some cases, space around roads are not available. Traffic management [2] [3] with the help of wireless sensor networks is used to avoid traffic congestion and traffic flow. Different types of wireless sensors such as inductive loop, pneumatic road tubes, piezoelectric cables, magnetometers, sonar and video cameras are installed to monitor the traffic density, velocity of vehicles and to detect congestion. In response to these information, drivers are informed about the alternate route and emergency exit.

## 1.3.2 Health Care

Multiple health care applications [4] are developed to monitor the different diseases of patients such as Heart diseases, Epilepsy, Parkinson's diseases and Heart attack. In wireless body area networks (WBAN) [5] [6], different types of sensors are attached with human body to monitor its conditions such as pulse rate, ECG, EMG, EEG, body temperature, body posture, sweat etc. Health care applications are attached with the emergency response units to save a patient's life. The observed information is also helpful for the concerned physician for timely medication to the patient.

## 1.3.3 Precision Agriculture

Precision agriculture [7] [8] is another highly demanded application for WSNs. Conventionally, farmers apply water resources, pesticides and fertilizers to the whole agricultural farms uniformly by considering it as a homogeneous field. In reality, conditions throughout the farm are quite diverse in terms of soil condition and other nutrient contents. Diversity increases with the increase in farm area. Therefore, handling the whole farms uniformly does not produce efficient results.

Multi functional wireless devices are used for better crop management [9]. Wireless devices such as GPS, radar, aerial images, etc., micro monitors the agricultural fields and

apply the farming resources accordingly in an efficient manner.

### **1.3.4 Military Application**

WSNs are widely used in many military applications such as surveillance and tracking of enemies movements [10]. One of the most common applications in war field is to get an effective situational awareness in the battlefields. WSNs are also helpful in detecting snipers by using acoustic sensors [11]. Recent research in underwater WSNs applications [12] are also helpful in naval forces to determine the object under deep sea.

### **1.3.5 Structure Health Monitoring (SHM)**

SHM is another important application of WSNs [13] [14]. Building structures such as bridges, towers, heritage buildings [15] are real time monitored by using state of the art wireless sensors to save huge amount of money. Hong Kong Polytechnic University [16] designed and deployed WSNs to monitor bridge structure. This reduces the maintenance cost a lot.

### **1.3.6 Volcano Monitoring**

Most of the volcanoes occur due to the collision of the lithosphere plates (Slabs of Earth's outer most shell). Presently monitoring of active volcanoes is only possible through expensive and large devices which are deployed through vehicles and helicopters. data gathering from these devices is one of the major concern and compact flash cards are used to store data and whole data is retrieved periodically.

A large number of small, cheap and self-organizing wireless sensor nodes are deployed in that area to monitor the vast area of volcanoes field to observe events such as eruption, earthquakes and tremor activities. These events are used to happen in a short time intervals. Multiple researches are taking place in order to evaluate the different activities in volcanoes by deploying wireless sensor networks [17] [18].

## 1.3.7 Pipeline Monitoring

Monitoring the flow of gas, oil and water in a pipeline is another application of WSNs. Due to long length, high risk and difficult access, it is quite difficult and challenging task to monitor the flow in a pipeline. Corrosion, earthquakes, landsliding and material flaws may cause leakage in a pipeline. Determination of these leakages is some time very difficult and time taking task. In [19], Almazyad et al. proposed a WSNs to determine the water leakage in a long water pipe line. Yu et al. [20] provided an algorithm to monitor the underground gas and oil pipe lines.

## 1.3.8 Under ground mines Monitoring

Another application of WSNs is underground mining. Mining is really a highly risk job. WSNs can be deployed to monitor individuals under normal or abnormal situations. They may be used to identify the collapse holes, concentration of gases such as methane, oxygen,  $CO_2$  and to monitor the seismic shifts to determine the earthquake. Daingade et al. designed a prototype for monitoring of mines environments with the help of WSNs and MSP430 micro controller [21]. In [22], the performance of zigbee based WSN in terms of its received signal strength ratio and signal propagation was investigated by deploying it in an under ground gold mine.

## 1.4 Challenges in designing of MAC protocols

In most of the applications, the sensor nodes are intended to operate autonomously on the battery, therefore, WSNs protocols should be energy efficient to prolong the node's life-time. The large proportion of battery consumption is due to communication (transmission and reception) over wireless radio components in the node. The purpose of MAC protocols is directly relates with radio transceivers that's why energy efficiency is their main task in WSNs. In addition to energy conservation, scalability, autonomous network operations, end-to-end delay, throughput and control overhead are some of the major WSNs constraints in many WSNs applications. In this section we discuss the design parameters which are kept under consideration.

### 1.4.1 Design Parameters of MAC protocols

In this section, we discuss some of the important parameters required to design a MAC protocol in WSNs.

1. Medium access with collision avoidance is one of the core task of any MAC protocol. MAC protocols are designed to determine when and how a node access the medium in order to transfer its data successfully. Though collision can not be avoided completely but it can be minimized to the acceptance level with maximum chances of successful communication.
2. Energy conservation is one of the main objective while designing a MAC protocol in WSN as it directly controls the radio transceiver and major amount of energy is consumed when node is involved in a long range communication or keeping its radios ON for a long time without any data to transmit. MAC protocols are designed to conserve such energies as much as possible and keep its radios in OFF state when it has no data to transmit. Energy can also be minimized by avoiding collisions as well as by avoiding unnecessary transmission of messages.
3. Delay minimization is another important parameter in designing MAC protocols. Many WSN applications do not compromise larger data delivery latency and these data delivery latency varies against different WSN application. MAC protocol should be designed to meet the delay latency of most of the WSN applications.
4. Successful data transmission is one of the key performance indicator of a MAC protocol for all kinds of WSNs. The packet drop due to buffer overflow is one of the major reason in reliable transmission which can be managed by stopping the piggy-back packets when it exceeds buffer size limit. Signal interference also affects the successful data transmission which badly affects the reliability of the network. It can be avoided by increasing the transmission power as well as by avoiding contention with other neighboring nodes.
5. In WSNs, changes in WSNs such as network size, density and topology happen frequently and a MAC protocol should be able scalable and adaptable to meet such requirements.

6. Throughput is the amount of data successfully transferred from a sender to a receiver in a given time. Multiple factors such as collision avoidance, channel availability, latency, control overhead and link utilization affects the throughput in WSNs.

## 1.5 Contribution

Aim of this dissertation is to design delay and energy efficient MAC protocols tailored for specific WSNs applications. The research work comprises of two new MAC protocols and a modification in IEEE 802.15.4 standard in order to improve the delay and energy efficiency of WSN applications. In addition to it, we made a comprehensive comparison of contention based CSMA/CA of IEEE 802.15.4 standard for different frequency bands such as 868, 915 and 2400 MHZ and this work has been published in an international conference. Both of our proposed MAC protocols are scheduled based. In the first protocol, hierarchical TDMA based MAC protocol (BS-MAC) is introduced. Here cluster head (CH) efficiently manages the available slots to improve link utilization as well as better energy conservation with reduced delay. In BS-MAC, CH allows high data traffic nodes to efficiently assign those data slots which remains unused by the nodes having no data traffic. By assigning short address to each node causes reduced overheads which helps in less energy consumption throughout the network. Shortest Job First algorithm is used to assign data slots by the CH. This helps in better link utilization as well as reduces the network delay.

In the following work, we introduces another Bit map assisted Efficient and Scalable TDMA based MAC (BEST-MAC) protocol. In BEST-MAC, a complete cluster round has been modified by introducing contention access period. BEST-MAC accommodates new nodes to become a network member even after setup phase. Knapsack algorithm is introduced for better utilization of data slots. This helps in better link utilization and overall network delay is minimized. Furthermore, it allocates short addresses to nodes similar to BS-MAC in order to conserve network energy.

In the final work, we proposed an improved IEEE 802.15.4 standard. In this work, a new super-frame structure is introduced which reduces the data latency of GTS assigning nodes. It further improves the link utilization without compromising the existing standard's parameters.

# 1.6 Dissertation Organization

Rest of the dissertation is organized as follows. Chapter 2 discusses different types of MAC protocols designed for WSN along with their drawbacks. In order to overcome these limitations, we proposed BS-MAC and BEST-MAC as discussed in chapter 3 and 4 respectively. An improved superframe structure of IEEE 802.15.4 standard has been described in chapter 5. Finally chapter 6 summarizes this dissertation and references are mentioned in chapter 7.

## MAC Protocols

### 2.1 MAC Protocols for Wireless Sensor Networks

In the previous chapter, we briefly discussed some of the limitations of wireless sensor networks. In order to mitigate these challenges, multiple MAC protocols have been introduced. These MAC protocols are basically categorized into two main groups:

- Contention based
- Scheduling based

### 2.2 Contention Based MAC Protocols

Nodes in contention based MAC Protocols contend to access the medium when it has data to send without relying on transmission schedules. One of the main advantage of contention based techniques is its simplicity as it does not require to maintain schedules indicating transmission order. Node uses some mechanism in order to resolve the contention to access the medium. Contention increases when more than one node wants to access the same medium in order to send their data. This increases the chances of collisions, delay and causing more energy loss, which badly decreases wireless node's life span. Contention based MAC protocols face fairness issues rise as some of the nodes may access the channel more frequently as compared to other contending nodes in the same network. In a dense WSN, the number of collisions increase drastically and results in the

longer channel access delay. Some of the contention based MAC protocols are described below:

1. One of the standard for contention based MAC protocols is IEEE 802.11 [23]. In this standard, energy consumption during the idle listening mode is as high as of receiving mode. This idle listening energy consumption becomes more severe in a densely deployed network scenarios [24] i.e. WSN. That is why this standard is not recommended for WSN.

2. Power Aware Multi-Access with Signaling (PAMAS)

PAMAS [25] is a contention based MAC protocol and main focus of it is to save energy by avoiding unnecessary energy consumption during overhearing. PAMAS uses two separate signaling channels for data frame and control frames. Separate signaling channel allows nodes to turn off their transceivers for a specific time to avoid overhearing. Control frames like ready-to-send (RTS) and clear-to-send (CTS) are used to avoid energy consumption due to collision. In addition to control messages, devices also transmit busy tones to avoid those nodes from transmission, which have not received control messages. Every node turn off its transceiver on the basis of following decisions:

- node has no data to send and neighboring node begins the transmission
- node has no data to send and neighboring node begins the transmission

PAMAS attempts to minimize a significant amount of energy of those nodes which keeps their radios ON when there is no data to transmit and receive by that node. However, presence of two radios increases the energy and implementation cost of the node

3. Sensor MAC (SMAC) SMAC reduces energy consumption by avoiding collision and offer good scalability. Duty cycle of a node is reduced by increasing the sleep duration and node keep its radios ON for a very short time interval. Each node creates its own listening schedule in either of the two possibilities. Before creating its own schedule, node listens to the medium for a certain amount of time in order to receive a schedule from other node.



- If a node receives a schedule then it chooses its own listening schedule on the basis of the schedule received and become a follower.
- If node does not receive any schedule then it generates its own schedule and becomes a synchronizer.

Listen period of each node comprises of RTS/CTS control messages and SYNC packets. RTS/CTS are used to avoid contention. SMAC avoids collision by using RTS/CTS handshakes. When a node hears RTS and is unable to receive the message at that time then it turn off its radio to go to sleep mode. This helps a node in avoiding energy wastage due to overhearing of data. In this approach node has to overhear only control and sync packets.

SMAC avoids collision by using RTS/CTS messages that is, designed only for uni-directional traffic and does not work with broadcast messages. SMAC reduces duty cycle to make it energy efficient; however it may not be effective in a real scenario. RTS/CTS messages are used to avoid collision

4. Time-out Medium Access Control (TMAC) Fixed listening period is unable to tackle heavy traffic. Time out MAC protocol addresses the fixed listening duration of SMAC by introducing active period that adapts to traffic density. Active period increases with the increase in traffic flow and decreases with the reduced traffic flow.

TMAC is a contention based MAC and to minimize the collision, medium is accessed by allowing nodes to wait for random time interval in a fixed contention period. Minimum time for a node to remain active is  $TA$  and it is long enough to hear control messages from the neighbors. TMAC also addresses the early sleeping problem of nodes. In this problem node D is unable to listen any control messages during  $TA$  and turns its radio Off to go to sleep mode. This early sleep problem is addressed by introducing Forward request to send (FRTS) message from node C to node D immediately after receiving CTS to inform node D to keep its radio ON for next communication.

WSNs are generally deployed in large numbers, therefore, contention based MAC protocols are not suitable in such scenarios. On the other hand, in reservation and scheduling based MAC protocols, there is no contention because all nodes are assigned a separate Guaranteed Time Slots (GTS), e.g. TDMA, to carry out communication. Such protocols

avoid chances of collisions along with reduced duty cycle, which causes natural advantage of energy conservation as compared to contention based protocols.

## 2.3 Scheduling Based MAC Protocol

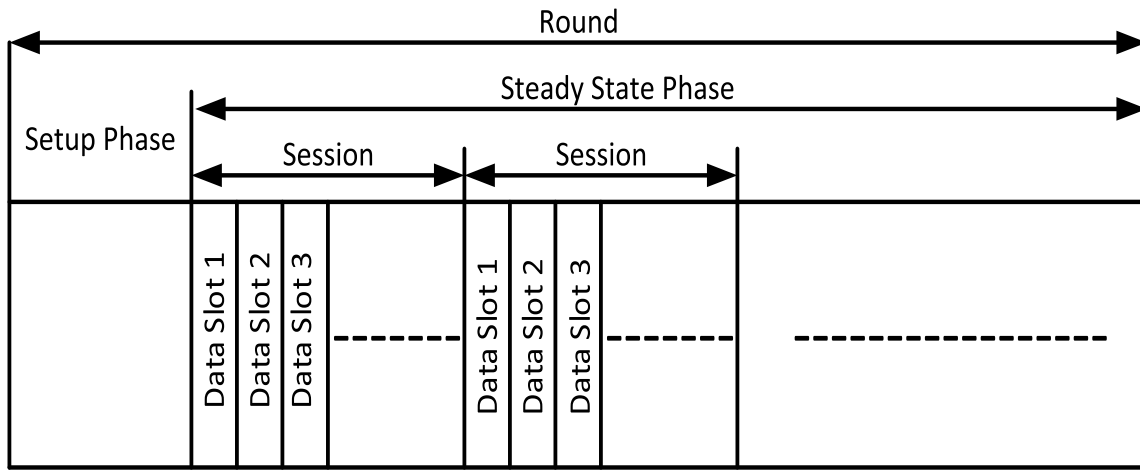
Energy conservation is one of the main objectives of the MAC protocols. TDMA based MAC protocols are energy efficient as they do not waste their energy due to collision as of contention based MAC protocols such as CSMA/CA. Many MAC protocols have been designed to achieve energy efficiency. Some of the scheduling based MAC protocols for WSNs are being briefly described as:

A TDMA based MAC protocol for Sensors named S-TDMA [26] is proposed by S. Boulfekhar et al., which exploits the essential features of TDMA causing unnecessary energy consumption and high latency in sensor networks. Energy consumption is addressed by keeping nodes in sleep mode when they have nothing to transmit or receive, however latency issues are addressed by emitting those time slots which are assigned to those nodes having no data to send.

### 2.3.1 Delay Guaranteed Routing and MAC

In [27], TDMA based MAC protocol, called DGRAM (Delay Guaranteed Routing and MAC), is proposed specifically for the delay sensitive applications in WSN. The deterministic delay is guaranteed by reusing the allocated time slots. In [28], authors proposed Intelligent Hybrid MAC (IH-MAC) for broadcast scheduling and link scheduling. The protocol intelligently uses the strength of CSMA and TDMA approaches in order to reduce the delay. At the same time energy consumption is minimized by suitably varying the transmit power.

In [29], Traffic Pattern Oblivious (TPO) scheduling scheme based MAC protocol is proposed. Unlike traditional TDMA scheduling, TPO is capable of continuous data collection with dynamic traffic pattern in an efficient manner. It allows the gateway to determine data collection on the basis of traffic load. In [30], performance of the proposed TDMA based MAC in prospects of link quality estimation was implemented on CC2530 hardware and tested in industrial field. In [31], E-BMA protocol is proposed for communication



**Figure 2.1:** A complete round in a cluster

between railway wagons. Energy consumption is minimized by minimizing node's idle listening mode and evaluate its performance with TDMA, energy efficient TDMA (EA-TDMA) and BMA. Authors claim that E-BMA and EA-TDMA are preferred over BMA and TDMA protocols for communication between railway wagons.

The Bit-Map-Assisted (BMA) [32] and BMA with Round Robin (BMA-RR) [33] are TDMA based MAC protocols. These protocols introduce varying scheduling techniques to efficiently allocate fixed time slots. The BMA MAC protocol allocates fixed duration time slots to the requesting nodes only and the other nodes are not assigned any time slot at all. In result, BMA conserves time slots and those slots may be allocated to the nodes with large volume of data. The BMA method was improved in [33] by introducing Round Robin scheduling technique, named BMA-RR, to assign time slots to the requesting nodes in a round robin fashion.

### 2.3.2 Conventional TDMA based Schemes

Conventional TDMA scheme comprises of multiple rounds whereas each round consists of a setup phase and a steady state phase as shown in Fig. 2.1

#### 2.3.2.1 Set-Up Phase

In setup phase one of the nodes is elected as a cluster head by following a simple algorithm on the basis of energy levels. Elected cluster head broadcasts an advertisement message. Non cluster head nodes respond to the Cluster head to become a member of that cluster.

#### 2.3.2.2 Steady-State Phase

The steady-state phase is divided into a contention period and frames. The duration of each frame is fixed. During the contention period, all nodes keep their radios on. The cluster-head builds a TDMA schedule and broadcasts it to all nodes within the cluster. There is one data slot allocated to each node in each frame. A node with data to transmit is called a source node. Each source node turns on its radio and sends its data to the cluster-head over its allocated slot-time, and keeps its radio off at all other times. With the basic TDMA scheme, a node always turns on its radio during its assigned time slot regardless whether it has data to transmit or not. If it has no data to send, the node operates in idle mode, which is a high energy-consuming operation. E-TDMA extends the basic TDMA in order to reduce the energy consumption due to idle listening. It means when a node has no data to transmit, it keeps its radio off during its allocated time slots. When a frame finishes, the next frame begins and the same procedure is repeated. The cluster-head collects the data from all the source nodes and forwards the aggregated and compressed data to the base station. After a predefined time, the system begins the next round and the whole process is repeated.

In TDMA like schemes, all nodes are required to form clusters like Bluetooth [34] and Leach [35]. Managing and interference avoidance in a cluster by allocating each communicating node a separate time slot is not an easy task. Each node in a communicating cluster is assigned a fixed duration time slot in order to transfer their data. This limitation causes intense problems, when a node requires to send adaptive data traffic or when number of nodes within a cluster change. As TDMA like MAC protocols are not scalable, so contention based MAC protocols are preferred in such scenarios. For example, Bluetooth may have at most eight active nodes in a cluster. The variant of TDMA, called Energy efficient TDMA (E-TDMA) [36], was proposed for the hierarchical WSN, where whole network is divided into groups or clusters. All nodes in that cluster send their information

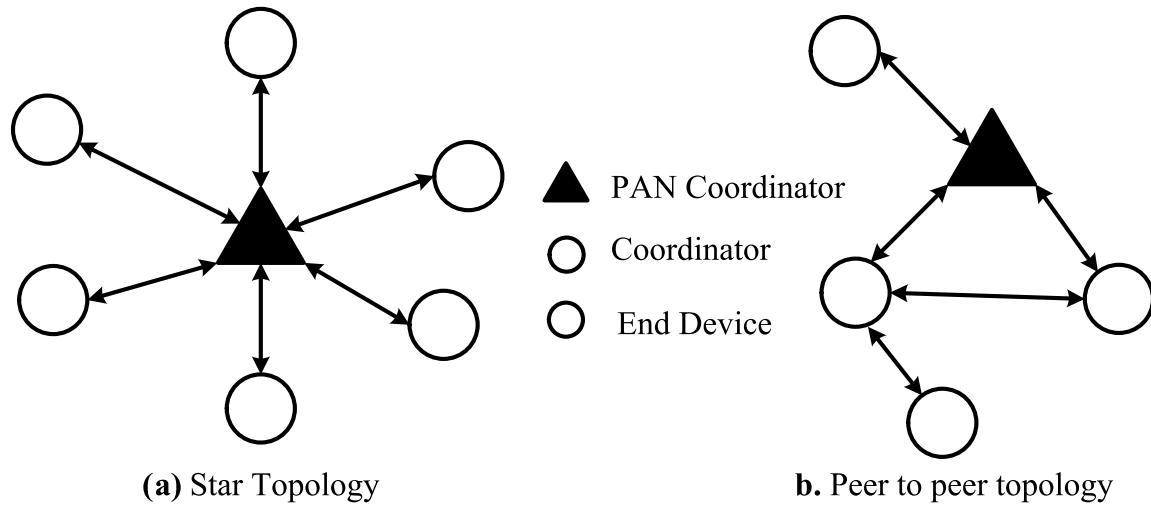
to the elected Cluster Head (CH) by using the E-TDMA. In E-TDMA, the CH turns its radio off to save energy when members have no data to send. Though, these protocols increase node's life time by conserving its energy; however, Link utilization badly affected when nodes have adaptive data traffic.

Many researchers have analyzed its performance in different aspects. A multi-hop communication scheme in GTS mechanism of IEEE 802.15.4 standard is proposed in [37], which follows superframe structure and claimed the reduced delay and higher packet delivery ratio as of the standard. An Unbalanced GTS Allocation Scheme (UGAS) is proposed in [38]. In this scheme, Link utilization is increased by introducing different duration time slots for different bandwidth requirements. Authors claim that UGAS improves the bandwidth utilization by 30% as of the standard.

Feng Xia et al [39] propose Adaptive and Real-Time GTS Allocation Scheme (ART-GAS) for such applications, where time sensitive and high-traffic is required and compatible with IEEE 802.15.4 standard. Authors claimed that proposed scheme increases the bandwidth utilization as of the standard. In [40], authors proposed a periodic wake-up scheme for nodes synchronization with coordinator. The scheme allows nodes to transmit their data during inactive period. Authors claim that scheme is backward compatible with IEEE 802.15.4 standard and energy consumption is reduced significantly as compared to beacon enabled mode of the standard.

[41] [42] [43] highlight the GTS under-utilization problem of IEEE 802.15.4 standard. In [41] Multi-Factor Dynamic GTS Allocation Scheme (MFDGAS) is proposed. In this scheme, nodes are assigned GTS on the basis of their data size, delay time and GTS utilization time. The scheme proposed in [42] increases the link utilization by dividing the CFP slots in 32 equal sized time slots without any changes in the frame format. In [43], authors proposed GTS allocation scheme on priority basis by considering emergency data. In this scheme traffic with higher data traffic is preferred.

Due to increase in wireless application needs, Institute of Electrical and Electronics Engineering (IEEE) developed some MAC standards such as IEEE 802.11, IEEE 802.16, IEEE 802.15.1 and IEEE 802.15.4. IEEE 802.11 and IEEE 802.16 are used for those wireless applications that require high data rate. IEEE 802.15.1 standard (Blue tooth) is used for very short range wireless communication applications. However, due to high power consumption during idle listening mode, they are not suitable for such wireless



**Figure 2.2:** Nodes communicating in star and peer to peer topology

applications that have power limitations as well as low processing is required such as WSN. IEEE 802.15.4 standard [44] was designed for low data rate applications with duty cycle even less than 0.1%. Due to very small duty cycle, the standard got attraction in WSN applications.

## 2.4 Overview of IEEE 802.15.4 Standard

IEEE 802.15.4 standard [44] is designed for Low Rate Wireless Personal Area Network (LR-WPAN). It operates at both Physical and MAC layer with duty cycle of less than 0.1. In LR-WPAN, two types of wireless nodes called as Fully Functional Device (FFD) and Reduced Functional Device (RFD). FFD may be a PAN Coordinator, a Coordinator or a simple node whereas RFD can only act as simple wireless node. FFD has capability to exchange its information both with FFD and RFD whereas RFD can not exchange its information with other RFD that's why RFD only placed as end node of any wireless network. LR-WPAN operates in star as well as in peer-to-peer fashion. Nodes associated with coordinator can communicate with coordinator in star pattern where as two or more coordinators exchange their information by following peer-to-peer topology. Figure 2.2 shows nodes communicating in Star as well as in Peer-to-Peer.

IEEE 802.15.4 standard is designed for Low Rate Wireless Personal Area Network

**Table 2.1:** Frequency Bands with Data Rate

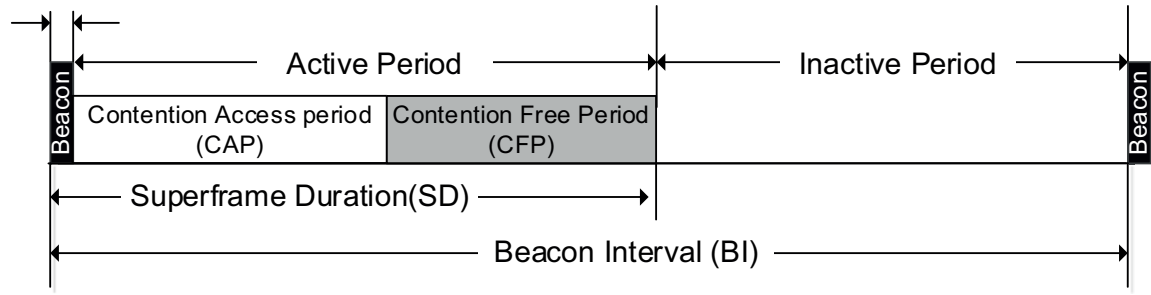
Frequency Band (MHz)	Modulation Scheme	Symbols / sec	Bits/ symbol	Symbol Duration (sec)	bits/sec	channels supported
868 - 868.6	BPSK	20000	1	$50 \times 10^{-6}$	20000	1
902 - 928	BPSK	40000	1	$25 \times 10^{-6}$	40000	10
2400 - 2483.5	O-QPSK	62500	4	$16 \times 10^{-6}$	250000	16

(LR-WPAN). It operates at both Physical and MAC layers. The standard operates at three different frequency bands; 868MHz, 915MHz and 2400MHz. In 868MHz and 915MHz, the standard uses BPSK modulation scheme, however 2400MHz frequency band uses O-QPSK modulation scheme with data rates of 20Kbps, 40Kbps and 250Kbps, respectively. These frequency bands with their respective data rates are shown in Table 2.1.

IEEE 802.15.4 operates either in a Beacon enabled or Non-Beacon enabled mode. Un-slotted CSMA/CA is used in non-beacon enabled mode. The Beacon enabled mode is divided into two main sections, active and inactive period, as shown in Fig. 2.3. All WSN nodes communicate during active period and remain in sleep mode during later inactive period to conserve energy. The active period of Beacon enabled mode consists of Contention Access Period (CAP) and optional Contention Free Period (CFP). Each Superframe in this mode is divided into 16 equal duration time slots. One or more slots are reserved for the Beacon frame because its size may vary due to number of remaining data frames for the associated nodes. Each node determine about the information relating to Length of active superframe duration, next beacon arrival time and slot duration for each slot can be attained from the superframe specs field of the beacon frame as shown in Fig. 2.4 and can be determined from equations 2.7, 2.8 and 2.9 respectively.

Calculating superframe parameters: Information about Beacon Intervals (BI) and Superframe Duration (SD) depends upon a constant value of aBaseSuperFrameDuration (BSFD) as well as the values of Beacon Order (BO) and Superframe Order (SO) as mentioned in superframe specs shown in Fig. 2.4. Whereas BSFD depends upon the fixed values of aNumSuperframeSlot (NSS) and aBaseSlotDuration (BSD). BI and SD can be calculated

## 2.4. Overview of IEEE 802.15.4 Standard



**Figure 2.3:** 802.15.4 Beacon enabled mode Superframe format.

as follows.

$$BI = BSFD \times 2^{BO} \quad (2.1)$$

Where value of BO ranges from 0 to 14 And

$$SD = BSFD \times 2^{SO} \quad (2.2)$$

Here value of SO ranges from 0 to BO. When SO and BO are same, then Inactive Period is not present in that superframe.

Whereas, BSFD is calculated as

$$BSFD = NSS \times BSD(Symbols) \quad (2.3)$$

According to IEEE 802.15.4 standard, default value of NSS is 16.

$$BSD = 3 \times aUnitBackoffPeriod \quad (2.4)$$

Default value of aUnitBackoffPeriod is 20 Symbols

$$BSD = 60(Symbols) \quad (2.5)$$

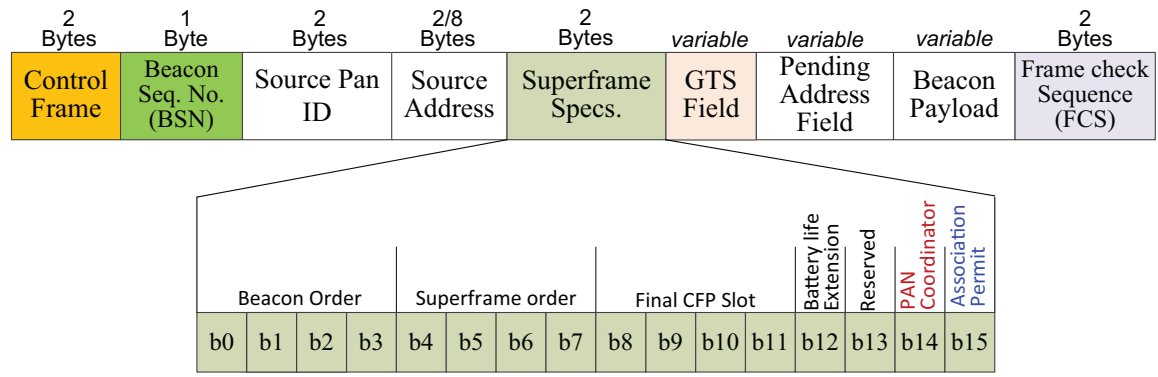
$$BSFD = 960(Symbols) \quad (2.6)$$

$$SD = 960 \times 2^{SO}(Symbols) \quad (2.7)$$

$$BI = 960 \times 2^{BO}(Symbols) \quad (2.8)$$



## 2.4. Overview of IEEE 802.15.4 Standard



**Figure 2.4:** Beacon frame with superframe specs field description

As in SD there are 16 slots so each slot duration (SID) is calculated as:

$$SID = \frac{960 \times 2^{SO}}{16} (\text{Symbols}) \quad (2.9)$$

If Number of Backoff Period against one slot is mentioned by BPS then these are calculated as:

$$BPS = \frac{960 \times 2^{SO}}{16 \times 20} \quad (2.10)$$

$$TotalBackoffPeriodsinSD = BPS \times 16 \quad (2.11)$$

$$bits/slotin868MHz = \frac{960 \times 2^{SO}}{16} \quad (2.12)$$

$$bits/slotin915MHz = \frac{960 \times 2^{SO}}{16} \quad (2.13)$$

$$bits/slotin2.4GHz = \frac{4 \times 960 \times 2^{SO}}{16} \quad (2.14)$$

From equations 2.9 and 2.10 one can analyzed that a slot Duration and number of Backoff Periods in a slot directly depend on the value of SO as their values increase with the increase in SO.

PAN coordinator originates the Beacon frame, which contains information about frame structure, next Beacon, network, and pending messages. The CAP consists of maximum

16 or minimum 9 slots. In CAP, nodes contend to access medium by following the slotted CSMA/CA mechanism [45]. On the other hand, the maximum number of slots in CFP can be up to 7 and are known as Guaranteed Time Slots (GTS).

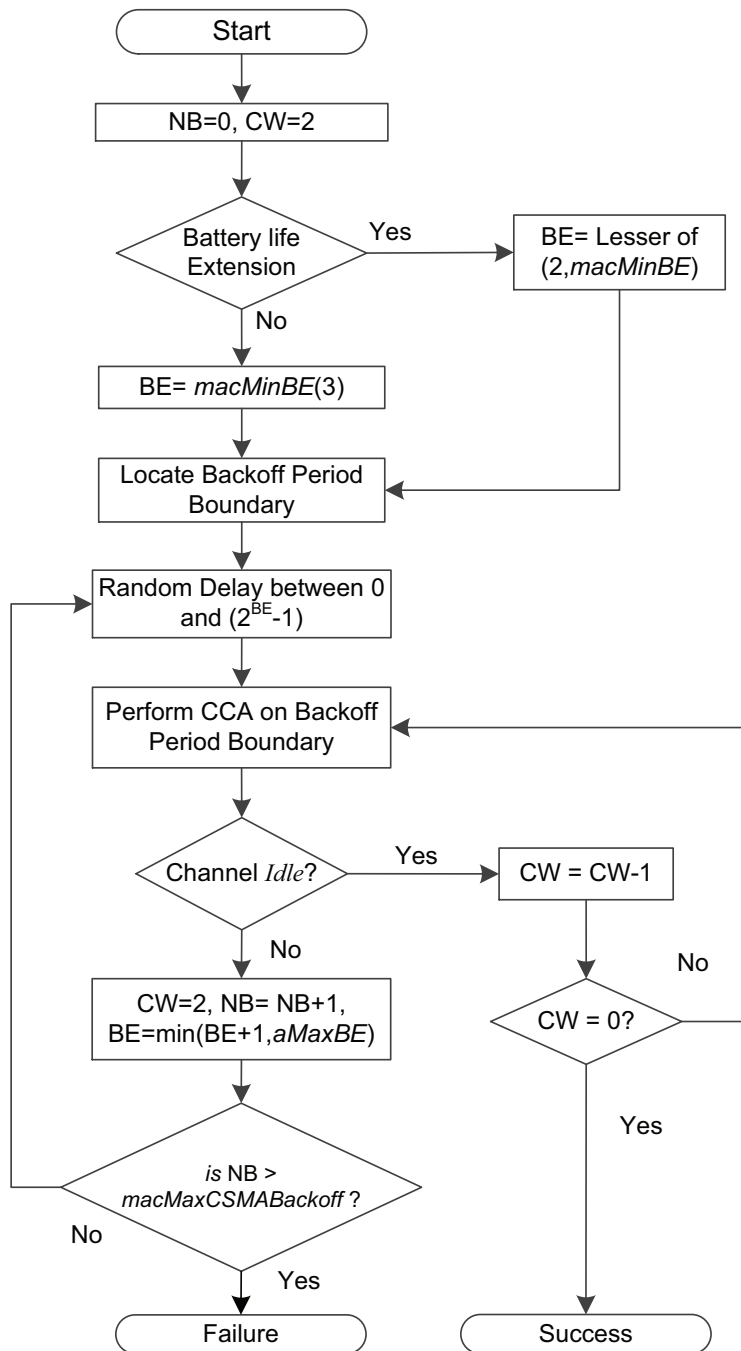
### 2.4.1 Slotted CSMA/CA Mechanism

During CAP, all nodes contend to access the medium by following CSMA/CA mechanism. This algorithm depends mainly on three parameters as number of Backoff (NB), Backoff Exponent (BE) and Contention Window (CW). Initial values of NB, BE and CW are 0, 3 and 2 respectively. When medium is found busy, value of NB is incremented by 1 unless it reaches its maximum limit of 4 as defined in MaxCSMABackoffs. The channel access is reported failure to the upper layer when NB exceeds its value as of MaxCSMABackoffs.

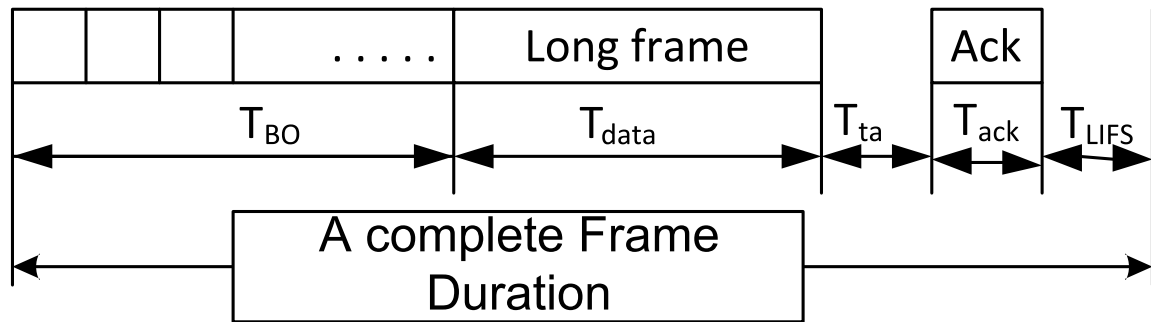
*BE* parameter defines the range of Backoff slots that is how many Backoff Slots node has to wait before going to assess the channel availability. The random number of backoff period ranges from 0 to  $2^{BE} - 1$ . Value of BE increments when medium access was found busy until *amacMaxBE* value of 5 which increases the random backoff duration from basic range of 0-7 to maximum range of 0-31.

*CW* parameter relates to Clear Channel Assessment (CCA) and its default value is 2 which means node will have to ensure two consecutive idle channels before transmitting frame to medium. The channel sensing is done during first 8 symbols of Backoff period. Flow diagram of CSMA/CA shows that when nodes need to transmit some frames, it first bring into line with the start of Backoff boundary and then waits for the random Backoff period slots. At the end of the Backoff period, node senses the channel by performing CCA at boundary of its Backoff period. If accessed channel is found busy, CCA value is re-initiated to its default value and values of NB and BE are incremented by 1 unless they reach their maximum limits. As maximum number of BE is 5 which means each time when channel is found busy, the random Backoff value increases. Maximum range of Backoff duration is from 0 to 620 Symbols.

Maximum number of backoffs is 4. By exceeding this limit, the algorithm reports a channel access failure. In case, channel is sensed idle after backoff countdown, the value of CW is decremented by 1. If its value approaches to 0 then packets are transmitted at next Backoff slot boundary as shown in Fig.2.5. This results in two consecutive channel access



**Figure 2.5:** Flow diagram of slotted CSMA/CA



**Figure 2.6:** Complete frame length including acknowledgment and inter frame Space

idle. The Backoff period countdown halts if superframe duration ends up and resumes at start of the next superframe. After successfully contending the channel access idle, the node computes whether its transmitting frame with data acknowledgment and inter-frame spacing can be completed within remaining superframe duration. If remaining superframe duration is larger than the computed frame transmitted time then the frame is transmitted otherwise node has to wait for start of the next superframe in order to transmit its data. Total time required to send data can be calculated as shown in Fig.2.6.

Nodes having critical data requests are allocated Guaranteed Time Slot (GTS) by the coordinator. The nodes that are allocated GTS can explicitly carry out communication during their allocated period to the PAN coordinator.

### 2.4.2 GTS allocation Procedure in IEEE 802.15.4 standard

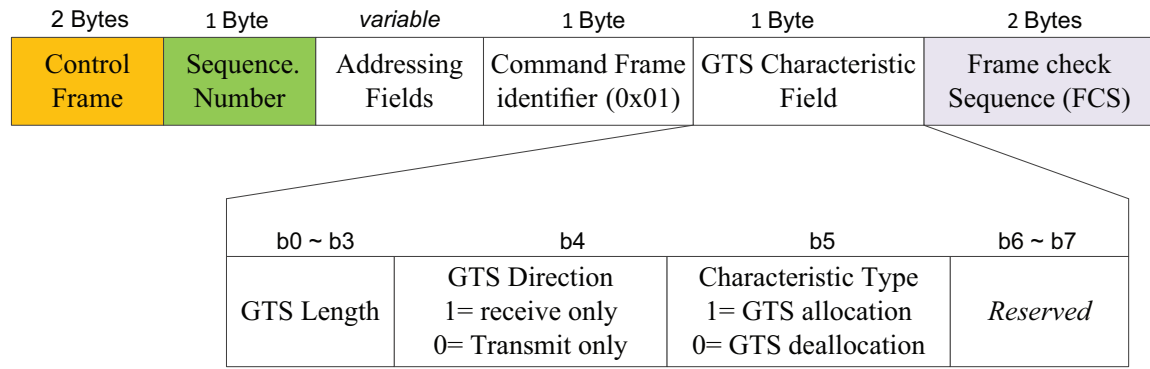
In IEEE 802.15.4 standard, CFP slots are only assigned to those nodes which have already become a member of the PAN. GTS requesting nodes are required to synchronize itself with the beacon of the coordinator to attain CAP duration. This will help nodes to send their GTS allocation requests to the PAN coordinator. A node requiring to send data (D) computes the number of CFP slots (S) as mentioned in eq.2.15.

$$S = \lceil D/BS \rceil \quad (2.15)$$

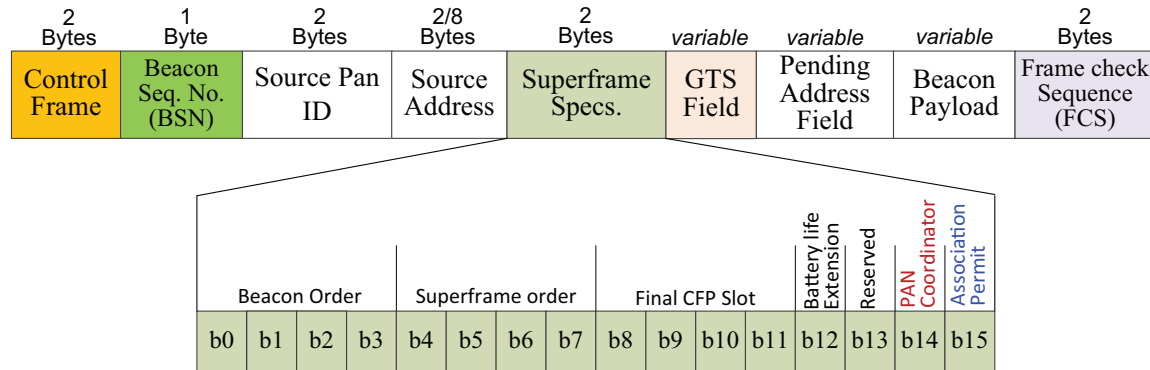
Here BS is the number of bits which can be transmitted in a slot and can be computed as:

$$BS = \frac{960 \times 2^{SO} \times 4}{16} \quad (2.16)$$

## 2.4.2. GTS allocation Procedure in IEEE 802.15.4 standard



**Figure 2.7:** GTS request frame format



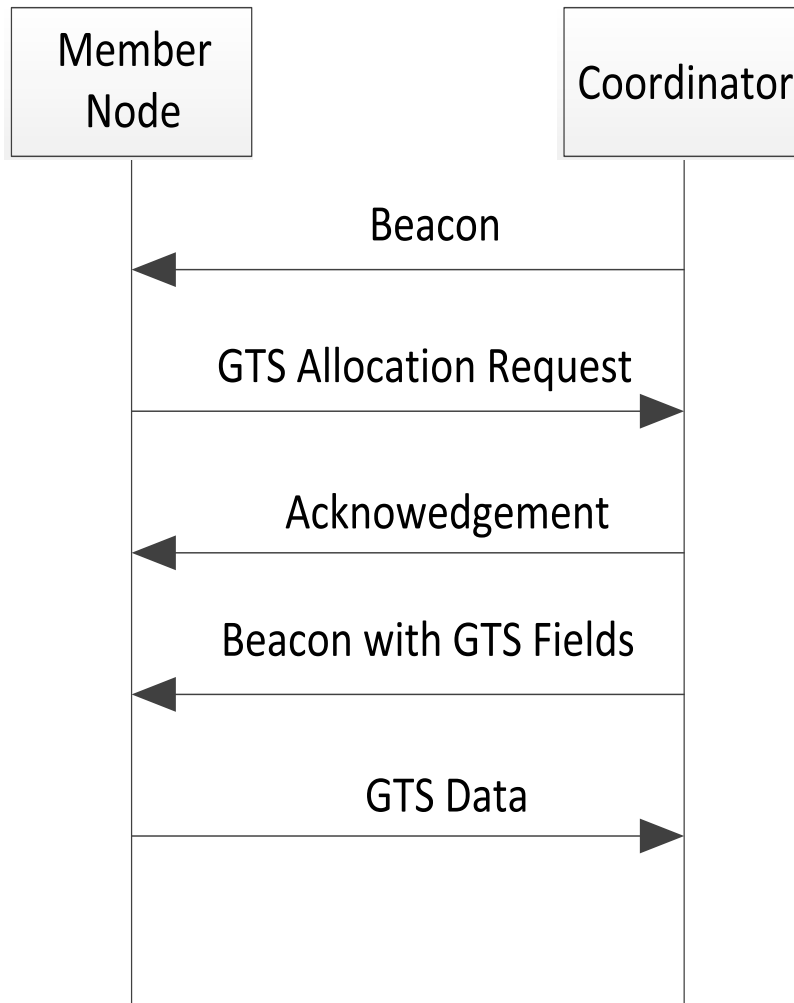
**Figure 2.8:** Beacon frame format with superframe specification field

Node after computing the number of CFP slots required to send data, generates a GTS request command to coordinator during CAP by following slotted CSMA/CA algorithm. The frame format of GTS request is shown in Fig. 2.7. The GTS direction can be defined as either transmit or receive. On receipt of this command, The PAN coordinator, on receiving this GTS request may send an acknowledgment message at once to indicate the node that its request has been reached successfully. At the end of CAP, PAN Coordinator upon receiving all these requests decides about the allocation of CFP slots to requesting node on first come first serve basis. If available slots are less than the requesting slots then nodes are refused to allocate time slots otherwise required GTS are allocated to the requesting nodes. Coordinator take cares that, allocated GTS would not reduce the CAP length from aMinCAPLength value. Coordinator informs about successful slots allocation in the GTS descriptor field available in next beacon frame as shown in Fig. 2.8. A node retrieves the information of its allocated CFP slots from GTS descriptor of the beacon frame and

### 2.4.2. GTS allocation Procedure in IEEE 802.15.4 standard

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node can send its data during its allocated CFP slots. If a node could not find its short address in the GTS list of the GTS descriptor, then GTS is not assigned to that node. A communication sequence for GTS allocation is shown in Fig. 2.9.



**Figure 2.9:** *GTS allocation procedure*

Next chapters covers our proposed research work including BS-MAC and BEST-MAC in chapter 3 and chapter 4, however modified IEEE 802.15.4 standard is described in detail in the chapter 5.

# **Enhanced TDMA based MAC Protocol for Adaptive Data Control in Wireless Sensor Networks**

## **3.1 Introduction**

Wireless Sensor Networks (WSNs) are used in wide variety of applications like temperature, humidity, etc. monitoring of such areas where human approach is almost impossible. Military organizations are also very much interested in huge deployment of wireless networks for surveillance and many tactical military applications [1]. Energy efficiency, scalability, autonomous network operations, end-to-end delay, throughput and control overhead are some of the major WSN constraints in these types of scenarios. In order to mitigate these challenges, multiple Medium Access Control (MAC) protocols have been introduced. These MAC protocols are basically categorized into two main categories: (a) Contention based and (b) Scheduling based.

In contention based MAC Protocols, WSN node contend to access the medium when it has data to send. Contention occurs when more than one node wants to access same medium in order to send their information. This increases the chances of collisions, delay and causing more energy loss, which badly decreases wireless node's life span. In case of a dense WSN, the number of collisions increases drastically and results in the longer channel access delay. One of the standard for contention based MAC protocols is IEEE 802.11 [23].

In this standard, energy consumption during idle listening mode is as high as of receiving mode. This idle listening energy consumption becomes more severe in a densely deployed network scenarios, i.e. WSN [24]. That is why this standard is not recommended for WSN. Sensor Medium Access Control (SMAC) [45], Time-out Medium Access Control (TMAC) [46], Berkley Medium Access Control (BMAC) and Utilization based duty cycle tuning Medium Access Control (UMAC) [47] are also contention based MAC protocols designed for WSN. They adjust duty cycle for efficient energy consumption.

WSN are generally deployed in large numbers, therefore, contention based MAC protocols are not suitable in such scenarios. On the other hand, in scheduled based MAC protocols, there is no contention because all nodes are assigned a separate Guaranteed Time Slots (GTS), e.g. Time Division Multiple Access (TDMA), to carry out communication. TDMA avoids interference by offering time based scheduling for nodes to access radio sub-channels. The variant of TDMA, called Energy efficient TDMA (E-TDMA) [35], is proposed for the hierarchical WSN, where whole network is divided into groups or clusters. All nodes in that cluster send their information to the elected cluster head (CH) by following E-TDMA. In E-TDMA, the CH turn its Radio off to save energy when members have no data to send. Though these protocols increase node's life time by conserving its energy, however, they are not scalable due to limited number of time slots that sometimes are insufficient in unpredictable scalability of WSN.

Due to different transmission behavior and variations in traffic loads, nodes do not have same volume of data to send. Even the nodes with similar task have different data collection time and transmitting time. To cope this adaptive data traffic load, different TDMA based MAC protocols have been proposed, e.g. Bit-Map-Assisted (BMA) [32] and BMA with Round Robin (BMA-RR) [33]. They utilize different scheduling schemes for allocation of the fixed time slots to the requesting member nodes. In result, they conserve and re-allocate those unused time slots to the nodes with large volume of data.

All the above discussed techniques overcome some of the limitations of traditional TDMA, however, control overhead increases in these schemes. The second issue in these schemes is that the number of time slots are equal to the number of member nodes. Due to these fixed number of time slots available in a round, these techniques do not properly address the adaptive traffic load problem. In result, it increases delay and reduces throughput.



In this chapter, we propose an adaptive TDMA based MAC protocol, called Bitmap-assisted Shortest job first based MAC (BS-MAC), that: (1) considers small size time slots and their number is not equal to number of member nodes. This will help in handling adaptive traffic loads of all members in an efficient manner. (2) Shortest Job First (SJF) algorithm is applied in order to reduce node's job completion time and to minimize the average packet delay of nodes. (3) The size of control packet is reduced by using short node address (1 byte instead of 8 bytes), which reduces the control overhead and makes our proposed scheme energy efficient.

Rest of the chapter is organized as follows: Section 3.2 discusses the previous work related to the proposed scheme. The proposed TDMA based MAC protocol is described in Section 3.3. Section 3.4 evaluates and compares the performance of the proposed BS-MAC protocol with the existing ones. Finally, Section 3.5 concludes the chapter.

## 3.2 Related Work

Energy conservation is one of the main objectives of the MAC protocols. TDMA based MAC protocols are energy efficient as they do not waste their energy due to collision as of contention based MAC protocols like CSMA/CA. Many MAC protocols have been designed to achieve energy efficiency. In this section, we briefly discuss the previous related work, e.g. contention free or TDMA based MAC protocols for WSN [32]- [29].

The Chinese remainder theorem based MAC (CMAC) [48] is one of the TDMA based MAC protocol proposed for the hierarchical WSN architecture. The Network Coordinator (NC) are selected to collect data from neighboring nodes and forward it to the sink node. It uses Chinese remainder theorem to find out the scheduled time slots for the associated nodes. When member node(s) transmit data on regular basis, then each node is allocated a time slot for data transmission on the basis of prime and remainder sequence calculated from Chinese remainder theorem. CMAC reduces latency in a session, however, if a node has no data to send, then it's slot remains unused and other nodes can not use these slots even if they have data to send.

In [27], TDMA based MAC protocol, called DGRAM (Delay Guaranteed Routing and MAC), is proposed specifically for the delay sensitive applications in WSN. The determin-

### 3.3. Proposed BS-MAC Protocol

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istic delay is guaranteed by reusing the allocated time slots. Wu et al. in [49] proposed a TDMA based MAC protocol by applying Coloring Algorithm, known as TDMA-CA. In TDMA-CA, different colors are allocated to the conflicting nodes in network and separate time slots are allocated to each color. Authors have compared the proposed protocol with SMAC and shown that TDMA-CA outperforms in terms of energy consumption and latency.

In [29], Traffic Pattern Oblivious (TPO) scheduling scheme based MAC protocol is proposed. Unlike traditional TDMA scheduling, TPO is capable of continuous data collection with dynamic traffic pattern in an efficient manner. It allows the gateway to determine data collection on the basis of traffic load.

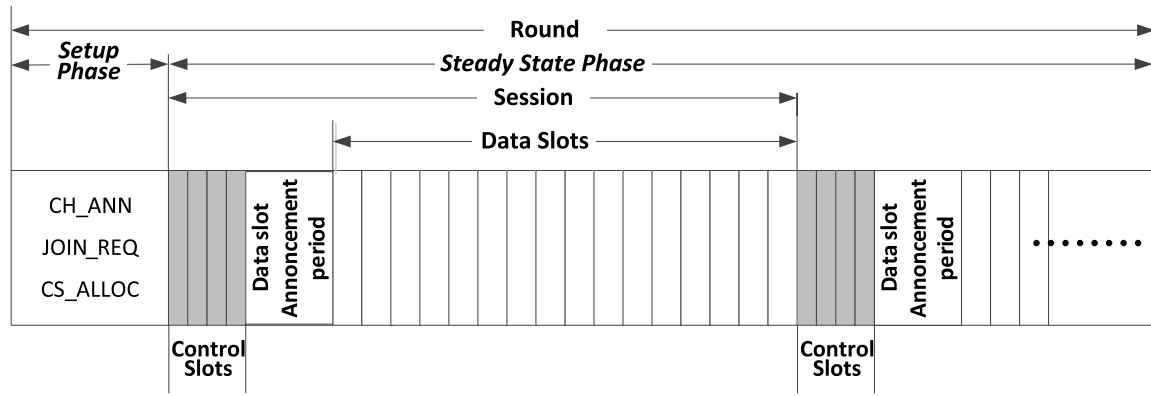
The Bit-Map-Assisted (BMA) [32] and BMA with Round Robin (BMA-RR) [33]. These protocols introduce varying scheduling techniques to efficiently allocate fixed time slots. The BMA MAC protocol allocates fixed duration time slots to the requesting nodes only and the other nodes are not assigned any time slot at all. In result, BMA conserves time slots and those slots may be allocated to the nodes with large volume of data. The BMA method was improved in [33] by introducing Round Robin scheduling technique, named BMA-RR, to assign time slots to the requesting nodes. Though these techniques overcome some of the limitations of traditional TDMA, however, control overhead increases in these schemes. The second issue in these schemes is that the number of time slots are equal to the number of member nodes. Due to fixed number of time slots available in a round, these techniques do not properly address the adaptive traffic load problem. As a result, it increases delay and reduces throughput.

Most of the research work has been focused on energy conservation of wireless nodes and to increase the life time of a WSN. However, in this work, we have focused on the overall performance of a WSN in terms of energy, throughput and transmission latency. The following section discusses our proposed scheme in detail.

### 3.3 Proposed BS-MAC Protocol

We propose a TDMA based MAC protocol, called Bitmap-assisted Shortest job first based MAC (BS-MAC), for cluster based or hierarchical communication scenarios in WSN.

### 3.3.1. Setup Phase (SP)



**Figure 3.1:** One round in a cluster.

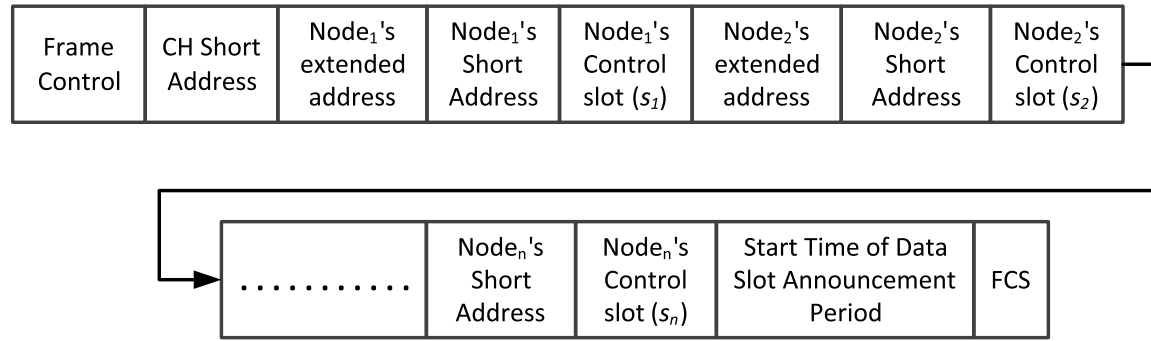
Various clustering techniques are proposed for efficient routing between wireless nodes and sink in a WSN [50]. Those schemes divide WSN in different groups, called *clusters*. In each cluster, a node is elected as a *Cluster Head* (CH) and all the other nodes join that CH and act as member nodes. The members of that cluster communicate with the sink node through their respective CH. In a cluster setup phase, wireless nodes are organized in a cluster. Each node at the start of new round decides whether it will become CH for this round or not. This decision is based on the stochastic algorithm. The probability of each node to become a CH is  $1/p$ , where 'p' is the desired percentage of CHs. Once the node becomes CH, it will not again be chosen as a CH until or unless rest of the nodes in that cluster becomes CH. After successful selection of a CH, the CH starts communication round(s). Each round comprises of a *Setup Phase* (SP) and *Steady State Phase* (SSP), as shown in Fig.3.1. The SSP is further divided into multiple *Sessions*. Following is a brief discussion related to each section of a round.

### 3.3.1 Setup Phase (SP)

The SP immediately starts after successful selection of a CH. Following steps will take place during the SP.

1. CH broadcasts CH Announcement (*CH\_ANN*) message. *CH\_ANN* message starts with control portion (1 Byte) along with CH's extended address (8 Bytes) and Frame Check Sequence (FCS) (2 Bytes) as redundant bits. Total length of a *CH\_ANN* message is 11 bytes.

### 3.3.2. Steady State Phase (SSP)

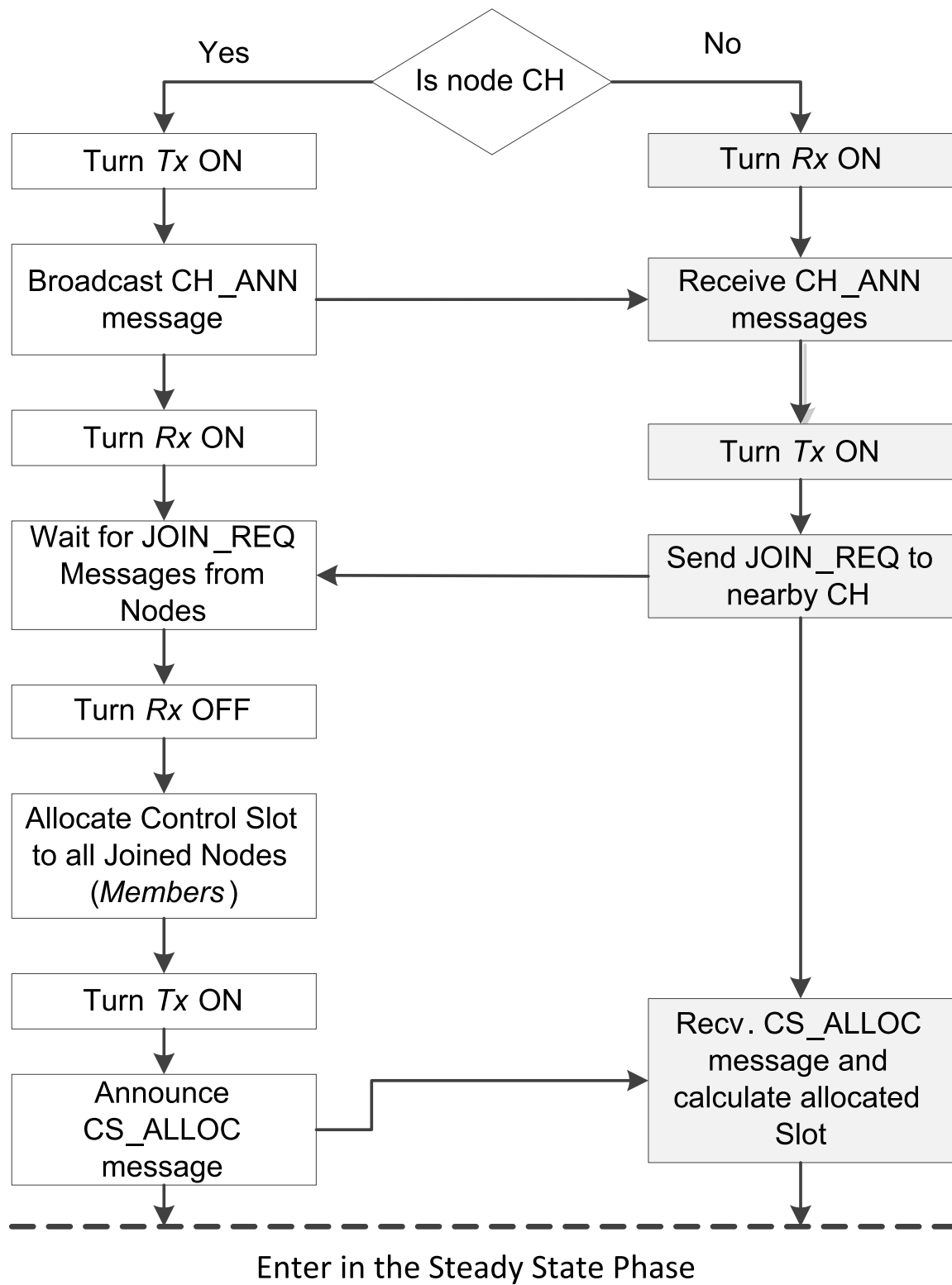


**Figure 3.2:** CS\_ALLOC Message Format.

2. Nodes in the range of CH, listens to CH\_ANN and replies with the Join Request (*JOIN\_REQ*) message to CH. This *JOIN\_REQ* includes a Control Byte, Node's extended address (8 Bytes), CH's extended address, and FCS. Hence, the size of a *JOIN\_REQ* is 19 bytes.
3. CH waits for a specific time period to receive *JOIN\_REQ*s from all nodes within its communication range.
4. CH calculates the total number of member nodes by counting the received *JOIN\_REQ*s and allocates a control slot to each node.
5. A unique 1 Byte short address is computed by a CH for all the associated members and for itself. Therefore, maximum 255 nodes can be associated with single CH. Afterward, CH allocates separate control slot to each member node and broadcasts the allocated control slot information to all its members through CS\_ALLOC message, as shown in Fig.3.2. CS\_ALLOC message mainly consists of control byte, CH's extended and short address, node<sub>*i*</sub>'s extended and short address, node<sub>*i*</sub>'s allocated Control Slot number,  $s_i$ , Start Time of Data Slot Announcement Period and FCS. The detailed flow diagram of *Setup Phase* is shown in Fig. 3.3.

### 3.3.2 Steady State Phase (SSP)

After successful completion of the SP, Steady State Phase starts immediately with control slots where source nodes (data sending member nodes) send their *DATA\_REQ* messages during their allocated control slots. Detailed flow diagram of SSP is shown in Fig.



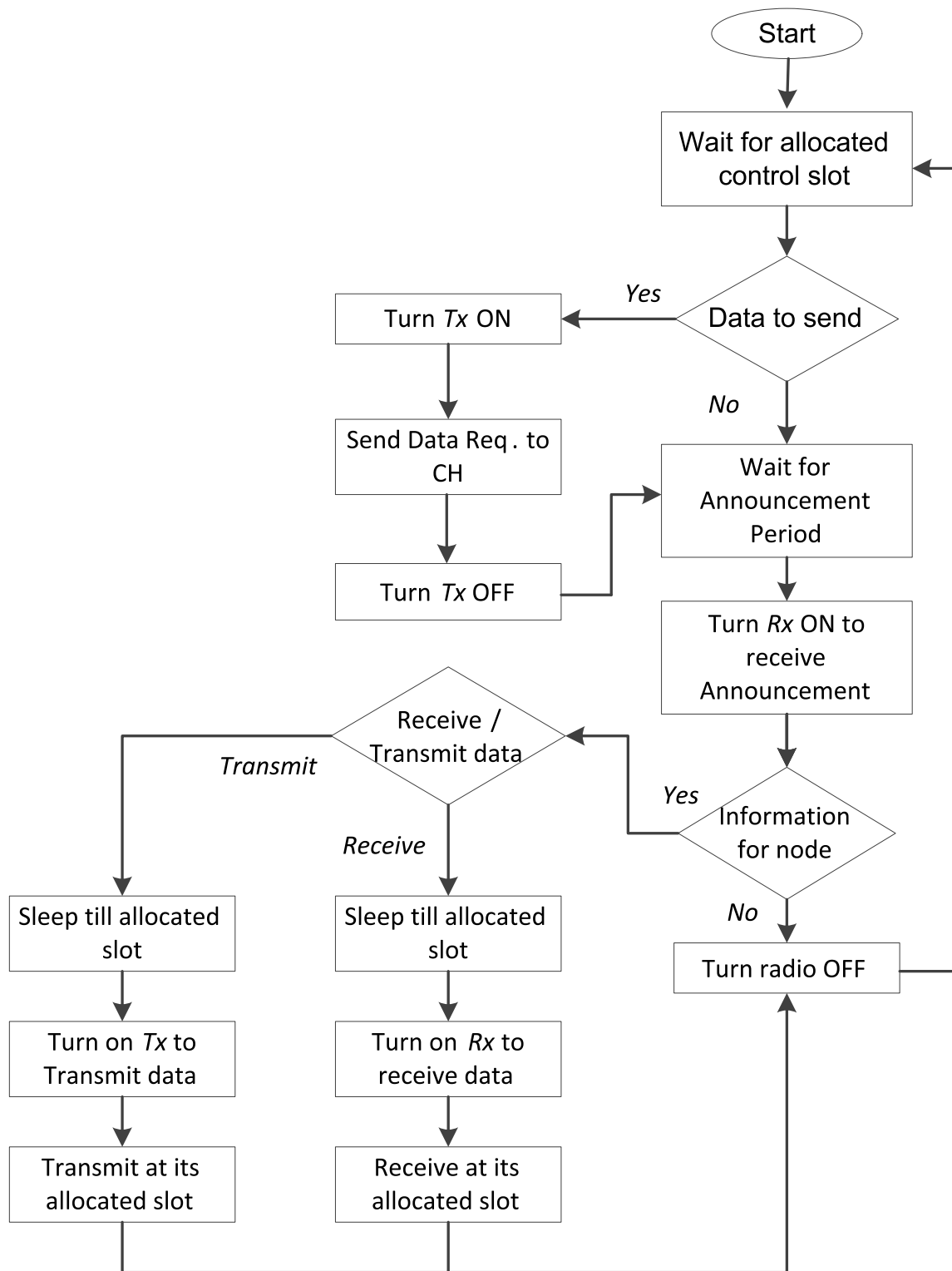
**Figure 3.3:** Setup Phase communication flow diagram between CH and Member node.

3.4 *DATA\_REQ* mainly consists the number of requested slots by the source node. The non-requesting member nodes (having no data to send,) keep their radios Off in order to save energy. However, the CH remains in receiving mode during the entire control period in order to receive *DATA\_REQ* messages from all source nodes. After completion of control period, CH computes number of *DATA\_REQ* messages (requesting nodes) and has complete information about the total number of data slots requested by source nodes. CH applies Shortest Job First (SJF) algorithm and informs all source nodes about their allocated data slots by broadcasting Allocated Data Slot Announcement (*ADS\_ANN*) frame, as shown in Fig. 3.5. The SJF algorithm for data slot allocation is briefly discussed in the next section. If the total number of requested data slots is more than the total number of available slots, then some of the nodes will not be entertained during that session. If a node wants to send data to its neighboring node then in first session, node sends the data to CH and then during next session that data is transmitted to the receiving node.

The *ADS\_ANN* message comprise of each source node's short address along with its allocated starting time slot and information of the next control period start time. Therefore, all member nodes have knowledge about their control slot in the next session also.

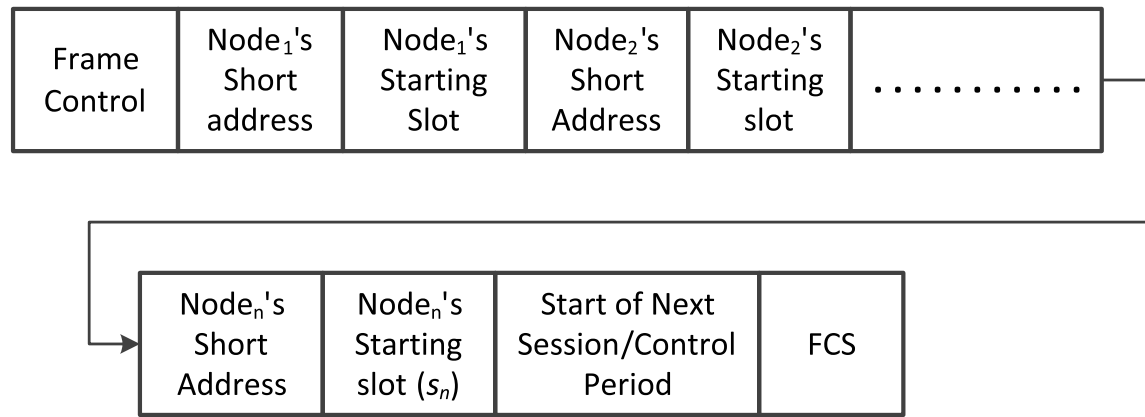
### 3.3.3 Shortest Job First (SJF) Algorithm

In our proposed BS-MAC, allocation of data slots to the source nodes are prioritized on the basis of Shortest Job First (SJF) algorithm. In SJF algorithm, nodes with less number of data slot requests are prioritized over nodes that require more data slots. In case, if two or more nodes have requested for the same number of data slots, then priority will be given to the node with small short address as of other nodes. The reason to adopt SJF instead of Round Robin is that in Round Robin mechanism source node(s) that require more than one time slot for data transmission has/have to wait for longer time to send their data to CH, as described in BMA-RR [33]. In addition to the increased delay, the source node(s) also consume extra energy by toggling their radios between Off and On states. On the other hand, the SJF technique saves energy by avoiding this radio toggling. Furthermore, average data transmission time (the average total duration between start and end of data transmission) of source nodes is faster than Round Robin, as shown in Table 3.1. We have compared SJF with RR by considering 5 source nodes requiring different data slots. It is evident from the results that the nodes with SJF complete their data transmission quickly



**Figure 3.4:** Steady State Phase (SSP) communication flow diagram of a member node.

### 3.3.4. Slot Duration



**Figure 3.5:** ADS\_ANN Message Format.

than the RR.

**Table 3.1:** Comparison between SJF and Round Robin Algorithm

Node	Data Slots Re- quested	Slots / job in SJF	Slots / job in RR	Job Completion ratio (SJF vs RR)
A	2	2	6	1:3
B	3	5	11	1:2.2
C	4	9	15	1:1.66
D	4	13	15	1:1.15
E	5	18	18	1:1

### 3.3.4 Slot Duration

Previous TDMA based schemes allocate fixed length data slot to source nodes and each data slot is of longer time duration. For efficient use of time slots, the slot duration is kept smaller as compared to traditional TDMA based schemes. Shorter times slots will be helpful in order to minimize unused time slots and consequently helps in minimizing unnecessary wait duration for other source nodes. Table 3.2 shows comparison between BMA-RR and our proposed BS-MAC protocol in terms of excessive delay calculation when nodes want to generate random data. It also shows that by introducing shorter data



### **3.3.4. Slot Duration**

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slots, as in proposed BS-MAC, nodes save substantial time as compared to larger data slots used in BMA-RR. As CH has to keep its radio in the receiving state throughout these data slots, therefore, the smaller length of data slots save significant amount of energy, which further improves the throughput.

**Table 3.2:** Comparison of Data Transmission delay between proposed BS-MAC and BMA-RR based MAC protocol

Node	Data Length (Bytes)	Data Rate (bps)	time to send data	bits/slot in BMA-RR	Slot length in BMA-RR MAC (msec)	Slots re-quired	Time required to send data in BMA-RR	bits/slot in BS-MAC	Slot length in BS-MAC	Slots re-quired	Time Re-quired to send data in BS-MAC	time lapsed in BMA-RR	time lapsed in BS-MAC
A	120	24000	40	2000	83.33	1	83.33	200	8.33	5	41.67	43.33	1.67
B	180	24000	60	2000	83.33	1	83.33	200	8.33	8	66.67	23.33	6.67
C	210	24000	70	2000	83.33	1	83.33	200	8.33	9	75.00	13.33	5.00
D	240	24000	80	2000	83.33	1	83.33	200	8.33	10	83.33	3.33	3.33
E	280	24000	93.33	2000	83.33	2	166.67	200	8.33	12	100.0	73.33	6.67

CH informs all source nodes about their allocated data slots with starting slot number by sending DSA\_ANN message. If there is no request for slot allocation by any source node, then DSA\_ANN contains only the start time information of next control period. On the other hand, the control slot sequence remains same throughout the round. As all control slots are of same length, as informed by CH during the setup phase, hence, member nodes only need to know start of the next control period to compute their control slot as well as start time of the next data slot announcement period.

### 3.3.5 Energy Consumption during SP

Total energy consumption during setup phase in  $N$  size cluster ( $E^{setup}$ ) is sum of energy consumed by CH and its associated  $(N - 1)$  member nodes. Energy consumed by a CH comprises of energy consumption during *Active* and *Idle* states. ( $E_{ch}^{SP-Active}$ ) is the energy consumed by a CH in active mode during setup phase and is calculated as:

$$E_{ch}^{SP-Active} = P_{ch}^{AT} \times T_{AT} + P_{ch}^{JR} \times T_{JR} \times (N - 1) + P_{ch}^{CS} \times T_{CS} \quad (3.1)$$

where,  $P_{ch}^{AT}$ ,  $P_{ch}^{JR}$  and  $P_{ch}^{CS}$  are the power consumed by the CH for transmitting the CH\_ANN, receiving JOIN\_REQ and transmitting of CS\_ALLOC message to all member nodes, respectively. The  $T_{AT}$ ,  $T_{JR}$  and  $T_{CS}$  are the time required to send CH\_ANN, receive JOIN\_REQ and send CS\_ALLOC messages, respectively. In same state, the energy consumed by a member node  $m$ ,  $E_m^{SP-Active}$ , where  $m \in (N - 1)$ , is calculated as:

$$E_m^{SP-Active} = P_m^{AT} * T_{AT} + P_m^{JR} * T_{JR} + P_m^{CS} * T_{CS} \quad (3.2)$$

where,  $P_m^{AT}$ ,  $P_m^{JR}$  and  $P_m^{CS}$  are the power consumed by a member node for receiving CH\_ANN, sending JOIN\_REQ and receiving CS\_ALLOC messages, respectively.

There are  $N - 1$  member nodes in a cluster and energy consumed by all member nodes in active mode, ( $E_{am}^{SP-Active}$ ), is computed as in eq.(3.3).

$$E_{am}^{SP-Active} = \sum_{i=1}^{i=(N-1)} E_i \quad (3.3)$$

During SP, some of the energy also consumed when CH and member nodes are in idle listening mode. If  $P_{ch}^{SP-Idle}$  is the power consumed by CH during idle state as it has to

### 3.3.6. Energy Consumption during SSP

keep its receiver ON in order to receive member node's JOIN\_REQ messages and  $T_{ch}^{SP-Idle}$  is the time for idle period, then total energy consumed by CH during idle period in SP ( $E_{ch}^{SP-Idle}$ ) is calculated as:

$$E_{ch}^{SP-Idle} = P_{ch}^{idle} * T_{ch}^{SP-Idle} \quad (3.4)$$

All member nodes after sending JOIN\_REQ messages keep their radios ON and wait to receive CH's CS\_ALLOC message. Member nodes in idle mode also wait to receive CH\_ANN message from CH in the beginning of the SP, as shown in Fig.3.3. If a member node  $m$  consumes  $P_m^{SP-Idle}$  power and has  $T_m^{SP-Idle}$  idle listening period, then the overall energy consumption of a member node  $m$  during idle listening period in SP,  $E_m^{SP-Idle}$ , is computed as:

$$E_m^{SP-Idle} = P_m^{SP-Idle} * T_m^{SP-Idle} \quad (3.5)$$

Total energy consumed by  $N - 1$  member nodes during idle mode in SP ( $E_{am}^{SP-Idle}$ ) is calculated as:

$$E_{am}^{SP-Idle} = \sum_{i=1}^{i=(N-1)} E_i^{SP-Idle} \quad (3.6)$$

Total energy consumption in a cluster during setup phase,  $E^{setup}$ , is computed as in eq.(3.7):

$$E^{Setup} = E_{ch}^{SP-Active} + E_{am}^{SP-Active} + E_{ch}^{SP-Idle} + E_{am}^{SP-Idle} \quad (3.7)$$

### 3.3.6 Energy Consumption during SSP

In a round, there is one SP and one SSP. A SSP comprises of multiple sessions and each session starts with control period followed by data slot allocation period and dedicated data slots for communication. In session  $j$ , source node(s) send their data request(s), DATA\_REQ message(s), during their allocated control slot, whereas all the other nodes keep their radios off to save energy. Energy consumed by a source node  $s$  during control period in session  $j$ , ( $E_s^{CP_j}$ ), is calculated as:

$$E_s^{CPj} = P_s^{CPj} * T_s \quad (3.8)$$

where,  $P_s^{CPj}$  is power consumed during transmitting DATA\_REQ message and  $T_s$  is the control slot duration in session  $j$ .

CH in that control slot period always remains in receiving mode to receive DATA\_REQ messages. If there are  $x$  number of source nodes, then the energy consumption during complete control period ( $E^{CPj}$ ) is computed as:

$$E^{CPj} = E_s^{CPj} \times x + (N - 1 - x) \times P_{ch}^{CP-Idlej} \times T_s + x \times P_{ch}^{CP-Rxj} \times T_s \quad (3.9)$$

Here,  $P_{ch}^{CP-Idlej}$ , is power consumed by CH during idle listening in the control period and  $P_{ch}^{CP-Rxj}$  is power consumed in receiving DATA\_REQ message during control period by CH.

Control period is followed by data slots allocation period in which CH announces data slots allocation information to all member nodes, ADS\_ANN message, in the cluster along with starting of next control period. Total energy consumed during data slots allocation period in session  $j$ , ( $E^{ADSj}$ ), is calculated as:

$$E^{ADSj} = P_{ch}^{ADSj} \times T^{ADSj} + \sum_{i=1}^{i=(N-1)} P_i^{ADS-Rxj} \times T^{ADSj} \quad (3.10)$$

where,  $P_{ch}^{ADSj}$  is power consumed by a CH in transmitting ADS\_ANN message,  $P_i^{DSA-Rx}$  is power consumed by node  $i$  to receive that message, and  $T^{ADSj}$  denotes the time required to send and receive ADS\_ANN message during session  $j$ .

Next, we calculate the energy consumed by all member nodes to transmit data in session  $j$ ,  $E^{DTj}$ , as in eq. (3.11).

$$E^{DTj} = \sum_{i=1}^{i=(N-1)} P_i^{DTj} * k * T^{DS} \quad (3.11)$$

here,  $k$ ,  $P_i^{DTj}$  and  $T^{DS}$  are number of time slots used by source node  $i$  to transmit data, power consumed to transmit data and duration of a single data slot in session  $j$ , respectively.

Energy consumed by a CH in receiving all data packets, ( $E_{ch}^{DTj}$ ), from source nodes

during same session is computed as:

$$E_{ch}^{DTj} = P_{ch}^{DRj} * k * T_{DS} \quad (3.12)$$

where  $P_{ch}^{DRj}$  is power consumed by CH in receiving data packets from all source nodes during session  $j$ . Therefore, the overall energy consumption during session  $j$ ,  $E_j^{Steady}$ , is:

$$E_j^{Steady} = E^{CPj} + E^{ADSj} + E^{DTj} + E_{ch}^{DTj} \quad (3.13)$$

If there are  $n$  steady state sessions in a round, then the total energy consumed during SSP is:

$$E^{Steady} = \sum_{l=1}^n E_l^{Steady} \quad (3.14)$$

Total energy consumed in a cluster is sum of energy consumed in SP as well as in SSP and is computed as:

$$E_{total} = E^{Setup} + E^{Steady} \quad (3.15)$$

## 3.4 Simulation Analysis

This section discusses the simulation analysis of our proposed BS-MAC protocol in contrast with the BMA-RR [33] and E-TDMA [35] that are considered as conventional schemes. As we discussed that our proposed BS-MAC protocol improves throughput, minimizes delay and increases energy efficiency of the whole network. In order to evaluate the effectiveness of the proposed BS-MAC protocol, we compared throughput, energy efficiency and delay with E-TDMA and BMA-RR, through simulations. During simulations, we considered the network of size  $N = 11$ , off which one node acts as CH and rest as member nodes. These nodes are deployed in an area of  $100 \times 100$  meters. Probability  $P$  is set on the basis of nodes having data requests e.g. if  $P = 0.1$ , then only one out of 10 member nodes require to send data. Random data traffic is generated by the data requesting nodes within the range of 0.175 KB to 2.875 KB. The data slots are varied and are analyzed for 4 and 6 steady state sessions.

The impact of varying network size is analyzed for the network size of 11, 21 and 31 nodes, off which one node act as CH and remaining are member nodes. Transmitted

**Table 3.3:** Simulation Parameters

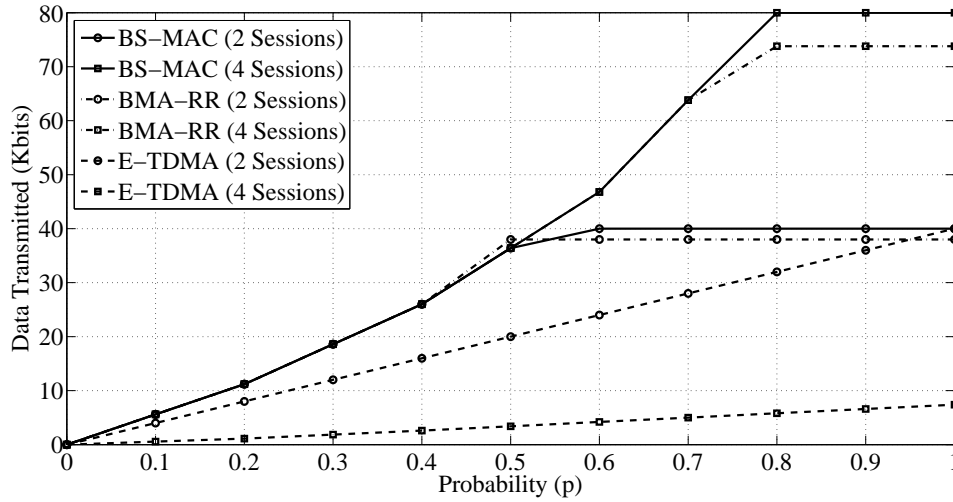
Parameters	BS-MAC	BMA-RR	E-TDMA
Data rate (bps)	24000	24000	24000
Control Packet Size (bits)	32	144	1
Control Slot Length (sec)	0.00133	0.006	0.00004166
Data Slot Length (sec)	0.0083	0.083	0.083
Transmitting Energy (nJ)	50	50	50
Receiving Energy (nJ)	50	50	50
Idle Energy (nJ)	5	5	5

data along with energy consumption and average transmitted delay are analyzed for three sessions. Rest of the simulation parameters are shown in Table 3.3.

### 3.4.1 Transmitted Data

The transmitted data is calculated as amount of data sent from source to the destination node successfully. Figure 3.6 and 3.7 show the transmitted data for varying probability ( $p$ ) and sessions, respectively. It is evident from the results that BS-MAC transmits data prior to E-TDMA and BMA-RR. In Fig. 3.6, for 2 and 4 session, it is observed that BS-MAC transmits more data as of the other two MAC protocols when number of source nodes increases. However, when  $p$  increases from 0.6 and 0.8, then BS-MAC does't send more data because all data slots are occupied, for 2 and 4 sessions, respectively. In Fig. 3.7, the similar increase in transmitted data is observed. It shows that BS-MAC transmits more data as of the other two MAC protocols in first 2 for  $p = 0.4$  and 3 sessions for  $p = 0.6$ . In order to further validate our results, we analyzed its performance for network size of 11, 21 and 31 nodes. Figure 3.8 shows, that BS-MAC transmits more data as compared to other two protocols for network size of 11, 21 and 31 nodes. It is evident from the results that BS-MAC perform better in transmitting more data as of other two protocols in each network size.

It is noticed that average improvement in transmitted data by BS-MAC is 3% and



**Figure 3.6:** Transmitted data versus Probability ( $p$ ) for 2 and 4 Sessions.

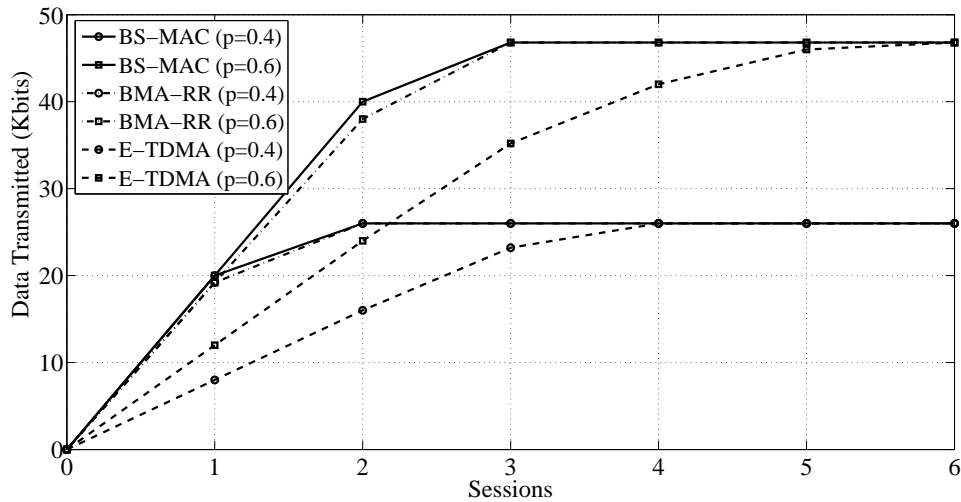
35.4% for 2 sessions and 4.3% and 16.3% for 4 sessions, refer Fig. 3.6. This significant improvement in transmitted data by BS-MAC is due to the selection of smaller data slots, which can accommodate different data requirements effectively. Whereas, in other two TDMA based MAC protocols, larger data slots are used that cannot accommodate adaptive data traffic requirements efficiently.

### 3.4.2 Total Energy Consumption

Energy efficiency of sensor nodes is required to increase life time of a WSN. Total energy consumption versus probability and sessions are shown in Fig. 3.9 and 3.10, respectively. It is evident from the figures that BS-MAC, while transmitting same amount of data, consumes less energy as compared to other two MAC protocols. It is evident from Fig. 3.9 that BS-MAC consumes less energy throughout 2 sessions, however, for 4 sessions, BS-MAC consumes less energy when  $p = 0.8$  and consumes more energy when  $p > 0.8$ . This is due to the increase in amount of data transmitted during that period. On the other hand, E-TDMA consumes less energy compared to the proposed MAC protocol as well as BMA-RR. It is only because it fails to transmit more data compared to both the protocols. The similar behavior is also observed in Fig. 3.10.

To further validate our results we analyzed energy consumption of BS-MAC with other two TDMA based MAC protocols for varying network size. It is evident from the results





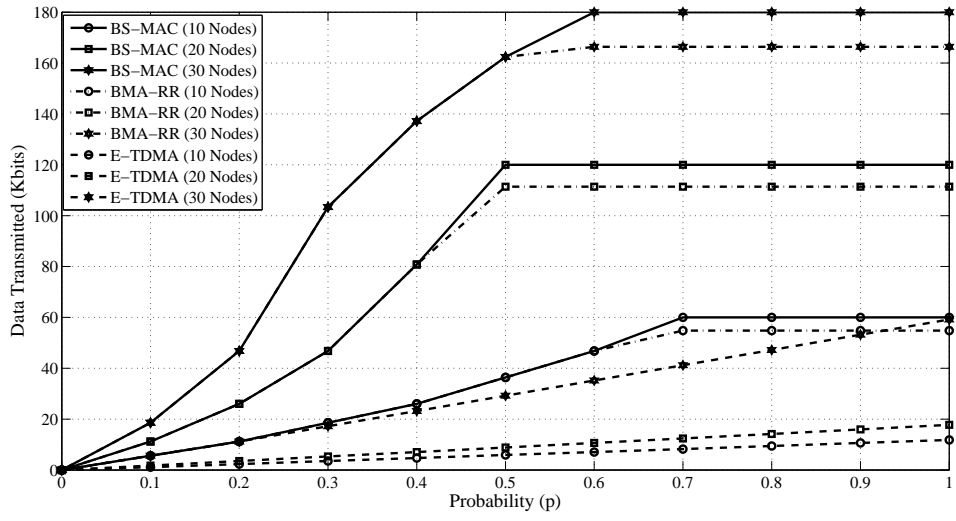
**Figure 3.7:** Transmitted data versus Session for  $p = 0.4$  and  $0.6$ .

shown in Fig. 3.11, that BS-MAC consumes less amount of energy for  $N=11, 21$  and  $31$  while transmitting same amount of data, however energy consumption increases with the increase in probability. This is because of larger amount of data transmitted in BS-MAC.

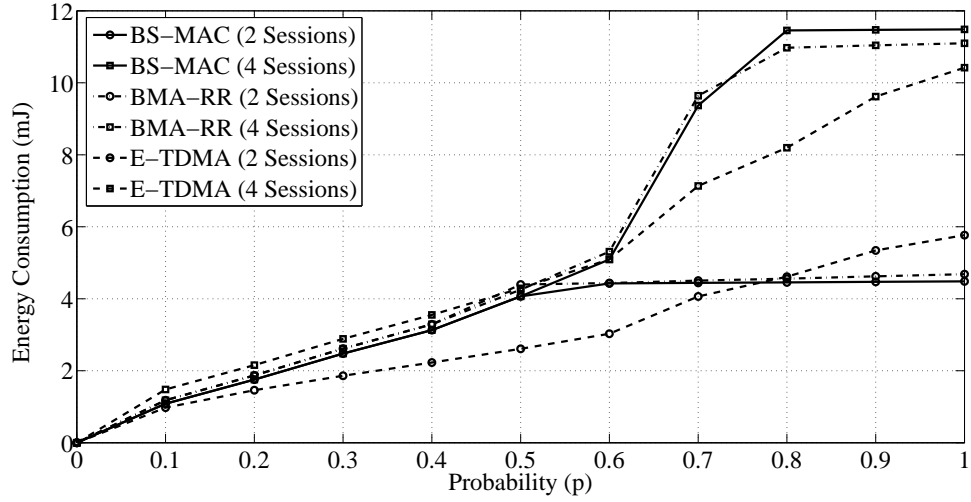
### 3.4.3 Transmission Delay

Transmission delay of a node is calculated from the time when node has a data request till the time it sends all of its data to the destination successfully. Figure 3.12 and 3.13 show the transmission delay versus  $p$  and session, respectively. The BS-MAC has significantly less transmission delay as of BMA-RR and E-TDMA, which is obvious from the results. This is due to the implication of SJF algorithm as nodes transmit their data at once instead of transmitting in parts. This results in avoiding nodes to keep data in their buffer for longer time, as shown in Table 3.1. Smaller slot length further improves the network delay, as shown in Table 3.2. The same trend is observed for network size of  $11, 21$  and  $31$  nodes. Results shown in Fig. 3.14 verify that average transmission delay of BS-MAC for  $31$  nodes is even smaller than  $10$  nodes of other two TDMA schemes.

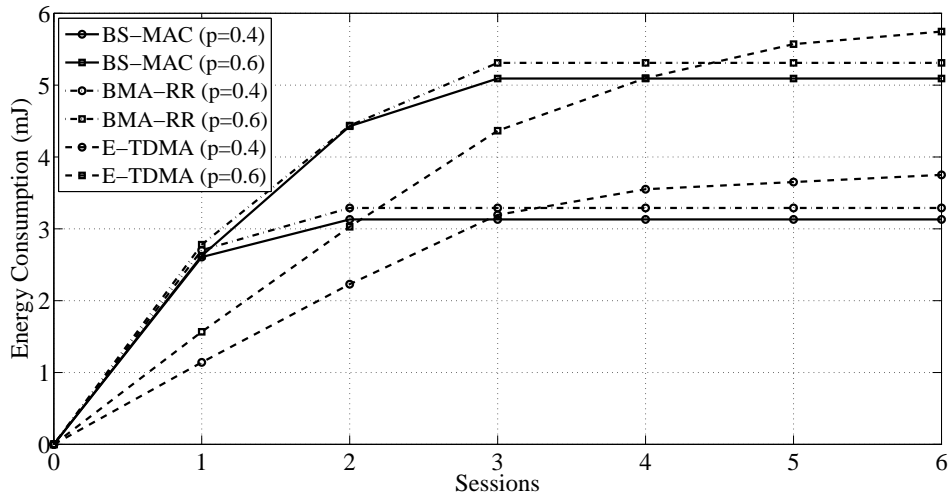
The results in Fig. 3.12 show that average transmission delay of the network is minimized by BS-MAC upto  $72\%$  and  $79\%$  for  $2$  sessions and  $80\%$  and  $85\%$  for  $4$  session, compared to BMA-RR and E-TDMA, respectively. Similar amount of delay has been reduced by the BS-MAC for varying sessions as shown in Fig. 3.13.



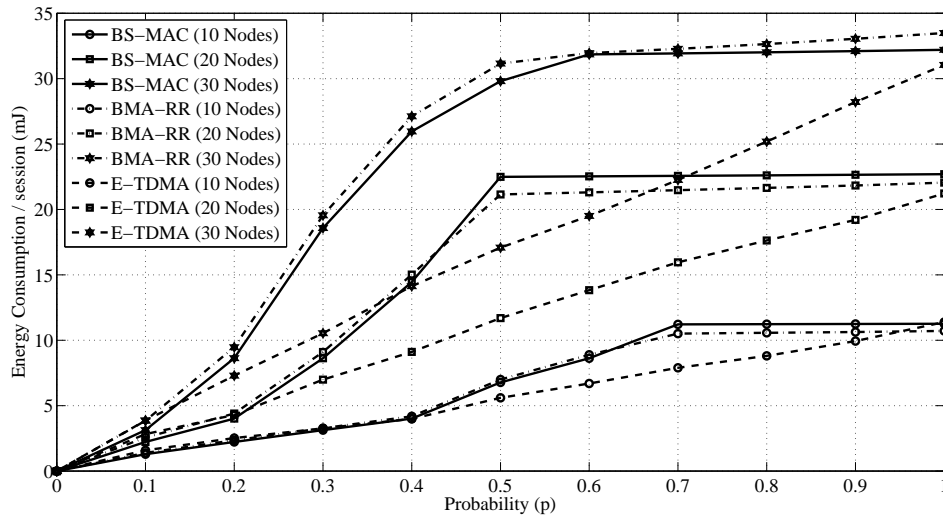
**Figure 3.8:** Transmitted data of 11, 21 and 31 nodes versus  $p$  for 3 Sessions.



**Figure 3.9:** Energy consumption of the network versus  $p$  for 2 and 4 Sessions.



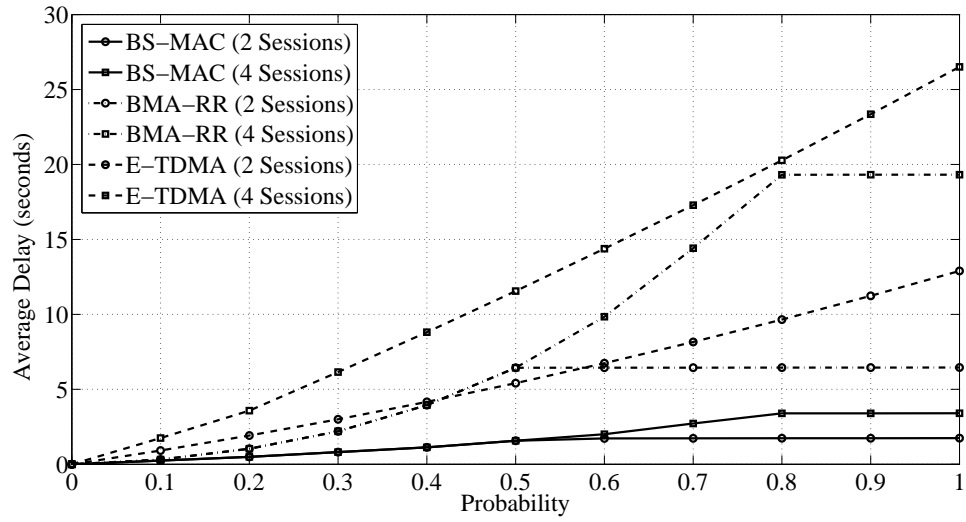
**Figure 3.10:** Energy consumption of the network versus sessions for  $p = 0.4$  and  $0.6$ .



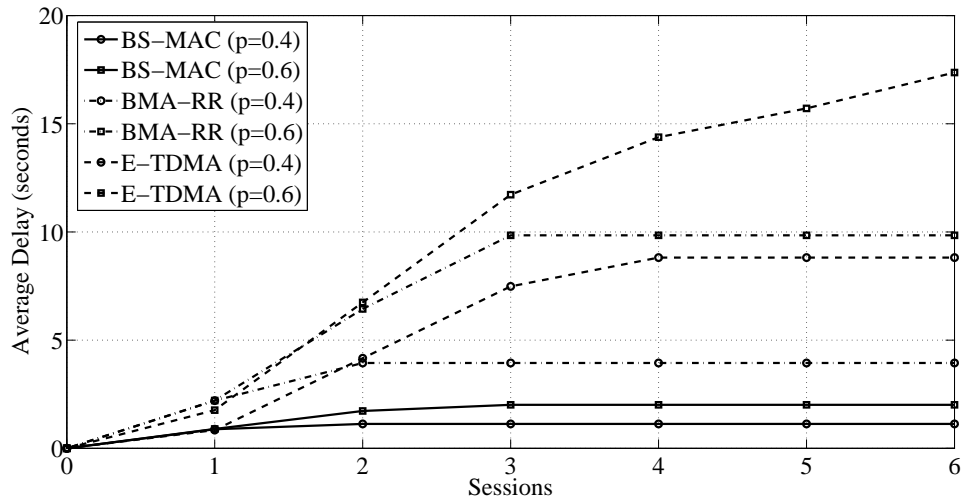
**Figure 3.11:** Energy consumption of 11, 21 and 31 nodes network versus  $p$  for 3 sessions.

## 3.5 Conclusion

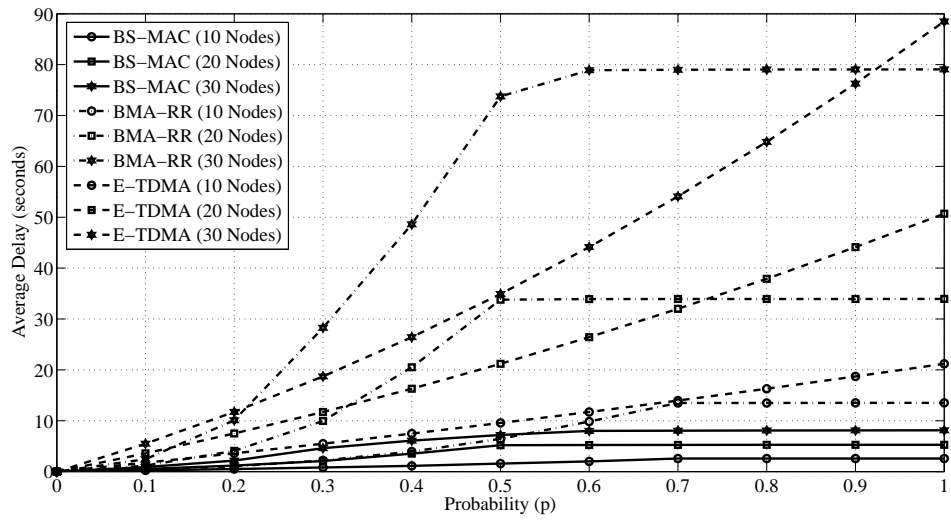
In this work, we proposed TDMA based MAC protocol, called BS-MAC, that adaptively handles the varying amount of data traffic by using large number of small size data slots. In addition, it implements Shortest Job First algorithm to reduce node's job completion time that results in significant improvement in average packet delay of nodes. The control overhead and energy consumption is also minimized by introducing the 1 byte short address to identify the member nodes. The performance of the proposed BS-MAC protocol is compared with the BMA-RR and E-TDMA through simulations. It shows that BS-MAC achieves more than 70% and 80% efficiency in data transmission delay and more than 3% and 17% data is transmitted compared to BMA-RR and E-TDMA without compromising energy consumption.



**Figure 3.12:** Transmission Delay of the network versus  $p$  for 2 and 4 Sessions.



**Figure 3.13:** Transmission Delay of the network versus sessions for  $p = 0.4$  and  $0.6$ .



**Figure 3.14:** Transmission Delay of 11, 21 and 31 nodes network versus  $p$  for 3 sessions.

# Bit Map Assisted Efficient and Scalable TDMA Based MAC protocol

## 4.1 Introduction

Wireless Sensor Networks (WSNs) are used in wide variety of applications like temperature, humidity, etc. monitoring of such areas where human approach is almost impossible. Military organizations are also very much interested in huge deployment of wireless networks for surveillance and many tactical military applications [1]. Energy efficiency, scalability, autonomous network operations, end-to-end delay, throughput and control overhead are some of the major WSN constraints in these types of scenarios. In order to mitigate these challenges, multiple Medium Access Control (MAC) protocols have been introduced. These MAC protocols are basically categorized into two main categories: (a) Contention based and (b) Scheduling based.

In contention based MAC Protocols, WSN node contend to access the medium when it has data to send. Contention occurs when more than one node wants to access same medium in order to send their information. This increases the chances of collisions with longer delay and more energy consumption, which badly decreases reduces the life span of a wireless node. In case of a dense WSN, the number of collisions increases drastically and results in the longer channel access delay. One of the standard for contention based MAC protocols is IEEE 802.11 [23]. This standard is designed for high data rate with high processing applications and is not suitable for low data rate and low processing applications

such as WSNs. That is why this standard is not recommended for WSN. Sensor Medium Access Control (SMAC) [45], Time-out Medium Access Control (TMAC) [46], Berkley Medium Access Control (BMAC) and Utilization based duty cycle tuning Medium Access Control (UMAC) [47] are also contention based MAC protocols designed for WSN. They adjust duty cycle for efficient energy consumption.

WSN are generally deployed in large numbers, therefore, contention based MAC protocols are not suitable in such scenarios. On the other hand, in scheduled based MAC protocols, there is no contention because all nodes are assigned a separate Guaranteed Time Slots (GTS), e.g. Time Division Multiple Access (TDMA), to carry out communication. TDMA avoids interference by offering time based scheduling for nodes to access radio sub-channels. The variant of TDMA, called Energy efficient TDMA (E-TDMA) [35], is proposed for the hierarchical WSN, where whole network is divided into groups or clusters. All nodes in that cluster send their information to the elected cluster head (CH) by following E-TDMA. In E-TDMA, the CH turn its Radio off to save energy when members have no data to send. Though these protocols increase node's life time by conserving its energy, however, they are not scalable due to limited number of time slots that sometimes are insufficient in unpredictable scalability of WSN.

Due to different transmission behavior and variations in traffic loads, nodes do not have same volume of data to send. Even the nodes with similar task have different data collection time and transmitting time. To cope this adaptive data traffic load, different TDMA based MAC protocols have been proposed, e.g. Bit-Map-Assisted (BMA) [32] and BMA with Round Robin (BMA-RR) [33]. They utilize different scheduling schemes for allocation of the fixed time slots to the requesting member nodes. In result, they conserve and re-allocate those unused time slots to the nodes with large volume of data.

All the above discussed techniques overcome some of the limitations of traditional TDMA, however, control overhead increases in these schemes. The second issue in these schemes is that the number of time slots are equal to the number of member nodes. Due to these fixed number of time slots available in a round, these techniques do not properly address the adaptive traffic load problem. In result, it increases delay and reduces throughput.

In this chapter, we propose Bit map assisted Efficient Scalable TDMA based MAC protocols (BEST-MAC), that:

1. Considers large number of small size time slots and these time slots are not equal to number of member nodes. This will help in handling adaptive traffic needs in an efficient manner with increase in Link Utilization.
2. Knapsack algorithm is applied not only to reduce node's job completion time but also to allow more nodes to transfer their data within available time slots. In addition to reduce the average packet delay of the network, it also increases the link utilization of the network.
3. A separate Contention access period is introduced in the proposed architecture to accommodate non-member nodes to become a member of the network during data transferring phase.
4. Overheads are reduced by allocating each node a short address of 1 Byte instead of 8 Bytes extended address.
5. Proposed scheme can accommodate 255 wireless nodes in a single cluster.

Rest of the chapter is organized as follows: Section 4.2 discusses the previous work related to the proposed scheme. The proposed TDMA based MAC protocol is described in Section 4.3. Section 4.5 evaluates and compares the performance of the proposed BEST-MAC protocol with the existing ones. Finally, Section 4.6 concludes the chapter.

## 4.2 Related Work

Energy conservation is one of the main objectives of the MAC protocols. TDMA based MAC protocols are energy efficient as they do not waste their energy due to collision as of contention based MAC protocols, i.e. CSMA/CA. Many MAC protocols have been designed to achieve energy efficiency. In this section, we briefly discuss the previous related work in contention free or TDMA based MAC protocols for WSNs [26]- [33].

A TDMA based MAC protocol for WSN (S-TDMA) is proposed in [26], in which authors exploit the essential features of TDMA causing un-necessary energy consumption and high latency in sensor networks. Energy consumption is addressed by keeping nodes in sleep mode when they have nothing to transmit or receive, however latency issues are



addressed by emitting those time slots which are assigned to those nodes having no data to send.

In [27], TDMA based MAC protocol, called DGRAM (Delay Guaranteed Routing and MAC), is proposed specifically for the delay sensitive applications in WSN. The deterministic delay is guaranteed by reusing the allocated time slots. In [28], authors proposed Intelligent Hybrid MAC (IH-MAC) for broadcast scheduling and link scheduling. The protocol intelligently uses the strength of CSMA and TDMA approaches in order to reduce the delay. At the same time energy consumption is minimized by suitably varying the transmit power.

In [29], Traffic Pattern Oblivious (TPO) scheduling scheme based MAC protocol is proposed. Unlike traditional TDMA scheduling, TPO is capable of continuous data collection with dynamic traffic pattern in an efficient manner. It allows the gateway to determine data collection on the basis of traffic load. In [30], performance of the proposed TDMA based MAC in prospects of link quality estimation was implemented on CC2530 hardware and tested in industrial field. An energy efficient TDMA (EA-TDMA) is proposed for communication between wireless sensor nodes placed at railway wagons [31].

The Bit-Map-Assisted (BMA) [32] and BMA with Round Robin (BMA-RR) [33] are TDMA based MAC protocols. These protocols introduce varying scheduling techniques to efficiently allocate fixed time slots. The BMA MAC protocol allocates fixed duration time slots to the requesting nodes only and the other nodes are not assigned any time slot at all. In result, BMA conserves time slots and those slots may be allocated to the nodes with large volume of data. The BMA method was improved in [33] by introducing Round Robin scheduling technique, named BMA-RR, to assign time slots to the requesting nodes in a round robin fashion.

Most of the research work has been focused on energy conservation of wireless nodes and to increase the life time of a WSN. However, in this work, we have focused on the overall performance of a WSN in terms of energy, throughput and transmission latency. The following section discusses our proposed scheme in detail.

## 4.3 Proposed BEST-MAC Protocol

We propose a TDMA based MAC protocol, called Bitmap-assisted Efficient Scalable MAC (BEST-MAC), for cluster based or hierarchical communication scenarios in WSN.

## 4.4 TDMA based MAC Protocol

Bitmap-assisted Efficient Scalable MAC (BEST-MAC) is a TDMA based MAC protocol for cluster based or hierarchical communication scenarios in WSN.

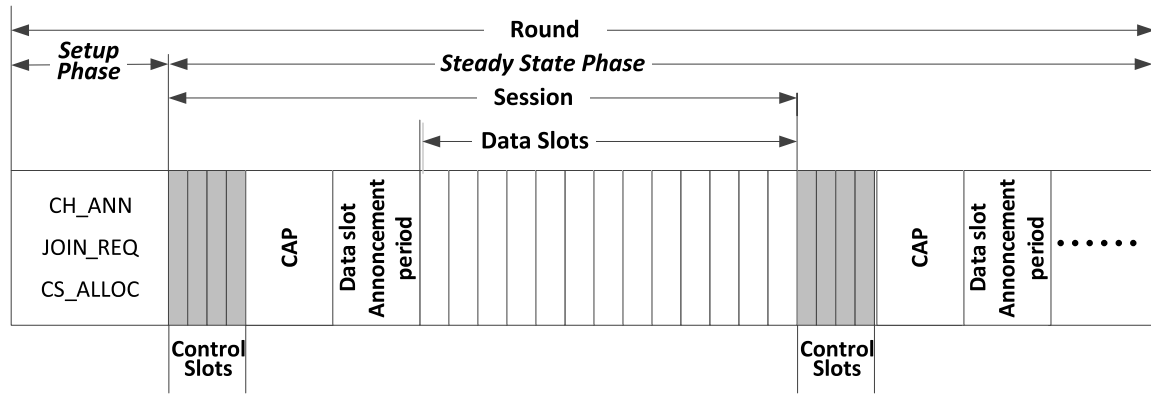
Various clustering techniques are proposed for efficient routing between wireless nodes and sink in a WSN [50]. Those schemes divide WSN in different groups, called *clusters*. In each cluster, a node is elected as a *Cluster Head* (CH) and all the other nodes join that CH and act as member nodes. The members of that cluster communicate with the sink node through their respective CH. In a cluster setup phase, wireless nodes are organized in a cluster. Each node at the start of new round decides whether it will become CH for this round or not. This decision is based on the stochastic algorithm. The probability of each node to become a CH is  $1/p$ , where 'p' is the desired percentage of CHs. Once the node becomes CH, it will not again be chosen as a CH until or unless rest of the nodes in that cluster becomes CH. After successful selection of a CH, the CH starts communication round(s). Each round comprises of a *Setup Phase* (SP) and *Steady State Phase* (SSP), as shown in Fig.4.1. The SSP is further divided into multiple *Sessions*. Following is a brief discussion related to each section of a round.

### 4.4.1 Setup Phase (SP)

The SP immediately starts after successful selection of a CH. Following steps will take place during the SP.

1. CH broadcasts announcement (*CH\_ANN*) message. *CH\_ANN* message starts with control portion of 1 Byte, along with CH's extended address of 8 Bytes and ends with Frame Check Sequence (FCS) of 2 Bytes.
2. Nodes in the range of CH responds with the Join Request (*JOIN\_REQ*) messages

#### 4.4.1. Setup Phase (SP)



**Figure 4.1:** One round in a cluster.

upon receiving advertisement message. This JOIN\_REQ includes a Control Byte, Node's extended address (8 Bytes), CH's extended address and FCS. Hence, the size of a JOIN\_REQ is 19 bytes.

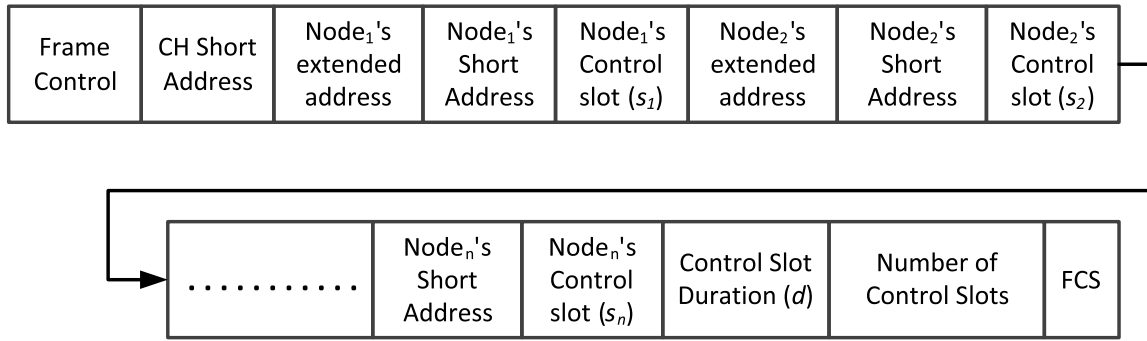
3. CH waits for JOIN\_REQ messages from all nodes within its communication range.
4. CH calculates the total number of member nodes by counting the received JOIN\_REQs.
5. A unique 1 Byte short address is computed by a CH for all the associated members and for itself. Therefore, maximum 255 nodes can be associated with single CH. Afterward, CH allocates separate control slot to each member node and broadcasts the allocated control slot information to all its members through CS\_ALLOC message, as shown in Fig.4.2.

CS\_ALLOC message mainly consists of control byte, CH's extended and short address, node<sub>i</sub>'s extended and short address, node<sub>i</sub>'s allocated Control Slot number, Control Slot Duration (CSD), Total number of control slots (*TOT\_CS*), *s<sub>i</sub>*, Start Time of Data Slot Announcement Period and FCS. The detailed flow diagram of *Setup Phase* is shown in Fig. 4.3.

Each node computes its allocated control slot by 4.1 E.g, if a member node has been assigned control slot number 'C' then it can compute about the start of its control slot time (*CS\_Start*) as:

$$CS\_Start = CSD \times (C - 1) \quad (4.1)$$

#### 4.4.2. Steady State Phase (SSP)



**Figure 4.2:** CS\_ALLOC Message Format.

Each member node must requires to listen CH's Allocated Data Slot Announcement (*ADS\_ANN*) message. In our proposed MAC architecture, *ADS\_ANN* message commences after Control Period (*CP*) and Contention Access Period (*CAP*), which can be computed by each member node as:

$$ADS\_ANN = CP + CAP \quad (4.2)$$

Here  $CP = TOT\_CS * CSD$  and  $CAP = 256 * CSD$

$$ADS\_ANN = (TOT\_CS + 256) \times CSD \quad (4.3)$$

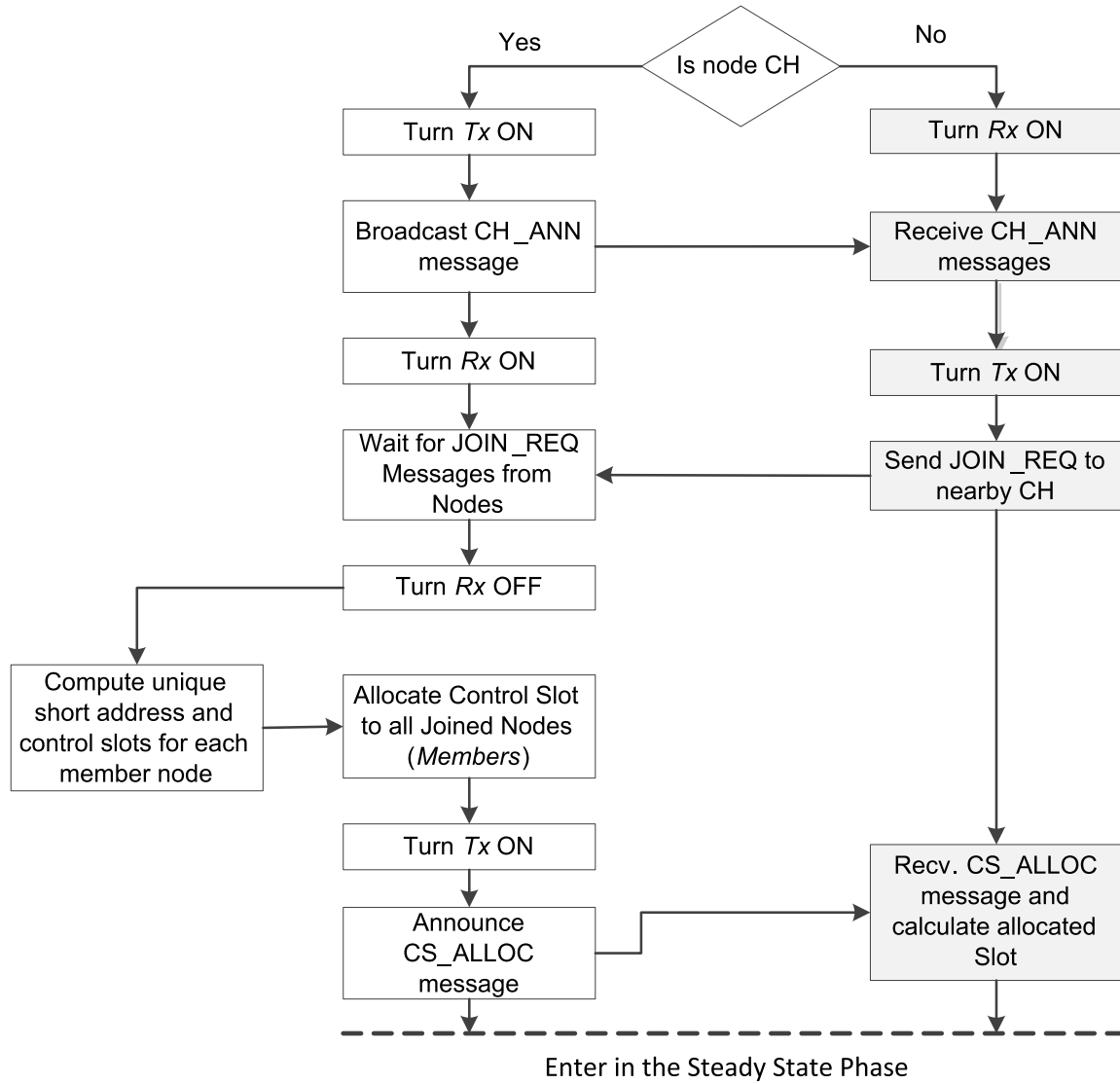
#### 4.4.2 Steady State Phase (SSP)

After successful completion of the SP, Steady State Phase starts immediately. SSP consists of multiple sessions which starts with CP and then followed by CAP, *ADS\_ANN* message and data slots respectively.

##### Control Period (CP)

All data sending nodes are required to send data request during their allocated control slots whereas, nodes, having no data request keep their radios off to save their energy. However, coordinator remains in idle listening mode during whole control period. This control frame contains of 48 bits. Each control frame comprises of following information.

1. Control frame pattern (4 bits).



**Figure 4.3:** Setup Phase communication flow diagram between CH and Member node.

2. Short message of data requesting node and coordinator (16 bits).
3. Number of data slots required to send data (12 bits). This means maximum capacity of transmitting data by a source node in BEST\_MAC is 24576 bytes.
4. Frame check sequence (16 bits).

In BEST\_MAC, each data slot is a simple multiple of CSD. Each node computes its Required Number of Data Slots ( $REQ\_DS$ ) as:

$$REQ\_DS = \lceil \frac{Data(bits)}{48} \rceil \quad (4.4)$$

##### *Contention Access Period (CAP)*

After the expiry of CP, CAP commences. CAP is fixed and comprises of 256 CSD. During CAP, those nodes who could not become member of the network during setup phase can become a member of this network. These non member nodes send JOIN\_REQ message to the CH by following slotted CSMA/CA algorithm and in response CH only acknowledges these nodes that their requests have been reached to the CH. Successful nodes who become member of this network are informed in the next ADS\_ANN message.

##### *Allocation Data Slot Announcement (ADS\_ANN) Message*

After CAP, CH's ADS\_ANN message starts. It is mandatory for all nodes to listen in order to synchronize themselves in order to attain necessary information. ADS\_ANN message comprises of:

1. List of new member whose JOIN\_REQ has been entertained by allocating them a unique short address of 8 bits along with their control slot number.
2. List of all those source nodes which have been assigned data slots in order to transmit its data. This includes short address of data requesting node, initial data slot number along with number of data slots allocated to each source node. If there is no request for slot allocation by any source node, then DSA\_ANN contains only the start time information of next control period. Priority of source nodes are determined by applying knapsack algorithm. Maximum Data Slot Duration (*DSD\_MAX*) allowed in a session is:

$$DSD\_MAX = CSD \times 2^{16} \quad (4.5)$$

In case, if requested number of data slots increase from maximum limit then some of the requested data will not be entertained during that session. Complete data transmission process from node to CH is shown in Figure 4.4

3. Nodes are also informed about the Start of CP (*CP\_START*) by simply providing a 16 bits information about total data slots assigned (*DSA\_TOT*). As, each member node already knows about its allocated control slot number, when their membership was confirmed by the coordinator, So nodes only need to know about the CP\_START which can be calculated as:

$$CP_{START} = DSA\_TOT \times 256 \quad (4.6)$$

### 4.4.3 Knapsack Optimization Algorithm

In our proposed BEST\_MAC, allocation of data slots to the source nodes are prioritized on the basis of Knapsack Optimization algorithm with following modifications.

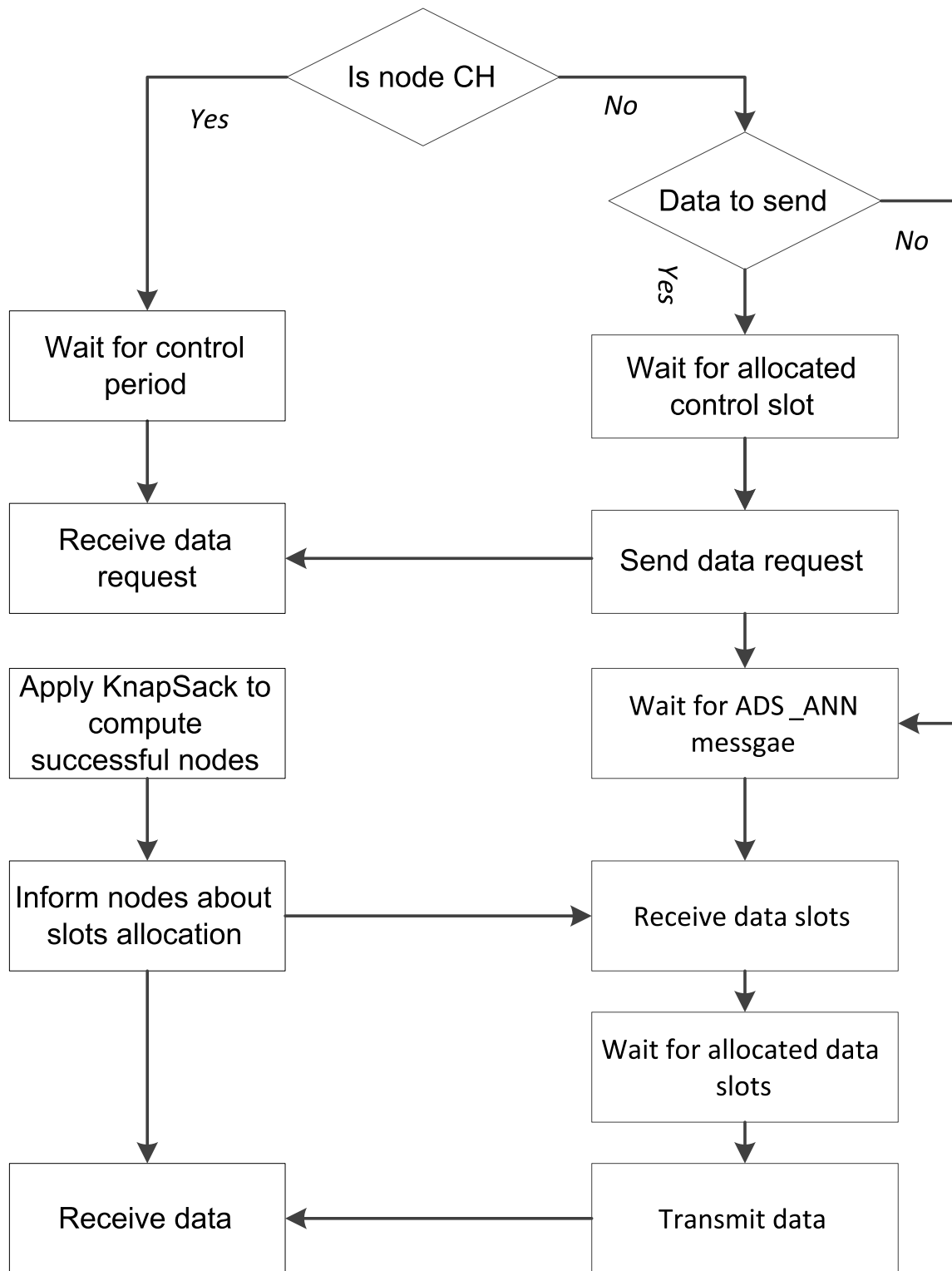
1.  $W$ : Total knapsack weight or total available slots.
2.  $w_i$ : Number of slots requested by  $i$ th node.
3.  $w$ : current slot number which ranges from 0 to  $W$ .

If coordinator receives  $j$  slot requests from  $n$  nodes, then it checks whether total requested slots are more than the available slots or not. If  $j$  slots are less than  $W$  then all requesting nodes are assigned data slots as per their requests but their priorities are determined by the knapsack algorithm. However, if requesting data slots increases than the available slots, then CH scrutinize source nodes which can transmit data during that session via knapsack as follows.

The knapsack problem is solved in terms of solving sub-problems with the help of knapsack algorithm. Let,  $C[i, w]$  represent the maximum slots of a subset  $S_i$  with slots  $w$  and  $C[n, W]$  is the required optimal solution, where  $n$  represents the nodes, which are successfully allocated CFP slots and  $W$  is the slot capacity which must be less or equal to the total slot capacity.

Optimized node selection is determined by following algorithm.

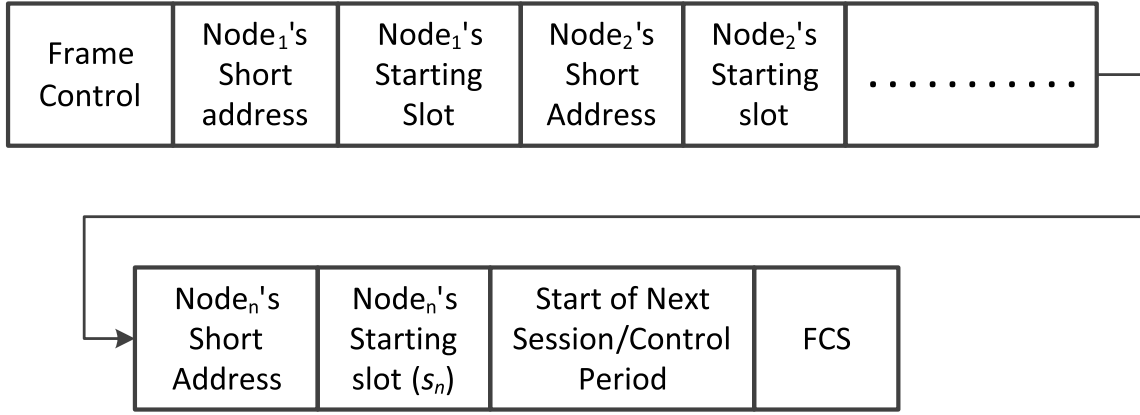
1. All the requesting nodes are placed in ascending order on the basis of their requested slots. i.e nodes requesting less slots are treated first as compared to nodes requesting more slots. E.g if five nodes  $a, b, c, d$  and  $e$  request for 3,4,2,1 and 1 data slots, respectively, then they are ordered as  $d, e, c, a$  and  $b$ . In case, if two or more nodes have requested for the same number of data slots, then priority will be given to the node with small short address as of other nodes.



**Figure 4.4:** Data transmission process during steady state phase.



#### 4.4.3. Knapsack Optimization Algorithm



**Figure 4.5:** ADS\_ANN Message Format.

```

 $w \leftarrow \text{Current slot};$ 
 $W \leftarrow \text{Max. no. of slots};$ 
 $i \leftarrow \text{Node ID};$ 
 $n \leftarrow \text{Max. no. of nodes};$ 
 $B[i, w] \leftarrow \text{Cell value of } i^{\text{th}} \text{ node with } w \text{ slot};$ 
 $w_i \leftarrow \text{No. of slots required or requested by } i^{\text{th}} \text{ node};$ 

for  $w = 0$  to  $W$  do
    |  $B[0, w] = 0$  // Initialize 1st row to 0's;
end

for  $i = 1$  to  $n$  do
    |  $B[i, 0] = 0$  // Initialize 1st column to 0's;
end

for  $i = 1$  to  $n$  do
    | for  $w = 0$  to  $W$  do
        | if  $w_i \leq w$  then
            | if  $w_i + B[i - 1, w - w_i] > B[i - 1, w]$  then
                | |  $B[i, w] = w_i + B[i - 1, w - w_i]$ 
            | end
            |  $B[i, w] = B[i - 1, w]$ 
        | end
        |  $B[i, w] = B[i - 1, w]$ 
    | end
end

```

**Algorithm 1:** BEST-MAC Algorithm: KnapSack table implementation

```

Initialize  $i$  and  $w$ ::
 $n \leftarrow i$ ;
 $W \leftarrow w$ ;

while  $i > 1$  and  $w > 1$  do
    if  $B[i, w] > B[i - 1, w]$  then
         $i^{th}$  node is included in optimized solution;
         $i = i - 1$ ;
         $w = w - w_i$ ;
    else
         $i = i - 1$ 
    end
end

```

**Algorithm 2:** Optimized Node Selection

2. Weights and values of each node will be same as of its required slots. e.g., value of nodes  $a, b, c, d$  and  $e$  will be 3, 4, 2, 1 and 1, respectively.

In knapsack algorithm, we select maximum number of nodes with maximum slots utilization. The selected nodes are required to transmit their data at once instead of Round Robin that require more than one time slot for data transmission in which source node/s has/have to wait for longer time to send their data to CH, as described in BMA-RR [33]. In addition to the increased delay, the source node(s) also consume extra energy by toggling their radios between Off and On states. On the other hand, the knapsack optimization saves energy by avoiding this radio toggling. Furthermore, average data transmission time (the average total duration between start and end of data transmission) of source nodes is faster than Round Robin and more number of nodes can complete their data transmission as compared to BMA-RR in a session.

#### 4.4.4 Slot Duration

Previous TDMA based schemes allocate fixed length data slot to source nodes and each data slot is of longer time duration. For efficient use of time slots, the slot duration is kept

#### 4.4.4. Slot Duration

---

**Table 4.1:** Filling of knapsack table

<div>Slot Size Node</div>	0	1	2	3	4	5
D	0	1	1	1	1	1
E	0	1	2	2	2	2
C	0	1	2	3	4	4
A	0	1	2	3	4	5
B	0	1	2	3	4	5

smaller as compared to traditional TDMA based schemes. In BEST\_MAC, each data slot is a simple multiple of control slot. Shorter times slots will be helpful in order to minimize unused time slots portion and consequently helps in minimizing unnecessary wait duration for other source nodes. Table 4.2 shows comparison between BMA-RR and our proposed BEST\_MAC protocol in terms of excessive delay calculation when nodes want to generate random data. It also shows that by introducing shorter data slots, nodes save substantial time as compared to larger data slots used in BMA-RR. As CH has to keep its radio in the receiving state throughout these data slots, therefore, the smaller length of data slots save significant amount of energy, which further improves the throughput.

**Table 4.2:** Comparison of Data Transmission delay between proposed BEST-MAC and BMA-RR based MAC protocol

Node	Data Length (Bytes)	Data Rate (bps)	time to send data	bits/slot in BMA-RR	Slot length in BMA-RR MAC (msec)	Slots re-quired	Time required to send data in BMA-RR (msec)	bits/slot in pro-posed MAC	Slot length in proposed MAC (msec)	Slots re-quired in pro-posed MAC	Time Re-quired to send data in proposed MAC (msec)	time lapsed in BMA-RR (msec)	time lapsed in pro-posed MAC (msec)
A	200	24000	066.67	2000	83.33	1	083.33	48	2.00	34	68	16.67	1.33
B	350	24000	116.67	2000	83.33	2	166.67	48	2.00	59	118	50.00	1.33
C	450	24000	150.00	2000	83.33	2	166.67	48	2.00	75	150	16.67	0.00
D	580	24000	193.33	2000	83.33	3	250.00	48	2.00	97	194	56.67	0.67
E	680	24000	226.67	2000	83.33	3	250.00	48	2.00	114	228	23.33	1.33

### 4.4.5 Energy Consumption during SP

Total energy consumption during setup phase in  $N$  size cluster ( $E^{setup}$ ) is sum of energy consumed by CH and the nodes which are going to be associated member ( $N-1$ ) nodes. its associated ( $N - 1$ ) member nodes. Energy consumed by a CH comprises of energy consumption during *Active* and *Idle* states. ( $E_{ch}^{SP-Active}$ ) is the energy consumed by a CH in active mode during setup phase and is calculated as:

$$E_{ch}^{SP-Active} = P_{ch}^{AT} \times T_{AT} + P_{ch}^{JR} \times T_{JR} \times (N - 1) + P_{ch}^{CS} \times T_{CS} \quad (4.7)$$

where,  $P_{ch}^{AT}$ ,  $P_{ch}^{JR}$  and  $P_{ch}^{CS}$  are the power consumed by the CH for transmitting the CH\_ANN, receiving JOIN\_REQ and transmitting of CS\_ALLOC message to all member nodes, respectively. The  $T_{AT}$ ,  $T_{JR}$  and  $T_{CS}$  are the time required to send CH\_ANN, receive JOIN\_REQ and send CS\_ALLOC messages, respectively. In same state, the energy consumed by a member node  $m$ ,  $E_m^{SP-Active}$ , where  $m \in (N - 1)$ , is calculated as:

$$E_m^{SP-Active} = P_m^{AT} * T_{AT} + P_m^{JR} * T_{JR} + P_m^{CS} * T_{CS} \quad (4.8)$$

where,  $P_m^{AT}$ ,  $P_m^{JR}$  and  $P_m^{CS}$  are the power consumed by a member node for receiving CH\_ANN, sending JOIN\_REQ and receiving CS\_ALLOC messages, respectively.

There are  $N - 1$  member nodes in a cluster and energy consumed by all member nodes in active mode, ( $E_{am}^{SP-Active}$ ), is computed as in eq.(4.9).

$$E_{am}^{SP-Active} = \sum_{i=1}^{i=(N-1)} E_i \quad (4.9)$$

During SP, some of the energy also consumed when CH and member nodes are in idle listening mode. If  $P_{ch}^{SP-Idle}$  is the power consumed by CH during idle state as it has to keep its receiver ON in order to receive member node's JOIN\_REQ messages and  $T_{ch}^{SP-Idle}$  is the time for idle period, then total energy consumed by CH during idle period in SP ( $E_{ch}^{SP-Idle}$ ) is calculated as:

$$E_{ch}^{SP-Idle} = P_{ch}^{idle} * T_{ch}^{SP-Idle} \quad (4.10)$$

All member nodes after sending JOIN\_REQ messages keep their radios ON and wait

#### 4.4.6. Energy Consumption during SSP

to receive CH's CS\_ALLOC message. Member nodes in idle mode also wait to receive CH\_ANN message from CH in the beginning of the SP, as shown in Fig.4.3. If a member node  $m$  consumes  $P_m^{SP-Idle}$  power and has  $T_m^{SP-Idle}$  idle listening period, then the overall energy consumption of a member node  $m$  during idle listening period in SP,  $E_m^{SP-Idle}$ , is computed as:

$$E_m^{SP-Idle} = P_m^{SP-Idle} * T_m^{SP-Idle} \quad (4.11)$$

Total energy consumed by  $N - 1$  member nodes during idle mode in SP ( $E_{am}^{SP-Idle}$ ) is calculated as:

$$E_{am}^{SP-Idle} = \sum_{i=1}^{i=(N-1)} E_i^{SP-Idle} \quad (4.12)$$

Total energy consumption in a cluster during setup phase,  $E^{setup}$ , is computed as in eq.(4.13):

$$E^{Setup} = E_{ch}^{SP-Active} + E_{am}^{SP-Active} + E_{ch}^{SP-Idle} + E_{am}^{SP-Idle} \quad (4.13)$$

#### 4.4.6 Energy Consumption during SSP

In a round, there is one SP and one SSP. A SSP comprises of multiple sessions and each session starts with control period followed by data slot allocation period and dedicated data slots for communication. In session  $j$ , source node(s) send their data request(s), DATA\_REQ message(s), during their allocated control slot, whereas all the other nodes keep their radios off to save energy. Energy consumed by a source node  $s$  during control period in session  $j$ , ( $E_s^{CP_j}$ ), is calculated as:

$$E_s^{CP_j} = P_s^{CP_j} * T_s \quad (4.14)$$

where,  $P_s^{CP_j}$  is power consumed during transmitting DATA\_REQ message and  $T_s$  is the control slot duration in session  $j$ .

CH in that control slot period always remains in receiving mode to receive DATA\_REQ messages. If there are  $x$  number of source nodes, then the energy consumption during

complete control period ( $E^{CP_j}$ ) is computed as:

$$E^{CP_j} = E_s^{CP_j} \times x + (N - 1 - x) \times P_{ch}^{CP-Idle_j} \times T_s + x \times P_{ch}^{CP-Rx_j} \times T_s \quad (4.15)$$

Here,  $P_{ch}^{CP-Idle_j}$ , is power consumed by CH during idle listening in the control period and  $P_{ch}^{CP-Rx_j}$  is power consumed in receiving DATA\_REQ message during control period by CH.

Control period is followed by contention access period in which those nodes who are in the range of CH and wants to become member send their JOIN\_REQ to CH during this period and CH response with an acknowledgment confirming that request has been successfully received. Energy consumed by CH in session  $j$  during CAP is calculated as:

$$E_{ch}^{CAP_j} = P_{ch}^{JR_j} \times T_{JR} + P_{ch}^{ACK_j} \times T_{ack} + P_{ch}^{CAP_{idle_j}} \times T_{ch}^{CAP_{idle}} \quad (4.16)$$

Here,  $P_{ch}^{JR}$ ,  $P_{ch}^{ACK}$  and  $P_{ch}^{idle}$  are the power consumed in receiving JOIN\_REQ, sending acknowledgment and during idle state respectively. where as  $T_{ack}$  and  $T_{idle}$  are time required to send acknowledgment and idle time of CAP during CAP respectively.

If  $P_{nm}^{JR_j}$ ,  $P_{nm}^{ACK_j}$  and  $P_{nm}^{CAP_{idle_j}}$  are power consumed in sending JOIN\_REQ message, receiving acknowledgment message and power consumed in waiting for acknowledgment messages during session  $j$ , then Energy consumed by a non member node ( $E_{nm}^{CAP_j}$ ) during  $j$  session of CAP is calculated as:

$$E_{nm}^{CAP_j} = P_{nm}^{JR_j} \times T_{JR} + P_{nm}^{ACK_j} \times T_{ACK} + P_{nm}^{CAP_{idle_j}} \times T_{nm}^{CAP_{idle}} \quad (4.17)$$

Here,  $T_{nm}^{CAP_{idle}}$  is the time when non member node remains in idle state.

If there are  $d$  nodes send their request to become a part of this network then total energy consumed during CAP in  $j$  session ( $E^{CAP_j}$ ) is calculated as:

$$E^{CAP_j} = \sum_{i=1}^{i=(d)} E_{nm}^{CAP_j} + E_{ch}^{CAP_j} \quad (4.18)$$

Contention access period is followed by data slots allocation period in which CH announces data slots allocation information to all member nodes, ADS\_ANN message in the cluster along with starting of next control period. Total energy consumed during data slots allocation period in session  $j$ , ( $E^{ADS_j}$ ), is calculated as:

$$E^{ADS_j} = P_{ch}^{ADS_j} \times T^{ADS_j} + \sum_{i=1}^{i=(N-1)} P_i^{ADS-Rx_j} \times T^{ADS_j} \quad (4.19)$$

where,  $P_{ch}^{ADS_j}$  is power consumed by a CH in transmitting ADS\_ANN message,  $P_i^{DSA-Rx}$  is power consumed by node  $i$  to receive that message, and  $T^{ADS_j}$  denotes the time required to send and receive ADS\_ANN message during session  $j$ .

Next, we calculate the energy consumed by all source nodes to transmit data in session  $j$ , if out of  $x$  nodes,  $y$  nodes have been successfully allocated time slots then  $E_{SN}^{DT_j}$  is determined as:

$$E_{SN}^{DT_j} = \sum_{i=1}^{i=y} P_i^{DT_j} * k * T^{CS} \quad (4.20)$$

here,  $k$  are number of data slots and  $P_i^{DT_j}$  is power consumed in transmitting data by source node  $i$  in session  $j$ .

Energy consumed by a CH in receiving all data packets, ( $E_{ch}^{DT_j}$ ), from source nodes during same session is computed as:

$$E_{ch}^{DT_j} = P_{ch}^{DR_j} * k * T^{DS} \quad (4.21)$$

where  $P_{ch}^{DR_j}$  is power consumed by CH in receiving data packets from all source nodes during session  $j$ . Therefore, the overall energy consumption during session  $j$ ,  $E_j^{Steady}$ , is:

$$E_j^{Steady} = E_{CP_j} + E^{ADS_j} + E^{CAP_j} + E^{DT_j} + E_{ch}^{DT_j} \quad (4.22)$$

If there are  $n$  steady state sessions in a round, then the total energy consumed during SSP( $E^{Steady}$ ) is:

$$E^{Steady} = \sum_{j=1}^n E_j^{Steady} \quad (4.23)$$

Total energy consumed in round of a cluster ( $E_{total}$ ) is sum of energy consumed in SP as well as in SSP and is computed as:

$$E_{total} = E^{Setup} + E^{Steady} \quad (4.24)$$



**Table 4.3:** Simulation Parameters

Parameters	BEST-MAC	BMA-RR	E-TDMA
Data rate (bps)	24000	24000	24000
control Packet Size (bits)	48	144	1
Control Slot Length (sec)	0.002	0.006	0.00004166
Data Slot Length (sec)	0.002	0.083	0.083
Transmitting Energy (nJ)	50	50	50
Receiving Energy (nJ)	50	50	50
Idle Energy (nJ)	5	5	5

## 4.5 Simulation Analysis

This section discusses the simulation analysis of our proposed BEST-MAC protocol in contrast with conventional scheme such as E-TDMA [35] and BMA-RR [33]. As we discussed that our proposed BEST-MAC protocol improves throughput, minimizes delay and increases energy efficiency of the whole network. To evaluate and validate the effectiveness of the proposed BEST-MAC protocol, we compared throughput, energy efficiency and delay with E-TDMA and BMA-RR in respect of varying probability and number of sessions. During simulations, we considered a different size network, off which one node acts as CH and rest as member nodes. These nodes are deployed in an area of  $100 \times 100$  meters. Probability  $P$  is set on the basis of nodes having data requests, that is, if  $P = 0.1$ , then only 10% member nodes are allowed to send data. Random data traffic is generated by source nodes within the range of 175 Bytes to 2.85 KB.

Rest of the simulation parameters are shown in Table 4.3.

### 4.5.1 Transmitted Data

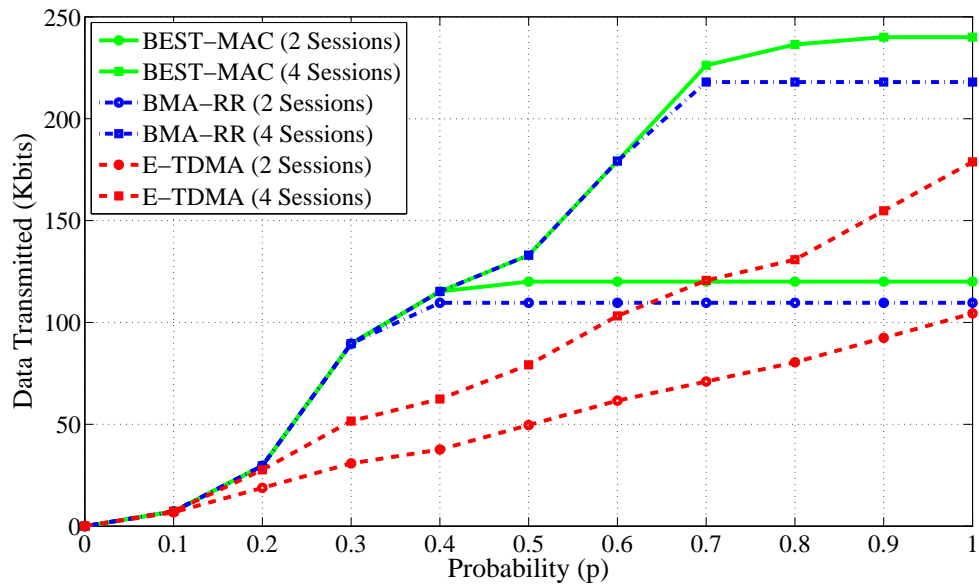
The transmitted data is calculated as the amount of data successfully sent from source to the destination node. Figure 4.6 and 4.7 show the transmitted data for varying probability

( $P$ ) and sessions, respectively. It is evident from the results that BEST-MAC transmits more data as compared to E-TDMA and BMA-RR. In Fig. 4.6, probability of source nodes are increased for 2 and 4 session, the results show that, BEST-MAC transmits more data as of the other two MAC protocols when number of source nodes increases in both scenarios. It has been observed that BEST-MAC is unable to transmit more data, when  $P$  increases from 0.4 and 0.9 for 2 and 4 sessions, respectively. This is because, all of its data slots are already occupied. In Fig. 4.7, performance of MAC protocols is determined for varying sessions with  $P = 0.4$  and  $P = 0.6$ . This helps in analyzing BEST-MAC performance when amount of data required to send is less than the available number of data slots. It is obvious from the results, BEST-MAC sends the required data prior to other two MAC protocols. Results further show that BEST-MAC transmits more data as of the other two MAC protocols during first 2 and 3 sessions for  $P = 0.4$  and  $P = 0.6$  respectively. However, when session increases from 3 and 4 for 0.4 and 0.6 probabilities, then BMA-RR and BEST-MAC are unable to transmit further data. This is because of source nodes have already sent their data, where as ETDMA keeps on transmitting its data as it is unable to transmit the same amount of data even in 6 sessions. It is evident from the results that BEST-MAC perform better in transmitting more data as of other two protocols in each network size.

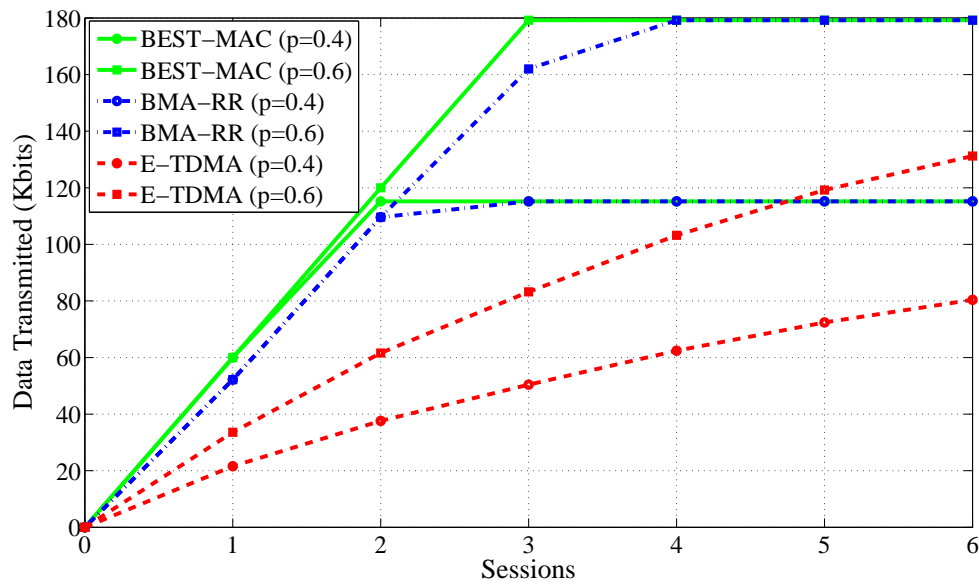
It is noticed that average improvement in transmitted data by BEST-MAC is 10.1% and 34.2% for 2 sessions and 9.5% and 15% for 4 sessions as compared to BMA-RR and ETDMA respectively, refer Fig. 4.6. This significant improvement in transmitted data by BEST-MAC is due to the selection of smaller data slots and implementing knapsack optimization technique, which increase the link utilizations by accommodating different data requirements effectively. Whereas, in other two conventional TDMA based MAC protocols, larger data slots are used that cannot accommodate adaptive data traffic requirements efficiently.

#### 4.5.2 Total Energy Consumption

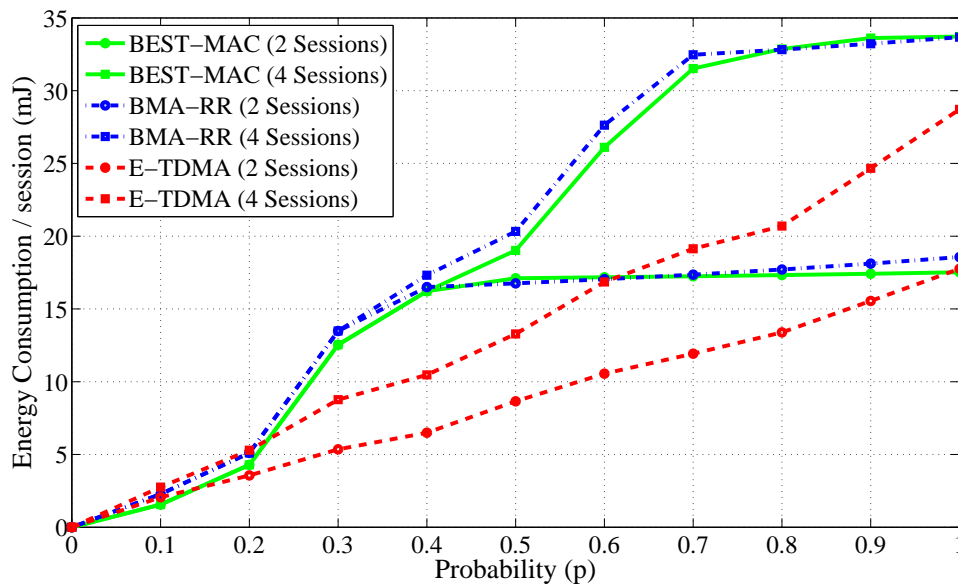
Energy consumption of sensor nodes effects the life cycle of a WSN. Total energy consumption versus probability and sessions are shown in Fig. 4.8 and 4.9, respectively. Figure 4.8 shows, that, when probability approaches to 0.3 and 0.6 for 2 and 4 sessions, BEST-MAC consumes less amount of energy as of BMA-RR while transmitting same data



**Figure 4.6:** Transmitted data versus Probability ( $P$ ) for 2 and 4 Sessions.



**Figure 4.7:** Transmitted data versus Session for  $P = 0.4$  and  $0.6$ .

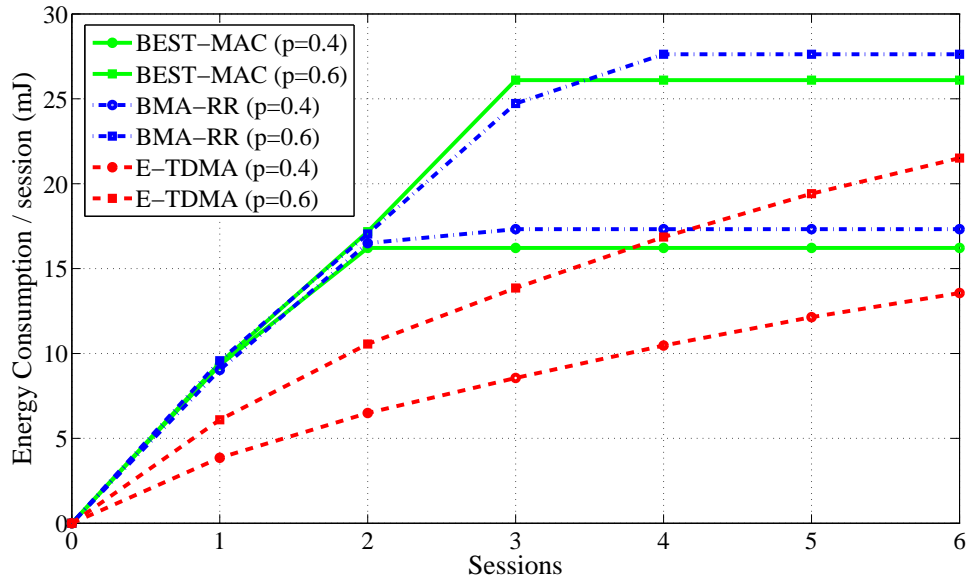


**Figure 4.8:** Energy consumption of the network versus  $P$  for 2 and 4 Sessions.

traffic. At  $P = 0.4$  and  $P = 0.7$  for 2 and 4 sessions, the energy consumption of both BEST-MAC and BMA-RR are almost same. This is due to the fact that at this stage BEST-MAC transmitted more data as of BMA-RR. However, energy consumption of ETDMA is less than other two, This is because of transmitting less amount of data as compared to the other two MAC protocols. The similar behavior is also observed in Fig. 4.9. Here, BEST-MAC conserve more than 5% energy while transmitting same amount of data as of BMA-RR. However ETDMA follows the same trend as it consumes less amount of energy than the other two protocols because of transmitting less amount of data.

### 4.5.3 Transmission Delay

Transmission delay of a node is calculated from the time when node has a data request till the time it sends all of its data to the destination successfully. Figure 4.10 and 4.11 show the transmission delay versus  $P$  and session, respectively. It is obvious from the results, that BEST-MAC has significantly less transmission delay as of BMA-RR and E-TDMA. This is due to the implication of knapsack algorithm, which helps in allowing more nodes to transmit their data at once instead of transmitting in parts. This results in avoiding more nodes to keep data in their buffer for longer time, as described in section 4.4.3. Smaller



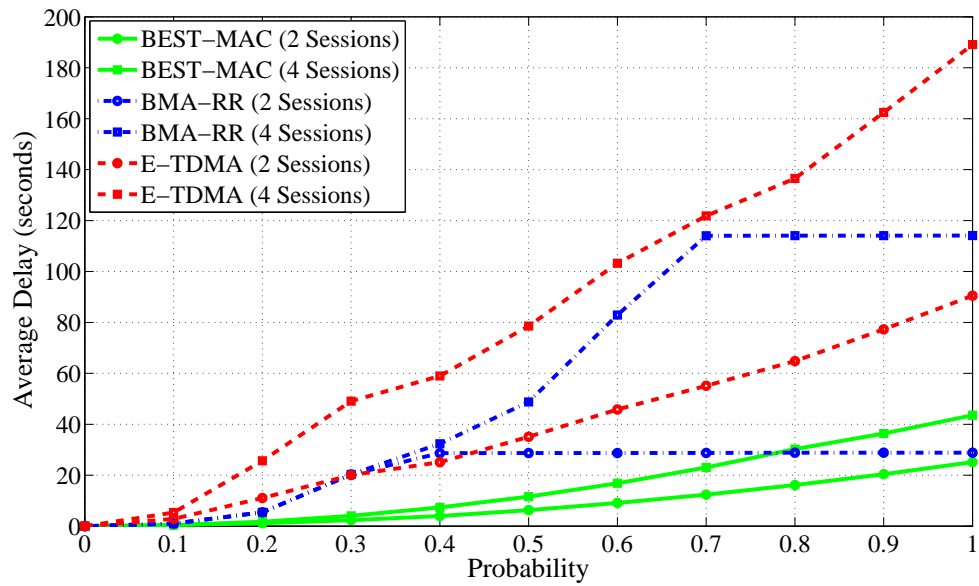
**Figure 4.9:** Energy consumption of the network versus sessions for  $P = 0.4$  and  $0.6$ .

slot length further helps in improvement of the network delay, as shown in Table 4.2.

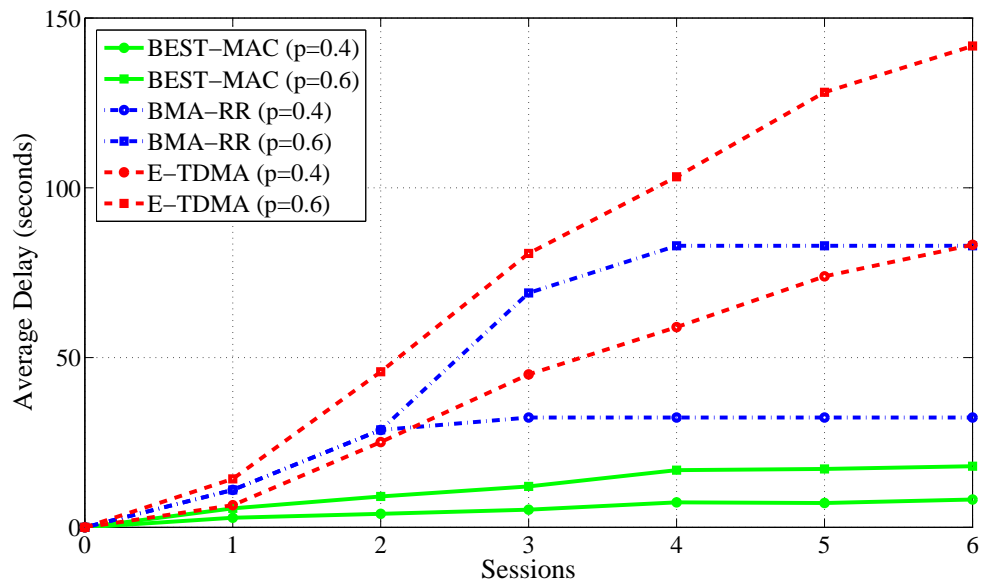
The results in Fig. 4.10 show that average transmission delay of the network is minimized by BEST-MAC upto 57% and 77% for 2 sessions and 73% and 81% for 4 session, compared to BMA-RR and E-TDMA, respectively. Same pattern is also observed for varying sessions as shown in Fig. 4.11.

## 4.6 Conclusion

In this work, we proposed TDMA based MAC protocol, called *BEST – MAC*, that adaptively handles the varying amount of data traffic by using large number of small size data slots. In addition, it implements Knapsack optimization technique for better link utilization as well as, to reduce node’s job completion time that results in significant improvement in average packet delay of nodes. Energy consumption is also minimized by reducing the control overhead by introducing a unique 1 byte short address to identify the member nodes. The performance of the proposed BEST-MAC protocol is compared with the BMA-RR and E-TDMA through simulations. It shows that BEST-MAC achieves more than 70% and 80% efficiency in data transmission delay and more than 7% and 17% data is tran-



**Figure 4.10:** Transmission Delay of the network versus  $P$  for 2 and 4 Sessions.



**Figure 4.11:** Transmission Delay of the network versus sessions for  $P = 0.4$  and  $0.6$ .

#### **4.6. Conclusion**

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mitted compared to BMA-RR and E-TDMA without compromising energy consumption.

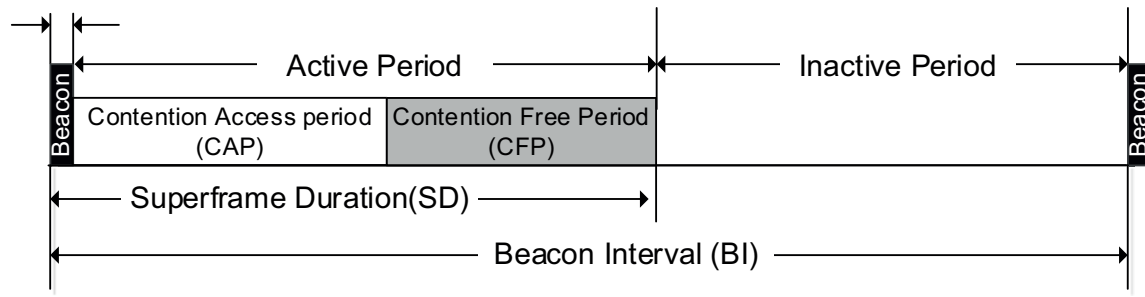
# **Improved superframe structure of IEEE 802.15.4 standard with Minimum Delay and Maximum CFP Link Utilization for WSNs**

## **5.1 Introduction**

Wireless Sensor Networks (WSNs) have been main focus of global research community due to its wide range of applications. The major application areas of WSN include health-care, military, environmental monitoring, civil engineering, etc. [51]. WSN comprises standalone, autonomous and tiny battery operated wireless nodes with limited energy, computation, processing and communication capabilities. These constraints led the emergence of new physical and Medium Access Control (MAC) stack named IEEE 802.15.4 because the existing communications stacks i.e. IEEE 802.11 and 802.16, were not designed to function under these constraints. IEEE 802.15.4 standard was designed for Low Rate Wireless Personal Area Network (LR-WPAN) applications where low data rate, higher reliability with less power consumption is required [52]. The standard is suitable for fixed as well as for low cost mobile wireless nodes with limited battery power with high reliability [53].

In most of the applications the sensor nodes are intended to operate autonomously on





**Figure 5.1:** 802.15.4 Beacon enabled mode Superframe format.

the battery, therefore, the WSN protocols should be energy efficient to prolong the node's life-time. The large proportion of battery consumption is due to communication (transmission and reception) over wireless radio component in the node. The MAC protocol is responsible to control the radio transceiver and in 802.15.4, MAC layer keeps sensor nodes in sleep state for more than 99% (0.1% duty cycle).

IEEE 802.15.4 operates at three different frequency bands such as 868MHz, 915MHz and 2.4GHz and works either in a *Beacon* enabled or *Non-Beacon* enabled mode. The Beacon enabled mode is divided into two main sections, *active* and *inactive* period, as shown in Fig. 5.1. All WSN nodes communicate during active period and remain in sleep mode during later inactive period to conserve energy. The active period of Beacon enabled mode consists of Contention Access Period (CAP) and optional Contention Free Period (CFP). Each Superframe in this mode is divided in to 16 equal duration time slots. One or more slots are reserved for the Beacon frame because its size may vary due to number of remaining data frames for the associated nodes. The Beacon frame is generated by the PAN coordinator and contains information about frame structure, next Beacon, network, and pending messages.

The CAP consists of maximum 16 or minimum 9 slots. In CAP, nodes contend to access medium by following the slotted CSMA/CA mechanism [54]. On the other hand, the maximum number of slots in CFP can be up to 7 and are know as Guaranteed Time Slots (GTS). Nodes having critical data requests are allocated Guaranteed Time Slot (GTS) by the coordinator. The nodes that are allocated GTS can explicitly carry out communication during their allocated period to the PAN coordinator. All research related to maximize the throughput and reduce communication delay of the traffic in CFP consider the above

### 5.1.1. Major Contributions

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mentioned scenario mentioned in the 802.15.4. standard [52]. However, this standard has some limitations for GTS allocations.

1. The cumulative delay from GTS allocation till transferring of data causes a significant delay, which is in appropriate for time sensitive WSN applications.
2. Due to limited number of CAP time slots maximum 7 nodes can be allocated GTS.

In this work, we propose an efficient superframe structure for 802.15.4 that is backward compatible with the original standard and compared it with the current superframe structure. This new superframe structure significantly minimizes the delay and can assign GTS slots up to 14 nodes without compromising the CFP duration. The proposed Superframe structure is suitable to support communication within the medium size Personal Area Networks (PANs). The medium size PAN scenarios contain more than 7 nodes in the PAN. Examples of PAN scenarios include home automation, industrial monitoring, hospital storage or ward monitoring, structural monitoring, etc.

### 5.1.1 Major Contributions

The major contributions of our proposed MAC frame are as follows:

- An efficient super-frame structure where CFP precedes the CAP, which has never been proposed earlier.
- Delay of GTS traffic is minimized due to this superframe structure.
- GTS utilization has also been improved by reducing the CFP slot size to its half as of the original IEEE 802.15.4 standard. This also accommodates more number of GTS requesting nodes as compared to existing standard.
- Our proposed superframe format is fully compatible with the IEEE 802.15.4 standard.

Rest of the chapter is organized in the following manner: Section 5.2 highlights the previous work by different authors followed by the overview of IEEE 802.15.4 standard in section 5.3. Section 5.4 briefly discusses the proposed Superframe format along with the

necessary modifications in the Beacon frame fields. The numerical estimators for delay and link utilization for the proposed Superframe format are also presented in this section. Numerical results of our proposed scheme are compared with the original IEEE 802.15.4 Beacon enabled mode in Section 5.5. In last, Section 5.6 concludes the chapter.

## 5.2 Related Work

The performance analysis of IEEE 802.15.4 standard in different prospects is under many research studies. These research studies include performance of CAP as well as CFP. Some interesting algorithms have also been proposed by different researchers to improve the efficiency in terms of power consumption, better link utilization and delay minimization. Valero et al. [59] propose an incrementally deployable energy efficient scheme based on IEEE 802.15.4 standard for better energy conservation. In [40], Li et al. introduce a novel approach by utilizing a synchronous low power listening technique in order to minimize power consumption. In [60], Kajima and Harada address the power wastage issue in Superframe structure due to periodic transmission and introduce a turn off beacon employment. In it, authors optimize the allocated active period by proposing a dynamic re-association procedure for energy conservation.

The standard is widely used in health care systems where Quality of Service (QoS) is to minimize the delay for emergency messages. In [61] [62] [63], authors address the delay minimization problems by proposing different ideas during CAP, whereas improvement in GTS mechanism are proposed in [58] [38] [64]. Kobayashi and Sugiyura [61] optimize traditional CSMA/CA mechanism and propose a timing group division method for faster communication by minimizing delays. Khan et al. [62] exhibits QoS improvement in IEEE 802.15.4 standard in terms of decrease in latency. These developments are achieved by adopting an improved Binary Exponential Backoff algorithm, which avoids collision. In [63], a backoff control mechanism is introduced for cluster based WSN. Authors claim that, the scheme not only minimize the delay but also improves the throughput of the system.

Chen et al. [58] introduces Explicit GTS Sharing and Allocation Scheme (EGSA) for real time communication applications, where tighter delay bounds are required. A multi-hop communication scheme in GTS mechanism of IEEE 802.15.4 standard is proposed

in [37], which follows superframe structure and claim for decrease in delay and better packet delivery ratio as of the standard. An Unbalanced GTS Allocation Scheme (UGAS) is proposed in [38]. In this scheme, Link utilization is increased by introducing different duration time slots for different bandwidth requirements. Authors claim that UGAS improves the bandwidth utilization by 30% as of the standard. Feng Xia et al [39] propose Adaptive and Real-Time GTS Allocation Scheme (ART-GAS) for such applications, where time sensitive and high-traffic is required and compatible with IEEE 802.15.4 standard. Authors claim that proposed scheme increases the bandwidth utilization as of the standard. In [64], authors develop an admission control and scheduling algorithm for body area network and claim for 100% compliance in time constraints.

Many solutions have been proposed to efficiently allocate GTS slots to the requesting nodes [55] [56]. These schemes try to improve QoS in LR-WPANs by minimizing delay, increasing throughput and allocating CFP slots to more number of nodes than the predefined limit in the standard [57] [58]. However, most of the previous work follow the same superframe structure of 802.15.4 standard and just try to increase or shrink the size of GTS area or slots to optimize the GTS utilization. In result, those schemes fail to minimize the delay of GTS traffic due to intrinsic gap of CAP between Beacon and the CFP. Similarly, most of the schemes compromise the CFP duration to increase the GTS efficiency. In this work, we made the link utilization and delay comparison of our proposed superframe structure with the superframe structure of the current standard in multiple scenarios.

## 5.3 IEEE 802.15.4 standard overview

Institute of Electrical and Electronic Engineering (IEEE) finalized 802.15.4 standard for low rate, low power and low cost, wireless personal area network (Lo-WPAN). The standard operates in three different frequency bands such as 868MHz, 915MHz and 2400MHz. 868Mhz and 915MHz use BPSK modulation scheme, however 2400MHz use O-QPSK modulation scheme with data rates of 20Kbps, 40Kbps and 250Kbps respectively. These frequency bands with their respective data rates are shown in table 5.1. In each frequency band, standard offers non-beacon enabled mode and beacon enabled mode.

During non-beacon enabled mode, nodes follow unslotted CSMA/CA mechanism in order to access the channel, however superframe structure is introduced I beacon enabled

**Table 5.1:** Frequency Bands with Data Rate

Frequency Band (MHz)	Modulation Scheme	Symbols / sec	Bits / symbol	Symbol Duration (sec)	Data rate (bits/sec)
868 - 868.6	BPSK	20000	1	50*e-6	20000
902 - 928	BPSK	40000	1	25*e-6	40000
2400 - 2483.5	O-QPSK	62500	4	16*e-6	250000

mode. Beacon enabled mode consists of active period and an optional in-active period. Active period also known as Superframe Duration (SD) comprise of 16 equal sized time slots. SD initiates with beacon frame generated by the coordinator followed by Contention Access Period (CAP) and optional Contention Free Period (CFP). Out of these 16 time slots, minimum 9 time slots are reserved for beacon frame and CAP and maximum 7 slots can be allocated for CFP.

Beacon frame is used for synchronization and possess the information of arrival of next beacon frame. Duration from start of current beacon frame till the arrival of next beacon is known as Beacon Interval and can be calculated by equation 5.1.

$$BI' = 960 \times 2^{SO} \quad (5.1)$$

During CAP, all nodes contend to access the medium by following slotted CSMA/CA mechanism in order to send their request to the coordinator. During CFP, TDMA based Guaranteed Time Slots (GTS) are allocated to nodes for time sensitive data transmission. In this work, we focus on GTS allocation mechanism.

In IEEE 802.15.4 standard, nodes requiring certain bandwidth in order to transmit their data, send GTS request commands to coordinator during CAP. Coordinator upon receiving all these requests decides about the allocation of CFP slots to requesting nodes on first come first serve basis. If available CFP slots remain less than the requesting slots by a node then that CFP slots are not assigned to that node, contrary requested GTS are allocated to the requesting nodes. Coordinator take cares that, allocated GTS would not reduce the CAP length from *aMinCAPLength* value. Coordinator informs about successful slots allocation in the GTS descriptor field available in next beacon frame and nodes can

send their data by using these GTS in the following superframe.

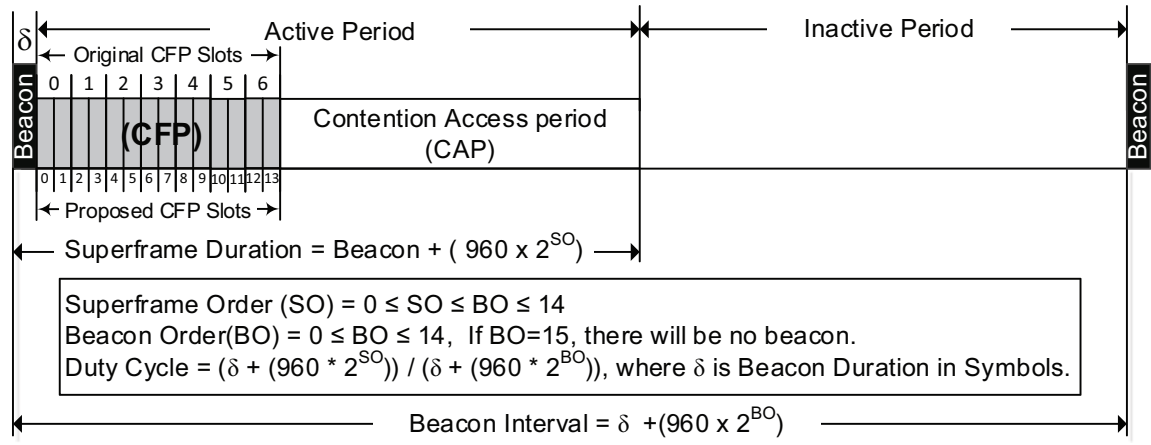
Delay of a node is calculated, when a node has a data to send till the time when it successfully transmit its information to the coordinator. A noticeable delay is observed, when a node generates GTS request till the allocation of its CFP slots. This delay in most of the cases longer than the Beacon Interval. This delay become more prominent when value of BO increases, which is not affordable for time critical applications. During a PAN, maximum 7 CFP slots can be allocated for GTS allocation, which are insufficient as PAN size increases. At the same time, these limited 7 slots are not efficiently utilized due to varying data traffic. The slot utilization inefficiency rises with the increase in slot size. These limitations in the existing standard regarding GTS allocation have been improved in this work.

## 5.4 Proposed MAC Protocol for WSN

In this section we discuss the novel MAC protocol for WSN. The *superframe* format of the proposed MAC protocol is shown in Fig. 5.2. It shows that the CFP starts immediately after Beacon frame and followed by the CAP. However, when there is no GTS request then CAP will commence right after Beacon frame. Though maximum duration of CFP in superframe is same as of IEEE 802.15.4 standard however maximum number of CFP slots have been extended to 14 equal slots instead of 7 maximum slots used in IEEE 802.15.4 standard. Each of the CFP slots is exactly one half duration of the CAP slot. The main advantage behind this scheme is to minimize unnecessary delay faced by nodes that communicate during GTS due to presence of CAP between Beacon and GTS. In addition, it further increases the efficiency in terms of throughput. To achieve this superframe format and compatibility with the existing 802.15.4 standard, we proposed some changes in parameters of the existing standard.

In our proposed scheme, superframe slots are of two durations, slot duration in CAP is same as computed by SO in the existing standard and CFP slot size is exactly one half of the CAP. The superframe contains minimum 9 CAP slots and maximum 14 CFP slots excluding the Beacon frame. This exclusion of Beacon frame will help without compromising the *aminCAPlength* parameter as the minimum CAP length will never be less than 540 Symbols. The superframe duration (SD) depends upon the value of superframe order

## 5.4. Proposed MAC Protocol for WSN



**Figure 5.2:** Proposed Superframe Format.

(SO), aNumSuperframeSlot (NSS) and aBaseSlotDuration (BSD) as:

$$SD = \delta + (NSS \times BSD \times 2^{SO}) \quad (5.2)$$

where, NSS = 16, SO ranges between 0 and Beacon Order (BO)  $0 \leq SO \leq BO$ . BSD in above expression is computed as:

$$BSD = 3 \times aUnitBackoffPeriod \quad (5.3)$$

Default value of *aUnitBackoffPeriod* is 20 Symbols. The Beacon Duration in symbols,  $\delta$ , in Eq. (5.2) is computed as:

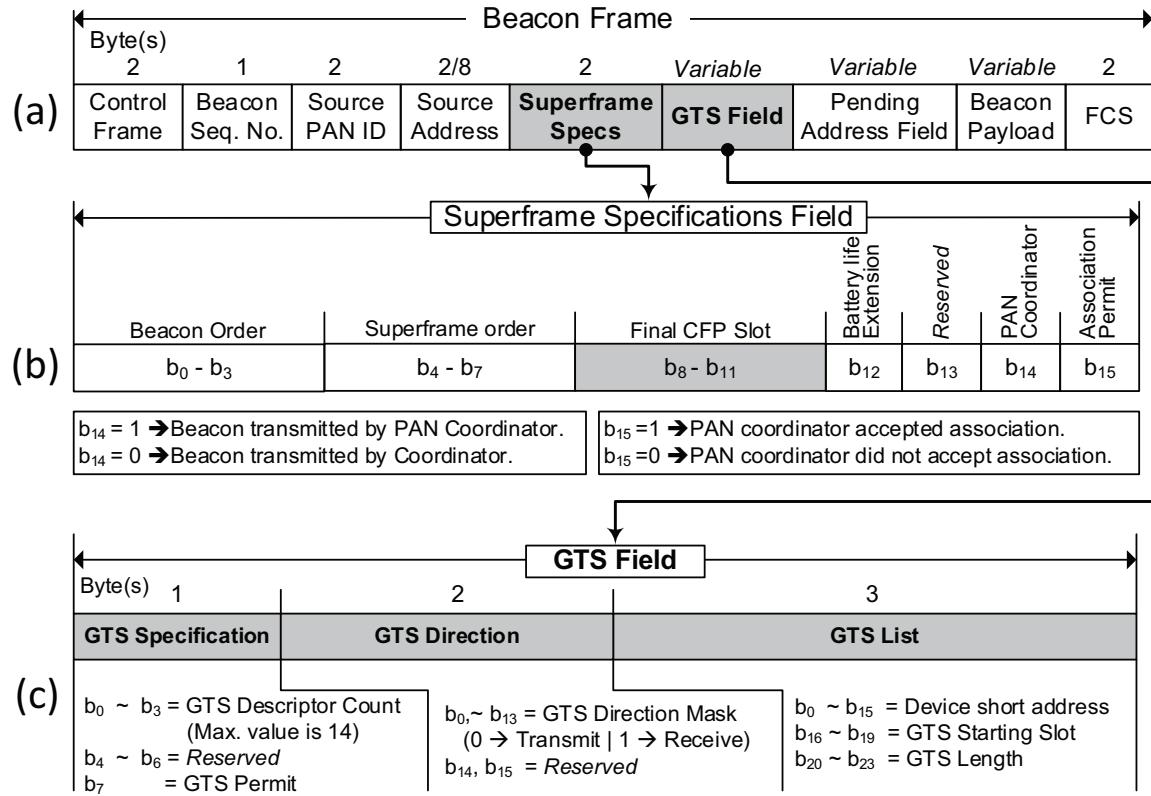
$$\delta = (m + 3 \times n) \times 2(\text{Symbols}) \quad (5.4)$$

$$BI = \delta + (NSS \times BSD \times 2^{BO}) \quad (5.5)$$

$$DC = SD/BI \quad (5.6)$$

Time duration of the next Beacon arrival ( $Beacon_{start}$ ) is calculated since the expiry of current Beacon and is computed by knowing the value of BO through following formula.

## 5.4. Proposed MAC Protocol for WSN



**Figure 5.3:** Proposed Superframe Format.

$$Beacon_{start} = NSS \times BSD \times 2^{BO} \quad (5.7)$$

Nodes compute the beginning of CAP ( $CAP_{Start}$ ) by multiplying each CFP slot duration with number of CFP slots ( $N_{CFP}$ ) mentioned in Final CAP Slot of Superframe Specification Field by following formula.

$$CAP_{Start} = 15 \times 2^{SO+1} \times N_{CFP} \quad (5.8)$$

To achieve the proposed Superframe format, the Beacon frame format along with the *Superframe Specification* and *GTS fields* has been modified and are shown in Fig. 5.3(a), 5.3(b) and 5.3(c), respectively.

Bits ( $b_8$  to  $b_{11}$ ) in *Superframe specification* field represent the *Final CFP Slot*, which indicate the start of the CAP. However, in the original 802.15.4 standard these bits express the *Final CAP Slot*. Similarly in GTS Filed, we extended the *GTS Direction* field to 2



### 5.4.1. Delay calculation

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bytes to augment 14 slots in CFP period. If  $N_{bps}$  is the number of bits can be transmitted during each CFP slot and  $D$  is the data required to be sent, then each GTS requesting node calculates the number of CFP slots  $N_{GTS}$  in order to send  $D$  bits of data in proposed scenario by following formula.

$$(N_{GTS}) = \left\lceil \frac{D}{N_{bps}} \right\rceil \quad (5.9)$$

Where,  $N_{bps}$  for 2400MHz is  $15 \times 2^{SO+3}$ .

### 5.4.1 Delay calculation

Transmission delay of a node is calculated when a node has data to send till the end of CFP slot where it successfully sends its data to PAN coordinator. A node  $i$  has data  $D_i$  just at the beginning of the Beacon frame, its time required to complete its transmission by the end of the allocated GTS is calculated as;

$$D_i = BI + \left( \sum_{b=1}^{b=i} K_b \times t_s \right) \quad (5.10)$$

Here,

$D_i$  = Time required to send data by node  $i$ ,

$K_b$  = Number of slots allocated to node  $i$  and its preceding nodes

$t_s$  = Duration in seconds of each CFP slot, which is a multiple of number of symbols per slot in proposed model ( $N_{spsp}$ ) and time required in seconds for each symbol ( $t_{es}$ ) as shown in equation 5.11.

$$t_s = N_{spsp} \times t_{es} \quad (5.11)$$

Here,

$$N_{spsp} = 15 \times 2^{SO+1}$$

$$t_{es} = 16 \times e^{-6}$$

If  $p$  nodes have been successfully assigned GTS then total delay of the network is calculated as

$$D_{p\_max} = \sum_{i=1}^{i=p} [BI_i + (\sum_{b=1}^{b=i} K_b \times t_s)] \quad (5.12)$$

However, in the current IEEE802.15.4 standard, Delay of a node  $i$  is calculated as

$$D_i = BI' + SD' - (\sum_{b=1}^{b=i} K_{b-1} \times t_o) \quad (5.13)$$

Here,

$$BI' = 960 \times 2^{BO}$$

$$SD' = 960 \times 2^{SO}$$

$t_o$  = Duration in seconds of each CFP slot, which is a multiple of number of symbols per slot in current standard ( $N_{spso}$ ) and time required in seconds for each symbol ( $t_{es}$ ) as shown in equation 5.14

$$t_o = N_{spso} \times t_{es} \quad (5.14)$$

where,  $N_{spso}$  for all frequency bands is  $15 \times 2^{SO+2}$ .

If  $p$  nodes have been successfully assigned GTS, then total delay of the network in current standard is calculated as

$$D_{o\_max} = \sum_{i=1}^{i=p} [(BI' + SD')_i - \sum_{b=1}^{b=i} K_{b-1} \times t_s'] \quad (5.15)$$

## 5.4.2 Link Utilization

It has been observed that significant amount of bandwidth is wasted during CFP. This wastage becomes more significant as CFP slot size increases. By increasing CFP slots will help in accommodate data in an efficient manner. If  $D_i$  data is required to be sent by node  $i$  then time required to transmit this data  $t_d$  to PAN coordinator is estimated as:

$$t_i = \frac{D_i}{C} \quad (5.16)$$

Here  $C$  is the data rate through which node communicate. If  $K_i$  is the number of CFP slots required to send  $D_i$  data, then it is computed as

$$K_i = \frac{D_i}{N_{bps}} \quad (5.17)$$

If a node  $i$  requires  $K_i$  slots in transmitting its data  $D_i$  to PAN-coordinator then link utilization ( $U_i$ ) for node  $i$  is calculated as:

$$U_i = \frac{t_i}{K_i \times t_s} \quad (5.18)$$

If  $p$  nodes are successfully allocated CFP slots, then the link utilization,  $U_{CFP}$ , for  $p$  nodes is computed as:

$$U_{CFP} = \sum_{i=1}^p \frac{t_i}{K_i \times t_s} \quad (5.19)$$

However, link utilization of same node  $i$  for current standard,  $U_{o_i}$ , is calculated as:

$$U_{o_i} = \frac{t_i}{K_o \times t_o} \quad (5.20)$$

here  $k_o$  is number of CFP slots required to send data during CFP in current standard. If  $q$  nodes have been successfully assigned CFP slots, then link utilization  $U_{CFP_o}$  during a specific BI is calculated as:

$$U_{CFP_o} = \sum_{i=1}^q \frac{t_i}{K_o \times t_o} \quad (5.21)$$

## 5.5 Numerical Analysis and Discussion

In order to evaluate our proposed scheme with the existing standard, a simulation environment is created with multiple nodes with varying data traffic from 10 to 180 Bytes is considered. The effects of different values of BO and SO parameters on performance of CFP are analyzed. For better comparison of our proposed scheme with the original standard, we have analyzed our proposed Superframe structure in different prospects including delay calculations, link utilization and slot(s) allocation to GTS requesting nodes.

### 5.5.1 Delay Analysis

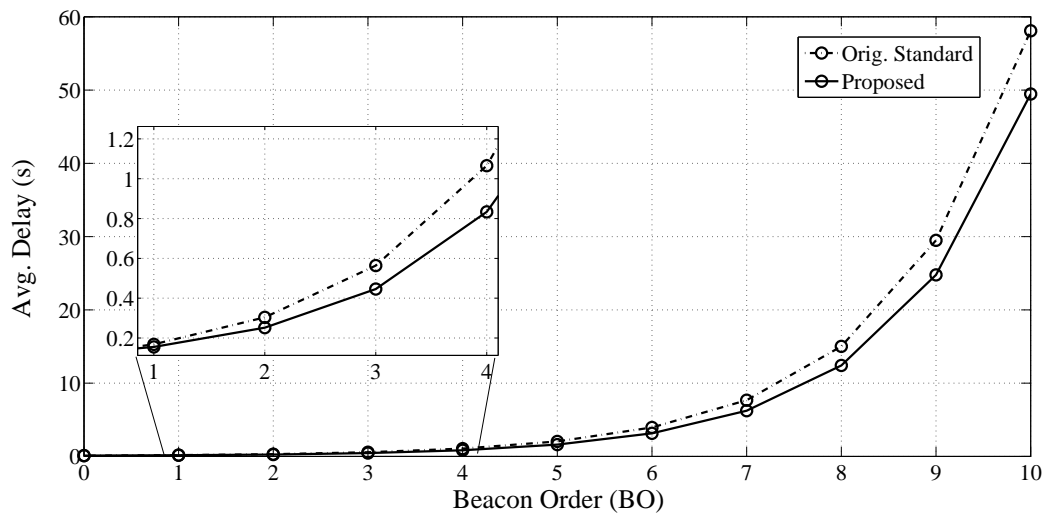
Figures 5.4, 5.5 and 5.6 show the average delay for 868MHz, 915MHz and 2400Mhz frequency bands respectively and is calculated for varying BO against all possible values of SO as follows:

$$\eta_{BO} = \frac{\sum_{SO=0}^{BO} D_{p,max_{SO}}}{BO} \text{ where } BO = 0..10 \quad (5.22)$$

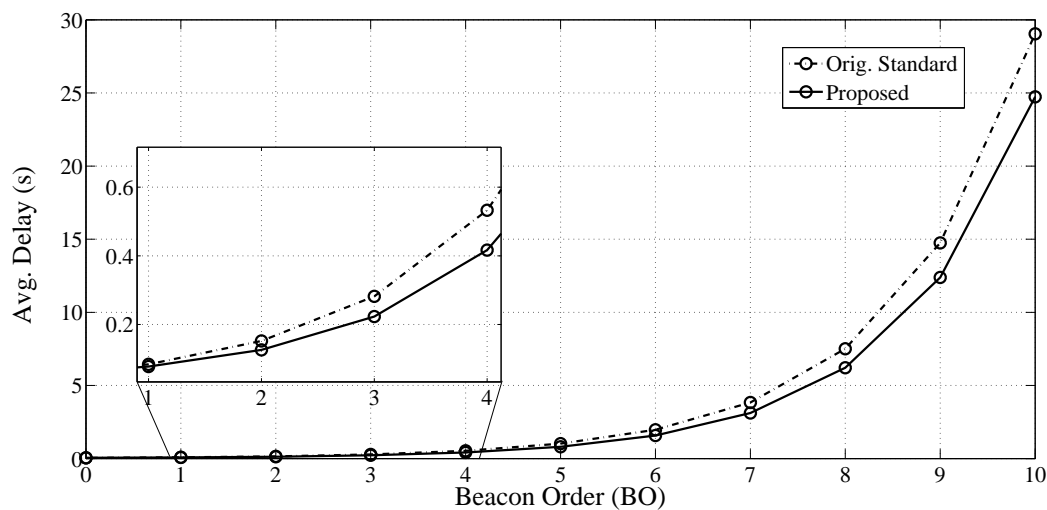
It is evident from the results that average delay rises with the increase in BO in current and proposed scenarios. It has also been observed from these results that the average delay increases gradually as frequency band decreases, however ratio of the delay between current and proposed schemes for all BO values remain almost similar.

The average delay is computed for the data packet of 125 bytes. Result shows that average delay of the network in proposed scheme is exceptionally better than the original standard. This improvement is only because node(s) do(es) not wait for the whole CAP period after successful assignment of the GTS in our proposed scheme. The detailed results of delay for fixed BO and varying SO are also analyzed. Figures 5.7, 5.8 and 5.9 show the delay for 868MHz, 915MHz and 2400MHz frequency bands, whereas each figure comprises of four parts as a,b,c and d and these sub figures are showing delay for varying values of SO and the fixed value of BO that is 10, 8, 6, and 4, respectively. It is obvious from this detailed delay analysis that our scheme has comparatively very less delay than the original standard in all three frequency bands.

Figures 5.10, 5.11 and 5.12 represent, how the delay has been reduced by calculating the difference between average delay of both the proposed and original standard for different values of BO ranges from 0 to 10. This average delay is calculated by summing up the delay for each SO value and then dividing it by the number of SO in that range. The difference between the delay experienced by the original standard and the proposed scheme is clearly evident from these figures. It has also been observed from the results that these differences in delay increase as BO range increases. This is due to the fact that larger value of BO causes increase in slot duration and consequently node/s has/have to wait for longer duration during CAP in the current standard, whereas the same is avoided in the proposed scheme by moving GTS immediately after beacon frame.



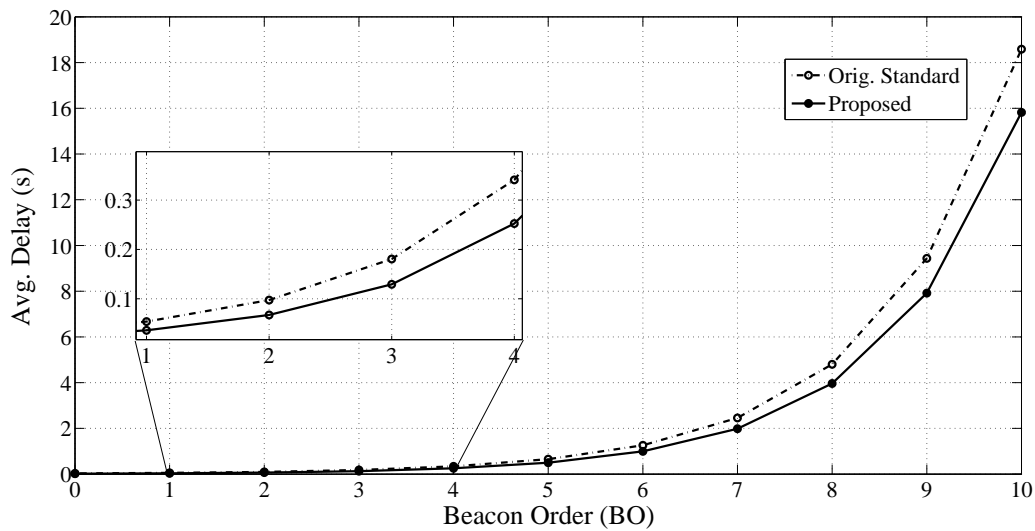
**Figure 5.4:** Average delay  $\eta_{BO}$  vs BO where  $0 \leq BO \leq 10$  and  $0 \leq SO \leq BO$  in 868MHz



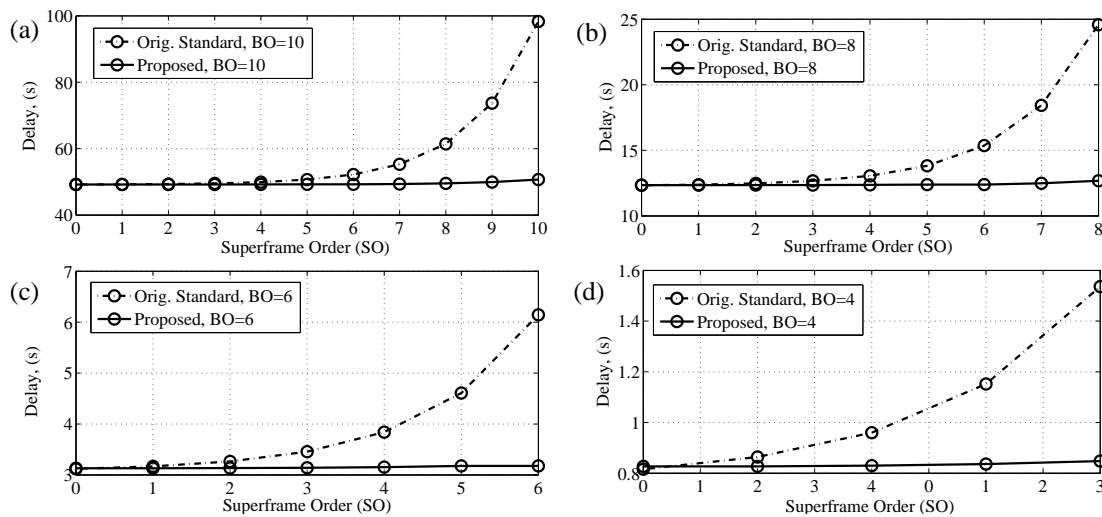
**Figure 5.5:** Average delay  $\eta_{BO}$  vs BO where  $0 \leq BO \leq 10$  and  $0 \leq SO \leq BO$  in 915MHz

## 5.5.2 Link Utilization

Link utilization is calculated by finding the total usage of available GTS space against total allocated GTS in the Superframe. Figures 5.13, 5.14 and 5.15 show the link utilization against varying data traffic for different values of SO for 868MHz, 915Mhz and 2400MHz frequency bands respectively. There are 14 nodes and their request data size varies from 10 to 180 bytes per node. The results show that link utilization improves in the proposed

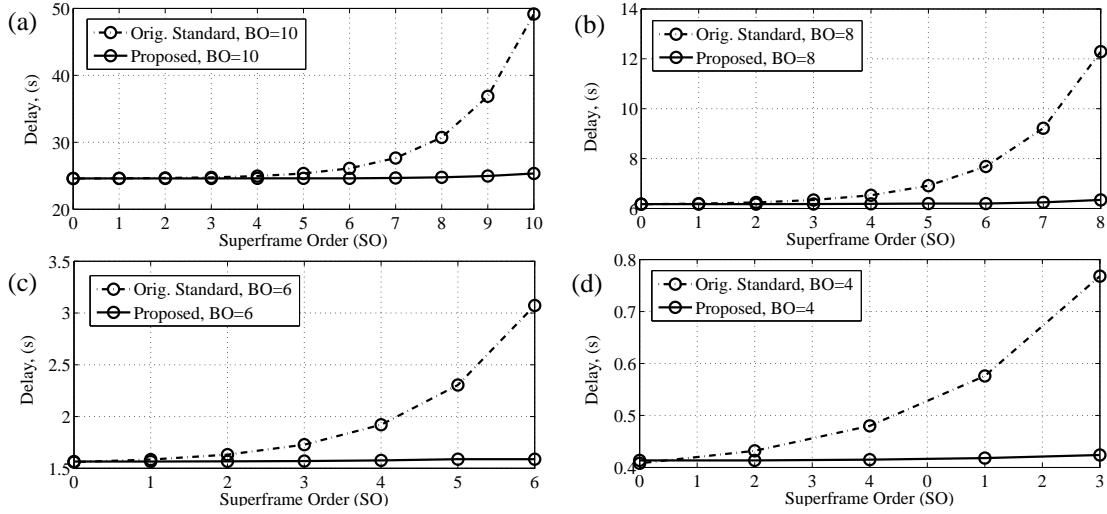


**Figure 5.6:** Average delay  $\eta_{BO}$  vs BO where  $0 \leq BO \leq 10$  and  $0 \leq SO \leq BO$  in 2400MHz

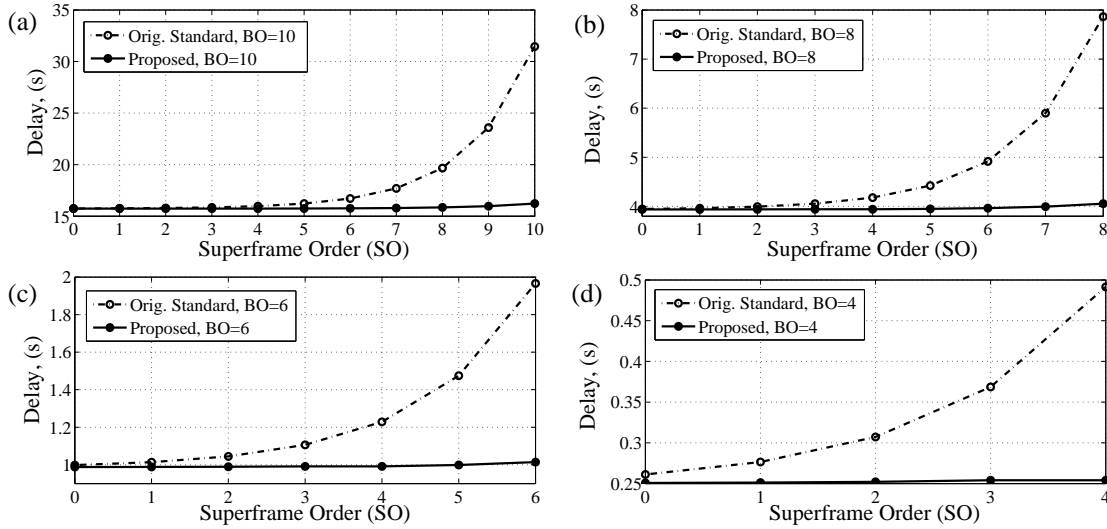


**Figure 5.7:** Average delay vs varying SO in 868MHz

standard for different values of SO. This increase in link utilization in the proposed scheme is due to the allocation of smaller time slots of CFP to each GTS requesting node, which avoids link wastage. It has been noticed that link utilization increases at an average of 6.9%, 6.4% and 29.3% for both 868MHz and 915MHz frequency bands and 6.5%, 29.3% and 100% for 2400MHz frequency band for SO of 0,2 and 4 respectively.



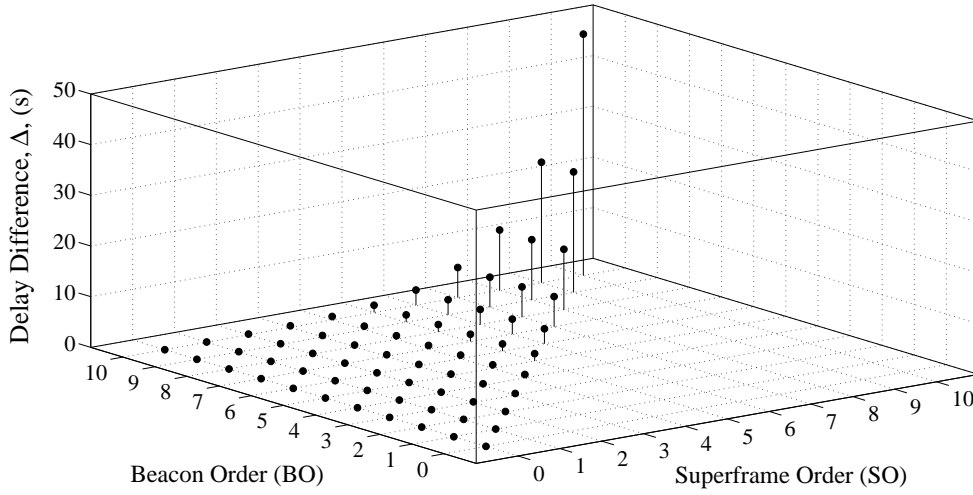
**Figure 5.8:** Average delay vs varying SO in 915MHz



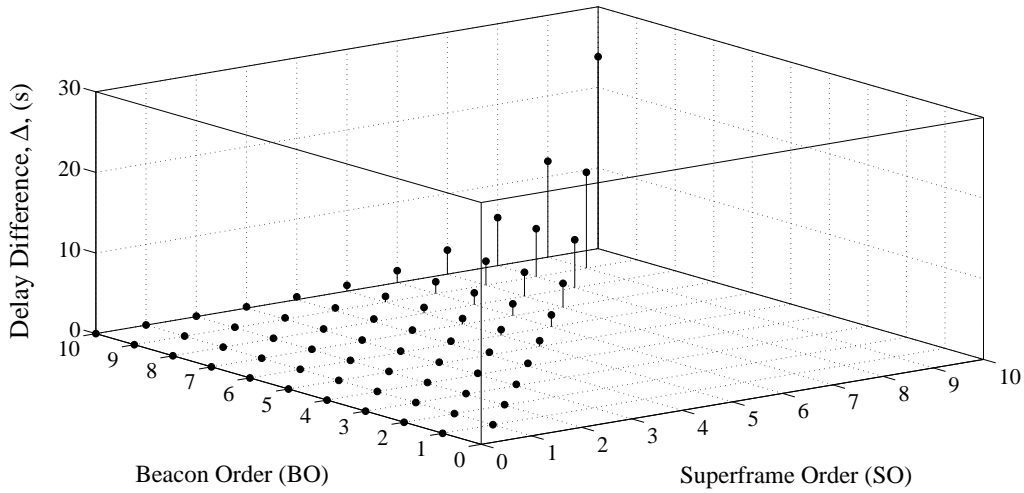
**Figure 5.9:** Average delay vs varying SO in 2400MHz

### 5.5.3 GTS allocation nodes

It has been observed that increase in  $SO$  value causes longer slot duration and each slot that can accommodate large data traffic. In our proposed model, 14 CFP slots of shorter duration can manage sufficient amount of data and in response can entertain maximum number of nodes. Figures 5.16, 5.17 and 5.18 show assignment of GTS to nodes during 868MHz, 915Mhz and 2400MHz frequency bands. It is evident from the results that proposed model



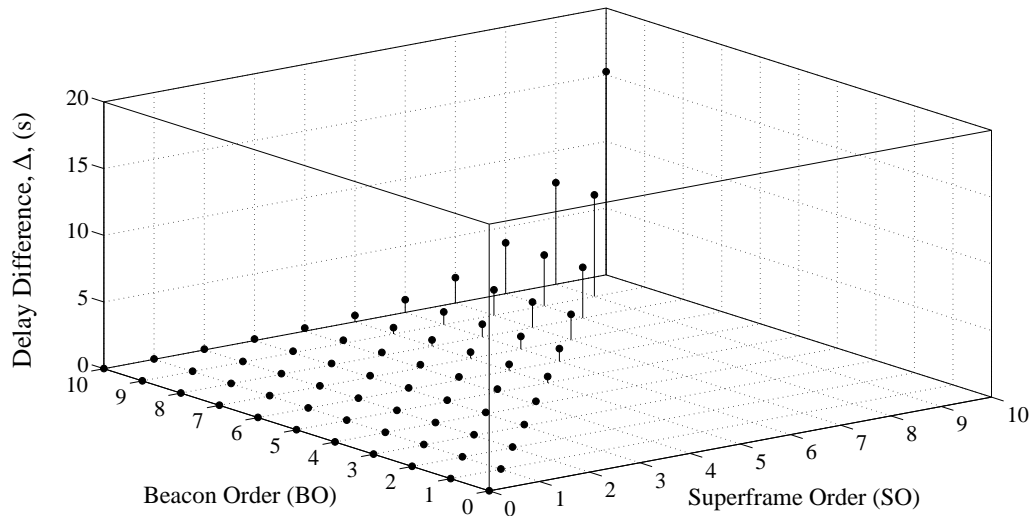
**Figure 5.10:** Difference in average delay for varying BO in 868MHz



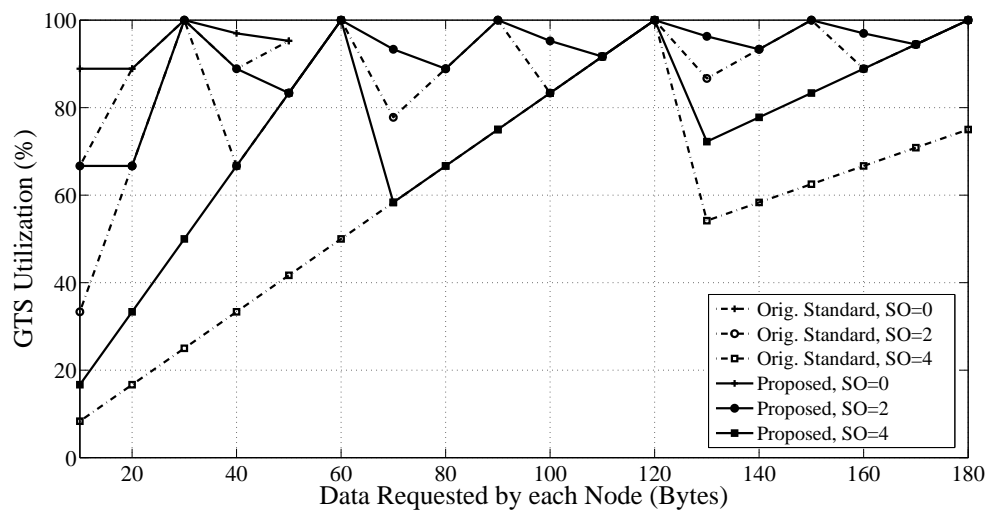
**Figure 5.11:** Difference in average delay for varying BO in 915MHz

can assign GTSs to large number of nodes as of the original standard. As  $SO$  increases, each node is assigned one slot and hence maximum of 14 nodes can be entertained as of the original standard where only 7 nodes can be entertained for the same data traffic for each node. Similarly, for the smaller values of  $SO$  and large volume of data requests from the nodes, our proposed scheme entertains equal or more number of nodes compared to the original standard in all frequency bands.





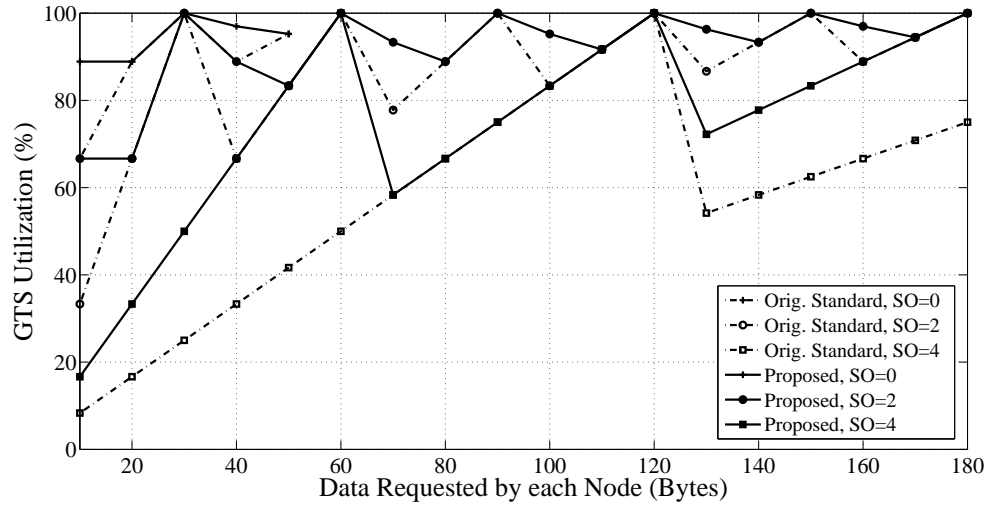
**Figure 5.12:** Difference in average delay for varying BO in 2400MHz



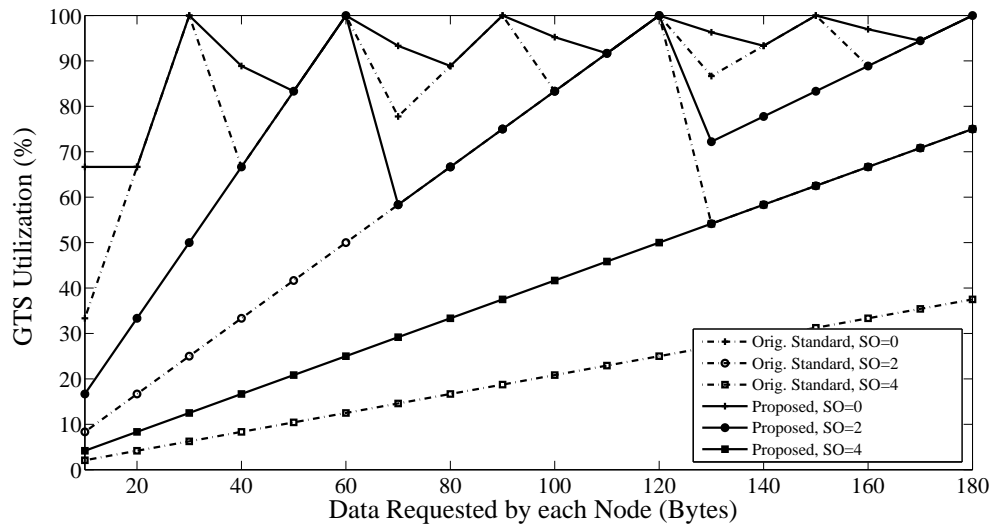
**Figure 5.13:** Link Utilization of nodes vs varying data request in 868MHz

## 5.6 Conclusion

In this chapter, we proposed an efficient Superframe structure for IEEE802.15.4 standard. The Beacon frame format along with all suitable parameters is also proposed to prove that the our Superframe structure is backward compatible with the current standard with very minor modifications. The analytical results show that this Superframe format improves

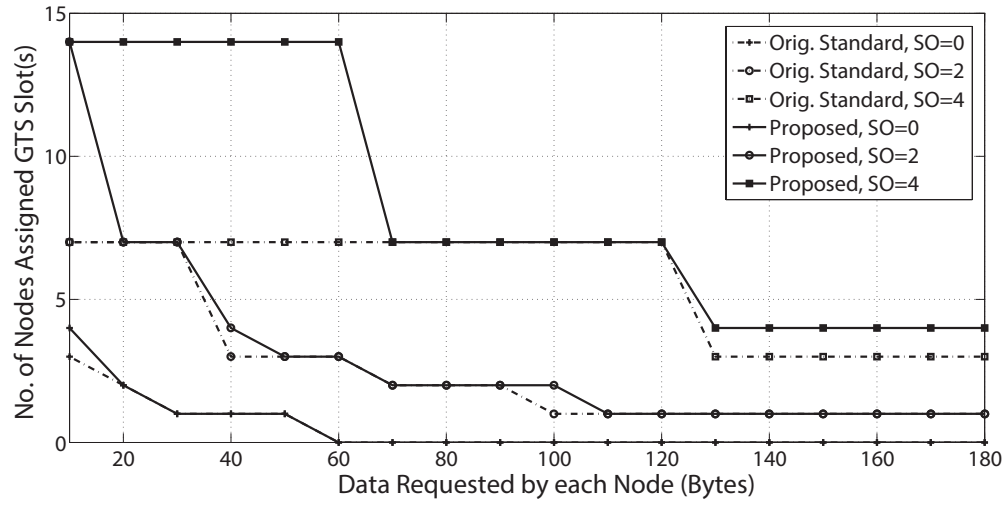


**Figure 5.14:** Link Utilization of nodes vs varying data request in 915MHz

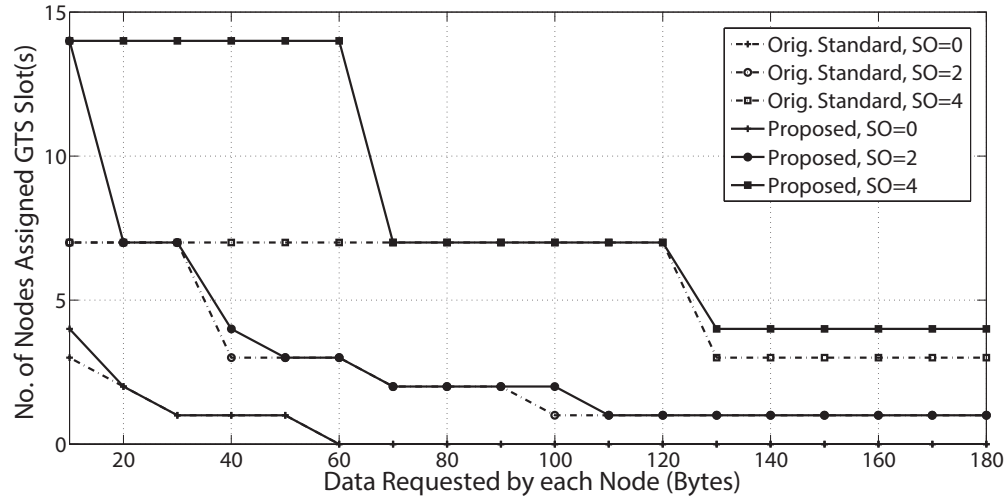


**Figure 5.15:** Link Utilization of nodes vs varying data request in 2400MHz

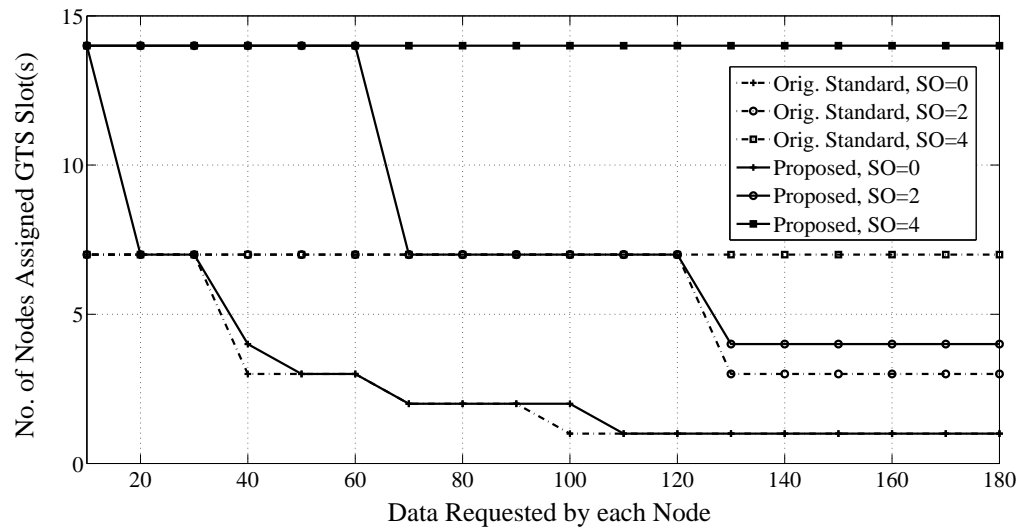
delay, accommodates more number of nodes and better utilizes the CFP slots compared to the original 802.15.4 standard in all three frequency bands.



**Figure 5.16:** No. of GTS assigned vs varying data request in 868MHz



**Figure 5.17:** No. of GTS assigned vs varying data request in 915MHz



**Figure 5.18:** No. of GTS assigned vs varying data request in 2400MHz

## Conclusions and Future Work

In this chapter, an overall conclusion of the research work is presented. In this work we have introduced two new TDMA based MAC protocols and suggested an efficiency enhancement in IEEE 802.15.4 standard. Main aim of these MAC protocols is to enhance the link utilization in addition to delay minimization.

Two TDMA based MAC protocols *BS – MAC* in chapter 3 and *BEST – MAC* in chapter 4 are proposed in this work. Both of them are bit map assisted TDMA based MAC protocols that adaptively handles the varying amount of data traffic by using large number of small size data slots.

In *BS-MAC*, Shortest Job First algorithm is implemented to minimize a node's job completion time and also to enhance the link utilization of the network. Energy consumption in *BS-MAC* is minimized by introducing the 1 byte short address instead of 8 bytes extended address to identify the member nodes. The performance of the proposed *BS-MAC* protocol is compared with the *BMA-RR* and *E-TDMA* through simulations. It shows that *BS-MAC* achieves more than 70% and 80% efficiency in data transmission delay and more than 3% and 17% data is transmitted compared to *BMA-RR* and *E-TDMA* without compromising energy consumption.

In *BEST – MAC*, Knapsack optimization technique is introduced for better link utilization as well as to reduce node's job completion time that results in significant improvement in average packet delay of nodes. Scalability is introduced in *BEST – MAC* so that new node may become a part of the networks during steady state phase which was not possible in previous TDMA based MAC protocols. Energy consumption is also minimized

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by reducing the control overhead by introducing a unique 1 byte short address to identify the member nodes. The performance of the proposed BEST-MAC protocol is again compared with the BMA-RR and E-TDMA. The simulations verifies that BEST-MAC achieves more than 60% and 70% efficiency in data transmission delay and more than 7% and 17% data is transmitted compared to BMA-RR and E-TDMA without compromising energy consumption.

In chapter 5, improvements in Superframe structure for IEEE 802.15.4 standard are suggested to minimize the delay of all data requesting nodes who have been assigned GTS. In the proposed scheme, CFP slots are doubled not only to accommodate more data requesting nodes but also to improve the link utilization. All of these improvements are without compromising the addition of existing parameters. The Beacon frame format along with all suitable parameters are also suggested and discussed to prove that the our Superframe structure is backward compatible with the current standard with very minor modifications. The analytical results show that this Superframe format improves delay, accommodates more number of nodes and better utilizes the CFP slots compared to the original 802.15.4 standard in all three frequency bands.

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