Energy Efficient Medium Access Protocol for DS-CDMA based Wireless Sensor Networks

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Submitted in fulfilment of the academic requirements
for the degree of Doctor of Philosophy in Computer Engineering
in the School of Engineering
at the University of KwaZulu-Natal, Durban, South Africa

February 2012

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As the candidate’s supervisor I have approved this thesis for submission.

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Date: February 2012

Declaration

I, **Muddenahalli Nagendrappa Thippeswamy**, declare that

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Acknowledgements

I would like to sincerely thank my supervisor, Professor Fambirai Takawira, who has been my teacher, guide and companion on the long journey to complete the work for this thesis. His passion for research and his persistent support and encouragement for his students are extraordinary. I feel thankful that I have had the opportunity to stand on the shoulders of a giant.

I wish to thank Narushan Pillay, Seare Rezenom, colleagues and friends from the School of Engineering (Electronic Engineering), University of KwaZulu-Natal for sharing their thoughts and proof reading parts of this thesis. A special thanks to Prof. K.K. Gopinathan from the faculty of science and technology, National University of Lesotho, Lesotho, who inspired me to pursue a PhD degree.

Many thanks go to the Telkom Centre for Radio Access and Rural Technologies at the School of Engineering and the Research office, University of KwaZulu-Natal for the initial support for this project.

And last, but not least, I would like to thank my wife Smitha, and our sons Chirag and Chiranth, who had to endure with my lack of sleep after many late nights and not paying enough attention to their requests.

Abstract

Wireless Sensor Networks (WSN), a new class of devices, has the potential to revolutionize the capturing, processing, and communication of critical data at low cost. Sensor networks consist of small, low-power, and low-cost devices with limited computational and wireless communication capabilities. These sensor nodes can only transmit a finite number of messages before they run out of energy. Thus, reducing the energy consumption per node for end-to-end data transmission is an important design consideration for WSNs.

The Medium Access Control (MAC) protocols aim at providing collision-free access to the wireless medium. MAC protocols also provide the most direct control over the utilization of the transceiver, which consumes most of the energy of the sensor nodes.

The major part of this thesis is based on a proposed MAC protocol called Distributed Receiver-oriented MAC (DRMACSN) protocol for code division multiple access (CDMA) based WSNs. The proposed MAC protocol employs the channel load blocking scheme to reduce energy consumption in the network.

The performance of the proposed MAC protocol is verified through simulations for average packet throughput, average delay and energy consumption. The performance of the proposed MAC protocol is also compared to the IEEE 802.15.4 MAC and the MAC without the channel load sensing scheme via simulations.

An analytical model is derived to analyse the average packet throughput and average energy consumption performance for the DRMACSN MAC protocol. The packet success probability, the message success and blocking probabilities are derived for the DRMACSN MAC protocol.

The discrete-time multiple vacation queuing models are used to model the delay behaviour of the DRMACSN MAC protocol. The Probability Generating Functions (PGF) of the arrivals of new messages in sleep, back-off and transmit states are derived. The PGF of arrivals of retransmitted packets of a new message are also derived.

The queue length and delay expressions for both the Bernoulli and Poisson message arrival models are derived. Comparison between the analytical and simulation results shows that the analytical model is accurate.

The proposed MAC protocol is aimed at having an improved average packet throughput, a reduced packet delay, reduced energy consumption performance for WSN.

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Notations

ρ_s : Message arrival rate (messages/frame)

μ_s,μ_B and μ_x : Message termination in sleep, back-off and transmit state

M : Length of a message

L : Packet length

T_p : Packet time

L_x : Total number of messages in transmit state

L_x^{beg} : The number of messages at the beginning of transmit state

$L_x^{R,beg}$: The number of retransmitted packets of the original message

L_x^{new} : The number of new message arrivals during transmit state

$L_x^{R,new}$: The number of retransmitted packets of new message

$N_{slots,S}$, $N_{slots,B}$ and $N_{slots,x}$: Length in slots of the Sleep, Back-off and Transmit state respectively

$G_{m_j,new}(z)$: PGF of the new message, L_x^{beg}

$m_{j,R}(z)$: PGF of retransmitted packets of the new message, L_x^{beg}

$G_{L_x^{Beg}}(z)$: PGF of the total number of messages at the beginning of transmit state

$G_{N_{slots,S}}(z)$, $G_{N_{slots,B}}(z)$ and $G_{N_{slots,x}}$: PGF of the number of slots in Sleep, Back-off and Transmit state respectively

$G_K(z\ )$: PGF of the number of Poisson message arrivals

$G_X(z)$: PGF of the number of Bernoulli message arrivals

$G_{new,S_n}(z)$: PGF of the number of messages arrivals in Sleep state

$G_{new,B_n}(z)$: PGF of the number of messages arrivals in Back-off state

T_S : Time spent in Sleep state

T_B : Time spent in Back-off state

T_x : Time spent in Transmit state

T_f : Frame duration

List of Acronyms

ACK	Acknowledgement
ARQ	Automatic Repeat Request
AWGN	Additive White Gaussian Noise
BLER	Block Error Rate
CQI	Channel Quality Information
CTS	Clear To Send
DS	Data Sending
IEEE	Institute of Electrical and Electronic Engineers
MAC	Medium Access Control
MACA/PR	Multiple Access Collision Avoidance/Packet Reservation
NAV	Network Allocation Vector
NACK	Negative Acknowledgement
NRT	Neighbourhood Reservation Table
PER	Packet Error Rate
PGF	Probability Generation Function
PN	Pseudo-Random Number
QoS	Quality of Service
RTR	Ready to Receive
RTS	Ready to Send
RV	Random Variables
SR-ARQ	Selective Repeat Automatic Repeat Request
SNR	Signal-to-Noise Ratio
SSA	Spread Slotted Aloha
TBS	Transmission Block Size
TDMA	Time Division Multiple Access
WSN	Wireless Sensor Network

Chapter 1

Introduction

1.1 Background

Recent advances in wireless technology, micro electro-mechanical systems (MEMS) and the trend in digital electronics have enabled the manufacture of low-power, multifunctional, small, inexpensive sensor devices that can be connected via wireless networks [1, 2]. Typically, in the field under study, a wireless sensor network (WSN) consists of a large number of sensor nodes, which are randomly deployed in an ad hoc fashion and without careful planning. The sensor nodes' capabilities can vary widely in a WSN. Sensor nodes may be used to monitor a single physical phenomenon. Additionally, more complex devices can be combined with many different sensing technologies (e.g., acoustic, optical, magnetic) to perform sensing activities. In a WSN, each sensor node is able to independently perform some sensing and processing tasks. In addition, these sensor nodes can communicate with each other to forward the sensed information to a central processing unit for further processing as shown in Figure 1.1.

This chapter describes the design of sensor nodes and the applications of WSNs. Then, the main requirements of WSNs are introduced. Finally, the research statement, objectives and thesis outline are presented.

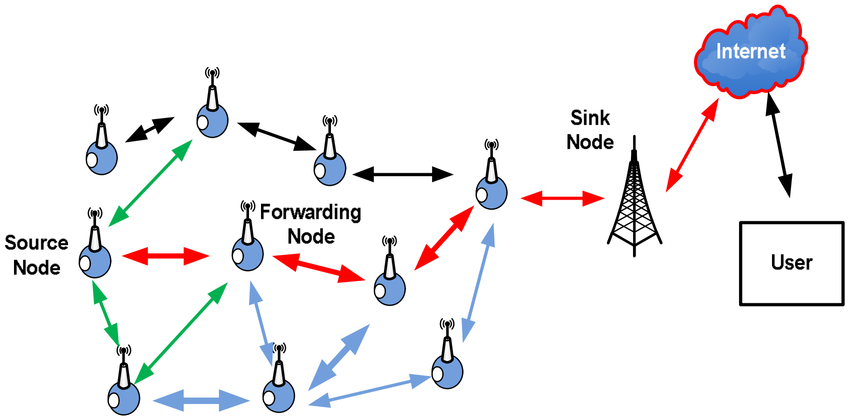


Figure 1.1: WSN architecture

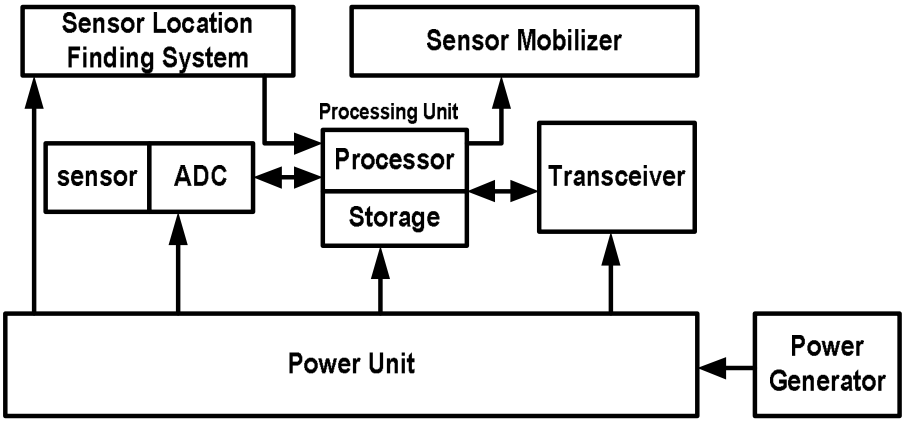


Figure 1.2: Components of a sensor node

1.2 Design of Sensor Node and Architecture

A WSN is made up of individual multifunctional sensor nodes [1- 4]. As shown in Figure 1.2, the main components of a sensor node are:

a) **Computing** s**ubsystem**: This consists of a microcontroller unit (MCU), which is responsible for the control of the sensors and execution of communication protocols [1- 4]. MCUs usually operate under various operating modes for power management purposes. Switching between these operating modes involves consumption of energy and hence, the energy consumption levels of the various modes should be considered while looking at the battery life of each node.

b) **Communication subsystem**: This consists of a short range transceiver radio [1 - 4], which is used to communicate with neighbouring nodes and the outside world. The transceiver radio can operate in four modes, viz. transmit, receive, idle and sleep. It is important to completely shut down the radio rather than put it in the idle mode when it is not transmitting or receiving information because of the high power consumed in these modes.

c) **Sensing subsystem**: This consists of a group of sensors and actuators that can observe or control physical parameters of the environment [1 - 4]. These sensor transducers translate physical phenomenon into electrical signals. There are different types of sensors today such as light, temperature, sound, etc [3, 4].

d) **Power supply subsystem**: This consists of a battery which supplies power to the node [1- 4]. Some form of recharging by obtaining energy from the environment is available such as solar cells.

1.3 WSN Application Scenarios

Before discussing a WSN in detail, it is crucial to think about its applications. The applications allow the designer to understand the requirements of the network and exploit its application-specific characteristics. In this section, some of the applications of WSNs are briefly discussed.

a) **Wildlife monitoring:** In [4], a WSN is designed to monitor the environmental conditions of an animal’s habitat such as light intensity, as well as to monitor the body temperature of the animal itself, and then relay the processed data to a base station for further processing.

b) **Traffic Monitoring:** Sensor nodes incorporated within magnetic sensors can be deployed to perform vehicle detection and classification [5].

c) **Parking Lot Monitoring:** The sensor nodes associated with magnetic sensors can be used in parking lots to determine free parking spots. Each parking spot contains one, or more, sensor node, which relays vehicle presence information to a central controller upon detection of a vehicle in a spot. The controller may then use this information to guide customers to vacant spaces [7].

d) **Medical Care:** The use of WSN in health care applications is potentially beneficial to developing countries, including medical emergency care, disaster response, and stroke patient rehabilitation [8, 9].

1.4 WSN Challenges

The applications of WSNs, some of which are discussed in the previous section, introduce many challenges. The main design constraints of these applications are [2, 10]:

a. **Energy efficiency:** The sensor nodes are expected to operate on battery power for a long time. Therefore, the energy conservation scheme plays a key role in determining the lifetime of the sensor network.

b. **Scalability:** A large number of nodes deployed in the physical sensing area may be in the order of hundreds, or thousands or even more. Thus, the network protocols should be able to handle large networks and take advantage of the high density of WSNs to ensure reliable communication.

c. **Life time:** WSNs must last as long as possible based on the available initial amount of energy and also by reducing energy consumption in the network when it is in operation.

d. **Multi-hop communication:** Limited energy capacity of the node dictates the way communications must be performed inside WSNs. In order to prolong the lifetime of WSNs, nodes should avoid direct communication with distant destination nodes, since high transmission power is required to achieve successful transmission [1, 10]. Thus, from an energy efficiency point of view, nodes should use multi-hop communication to transmit information.

1.5 The Major Sources of Energy Waste in WSNs

The following are the major sources of energy wastage in WSNs [2, 10-13].

a) **Collision avoidance**: If two nodes try to transmit the data at the same time and interfere with one another's transmissions, packets are corrupted. The follow-on re-transmissions increase energy consumption as well as latency in the network.

b) **Control packets overhead:** Most protocols require control packets. Sending and receiving control packets consumes energy as these packets contain no application data. Energy used for transmitting and receiving these packets may be considered as overhead.

c) **Overhearing avoidance**: A sensor node spends energy when a node picks up packets that are destined to other nodes.

d) **Idle listening:** Most energy in MAC protocols is wasted in idle listening. If nothing is sensed, nodes are in the idle mode for most of the time. Since a node does not know when it will be the receiver of a message, it must keep its radio in receive mode at all times.

1.6 Research Statement and Objectives

The main purpose of designing the MAC layer is to decide when a node accesses a shared medium and to resolve any potential conflicts between competing nodes. The design of energy efficient MAC protocol has received a great deal of attention in the context of random access based WSNs. Several MAC protocols have been proposed in the literature, but each protocol presents some advantages and suffers from some shortcomings.

One of the drawbacks of these MAC protocols is that the re-transmission of entire messages can increase the energy consumption of the sensor node when the packets are dropped or blocked due to a high channel load. This motivates the proposal of a new distributed energy efficient MAC protocol for WSNs. Furthermore, the channel load sensing scheme has attracted less interest in the context of random access based WSNs. The aim of this research work is to design a MAC protocol and evaluate its performance using Markov chain and Queuing theoretic models for WSNs to achieve energy efficiency. In order to accomplish this objective, the different energy efficient scheme viz. channel load detection and blocking is considered. The following objectives are identified for this thesis work.

a) To review the existing MAC protocols of WSNs.

b) To develop a new distributed CDMA based MAC protocol (DRMACSN) for WSNs, which achieve good packet throughput and energy efficiency in WSNs.

c) To develop an analytical model to evaluate the packet throughput and energy consumption performance of the DRMACSN MAC protocol.

d) To develop a node energy consumption model to evaluate the energy consumption at each sensor node for the DRMACSN MAC protocol.

e) To develop a queuing model to analyse the delay performance of the DRMACSN MAC protocol.

1.7 Thesis Outline

The following five areas are investigated under this research and each of them are briefly described in this subsection.

1.7.1 Literature review

The initial phase of the research focuses on literature survey on the current MAC protocols designed for WSN. The MAC protocols which have been classified into various categories such as centralized, distributed and hybrid are examined and issues related to WSNs, advantages and disadvantages of each MAC protocols are discussed.

1.7.2 Developing New MAC Protocol for WSNs

The literature review was followed by developing a new MAC called DRMACSN MAC protocol [15] for CDMA based WSNs, which employs the channel load blocking scheme to achieve energy efficiency in the WSNs. The DRMACSN MAC protocol is a distributed protocol, i.e. there is no central coordinator in the system, and it is a receiver-oriented protocol because only the receiver side needs to be protected with respect to collisions. In the

DRMACSN MAC protocol, the transmission rate selection is done at the sender node, which can be improved by providing timely channel quality information (CQI) to a sender node. The DRMACSN MAC protocol is a slotted reservation-based protocol, which allows sensor nodes to reserve their slots to avoid collisions. An event-driven simulator in VC++ 2008 was developed to evaluate the performance of the DRMACSN MAC protocol for the throughput, delay and energy consumption. The simulation results show that a significant increase in the performance of the system in terms of improved throughput, reduced energy consumption and delay can be obtained by implementing channel load sensing technique. Finally, a comparison of DRMACSN MAC protocol with the IEEE 802.15.4 MAC protocol and the MAC without channel load sensing scheme, is presented and the performance enhancements that can be gained through the application of a channel load sensing scheme are quantified.

1.7.3 Throughput and Energy Analysis of DRMACSN for WSNs

In this work, an analytical model is developed using a single-dimensional homogenous Markov chain to evaluate the performance of DRMACSN MAC protocol. The state transition probabilities for the proposed MAC protocol are obtained. The expression for the packet throughput and the node energy consumption model is derived to evaluate the throughput and energy efficiency of the DRMACSN MAC protocol for WSNs. The energy consumption of a node for transmission, sleep and back-off states is derived. Further, the packet success probability, message success and blocking probabilities are derived. The results show that the analytical model is accurate and also confirm that node performance in terms of improved average packet throughput and reduced energy consumption can be achieved through the use of the channel load sensing technique.

1.7.4 Queuing Analysis of DRMACSN for WSNs

The DRMACSN MAC protocol is a distributed and receiver-oriented protocol, which employs a channel load sensing technique to reduce the delay in the network. The queuing analysis of the DRMACSN MAC protocol for WSNs is undertaken. The discrete-time $Geom/G/1$ and $M/G/1$ multiple vacation queuing models are used to model the behaviour of the DRMACSN MAC protocol. The results show that the queuing model is accurate and reduced delay performance can be achieved by implementing the channel load blocking technique.

1.8 Original Contributions of the Thesis

The original contributions to this thesis may be summarised as follows:

a. The derivation of a new MAC protocol for CDMA based WSNs (presented in Chapter 3). The originality of the proposed MAC protocol lies in the implementation of a distributed, receiver-oriented and reservation-based scheme to reduce delay and energy consumption. In addition, a channel sensing scheme is implemented to improve the packet throughput.
b. The derivation of an accurate Markov analysis (presented in Chapter 4) to predict the performance of the proposed MAC protocol for the packet throughput and energy consumption.
c. The derivation of node energy analysis model (presented in Chapter 4) to analyse the energy consumption of the proposed MAC protocol.
d. Discrete-time $Geom/G/1$ and $M/G/1$ multiple vacation queuing models are used to model the behaviour of the DRMACSN MAC protocol to analyse the delay performance of the proposed MAC protocol.

Parts of the research work presented in this thesis have been presented in the following publications/submissions:

a) Thippeswamy Muddenahalli N and F. Takawira, "DRMACSN: New MAC protocol for Wireless Sensor Networks," *Proc. Southern Africa Telecommunication Networks and application conference (SATNAC2009)*, 30 August – 2 September, Royal Swazi spa, Swaziland, 2009.
b) Thippeswamy Muddenahalli N and F Takawira, "Queuing analysis of DS-CDMA based MAC protocol for Wireless Sensor Networks," **Accepted** for publication, IET WSN, 2012.

c) Thippeswamy Muddenahalli N and F Takawira, "Performance Analysis of DRMACSN: Distributed DS-CDMA based MAC protocol for Wireless Sensor Networks," in the final preparation to submit to *IETE Journal*, 2012.

d) Thippeswamy Muddenahalli N and F Takawira, "Energy-Efficient Distributed DS-CDMA based MAC protocol for Wireless Sensor Networks," in the final preparation to submit to International Journal of Distributed Sensor Networks(IJDSN), Hindawi, 2012.

Chapter 2

Review of MAC protocols for WSNs

2.1 Introduction

Energy management in WSNs is crucial since battery-operated sensor nodes are severely energy constrained [2]. Thus, in order to conserve energy in WSNs, energy efficient techniques are required. The MAC protocols aim at providing collision-free access to the wireless medium, and collision can only be prevented by accurate knowledge of potential interfering nodes. Thus, an accurate wireless channel model is required for both evaluation and design of MAC protocols.

2.1.1 Energy Saving Mechanisms

The choice of the MAC scheme is the main determining factor in the performance of a WSN. Several mechanisms have been proposed to solve the shared medium access problem. These mechanisms attempt to achieve the energy savings for WSNs. In this sub-Section, some of the common mechanisms are presented and briefly discussed.

2.1.1.1 Wakeup Scheme

Wakeup scheme has great potential in energy saving for WSNs. The MAC protocol uses this scheme to turns off sensor’s radio when communication is not necessary and events occur infrequently to save energy in WSNs [10]. Furthermore, a wakeup tone is used to wakeup neighbour nodes.

2.1.1.2 Back-off Scheme

A back-off scheme is used when the contention interval increased due to higher traffic. The Back-off scheme is used in contention-based protocols; these nodes need to wait for a random time within a contention interval after detecting a collision. The back-off scheme reduces the probability of collisions when the traffic load is high and when the traffic load is low, it reduces the latency [13].

2.1.1.3 Reservation Scheme

The increasing density and large size of the WSNs has presented a new challenge in terms of network scalability. A reservation scheme is used in monitoring applications, where the traffic follows a periodic pattern. The reservation schemes have the advantage of collision-free communication since each node in the network transmits its data to a sink node during its reserved slot. Thus, the duty cycle of the nodes is decreased resulting in further energy efficiency.

2.1.1.4 Request to Send/Clear to Send (RTS/CTS) scheme

The MAC protocol uses RTS/CTS scheme [10, 11] to reduce frame collisions introduced by the hidden node problem in WSNs. When a transmitter node wants to transmit data to another node, it sends out a RTS packet. The receiver node replies with a packet called CTS packet. After the transmitter node receives the CTS packet, it transmits the data packets. The duration field is set such that the data transmission can be completed within the designated time period. If a transmitter node does not receive a CTS packet it enters into an exponential back off mode.

2.1.1.5 Clustering schemes

Clustering schemes are especially effective in large multi-hop WSNs for obtaining network scalability, reducing energy consumption, data latency and achieving better network performance. In WSNs, the clustering is primarily characterised by data aggregation by each cluster head (CHs), which significantly reduces the traffic cost. The major problem with this scheme is that an energy-efficiency algorithm may select a few CHs for energy-saving, but if these CHs do not have good connectivity (due to low battery) or if they are not stable, the retransmission and the dropped packets may significantly degrade the network performance and the total energy wasted may end up to be higher. Therefore, taking reliable communication into account is essential for any clustering algorithm, which aims to reduce the energy consumption in a network.

2.1.1.6 The use of beacons

The MAC protocols use the beacon to synchronize nodes in the network, to identify the coordinators and wakeup neighbour nodes. This synchronization allows nodes to sleep between coordinated transmissions between transmitter and receiver nodes, which results in energy saving for WSNs. The use of beacons also helps in prolonging the network lifetime.

In this chapter, the review of MAC protocols for WSNs is presented in Section 2.2. In Section 2.3, the IEEE 802.15.4 standard and MAC protocols is briefly discussed. Finally, in Section 2.4, the summary of the chapter is presented.

2.2 MAC for WSNs

The design of a new MAC protocol for a WSN is a difficult task due to the dynamic application environment and the ad-hoc nature of the system. Additionally, the primary concerns for MAC protocols for WSNs are energy efficiency, effective network control and network management [16]. In the literature, numerous MAC protocols have been proposed for different application areas of WSNs. It is a complex task to classify these MAC protocols due to diversity in their use of methodologies [17]. Many authors have classified MAC protocols in various categories such as centralized, distributed and hybrid [16, 18]. They have further presented classification based on other criteria, namely contention-based protocols and contention-free protocols.

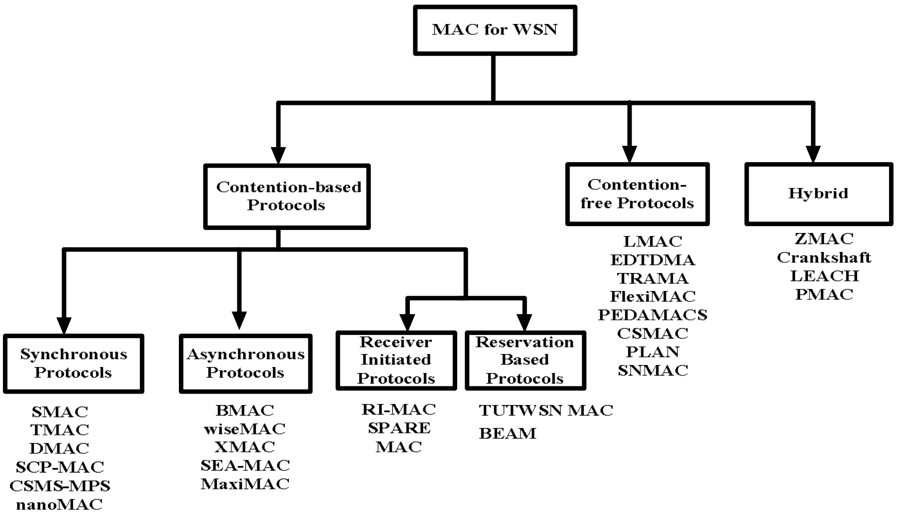


Figure 2.1: MAC classification tree for WSNs

In this thesis, the MAC classification adopted [16] is as shown in Figure 2-1. The authors in [18], classified the MAC protocols according to time and historic development. In this subsection, the performance of these schemes in the context of WSNs is reviewed.

2.2.1 Contention-Based Protocols (Synchronous)

The primary idea in conflict-based protocols is that when sensor nodes have collected data and is ready for transmission, then; these nodes need to compete for the wireless channel. Note that no coordination is required among the nodes while accessing the channel. For a random period of time, nodes remain in the back off state before retrying to gain access to the channel.

2.2.1.1 Sensor MAC protocol

The authors in [10, 11] proposed a MAC protocol called Sensor MAC (SMAC), which assures a low duty cycle without the need for extra synchronization between the receiver and source node. The SMAC uses the CSMA/CA approach to avoid collisions in the network. A scheduled periodic sleep and listening pattern is used in SMAC to decrease energy consumption in the idle mode. The protocol reduces energy waste caused by idle listening by using periodic sleep schedules. The basic idea of the SMAC protocol is that time is divided into fairly large frames. The SMAC protocol adopts a periodic wakeup scheme, i.e., each node switches between the sleep period and active period. During the sleep period, a node turns its radio off to conserve energy. During the active period, a node starts capturing the medium. Once it succeeds in accessing the medium, it starts sending an RTS packet to inform the receiver node to remain awake for the data transmission. In the SMAC protocol, nodes send the SYNC message periodically at the beginning of the active frame time. The nodes update neighbourhood information by exchanging packets periodically so they can wake-up at the appropriate time to transmit data packets. In order to achieve further energy conservation, the SMAC protocol exploits the concept of fragmentation to transmit large messages. Accordingly, sensor nodes can transmit large messages as small fragments using a single RTS/CTS exchange. Thus, if one fragment is not successfully received either due to collision or channel error, the sender only has to retransmit the corrupted small fragment instead of the whole data message. Another feature of the SMAC protocol is that when the traffic load was increased, an overhearing-avoidance mechanism was used to reduce the energy consumption. The main drawback of SMAC is that the protocol is specially designed to sacrifice message delivery latency for energy savings.

2.2.1.2 Timeout-MAC Protocol

The Timeout-MAC (TMAC) protocol presented in [13] aims to improve the performance of SMAC [10, 11] by dynamically adjusting the duration between sleep intervals in which sensor nodes are awake based on communication of nearby neighbours. In order to handle load variations in time and location, the TMAC protocol introduces an adaptive duty cycle in a novel way by dynamically ending the active part of the node. It dynamically adapts a listen/sleep duty cycle through fine-grained timeouts, while having minimum complexity. This reduces the amount of energy wasted on idle listening, in which nodes wait for potential incoming messages, while maintaining a reasonable throughput. In addition, to decrease the latency of messages and provide simple form of flow control, two improvements were presented in [13]. Furthermore, the authors in [13] have introduced a future request to send a message (Future RTS) to reduce the message latency. The TMAC protocol also proposes the method to solve the early sleeping problem that limits the number of hops a message could travel in each frame time. The TMAC protocol also considers the buffer size of the sensor node when calculating the contention period. Sensor nodes that have a full buffer may take priority and control the channel by immediately sending an RTS message after receiving an RTS message from another sensor node. In this way sensor nodes can utilize a simple flow control mechanism to limit buffer overflow by giving a chance to transmit their queued messages when the sensor node has no room to receive a message. The major problem in TMAC is that the protocol is inclined to shut down the radio, this leaves messages queued in the next slot, thus, increasing the latency and reducing throughput.

2.2.1.3 Data Gathering MAC Protocol

The data gathering MAC (DMAC) protocol for WSNs was proposed in [19]. The goal of the DMAC protocol is to be an energy efficient and low latency MAC scheme. The DMAC includes an adaptive duty cycle like TMAC [13] to achieve energy efficiency and ease of use. DMAC is proposed to deliver data along the data gathering tree. The primary idea in [19] is that data can quickly flow through from the branch nodes to the controller depending on the level and active time of nodes. Each node first listens to its ‘children’, then propagates any messages up to the ‘parent’. In the DMAC protocol, the activity schedule interval is divided into three periods, viz. receive, send and sleep periods. A node is expected to receive a packet and send an ACK packet to the sender in the receiving state. In the sending state, a node will try to send a packet to its next hop and receive an ACK packet. When the nodes lose access to the channel in this protocol, they may not need to wait for flow of information but may rather retry later. When demand for transmission is increases, the protocol then automatically adapts to the traffic load, similar to TMAC [13]. In the DMAC protocol, time synchronization among the nodes is needed. There are no measures to avoid collisions in the DMAC protocol. Moreover, the data paths are not known in advance, which prevents the construction of data-gathering trees.

2.2.1.4 Scheduled Channel Polling MAC Protocol

A new protocol was proposed called *scheduled channel polling MAC* (SCPMAC) for WSNs in [20], and is based on scheduled channel polling, which enables sensor network nodes to operate at ultra-low duty cycles and enhances the SMAC [10, 11] expensive contention intervals with wake-up tone transmission and low power listening (LPL) like channel polling. The basic scheme of SCPMAC combines the strengths of channel polling and scheduling. The channel polling scheme minimizes the cost of wakeup checking for the presence or absence of network activity rather than checking what that activity is. Similar to LPL, the SCPMAC puts nodes into periodic sleep state when there is no traffic, and they perform channel polling periodically. Using a short wake-up tone also makes SCPMAC more robust in the face of varying traffic load. It combines the strengths of both scheduling and low-power listening. The SCPMAC supports fast-path schedule allocation, where nodes can coordinate the schedules of all other nodes along a path to avoid all schedule-based delays. The SCPMAC periodically puts the nodes into a sleep mode; effectively this feature reduces the throughput.

2.2.1.5 CSMA with Minimum Preamble Sampling Protocol

The authors in [21] proposed a protocol called CSMA with minimum preamble sampling (CSMAMPS) to improve energy efficiency. In CSMAMPS, all the nodes sample the medium for a short time with a constant time period and check for the activity on the channel. When a node does not have a sampling schedule of its neighbours, it starts the CSMA algorithm immediately to check the channel status; otherwise it backs off for a random time to start sensing the carrier just at the right time before the receiver starts its periodic listening interval. One of the advantages of this protocol is that it achieves low energy consumption by making use of the shortest possible wake-up sequences and using high bit rate transceivers that allow for a lower duty cycle operation as well as quicker transitions between different states. The protocol does not send a node to sleep mode when the channel is busy. Thus, this scenario unnecessarily increases the energy consumption in the network.

2.2.1.6 P-non-persistent CSMA/CS MAC Protocol

In [22], the authors proposed a distributed and p-non-persistent CSMA/CS MAC protocol called nanoMAC which is suitable for low bit rate, low power wireless devices with high efficiency. The basic operation cycle in the nanoMAC protocol is defined by the RTS-CTS–nDATA and ACK hand-shaking schemes. A specialized sleep algorithm is proposed to conserve battery energy and to minimize idle listening in the network. Further, the nanoMAC protocol also maintains four sleep groups to save energy in the system. The nodes will operate in one of the four sleep groups depending on the traffic load and application requirements in WSNs. When a node in the nanoMAC protocol receives a new packet to transmit, it first performs carrier sensing. If the channel is found to be busy, the protocol performs a random back-off within a specified contention window (CW) and the node goes into sleep state. The carrier sensing is performed for long enough durations to ensure the presence of the carrier with high certainty. After obtaining the channel, the transmitting node sends a broadcast RTS frame, followed by data frames so that the receiving nodes extend their active periods to receive the data frames. The advantage of the nanoMAC protocol is that it allows nodes to store the measurements locally and to transmit large data on demand for many applications at a later stage. The receiving nodes do not acknowledge the data frames in broadcast transmission.

2.2.2 Contention-Based Protocols (Asynchronous)

In contention-based (asynchronous) protocols (also called Random access MAC protocols), nodes do not synchronise time and contend for access to the radio channel. These protocols shift the cost from the receiver node to the sender node in order to reduce idle listening by extending the MAC header. These protocols also allow nodes to check the channel periodically and sleep most of the time. The drawback of these protocols is that they are not flexible to changes in the topology and scalability in the network. There are many MAC protocols that have been developed under this scheme. In this section, these MAC protocols and their advantages and disadvantages for WSNs are presented.

2.2.2.1 The Berkeley-MAC Protocol

The authors in [23] have designed a MAC protocol called Berkeley MAC (BMAC) for WSNs, which saves energy by having the radios periodically wake-up to access the medium. Further, the BMAC employs an adaptive preamble sampling scheme to reduce the duty-cycle and minimize the idle listening time. Each node periodically awakes to check for any activity currently on the medium, and remains active to receive a possible incoming packet. A sender node sends a long preamble prior to its DATA transmission, which lasts longer than the receiver's sleep interval. This policy ensures that the receiver will wake up at least once during the preamble allowing each node to wake up, activate or sleep in its own schedule. The advantage of the BMAC protocol is that it can be configured to run at extremely low duty cycles and does not force applications to incur the overhead of synchronization and state maintenance. The problem with the BMAC protocol is that a long preamble increases the power consumption of all nodes in the sender's transmission coverage because of the overhearing issue, which is not solved in this protocol. Another problem of the BMAC protocol is that it loses efficiency as network traffic increases because all nodes remain awake throughout the entire packet transmission.

2.2.2.2 WiseMAC Protocol

In [24], the authors proposed a protocol called WiseMAC for WSNs. This protocol uses the preamble sampling technique as in [23] to minimize the power consumption when listening to an idle medium. The WiseMAC protocol is based on the preamble sampling technique to minimize idle listening. A novel idea in WiseMAC is to minimize the length of the wake-up preamble, exploiting the knowledge of the sensor nodes' sampling schedules. Knowledge of the sampling schedule of its direct neighbours, in order to minimize the wake-up preamble, is used in the protocol. With this information, a transmission is started just at the right time using a preamble of minimum size. Every acknowledgement packet contains the sampling information and on this account no set-up signalling and network-wide time synchronization is necessary. This protocol is based on non-persistent CSMA and uses the preamble sampling technique to minimize the power consumed when listening to an idle medium. If the medium is found to be busy, a sensor node continues to listen until a data frame is received or until the medium becomes idle again. At the transmitter, a wake-up preamble of size equal to the sampling period is added in front of every data frame to ensure that the receiver will be awake when the data portion of the packet arrives. This technique provides very low power consumption when the channel is idle. In order to mitigate collisions in the protocol, WiseMAC adds a medium reservation preamble of randomized length in front of the wake-up preamble. The sensor node that has picked the longest medium reservation preamble will start its transmission sooner, and thereby reserve the medium. The advantage of this protocol is that it can adapt to the traffic load and achieves variable power consumption depending on the traffic conditions. The problem of this protocol is its large power consumption overhead in transmission and reception.

2.2.2.3 Short Preamble MAC Protocol

In the short preamble MAC protocol (XMAC) [25], the authors solved the overhearing problem of BMAC [23] by using short preambles. A short preamble approach was adopted in [25] to reduce energy consumption at both nodes which reduces the per-hop latency. In addition this approach also provides additional benefits in terms of QoS. The XMAC [25] protocol allows more than one transmitter node to transmit preambles to a particular receiver. To achieve this, each sender node inserts a small pause-with-preamble; this gap allows the receiver node to transmit an early ACK back to the sender nodes. When a sender node receives an ACK, it stops sending the preamble and transmits the DATA packet to the receiver. After detecting the preamble, any other sender node attempting to transmit has to wait for channel clearance. When a node receives an ACK frame from the node that it wishes to send to, the node will back-off for a random time and then start sending its data frame without a preamble. This will allow more than one sender node to send the data frames without collisions. The XMAC protocol is energy efficient for light traffic loads in the system. On the other hand, this protocol fails to handle bursty traffic because of the chosen adaptation algorithm by the nodes. Another problem with this design is that the particular node will wait to receive the ACK from an intended receiver node; this might increase the idle listening time of a node in the network.

2.2.2.4 A Simple Energy Aware MAC Protocol

A Simple Energy Aware MAC protocol (SEAMAC) for WSNs, which is designed for environmental monitoring applications is proposed in [26]. The SEAMAC tries to reduce energy consumption in environmental monitoring applications by reducing the duty cycles of sensor nodes and idle listening times. In order to save energy in the SEAMAC, nodes periodically wake up to capture samples from the environment. This protocol considers that synchronization is unique for all nodes because the base station starts and maintains synchronization in the network. The SEAMAC maintains a schedule in which nodes wake up when a sample from the environment is ready because the entire traffic of environmental monitoring applications is periodic. Thus, this protocol eliminates the need for the periodic sleep/listen schedule as in SMAC [10, 11].

2.2.2.5 Maximally Adaptive MAC Protocol

In [27], the authors designed a new MAC called a maximally adaptive MAC protocol (MaxMAC) for WSNs, which has low power consumption with low traffic size and targets to achieve maximum adaptability with respect to throughput and latency. The MaxMAC protocol tries to tune essential parameters adaptively at run time to achieve high throughput and energy efficiency during the periods of sparse traffic. The MaxMAC protocol combines established design principles of recent research on energy efficient protocols that is preamble sampling [21] with preamble minimization [23] and overhearing avoidance using target addresses within preambles as in [25]. In addition, the MaxMAC protocol introduces traffic-adaptation features to instantly react to changing load conditions and attempts to allocate the energy resources of a node in an on-demand manner. The MaxMAC protocol allows nodes to exchange their states and allocation when the rate of incoming packets reaches a predefined threshold value and later de-allocates them when the rate drops below the threshold. The advantage of the MaxMAC protocol is that it can adapt maximally at run-time due to variation in the traffic loads. This feature reduces energy waste in the system. A disadvantage of the MaxMAC protocol is that the protocol works on packet-oriented radios, which is a more energy efficient technique for WSNs composed of bit-byte oriented radios.

2.2.3 Contention-Based Protocols (Reservation-based)

A contention-based reservation protocol has the potential of capturing most of the opportunities for energy conservation in WSNs. The reservation scheme provides guaranteed slots to all nodes so that they are flexible to load variations in the networks. In this section, two protocols designed for WSNs are presented.

2.2.3.1 Energy Efficient Reservation Based MAC Protocol

A novel protocol called TUTWSN MAC for low power WSNs was proposed in [28] which minimizes the energy overhead of idle time and collisions by strict frame synchronization and slot reservation. This MAC protocol achieves high scalability by employing frequency and time division between clusters. In order to achieve high energy efficiency, TUTWSN

MAC combines a dynamic bandwidth adjustment mechanism and a multi-cluster tree network topology. In [28], the channel access is based on super-frames that are repeated at regular intervals. These super-frames also include unique local schedules to avoid collisions in the network. A node can act as a cluster head to control the operation of nodes or participate as a member node in the network. Otherwise, in order to conserve energy, the node will be in sleep interval. A cluster head transmits a beacon at the beginning of each super-frame which contains information for channel access, routing and networking. Nodes in TUTWSN MAC maintain a reserved slot allocation table which is used for exchanging the neighbour information. The channel periods are divided into communication slots which are large enough for data transmission. In order to ensure reliability of all data transmissions, the acknowledgment is transmitted in the same slot with the data frame.

2.2.3.2 Burst-Aware Energy Efficient Adaptive MAC Protocol

The authors in [29] proposed a Burst-Aware Energy-Efficient Adaptive MAC (BEAM) protocol for WSNs. In order to balance the energy consumption and network performances, the BEAM protocol implements the physical layer of the IEEE 802.15.4 standard and also supports adaptive duty-cycling which enables a quick reaction to varying traffic loads and traffic patterns. The BEAM protocol consists of two operational modes to optimize sleep time of the receiver node depending on the payload size. The BEAM protocol is a contention-oriented protocol based on asynchronous duty cycles. In the BEAM protocol, the sender node transmits short preamble frames periodically which includes the payload. Then, the receiver node wakes up and listens to the channel. The receiver node checks the destination address in the received preamble frame. If it is the intended receiver node then it prepares and sends a data ACK frame. After receiving an ACK frame successfully, the sender node stops sending the data frame and goes into the sleep mode. If the sender node does not receive the data ACK frame due to channel errors or interference it continuously transmits the short preamble frames including the payload. The advantage of the BEAM protocol is that it performs very well in terms of energy consumption throughout for different traffic patterns. Thus, this protocol is a robust and high performing protocol that can be used in different environmental conditions. One of shortcomings of this protocol is that the source node enters into sleep mode after successful transmission. If any of the neighbour nodes want to send data frames to this node, they need to wait for this node to come back to wake-up mode. Thus, this situation introduces a small amount of delay in the system.

2.2.4 Contention-Based Protocols (Receiver-oriented)

In receiver-oriented MAC protocols, to effectively and efficiently operate over a wide range of traffic loads, a receiver node initiates the process of allowing some nodes to start a data transfer by sending small control packets. Furthermore, the receiver side needs to be secured with respect to the collisions. In this section, two protocols designed for WSNs to reduce collisions and energy consumption in the network are reviewed.

2.2.4.1 Receiver-Initiated MAC Protocol

In [30], the authors proposed a new MAC protocol called receiver-initiated MAC (RI-MAC), which uses receiver-initiated data transmission in order to operate efficiently over a wide range of traffic loads. In RI-MAC, each node periodically wakes up based on its own schedule and checks for any incoming DATA packets intended for this node. After waking up, a node immediately broadcasts a beacon message to inform others that it is ready to receive a data frame. After receiving this message, a node with a pending DATA frame for transmission starts sending its data frame to the receiver node and the receiver node will then acknowledge with another beacon for the correct receipt of the data frame and invite the same node to continue sending the data frame. Otherwise, the receiver node enters into sleep mode. In RI-MAC, the receiver controls the medium access among other sender nodes. The main advantage of the RI-MAC is that short beacon messages are used instead of long preambles which reduces energy consumption and delay. The drawback of the RIMAC is that the sender nodes have longer idle listening times. In other words, the source nodes should keep their radios on and remain active until an intended receiver node sends a beacon message.

2.2.4.2 Slot Periodic Assignment for Reception MAC Protocol

In [31], the authors proposed a MAC protocol called slot periodic assignment for reception (SPARE MAC) protocol which is a receiver-oriented and an energy efficient data centric MAC scheme for data collection for WSNs. This protocol basically belongs to the category of TDMA-based MAC protocols but its scheduling algorithm is receiver-oriented. In SPARE MAC, each node is assigned radio resources for data reception and exchanges these assignments with its neighbours. Transmitting nodes can become active in the receiving period of their intended receivers. This will limit overhearing, idle listening and unnecessary transmissions on the channel. The SPARE MAC implements a distributed scheduling algorithm to assign a reception schedule (RS) to each node and broadcasts this information to neighbouring nodes. If a node has data to transmit, it first prepares a list of its one-hop neighbour nodes with the corresponding RS, transmits data to a specific one-hop neighbour and goes to sleep. Each node will wake up according to its own RS to receive data from its neighbour node and continue to stay active for the entire RS period.

2.2.5 Contention-Free Protocols

The contention-free protocols eliminate interference by proper scheduling of nodes and ensure that communications are always successful. Examples of contention-free protocols include TDMA-based and CDMA-based protocols. The CDMA scheme enables simultaneous transmissions with minimal interference and allows a node to receive from multiple senders. In CDMA each node is assigned a unique code sequence for its transmission. A node spreads its data out over the entire channel bandwidth using its code sequence. The receiver de-spreads the bits and extracts data from the desired sender. Although CDMA allows transmissions to occupy the entire bandwidth of the channel at the same time, the special coding mechanism narrows the bandwidth for the node’s data. In this sub-section, some of the main TDMA-based and CDMA-based MAC protocols which have been developed for achieving high energy efficiency for WSNs are reviewed.

2.2.5.1 Light MAC Protocol

The Light MAC (LMAC) protocol in [32] is a TDMA-based MAC for WSNs. A time frame is divided into time-slots. The nodes can use these slots to transfer data without having to compete for the medium or having to deal with energy wasting collisions of transmissions. The LMAC assigns only one time slot to each node and gives the node control over this time slot. LMAC allows assigned time slots to be re-used at a non-interfering distance to limit the number of time slots necessary in the network. The LMAC protocol uses a distributed algorithm to assign the time slots among the nodes. A node, during its time slot, will always transmit a message which consists of two parts: a control message and a data unit. Since the LMAC protocol is a TDMA-based MAC protocol, its operation is not dependent on a central manager or base station. Nodes in the network are capable of choosing their own time slot, based only on local information. In the LMAC protocol, there is no hand-shaking mechanism before data can be exchanged. Thus, the number of transceiver state switches can be kept at a minimum. The number of nodes in any two-hop neighbourhood cannot exceed the number of slots in a frame in the LMAC protocol. This needs to be fixed before deployment. A drawback of the LMAC protocol is that all nodes must always listen to the control sections of all slots to receive data. Thus, it increases idle-listening overhead.

2.2.5.2 Event Driven TDMA MAC Protocol

An Event Driven TDMA (EDTDMA) protocol [33] is proposed for WSNs to improve the channel utility by changing the length of TDMA frame according to the number of source nodes. In [33], nodes can reduce the length of TDMA schedule packets with a bitmap-assisted TDMA schedule to decrease the schedule overhead. Besides, it employs intra-cluster coverage schemes to prolong network lifetime and to improve system scalability. In the EDTDMA protocol schedule phase, the cluster head is used to broadcast a schedule packet. In EDTDMA protocol, each frame begins with a reservation phase, followed by a TDMA schedule and data transmission. The operation of the EDTDMA protocol is divided into rounds. Each round begins with a set-up phase, followed by a steady phase. The set-up phase includes clustering and time synchronization. The steady phase consists of n TDMA frames that have different frame lengths. The reservation phase consists of m mini-slots where m is the number of members in the cluster. The members occupy the mini-slot according to their ID. A node which has the maximum ID occupies the first mini-slot and so on down until the node which has the minimum ID occupies the last mini-slot. A member sends a 1-bit reservation message to the cluster head if it has data to send in the current frame. Obviously, the length of the reservation phase is m bits. This scheme is not distributed and if a cluster head fails, nodes may not update/receive neighbourhood information.

2.2.5.3 Traffic Adaptive MAC Protocol

The authors in [34] propose a TDMA-based MAC protocol called traffic adaptive MAC (TRAMA) to increase the utilization of classical TDMA in an energy-efficient manner. TRAMA employs a traffic adaptive distributed election scheme that selects a receiver node based on schedules announced by transmitters. In this protocol, the identification of the nodes within a two-hop neighbourhood is used to give conflict-free access to the channel to a given node during a particular time slot. The TRAMA protocol addresses energy efficiency by having nodes going into sleep mode if they are not selected to transmit and are not the intended receivers of traffic during a particular time slot. The TRAMA protocol consists of three components: the Neighbour Protocol (NP); the Schedule Exchange Protocol (SEP), which allow nodes to exchange two-hop neighbour information and their schedules; and the Adaptive Election Algorithm (AEA), which uses neighbourhood and schedule information to select the transmitters and receivers for the current time slot, leaving all other nodes at liberty to switch to low-power mode. The time frame is divided into random-access and scheduled-access (transmission) periods. A random-access period is used to establish two-hop topology information where channel access is contention-based. A basic assumption is that, by the information passed by the application layer, the MAC layer can calculate the transmission duration needed which is denoted as *SCHEDULE_INTERVAL*. The NP propagates one-hop neighbour information among neighbouring nodes during the random access period using the signalling slots to obtain consistent two-hop topology information across all nodes. Transmission slots are used for collision-free data exchange and also for schedule propagation. Nodes use SEP to exchange traffic-based information, or schedules, with neighbours. Essentially, schedules contain current information on traffic coming from a node, i.e., the set of receivers for the traffic originating at the node. A node has to announce its schedule using SEP before starting actual transmission. SEP maintains consistent schedule information across neighbours and updates the schedules periodically. Several advantages arise out of the TRAMA protocol design. Firstly, the protocol is well suited for applications that are not delay-sensitive but require high delivery guarantees and energy efficiency. The scheduled access to the data slots reduces message collisions and reduces energy consumption. The protocol quickly adapts to changes in the network by providing random access slots once per frame time. Finally, the protocol allows the nodes to share the network state among the other nodes, thus it provides a good deal of flexibility to network and traffic conditions. The protocol has several disadvantages. Firstly, in TRAMA, sensor nodes may not operate optimally when inconsistent state information develops, and this leads to a decrease in performance. The TRAMA protocol uses a distributed hash function to determine a collision-free slot assignment. The TRAMA protocol builds a schedule when a node has data to send. This random scheduling scheme increases queuing delays.

2.2.5.4 Flexible TDMA Based MAC Protocol

In [35], the authors proposed a novel TDMA-based MAC protocol called Flexible MAC (FlexiMAC) for efficient data-gathering applications in WSNs. FlexiMAC protocol [35] is able to cope with some network dynamics and mode mobility. The contention period is defined to allow nodes to exchange their packets by building data-gathering tree rooted to a sink. The data-gathering tree is based on small links to reduce node's interference and to increase spatial reuse. FlexiMAC protocol [35] uses a depth-first-search (DFS) schedule to distribute slots. The Slot assignment is done according to a tree. Two kinds of slots exist in FlexiMAC[35]: data-gathering slots and multifunctional slots. Data-gathering slots are used for uplink traffic from nodes toward the sink. Multifunctional slots are used for downlink traffic and synchronization. In FlexiMAC[35], each node uses three lists: Receive Slot List (RSL), Transmit Slot List (TSL) and Conflict Slot List (CSL) for slot assignment and maintenance. The conflict slot list contains the slots of two-hop neighbouring nodes with which the node interferes. The advantages of FlexiMAC protocol[35] is that it offers a synchronized and flexible slot structure in which nodes in the network simply build, modify, or extend their schedules based on the local information available to nodes (RSL, TSL, and CSL). Further, in the FlexiMAC protocol [35], nodes can adaptively adjust node transmission power for a given topology. These nodes can increase their transmission range when they are repelled by an obstacle. Nodes can also increase their transmission range if their current range cannot reach any neighbour in a low-density network. The main problem in FlexiMAC protocol [35] is that the data-gathering tree structure lacks robustness and optimality. When a link fails a tree reconstruction even localized is necessary. In [35], only parent-child and child-parent communications are optimal. When a nodes wants to communicates with its neighbour node then it should pass by its nearest common parent node. This mechanism may consume large amounts of energy and also increases the latency.

2.2.5.5 Power Efficient and Delay Aware Medium Access Protocol

The MAC protocol proposed in [36] is called Power Efficient and Delay Aware Medium Access (PEDAMACS) for WSNs. This protocol uses the high-powered access point to gather information about the network topology to synchronize the nodes and to schedule their transmissions and receptions. This protocol improves the performance of the system in terms of power consumption, delay and fairness as it employs scheduled node transmissions. The protocol consists of several nodes and one access point (AP). It was assumed that the AP has enough power to reach all the sensor nodes in the network. The PEDAMACS protocol operates in three phases, i.e. the topology learning phase, the topology collection phase and the scheduling phase. In the first phase, every node learns about its neighbours, interferers and parent node. In the second phase, each node sends local topology information to the central controller (AP). At the end of this phase, the AP learns about the full network topology. At the beginning of the scheduling phase, the AP broadcasts a schedule. Each node then follows the schedule. In particular, a node sleeps when it is not scheduled to transmit a packet or listen for one.

2.2.5.6 CDMA Sensor MAC Protocol

The CDMA sensor MAC (CSMAC) is a self-organizing, location-aware MAC protocol proposed in [37] for direct sequence CDMA (DS-CDMA) based WSNs. The design objectives of the CSMAC protocol [37] include the energy efficiency, low latency, scalability and fault-tolerance. This was achieved through the use of a DS-CDMA system combined with frequency division to multiple-access interference. In CSMAC [37] protocol designed for high data-rate sensor applications, nodes explicitly exchange their location and maintain a neighbour location list. Minimal set of neighbouring nodes is identified from the list to provide reliable network information and sleep is enabled on other nodes to exploit the network redundancy.

The main advantage of CSMAC [37] is that the protocol is a contention-less system even though CDMA itself is not contention-less because of an MAI problem. There is no carrier sense and hand-shaking in the CSMAC protocol. The CSMAC uses a combination of CDMA and FDMA to reduce channel interference and consequently improve system capacity and throughput. The Simulation results in [37] have shown that CSMAC protocol significantly reduce average message latency and average energy consumption per message in comparison to traditional sensor network MAC protocols. The CSMAC is not a distributed MAC protocol for WSNs and location-awareness might require additional overhead (such as GPS).

2.2.5.7 MAC Protocol for Long-Latency Access Networks

In [38], the authors proposed a distributed MAC protocol for underwater WSNs called a MAC protocol for long-latency access networks (PLAN), which utilizes CDMA as the underlying multiple access technique to minimize multipath and Doppler effects, which are inherent in physical channels. The PLAN uses a three-way hand-shake which collects the RTS from multiple nodes before sending single CTS. It is therefore able to achieve high throughput performance using reduced overheads in view of severe energy constraints faced by sensor nodes. The simulation results show that the proposed scheme results in fewer overheads and shorter delays.

2.2.5.8 SNMAC Protocol

A CDMA-based power controlled MAC protocol (SNMAC) proposed in [39], uses a combination of DS- CDMA and TDMA on the MAC layer and reduces channel interference by using a power controlled mechanism and a separate code for control packets. The network is divided into clusters where each node could be any hop away from the clusterhead, which are kept intact for the whole network lifetime. A simple clustering algorithm (SCA) is developed in [39] to show that protocol does not need complex clustering and works fine even if only the basic requirements are met. The algorithm targets the MAC layer and provides through a cross layer design an optimum routing strategy that gives a best effort design to deliver data from the sensors towards the base station. The information flow traverses several nodes within a cluster reaching the clusterhead which in turn delivers the data to the base station. The clusters are divided into levels where each node chooses its best neighbour which is one level away from it, based on considerations of the battery state of the node and packet transmission information which are represented in the form of a priority function. The main problem with this protocol is that the topology is divided into clusters. A node uses the priority based algorithm to select the cluster head. If this node fails to work this means the whole network fails.

2.2.6 Hybrid-Based Protocols

There have been some hybrid-based MAC protocols developed on TDMA and CDMA access methods for WSNs. In this section, some of these protocols have been discussed.

2.2.6.1 Zebra MAC Protocol

In [40], a new MAC protocol called Zebra-MAC (ZMAC) for WSNs is presented, which can dynamically adjust the behaviour of MAC between CSMA and TDMA depending on the conditions of contention in the network. This protocol uses the knowledge of topology and loosely synchronized clocks to improve the performance of the MAC protocol. Whenever a node wakes up, it first runs a simple neighbour discovery operation where it periodically broadcasts a ping to its one-hop neighbours to gather its one-hop neighbour list. Nodes in ZMAC run a distributed slot algorithm to get a collision-free time slot in the network. Once a node gets its time slot, it can use this slot for data transmission. The ZMAC protocol has two modes (LCL and HCL) where each node can be in any of these modes. In LCL, nodes can compete for transmissions in any slot whereas in HCL, only the owners of the slot and one-hop neighbour nodes are allowed to access the channel to transmit their data. The node in ZMAC sends ECN messages when they experience high contention. The ZMAC protocol is easily adapted to varying traffic conditions. This leads to significant energy savings for WSNs.

2.2.6.2 Low-Energy Adaptive Clustering Hierarchy Protocol

A combined TDMA/CDMA based MAC approach was presented in [41] called Low-energy adaptive clustering hierarchy (LEACH) which was a self-organized, adaptive clustered protocol that uses randomized distribution of the energy load evenly among the sensor nodes in the network. Each node communicates with a dynamically elected cluster head directly (no multi-hop) using the TDMA scheme. Cluster heads use a CDMA approach to communicate with a remote destination (sink) directly. There are several advantages of LEACH, these are namely, (i) Energy requirements of the system will be distributed among all the nodes using adaptive clusters and rotating cluster heads and (ii) A local computation is performed at each cluster to reduce the amount of data which must be sent to the base station. However, this protocol has several disadvantages viz. (i) There is no scheme in LEACH to determine how to distribute the cluster-heads uniformly throughout the networks and (ii) LEACH is not appropriate for non-uniform energy nodes because it assumes that all nodes will have the same amount of energy capacity in each election round.

2.2.6.3 Pattern MAC Protocol

The authors in [42] proposed a novel MAC protocol for WSNs which allows nodes to determine their wake-up-sleep schedule adaptively. The nodes determine the schedule based on their own traffic and their neighbours' traffic. In Pattern MAC (PMAC), the node uses patterns to exchange neighbourhood information among other nodes. A pattern is actually a repetition of an n-sleep/1-awake cycle allowing for representation as a single number. After receiving these patterns, a node can decide to put itself into a long sleep for several frames when there is no traffic in the network. The frame format in the PMAC protocol consists of a number of reserved slots for pattern exchange and a number of slots for data transmission. A node's pattern is represented as a bitmap of time slots during which it plans to sleep (bit cleared) or wake up (bit set) during the next frame. During the pattern repeat period of a frame, nodes follow the sleep/wake schedule they have announced in the previous frame. In PMAC, nodes wake up during their own scheduled transmission slots and also wake up during scheduled transmission slots of their neighbours. The PMAC uses control packets such as RTS/CTS/DATA/ACK for data transmission to avoid collisions and provide reliability. In order to conserve energy in the network, nodes may wake up and listen for a short period and switch to sleep mode if there is no transmission activity in the channel. At the end of the pattern repeat period, sensor nodes start exchanging their chosen patterns. During this pattern exchange period, all sensor nodes with traffic proposal contend for the pattern exchange slots to send their pattern information. The pattern exchange period must be long enough to allow all nodes to successfully send their pattern information so the total number of pattern exchange slots must be at least as many as the maximum number of neighbours. Advantages of PMAC are that a node only needs to wake up in its own slots to check for incoming traffic instead of checking in every slot. This scheme would reduce the energy consumption of the network. It also provides good adaptability to changing traffic loads in the network. The main disadvantages of PMAC are that the protocol keeps the nodes in the sleep state for most of the time; this may reduce the throughput of the system. Another problem that arises in PMAC is that nodes may face inconsistencies in scheduling among nodes in the network and this leads to increased energy waste due to collisions, idle listening, and wasted transmissions. PMAC requires sensor nodes to perform a pattern exchange whenever their traffic is expected to change in the next frame. If the pattern exchange happens frequently, it significantly increases energy consumption because of the processing power and active power involved for updating the pattern.

2.2.6.4 Crankshaft Protocol

Crankshaft protocol proposed in [43] divides time into frames, with each frame divided into *n* slots. Crankshaft assumes global synchronization and assigns a wakeup slot to each receiver. If there are n unicast slots, the node own slot *i* that is the result of it’s as its MAC address module *n*. It is tolerated that two neighbours share the same slot. This protocol uses the channel polling scheme, which was used in the SCPMAC protocol [20] for node communication. Although there are more elaborated collision-free slot assignment methods, this way of assigning slots aims at reducing complexity. As many nodes may want to transmit a frame to a node at the same time, Crankshaft uses a contention mechanism prior to transmission and each transmission is followed by an acknowledgement packet. The duration of a slot should be large enough to contain contention, data, and acknowledgment. The Crankshaft protocol is best suited for environmental monitoring applications. This is because the Crankshaft protocol can lengthen the network lifetime of dense sensor networks by reducing the overhead of overhearing neighbours' activities and by utilising the efficient channel polling and contention scheme. Every receiver can use only a fixed slot in each time, making Crankshaft inflexible in handling bursty traffic that may occur in WSNs. In addition, using this fixed scheduling of receiver wakeup slots can lead to receivers repeatedly waking up at the same time, causing packet collisions.

2.3 IEEE 802.15.4 MAC protocols for WSNs

This subsection briefly discusses the IEEE 802.15.4 MAC protocol for WSNs. More details of the standard can be found in [44]. The IEEE 802.15.4 standard [44,45], which is used as a basis for the wireless sensor networking technology based on the highway addressable remote transducer protocol (WirelessHART), Zigbee and microchip wireless (MIWI) specifications, was originally designed for low-data rate, low-cost, low-powered Wireless personal area networks(WPAN). The standard has been adapted for use in WSNs, home automation and remote controls, etc. The IEEE 802.15.4 standard offers an implementation for the lower layers, PHY and MAC, for a typical WSN as discussed in [44] with no critical concerns about throughput and delay. The basic IEEE 802.15.4 framework defines a 10-20 meter communications area with a maximum transfer rate of 250kbits/s [44, 45]. IEEE 802.15.4 supports a star topology or a peer-to peer topology.

The protocol structure of 802.15.4 contains PHY and MAC layers only [45, 45]. The MAC layer is responsible for point-to-point delivery between nodes. Besides the data service, it offers a management interface and itself manages access to the physical channel and network beaconing. It also controls frame validation, guaranteed time slots (GTS) and handles node associations. The 802.15.4 MAC sub-layer controls access to the channel by using a CSMA-CA mechanism. The MAC protocol supports two operational modes [44-48]:

a. The **beacon-enabled mode**: In this mode, beacon frames are periodically sent by the Zigbee coordinator (ZC) to synchronize nodes that are associated with it, and to identify the PAN. The medium access is controlled by a slotted CSMA/CA mechanism. The beacon-enabled mode also enables the allocation of contention-free time slots to nodes requiring guaranteed bandwidth.

b. The **non-beacon-enabled mode**: When the ZC selects the non-beacon-enabled mode, the medium access is controlled by an un-slotted CSMA/CA mechanism and there are neither beacons nor super-frames.

There have been a number of studies [46-48] to improve the performance of IEEE 802.15.4 MAC standard in terms of Qos support in the literature. It is considered that surveying three of the examples [46-48] would be sufficient to understand the basics of the IEEE 802.15.4 MAC protocol as they mainly adopt similar strategies. The authors in [46], the IEEE 802.15.4 MAC beacon-enabled mode for broadcast transmissions in WSNs was proposed. A comprehensive simulation model is developed to evaluate the performance in terms of throughput, average delay and success probability. The work in [46] also introduced the concept of utility which is defined to determine the optimal offered load to achieve the best trade-off between all combined metrics. In [47], the authors briefly described an OPNET simulation model of the IEEE 802.15.4 GTS mechanism. The proposed methodology in [47] is developed to tune the MAC protocol parameters to obtain maximum data throughput and minimum frame delay.

In [48], the authors derived an extension for IEEE 802.15.4 CSMA/CA to include re-transmission limits of the nodes with packet collision probability. An analytical and simulation model is developed to analyse the throughput and energy consumption of the nodes. It is observed that the nodes having larger packet size could get a better throughput [48] and the energy consumption of the nodes increases with higher data rates.

2.4 Summary

In this chapter, the MAC protocols for WSNs were reviewed. Table 2-1 and 2-2 shows a summary of MAC protocols discussed in this chapter. The comparison of protocols is shown by taking parameter type of scheme used, efficiency, latency, application, traffic, lifetime, advantages and disadvantages. The majority of the MAC protocol designs are based on CSMA, TDMA for WSNs. Only a few MAC protocols are designed based on CDMA for WSNs (refer to [37-39]). All of the protocols are designed to achieve high energy efficiency for WSNs. In general, there is no "best" MAC protocol for WSNs, the choice depends on the type of application, expected load patterns and physical deployment environments.

Table 2-1: Comparison of MAC protocols

Protocol	**Type**	**Advantages**	**Disadvantages**
SMAC [10, 11]	CSMA	Idle listening is reduced by periodic sleep schedules and energy efficient.	Low fault-tolerance. Unsuitable for variable traffic load, high latency.
TMAC [13]	CSMA	Variable traffic load adaptation and overhearing avoidance.	Virtual cluster synchronization problem. Aggressive in shutting down nodes before emptying the buffer.
DMAC [19]	TDMA / Slotted Aloha	Low latency.	Lacks flexibility, time synchronization among the nodes. There are no measures to avoid collisions.
SCPMAC [20]	CSMA and low-power listening	Adapts very well to variable traffic, supports broadcast using clustering techniques and achieves good synchronization between nodes in clusters.	Long preamble costs more energy consumption. Increases contention. Overhearing problems is not addressed sufficiently.
CSMAMPS [21]	CSMA	Suitable broadcast transmissions, reduces preamble length.	The receiver node should always be in the wake up mode.
WiseMAC [22]	Preamble sampling scheme	Achieves good performance under variable traffic load.	High latency and energy efficiency not achieved.
BMAC [24]	Adaptive preamble sampling scheme	Idle time is reduced to minimum. Simple to implement and less overhead when the network is idle.	Overhearing problem is not addressed. Long preamble increases energy consumption in the network.
XMAC [26]	Preamble sampling scheme	Protocol has low latency and less overhead due to no need for synchronization and energy efficient	Protocol failed to handle bursty traffic. Idle time increases when a particular node waits for ACK from an intended receiver node.
MaxMAC [27]	Preamble sampling scheme	Adapts very well to varying traffic load and achieves good energy efficiency.	Does not work on packet-oriented radios.
BEAM [29]	Contention Based	Robust and high performing protocol can	Protocol has small amount of delay in the system.

	Reservation	be used in different environmental conditions.	
RIMAC [30]	Receiver oriented	The receiver controls the medium access among other sender nodes.	The sender nodes will have longer idle listening time.
SPARE MAC [31]	Receiver oriented TDMA	Reduced collisions and idle listening time of nodes.	Control packet overhead is large and the data delay is also very large. Poor scalability.
TRAMA [34]	TDMA	Quickly adapts to changes in the network. A scheduled access to the data slots reduces message collisions	Nodes may not operate optimally when inconsistent state information develops; this leads to decrease in performance.
FlexiMAC [35]	TDMA	Scalability, flexibility to adding new nodes or removing nodes in the network.	Maximizing the system throughput is not considered.
PEDAMACS [36]	TDMA	Provides a guaranteed bounded delay and eliminates network congestion and reduces energy consumption.	The protocol can be used for few applications as it requires powerful access points. This requirement weakens its attractiveness.
CSMAC [37]	CDMA	No carrier sense, hand-shaking, reduces the channel interference.	There is no reservation of slots, scheduling, and acknowledgement schemes.
SNMAC [39]	CDMA TDMA	Protocol uses the scheduling algorithm to reduce energy waste due to idle listening, overhearing and collisions.	Network fails if the cluster head fails.
ZMAC [40]	Hybrid	Easily adapted to varying traffic conditions.	Requires global clock synchronization once at the setup phase.
LEACH [41]	Hybrid	Energy requirements of the system will be distributed among all the nodes using adaptive clusters and rotating cluster heads.	There is no scheme to determine how to distribute the cluster heads uniformly throughout the networks and not appropriate for non-uniform energy nodes.
PMAC [42]	Hybrid	A node only needs to	Nodes may face

		wake up in its own slots and provides good adaptability to changing traffic loads.	inconsistencies in scheduling among nodes and protocol keeps the nodes in the sleep state for most of the time.
Crank soft [43]	Hybrid	Protocol can lengthen the network lifetime of dense sensor networks by reducing the overhead of overhearing neighbours' activities and by utilising the efficient channel polling and contention scheme.	Crankshaft comes at the cost of inflexibility, which limits the applicability of the protocol for other types of sensor network applications.

Table 2-2: Synthetically Comparing different MAC protocols

Protocol	**Efficiency**	**Latency**	**Lifetime**	**Overhearing**	**Traffic type**	**Application**
SMAC [10, 11]	Good	High due to fixed duty cycle	Good	Low	Not suitable for variable traffic loads	Event-driven, long idle periods, delay order of message time
TMAC [13]	Good	Low	Good	Low	Variable traffic loads	Event-driven
DMAC [19]	Good	Low latency	Good	Low	Not adaptive to traffic-pattern changes	Data Gathering application
SCPMAC [20]	Good	High due to long preamble	Low	Good	Static and periodic traffic	High levels of network contention and environmental monitoring applications
CSMAMPS [21]	Low	Low	Good	Good	Designed for high bit rate transceivers	Low duty cycle applications
WiseMAC [22]	Good	High latency	Low	Good	Adaptive to traffic , Supports sporadic, periodic	Applications tolerating large transmission delays

					and bursty traffic	
BMAC [24]	Low due to Long preamble increases energy consumption in the network	High	Low	Overhearing problem is not addressed	Unicast traffic, Periodic application	Delay tolerant applications
XMAC [26]	Energy efficient	Low latency	Good	Good	Adaptive to variable traffic load	Applications with very loose latency requirements
MaxMAC [27]	Achieves good energy efficiency	Low	Good	Good	Adapts very well to varying traffic load	Monitoring applications, disaster-aid systems or tracking applications
BEAM [29]	Energy efficiency	Protocol has small amount of delay in the system	Good	Good	Continuous data streams, data bursts and event-based traffic	Used in different environmental conditions
RIMAC [30]	Good	Low	Good	Reduces Overhearing problem	Unicast traffic, Burst traffic	Detection and tracking applications
SPARE MAC [31]	Low	Data delay is very High	Low	No overhearing problem	Periodic traffic	Data diffusion application
TRAMA [34]	Good	Low	Good	Good	Adapt to traffic, Synthetic Traffic	Event-tracking application
FlexiMAC [35]	Good	Low/ bounded latency	Good	No overhearing problem	Adapt to traffic	Query based applications
PEDAMACS [36]	Energy efficient	Provides a guaranteed bounded delay	Good	No overhearing problem	Periodic traffic	Traffic control and monitoring application

CSMAC [37]	Good	Low	Good	No overhearing problem	Unicast and broadcast traffic	Applications that have high traffic and stringent latency requirements
SNMAC [39]	Energy efficient	Low	Good	No overhearing problem	Periodic traffic	Intrusion detection, medical monitoring, animal tracking
ZMAC [40]	Energy efficient	Experiences high latency together with high transmission but achieves low-latency under low contention	Good	No overhearing problem	Easily adapted to varying traffic conditions	Can be used in applications where expected data rates and two- hop contention are high
LEACH [41]	Energy efficient	Low latency	Good	No overhearing problem	Periodic traffic	
PMAC [42]	Energy efficient	Low latency	Good	No overhearing problem	Good adaptability to changing traffic loads	
Crank soft [43]	Energy efficient	Low latency	Protocol can lengthen the network lifetime	Reduces overhearing problem	Convergecast traffic, broadcast traffic	Monitoring applications

Chapter 3

Energy Efficient Distributed DS-CDMA based MAC protocol for WSNs

3.1 Introduction

In the previous chapter, the MAC protocols developed for WSNs were reviewed. The majority of the MAC protocols are based on the TDMA scheme. However, the TDMA scheme has some disadvantages that limit its use in WSNs. The major problems with the TDMA scheme are the synchronization of nodes and adaptation to network topology changes, where these changes could be caused by the relay nodes' sleep schedules, broken links, adding new nodes into the networks or exhaustion of nodes' battery capacity. Only a few MAC protocols have been designed based on CDMA for WSNs. Further, the protocols proposed in [10, 12, 19-43, 46-48] do not consider the wastage of energy due to re-transmission of dropped or blocked packets when the channel load is high in the system. Thus, in this chapter, a new MAC protocol called Energy Efficient Distributed DS-CDMA based MAC protocol for WSNs (DRMACSN) is presented**.** This protocol employs a channel load sensing scheme to improve the packet throughput and reduce delay and energy consumption in the system**.** In the proposed MAC protocol, once the reservation for the transmission has been successfully completed with the receiver node, the control packets, such as the Preamble and ready to receive (RTR) packets, are not used any more for the duration of the transmission to conserve energy in the network. It is considered that each sensor node is assigned with the transmitter-based code to transmit the preamble packets and the receiver-based code [49-50] for the RTR, and the DATA/ACK transfer purposes. The sensor node also uses a common code for broadcasting the RTR and Data Sending (DS) packets to neighbour nodes. The details of PN codes or code allocation schemes are not discussed in this thesis. Rather, it is assumed that the code pool is large enough to satisfy a reasonably large number of sensor nodes in the network.

The motivation for a new MAC protocol is summarized as follows**:**

a) The proposed MAC protocol is a distributed protocol, i.e., there is no central coordinator in the system.

b) The proposed MAC protocol is a receiver–oriented protocol because only the receiver side needs to be secured with respect to collisions.

c) The transmission rate selection can be improved by providing timely CQI to a sender node.

d) The proposed MAC protocol is a slotted reservation-based protocol, which allows sensor nodes to reserve their slots.

3.1.1 Packets format

The following are the packet formats used in the proposed MAC protocol:

a) **Preamble:** The sender node uses this packet to send its request to transmit its packet to a receiver node. This packet has three entries: source node id, receiver node id, transmitter-based code.

b) **Ready to receive (RTR):** This packet used by the receiver node to send its confirmation to receive the data packets from the sender node after receiving the preamble packet. The receiver node checks the channel status before sending the RTR packet. This packet has four entries: source node id, receiver node id, Channel quality indicator (CQI), and a receiver-based code. The receiver node uses common code to notify its neighbour nodes about its ongoing transmissions with the current sender node.

c) **Data**: This packet contains source node id, receiver node id, receiver-based code, sequence number.

d) **Neighbour node table (NRT):** This table is used to maintain the number of neighbour's nodes. This table has four fields: sensor node id, receiving/transmitting, simultaneous transmissions (K) and the reservation of mini-slots**.**

e) **Data sending (DS) packet**: This packet used by the sender node to notify to its neighbour nodes before starting its data packet transmission. This packet has four entries: source node id, neighbour node id, NRT and common code.

f) **Acknowledgement (ACK):** This packet is used by the receiver node to notify about receipt of all packets from sender node. This packet contains the source node id, receiver node id, receiver-based code and sequence number.

This chapter is organized as follows. Section 3.2 presents the proposed DRMACSN MAC protocol in detail. The channel load sensing scheme is presented in Section 3.3. The sources of energy wastage for WSNs are discussed in Section 3.4. The traffic and channel models for the proposed MAC protocol are discussed in Section 3.5. Section 3.6 provides the performance metrics used to evaluate performance of the DRMACSN protocol. In Section 3.7, the performance results of DRMACSN protocol obtained through simulations for various blocking threshold values for the average packet throughput, energy consumption and packet delay are presented, the simulation results of DRMACSN protocol are validated with the results of IEEE 802.15.4 MAC and No blocking scheme for the average packet throughput, energy consumption and packet delay are also presented. The chapter concludes with a summary of the main contributions in Section 3.8. It is worthy to note that the work conducted under this chapter appears in [15] and in the forthcoming publication [51].

3.2 DRMACSN MAC Protocol Description

In this section, the DRMACSN MAC protocol functions are presented. In the DRMACSN MAC protocol, the Spread-Slotted-Aloha (SSA) protocol [24] is considered as the channel accessing technique. In the DRMACSN MAC protocol, it is assumed that each node can exist in one of three states: Sleep, Back-off or Active (Transmit) as shown in Figure 3.1. In this thesis work, it is assume that a route from the source node to the receiver node is known.

3.2.1 Frame Format of DRMACSN MAC Protocol

In the proposed MAC protocol, the time is divided into fixed length frames of duration, T_f (20 ms). The network is capable of supporting variable length data messages of any size. Each message is sub-divided into fixed length packets containing L bits, such that the transmission of a packet corresponds exactly with one frame. It is considered that messages with more than one packet are transmitted contiguously over as many frames as there are packets in the message. A frame is further sub-divided into three sub-frames as shown in Figure 3.2(a). Figure 3.2(b) shows the spreading codes available for selection by the nodes. The length of first sub-frame is 2ms and is called the preamble slot. The preamble slot is further divided into two sub-frames, the first sub-frame, preamble mini-slots, has a length of 1 ms and the second sub-frame in the first sub-frame, RTR slot, has a length of 1 ms to receive RTR information from the desired receiver node.

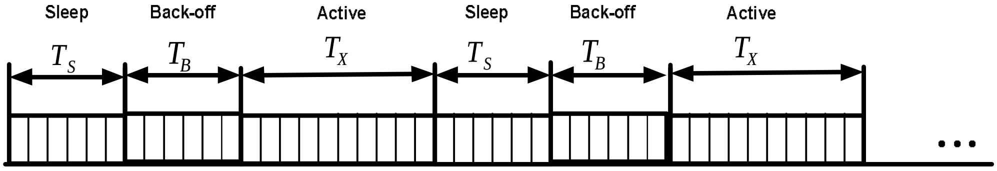


Figure 3.1: Protocol states of DRMACSN MAC protocol

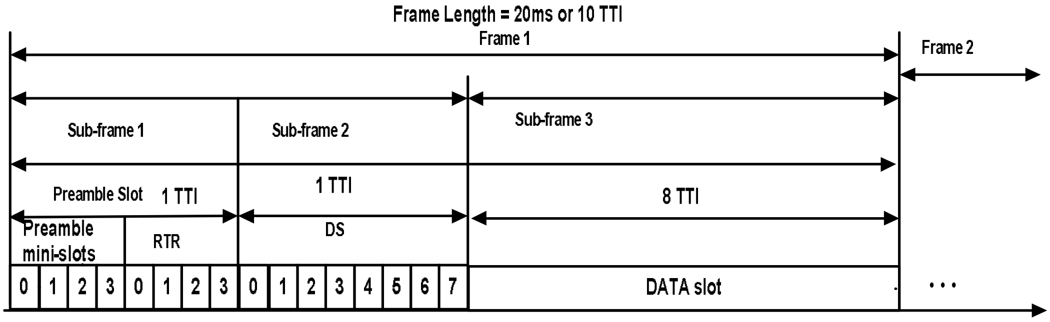


Figure 3.2(a): The basic frame structure for DRMACSN MAC protocol frames

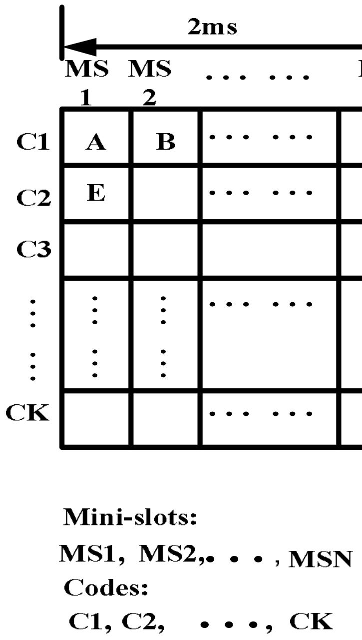


Figure 3.2(b): Spreading codes for DRMACSN MAC protocol

The second sub-frame is called data sending (DS) of size 2ms, which is used by the nodes to update the network status. The third sub-frame which occupies the remaining 16ms of the frame is called DATA slot as shown in Figure 3.2(a).

3.2.2 Description of the DRMACSN MAC Protocol Phases

In this section, the three phases of the DRMACSN MAC protocol are described in detail. In the DRMACSN MAC protocol, the node continues to stay in the sleep state for a random period of time. When messages start to arrive and the sleep timer expires the node enters into transmit state if the channel load, K is less than the blocking threshold, $\propto$, i.e., $K < \propto$, otherwise, the node enters the back-off mode from sleep state when the channel load K exceeds the blocking threshold.

The DRMACSN MAC protocol has three phases, namely, reservation of mini-slots, network status announcements, and data transmissions as shown in Figure 3.2(a). When a node is in transmit state, it executes reservation of mini-slots and network update phases before it starts data transmission. The three phases are discussed in detail with suitable examples.

3.2.2.1 Phase 1: Reserving of Mini-slots

When a node is in the transmit state and has data messages queued in its buffer, it randomly selects one mini-slot as the slot time to transmit its preamble request from the available mini-slots in the preamble slot (refer to Figure 3.2(a)). Once the sender node has reserved its mini-slot, it starts sending its preamble packet to its intended receiver node using the transmitter-based code, starts its timer, and waits for the RTR in the RTR slot of the next frame duration. If the RTR does not arrive within the timeout period, then it goes into sleep mode. This information will be broadcast to other nodes in the network when they exchange their neighbourhood information during the network update phase (sub-frame 2 in Figure 3.2(a)) in the next frame.

An example is illustrated in Figure 3.3. Source node A has data messages in its buffer to transmit to the receiver node B. It is assumed that node A has already determined the path to its destination node B. It then randomly chooses a mini-slot, i.e. ms1 from the available mini-slots (4 mini-slots are shown in Figure 3.3) and code C_1. After this reservation, it begins sending its preamble request to Node B using its selected transmitter-based code, C_1 (as shown in Figure 3.2(b)) and waits for the RTR reply in the next frame. Similarly, Node G has data packets in its buffer and has already selected a route to its sink node, and wants to send its data packets to its neighbour receiver node, B. Node G randomly selects the mini-slot, ms1 and the code C_4 in the same preamble slot as shown in Figure 3.3.

After reservation, it starts sending its preamble request to a receiver node B in the same preamble slot in the next frame using its selected transmitter-based code, C_1. Since the DRMACSN protocol is a distributed DS-CDMA-based MAC protocol, there will be simultaneous transmission on the same slot in the system. The receiver node, then first starts sending RTR packets to Node A using its chosen receiver-based code, C_7 and then to Node G using C_{12} code in frame j.

Similarly, Node E has data messages in its buffer to transmit to the receiver node F. It randomly chooses a mini-slot, i.e. mini-slot ms3 and code C_3 from the available mini-slots. After this reservation, it starts sending its preamble request to Node F using the C_3 code and waits for the RTR reply in the RTR slot of a next frame.

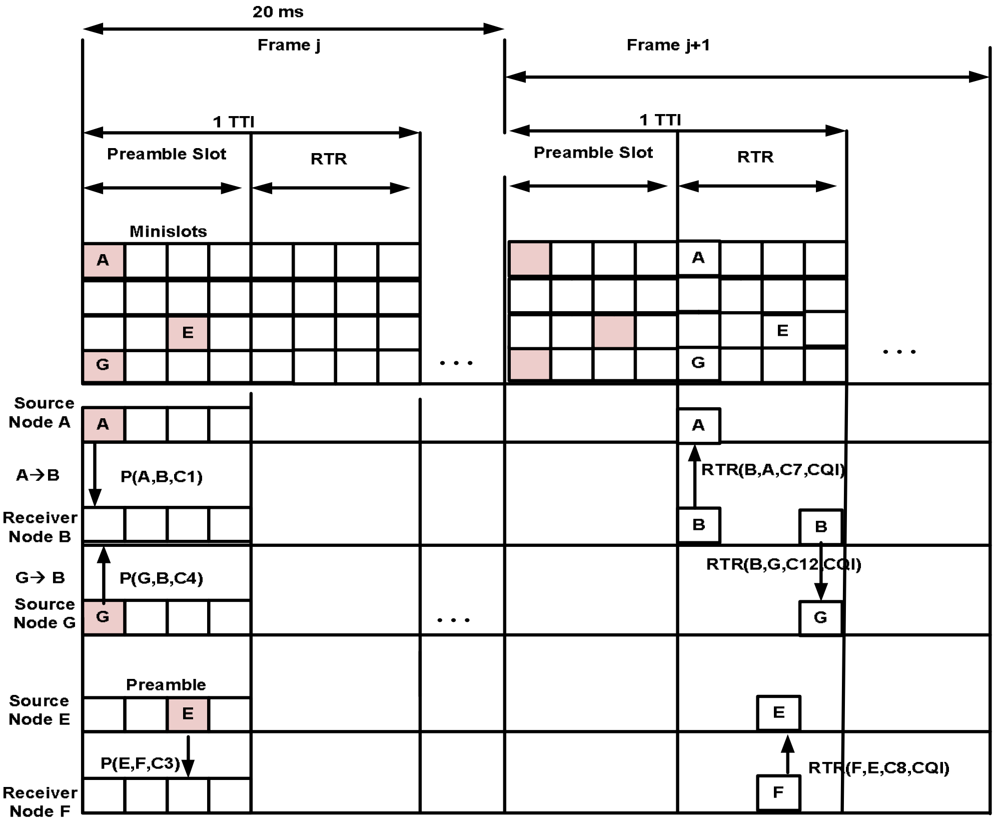


Figure 3.3: Example of reserving slots to transmit preamble and RTR packets in DRMACSN protocol

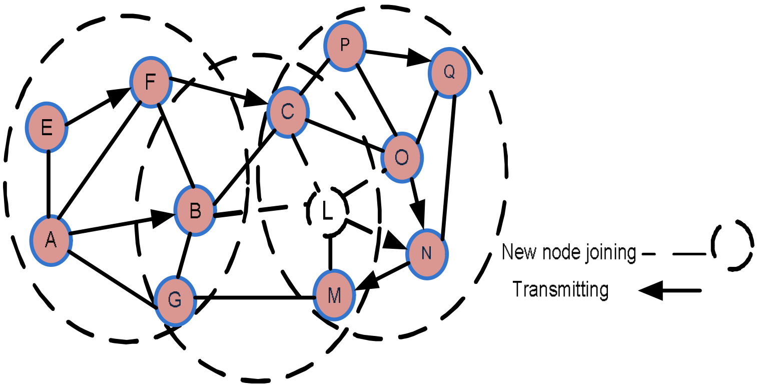


Figure 3.4: Transmissions in the current topology, where Node L is new node

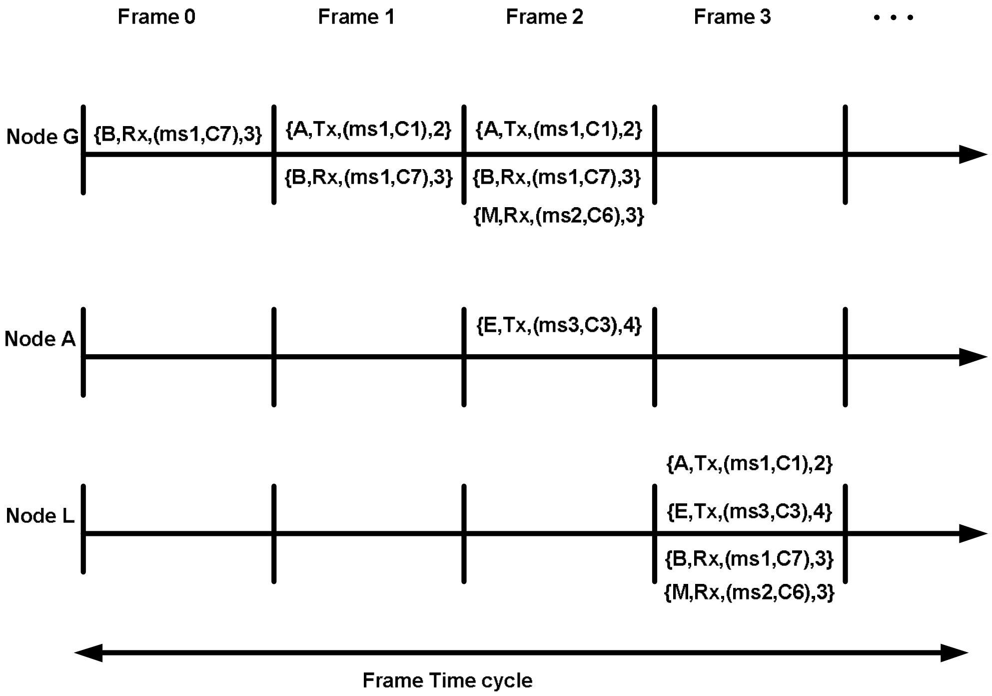


Figure 3.5: Neighbourhood reservation table of nodes

3.2.2.2 Phase 2: Network Update

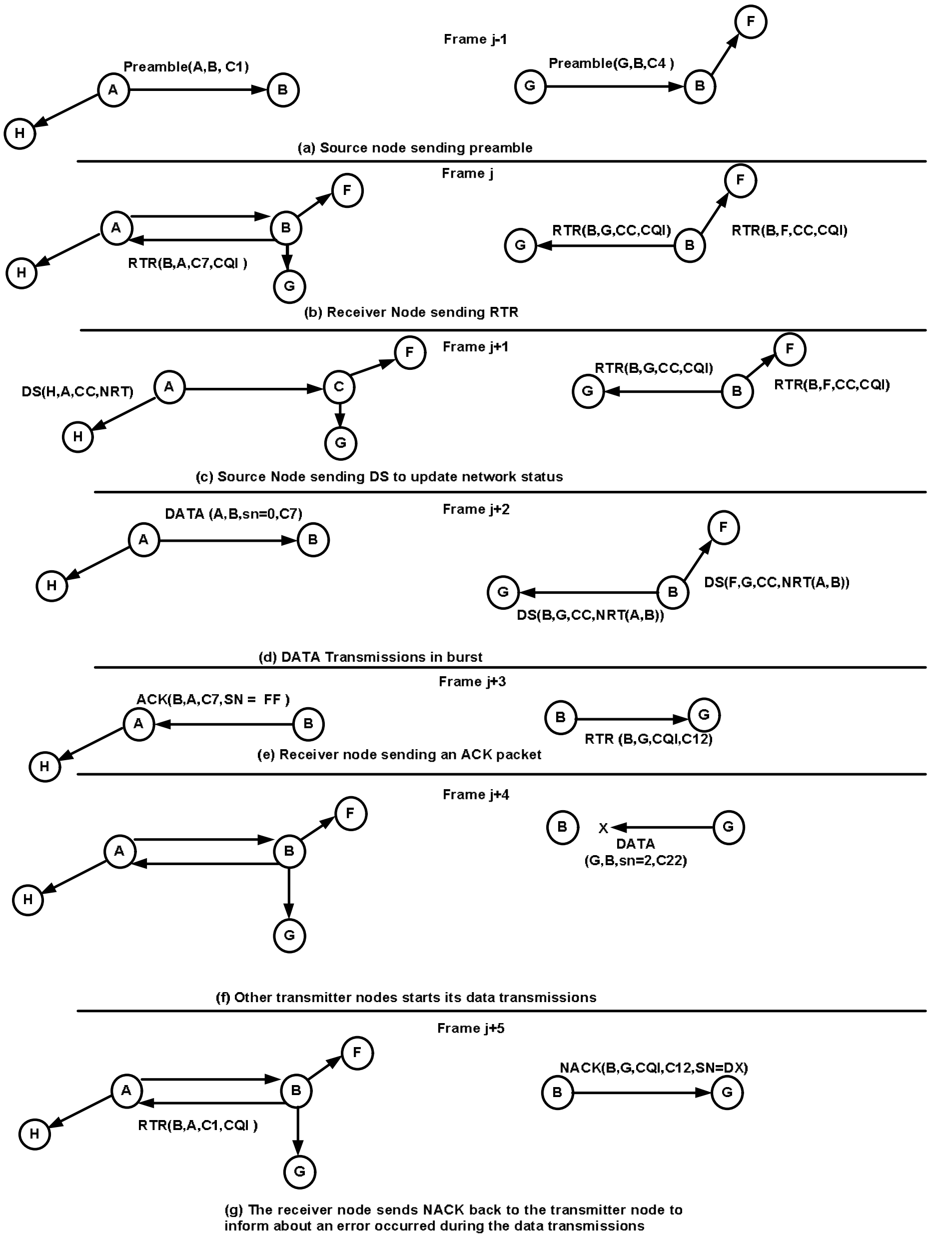
In the proposed MAC protocol, the receiver node is responsible for controlling the collisions that may occur when more than one source node sends preamble requests in the preamble slot. This could lead to a possible corruption at the receiver node [52]. Since the proposed MAC protocol is a distributed protocol, each node in the network is required to maintain the NRT as in [53], which gives information about the reservation and on-going simultaneous transmissions on a frame in the system. The table information will be exchanged with the other nodes in the network as in Multiple Access Collision Avoidance/Packet Reservation (MACA/PR) protocol [53]. This table is used to maintain the information about reservation slots and the number of simultaneous transmissions on a frame. This table has four fields: sensor node identity number, receiving/transmitting, simultaneous transmissions (K) and the reservation of mini-slots. Figure 3.4 shows an example of the topology with on-going transmissions shown by arrows. Figure 3.5 reports the reservation activity recorded by nodes A, G and L in the system. In Figure 3.5, for the link E→F, Node A receives a DS packet from Node E on frame 2, it records {(E,Tx,(ms3, C_3)),4} on frame 2 in its NRT. Node G records the reservation activity for each frame as follows. For example, for the link A→B, Node G receives an RTR packet from Node B in frame 0 and a DS packet from Node A in frame 1, Node G records (B, Rx,(ms1, C_7)),3 } on frame 0 and {(A,Tx,(ms1, C_1)), (B, Rx,(ms1, C_7)),3 } on frame 1. For the link N→M, Node G receives RTR from Node M in frame 2. Thus {M, Rx, (ms2, C_6),3} is recorded in the NRT of node G for the frame 2 as shown in Figure 3.5. Suppose that Node G wants to send its data packets to Node M, Node G must check the NRTs of both nodes (G and M) to choose randomly an empty mini-slot in frame 4 to make reservation for its future transmissions. It is therefore necessary to exchange NRT information periodically among the neighbours in order to notify any new reservation, or to maintain the proper bookkeeping of feasible slots in the network.

Consider now the case where Node L is a newly activated node in frame 2 (refer to Figure 3.4). Suppose that Node L wants to send its packet to Node N on the available free mini-slot in the next frame. In this thesis work, it is considered that Node L must wait for 1 frame duration to receive the NRTs from its neighbours and to gain knowledge of the on-going transmissions in the network, before attempting to reserve a free mini-slot, i.e. any free mini-slot in frame 3 for its exclusive use. It can update its NRT and exchange the NRT with other neighbouring nodes in the next frame. If there is no free mini-slot, then L enters the sleep mode to retry later.

3.2.2.3 Phase 3: Data Transmission Phase

Figure 3.6 illustrates the data transmissions on a frame in DRMACSN MAC protocol. In the DRMACSN MAC protocol, long data messages are fragmented into many small fragments and the protocol will transmit packets in a burst as in S-MAC [10, 13] except that the DRMACSN MAC protocol continues to send the packets without waiting for the acknowledgement (ACK) after every fragment’s transmission. Upon receiving the RTR packet from a receiver node as shown in Figure 3.6(b), nodes send the DS packet using the common code (CC) to its neighbour node in order to update the network status in the new frame. As shown in Figure 3.6 (c), Node A sends a DS packet (DS (A, H, CC, NRT)) to the neighbour nodes to upgrade the current network status. The transmitter node starts its transmission of packets using the receiver-based code to the receiver node as shown in Figure 3.6(d). Then, Node A starts its timer to receive an ACK back for its data transmissions.

When the receiving node receives data in full form (assuming no errors in transmission), it sends an ACK back to the sender node (refer to Figure 3.6(e)). The node then continues to be in the active mode to receive further transmissions from the same sensor node or from any of the other neighbour nodes otherwise it sets a random timer, goes into sleep mode and this node also updates the values of K in its NRT. If the receiver node does not receive any data packets as scheduled before the time period expires and there are no arrivals of new messages, it simply quits the receiving state and goes into the sleep state.


(a) Source node sending preamble

(b) Receiver Node sending RTR

(c) Source Node sending DS to update network status

(d) DATA Transmissions in burst

(e) Receiver node sending an ACK packet

(f) Other transmitter nodes starts its data transmissions

(g) The receiver node sends NACK back to the transmitter node to inform about an error occurred during the data transmissions

Figure 3.6 (a)-(g): Data transmission of the DRMACSN MAC protocol

In the DRMACSN MAC protocol, in order to update the network status, upon receiving the RTR, every other neighbour node updates the number of simultaneous transmissions, K in their NRT as shown in Figure 3.6(c). If there is no reply from a neighbour node or there are no preamble transmissions from any of its neighbour nodes, the sender node goes into the sleep state. For those messages that are corrupted due to multiple access interference (MAI), or if errors are detected in the received packet, the receiver node generates a negative acknowledgement (NACK) and sends it to the sender over the reverse channel as a retransmission request as shown in Figure 3.6(g). In the proposed MAC protocol, the source node is notified of any errors in transmission using the selective repeat automatic repeat request (SR-ARQ).

3.3 Channel Load Sensing Technique

In this section, the channel load sensing technique is presented. Channel load sensing techniques are useful in slotted systems or CDMA networks in which packets are transmitted over multiple slots [54]. However, the network performance can be improved by sensing the channel load [55] (defined as the number of simultaneous transmissions) of the sensor nodes. Once a value of the channel load has been computed by the nodes, it can be used to control channel status using the following method [54]. The purpose of the blocking threshold α is to regulate the channel load at a safe operating region [54] that is below α, so that the probability of collisions can be minimized. If the number of on-going transmissions K, is less than the blocking threshold α, then access to the channel is allowed otherwise access is denied until the channel load drops below α (refer to Figure 3.7).

3.3.1 Channel Load Sensing Algorithm

a) A sensor node that has a message in its buffer to transmit first checks the channel load K in its neighbourhood table before it is ready to send its messages in the frame, $j-1$.

b) If the channel load K is less than the blocking threshold α, the node initiates transmission of its first packet immediately in the next frame j and is known as a new transmitting node.

c) In frame j, nodes, which are admitted in the previous frames and are in the process of transmitting their packets, are known as transmitting nodes and continue to transmit their messages.

d) If the channel load K is greater than the blocking threshold α, in a frame j+1, then the message from the new nodes are blocked and these nodes will enter the back-off mode.

e) Blocked node messages are transmitted after a random time period, the duration of which is geometrically distributed with mean, ${\mu_B}^{-1}$, if the channel load K is less than the blocking threshold when they next attempt.

As illustrated in Figure 3.7, a collision occurs when the number of simultaneous transmitting nodes exceeds $\propto$. For example, a message from Nodes I and K arrive in frame 3 and together with previous transmitted messages from Nodes A, C, B and F causes the number of simultaneous transmitting nodes to exceed the blocking threshold, $\propto = 3$ nodes. If these messages are allowed to transmit in the next frame 4, there will be collisions and bandwidth wastage, which increases the energy overhead. Further it is assumed that the packets may be corrupted with high probability during the frame 4. Note that collisions, however, cannot be totally avoided but can be controlled [54]. Thus, the solution adopted in the DRMACSN MAC protocol is to abort or block the transmissions from those admitted nodes which are involved in the collisions when the maximum threshold is reached in the next frame. Therefore, nodes K and I enter into the back-off mode (refer to Figure 3.7) and need to wait until the channel load drops below the blocking threshold, α.

It can be observed from Figure 3.7 that Node J becomes an active node with a message to send in frame 10, checks its NRT, the channel load is less than the blocking threshold, α. It is admitted to start its first packet transmission in frame 11. Node I finds that the channel status is good in frame 14 and thus, gets a chance to transmit its packet in frame 15. In frames 16 and 17, other Nodes C, E and K are allowed to transmit their messages, because the channel load is less than the blocking threshold.

The novel features of the DRMACSN MAC protocol compared to other MAC protocols developed in the literature are:

a) The DRMACSN MAC protocol uses variable CQI values to improve the performance on the packet throughput.

b) The DRMACSN MAC protocol uses dynamic blocking threshold values to enhance the performance of the proposed MAC protocol.

The justification of these features is presented in the results section of this chapter (Section 3.72) where these features are discussed with the help of results.

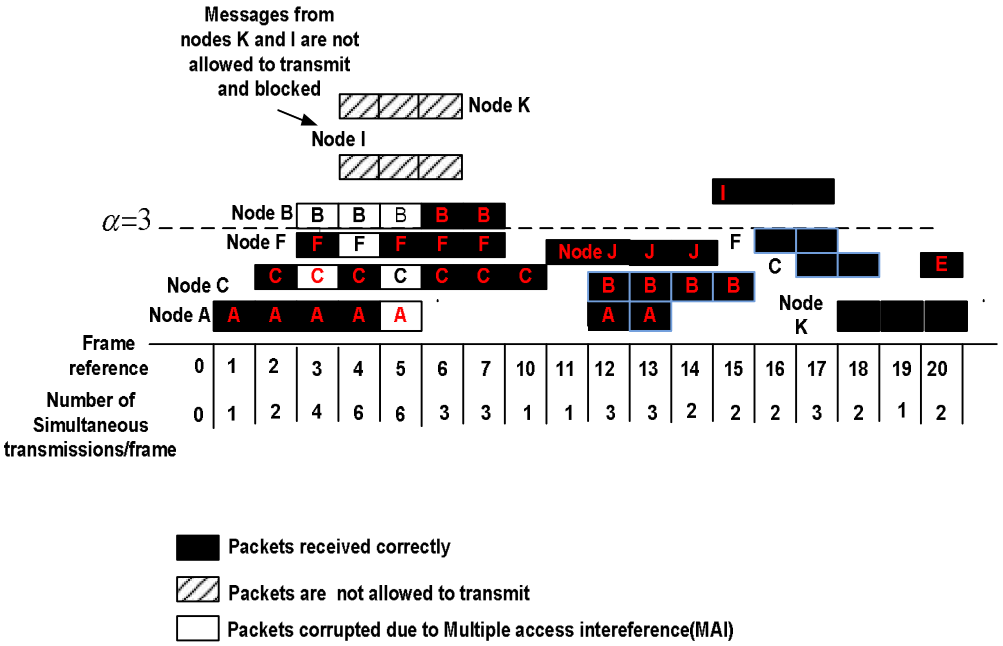


Figure 3.7: Admission control policy scheme

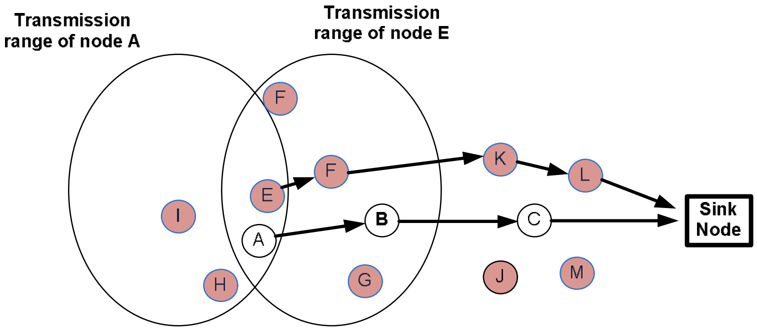


Figure 3.8: Paths from Source Node A and E to a Sink

3.4 Major Sources of Energy Wastages in WSNs

This section discusses the major sources of energy wastages in a MAC for WSNs. The proposed solutions to identify sources of energy waste are discussed with the help of an example for the DRMACSN MAC protocol.

3.4.1 Overhearing Avoidance

Overhearing of messages destined for other nodes is one of the sources of energy wastage in sensor networks [10, 11]. However, in dense deployments there are more neighbours that will overhear a message, which exacerbates the problem. In the proposed MAC protocol in [15], the source node has a list of routes to its desired destination. Only the nodes that are in the route will be active during the transmissions for the whole transmission period, T_x. Other nodes that are not in the route, may be in the sleep period or involved in transmission in the other routes. This will reduce the overhearing problem in the network. In Figure 3.8, the nodes A→B→C and E→F→K→L are in the path so these nodes will be in transmit mode until the transmissions end. Other nodes such as G, H, I are located within the transmission range of the source nodes, E and A so these receive the control packets such as DS and RTR from the source node A and the receiver node B, respectively. These neighbour nodes update their neighbourhood reservation table information (NRT), and enter into sleep mode or may receive the preamble request from other source nodes if they are located in their routes. In addition, Nodes J, and M are not located within the transmission range of source nodes E and A, respectively, so these nodes will go into their sleep periods for a random time, T_s.

3.4.2 Collision Avoidance

If two nodes transmit at the same time and interfere with each other’s transmissions, then packets get corrupted. The follow-on re-transmissions increase energy consumption. In the proposed MAC protocol [15], every node has its reserved mini-slots in the preamble slot and each node knows exactly when it is supposed to start its transmissions; this will avoid collision occurrence in the network. Furthermore, the receiver node (B in path 1) sends an RTR to its neighbour node G using the common code while it is sending the RTR back to the source node A (refer to Figure 3.8) after checking the network status. When the neighbour node G receives RTR from node B, it understands that there is communication that is going on between A and B, so it does not start its preamble request but rather goes into the sleep mode for the current transmission period. This would reduce possible collisions occurring at the receiver node in the proposed MAC protocol.

3.4.2.1 Idle Listening

Most of the energy in MAC protocols is wasted in Idle Listening [10, 11]. If nothing is sensed, nodes are in the idle mode for most of the time. Since a node does not know when it will be the receiver node of a message from one of its neighbours, it must keep its radio in receive mode at all times. In the proposed MAC protocol, the source node knows an accurate path to its destination and the list of its neighbour nodes. The remaining nodes, which are neither in the path nor in its neighbourhood, will be in the sleep period. This reduces the idle listening time of nodes in the network. In Figure 3.8, the nodes such as H, I, J, and M are not located within the transmission range of the source nodes E and A, respectively. So these nodes will go into the sleep period for the current transmission period.

3.5 Traffic Models and Channel Model

In order to evaluate performance of the proposed MAC protocol, it is important to select the appropriate traffic models that reflect the behaviour of the sensor nodes [56]. This section describes the adopted Data traffic models in order to evaluate the performances of the proposed MAC protocol.

3.5.1 Data Models

It is assumed that the message arrivals in sleep, transmit or back-off state follow a Bernoulli process (Model 1) probability ρ_S or a Poisson process (Model 2) with a rate, λ. In this work, the length of a data message is assumed to be geometrically distributed.

3.5.1.1 Model 1: Bernoulli Process

In this model, the arrival of messages for the DRMACSN MAC protocol is modelled based on a Bernoulli process with a probability, ρ_S. Thus, the probability of m messages arriving at each node in a frame [57] is:

$$f_A(m) = {\rho_s}^m(1- \rho_s)^{1-m} \qquad \text{for } m \in \{0,1\} \tag{3.1}$$

3.5.1.2 Model 2: Poisson Process

In this model, the new message arrival follows a Poisson process with arrival rate, λ messages per node per frame. Thus, the probability of m messages arriving at each node in a frame [57] is:

$$f_A(m) = \frac{\lambda^m}{m!}e^{-\lambda} \tag{3.2}$$

3.5.2 Channel Model

When a node is selected for the transmission of its packets to the destination node, it computes the data rate as per the CQI value. The CQI for the channel is computed from the value of signal to noise ratio (SNR) to determine the appropriate transmission block size (TBS) at which the source node starts its transmission. The corresponding TBS of the CQI value is determined from the look-up table presented in Table 3-1. Table 3-1 contains the number of codes used, modulation type and transport block size [58]. The channel state information is needed by the transmitter node to choose the transmission rate and modulation scheme. In this thesis, the following assumptions are made:

a) A CQI value is determined at the beginning of each Tx period using Eq. (3.10). This assumes that block error rate (BLER) is 10%. It is considered that the same CQI value is used throughout the Tx period.

b) The SNR changes in every frame. This means that the “True” CQI is not used except in first frame. The SNR is computed using the following Eq. (3.4). In this thesis work, the SNR is modelled as a random variable [59]. For a node, j, the SNR can be computed as follows:

$$SNR_j(t) = \frac{P_{Tx}\, G_j(t) PG}{\sum_{i=1, i\neq j}^{K} P_{Tx} G_i(t) + N_0 W} \tag{3.4}$$

where PG is the processing gain which is equal to W/R_b, W is the spreading bandwidth and R_b is the bit-rate that depends on the CQI feedback from the receiver node. P_{tx} is the transmitted power of the source node, N_0 is the noise spectral density, $G_j(t)$ is channel gain of a node j, $\sum_{i=1, i\neq j}^{K} P_{Tx} G_i(t)$ is the interference from other simultaneous transmitting nodes.

An expression for the channel gain can be derived for the transmission as follows:

$$G_{j(dB)}(t) = -L(t)_{dB} + S(t)_{dB} \tag{3.5}$$

where $S(t)$ is the shadowing component and $L(t)$ is the path-loss component[60-62].

$$L(t)_{(dB)} = L_0 + 10n \log_{10}(r) \tag{3.6}$$

where L_0 is the path loss at 1 meter, n is the path loss factor, r is the distance expressed in meters [60-62].

The shadowing component (in dB) can be modelled as a correlated log-normal random process denoted as $S(t)$ [63]:

$$\mathrm{S(t)} = \beta X(t) + (1-\beta)X(t-t_f) \tag{3.7}$$

where β is one step autocorrelation coefficient and the value of $\beta = 0.941872$ [64]. The method shown in Figure 3.9(a) is developed to generate the correlated Log-normal RVs using uncorrelated normal random process [65, 66]. As shown in Figure 3.9(a), first, a set of N statistically independent Gaussian RVs are generated, and then the correlated log-normal RV is generated as follows.

$$\mathrm{Z(t)} = \mathrm{f}(X(t), Y(t)) \tag{3.8}$$

where X(t) and Y(t) = X(t- t_f) are uncorrelated independent Gaussian RVs , f(.) is a function to convert from the non-correlated RVs to the correlated RVs using a correlation matrix. The correlated log-normal RV is generated as follows

$$\mathrm{S(t)} = \exp(\mathrm{Z(t)}) \tag{3.9}$$

c) The CQI for every corresponding SNR can be computed using the following Eq. (3.10) as proposed in [58, 67].

$$CQI = \begin{cases} 0 & \text{if SNR} \le -16 \\ \left\lfloor \frac{\mathrm{SNR}}{1.02} + 16.61 \right\rfloor & \text{if } -16 \le \mathrm{SNR} \le 14 \\ 30 & \text{if SNR} \ge 14 \end{cases} \tag{3.10}$$

where $\lfloor\cdot\rfloor$ is floor operator.

d) The BLER(t) can now be computed by using Eq. (3.11) as in [67,68], where SNR is equal to $SNR_j(t)$ and $CQI_j(j)$ is the value that is computed in the first frame.

$$BLER(j) = 10^{\left[2\frac{SNR_j(t)-1.03CQI_j(j)+17.3}{\sqrt{3}-\log_{10} CQI_j(j)}+1\right]^{-\frac{1}{0.7}}} \tag{3.11}$$

Figure 3.9(b) shows the density of the shadowing component using Eq. (3.7) for a correlation factor, {=0.5}. The curve in Figure 3.9(b) shows that the shadowing component, S(t) follows the correlated lognormal.

The SNR derived from channel parameters using Eq. (3.4) is shown in Figure 3.9(c). From Figure 3.9(c), it can be observe that the SNR values are computed at every frame. It can also be observed that SNR is not computed for some frame duration when the node takes the vacation.

Figure 3.9(d) shows the CQI distribution for the use of computing BLER(t) and transmitting rates on the SNR values. Figure 3.9(e) shows the computed average BLER(t) as a function of $SNR_j(t)$ and CQI(t) for different values of blocking threshold values. The constant CQI value is used to generate BLER(t).

It can be seen from Figure 3.9(e) that, the BLER is high for higher blocking thresholds, $\propto$ = 12 compared to the smaller value of threshold because a higher number of simultaneous transmitting nodes is allowed to transmit for $\propto$ = 12 at higher rates. Thus, the higher BLER performance can be observed for higher values of blocking threshold values.

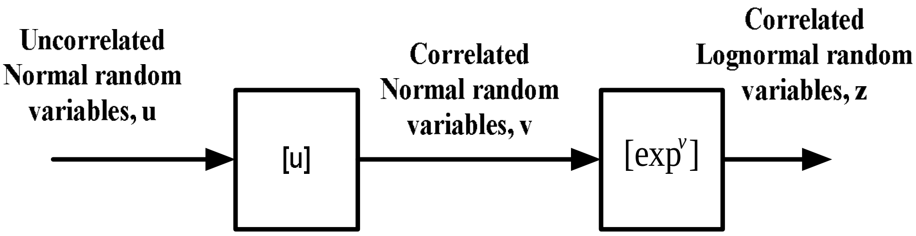


Figure 3.9(a): Method for generating correlated Log-normal RVs [65]

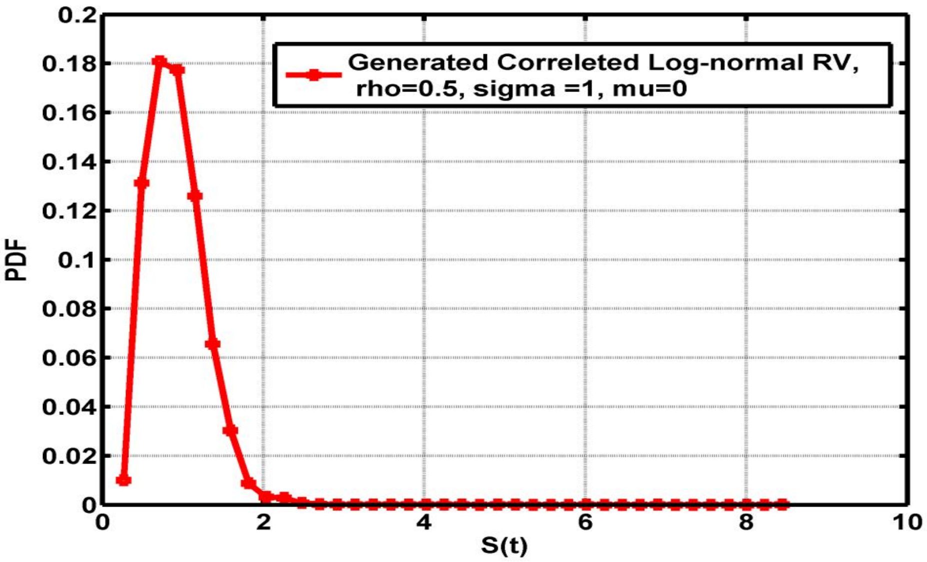


Figure 3.9(b): The distribution of shadowing component, S(t)

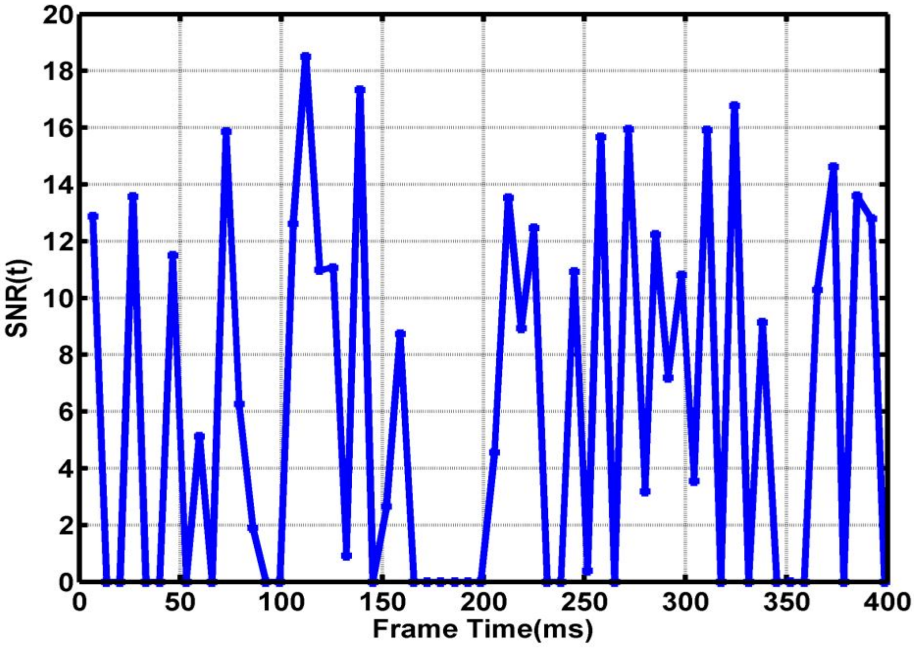


Figure 3.9(c): SNR derived from channel parameters for a single node, CQI = 26

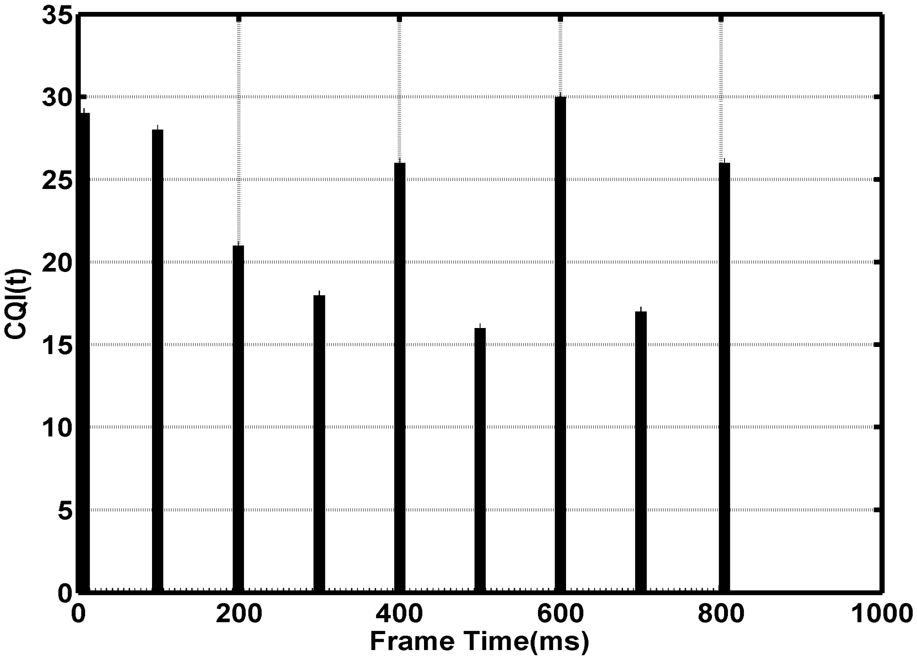


Figure 3.9(d): Resulting CQI distribution for the use of computing BLER and transmitting rates on the SNR values

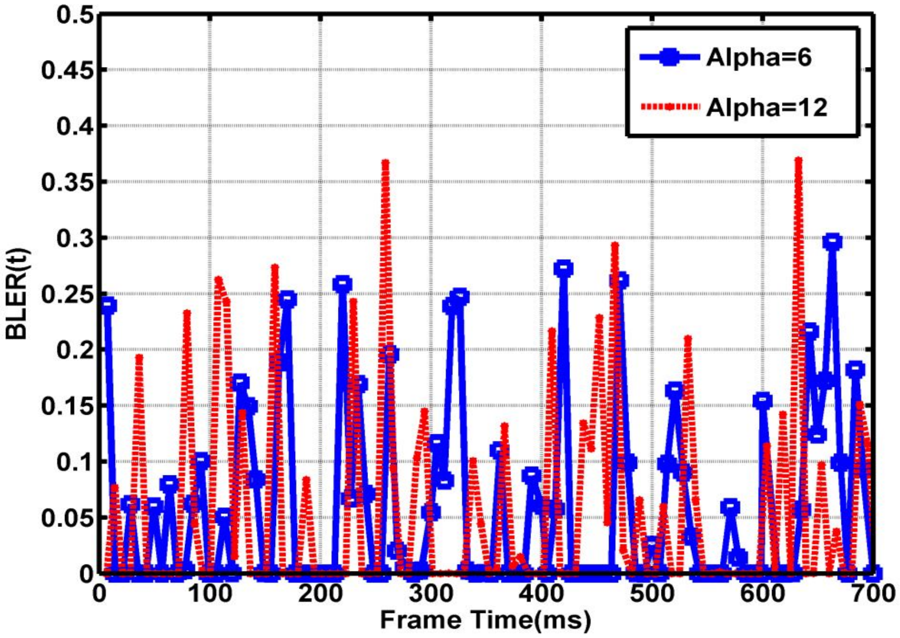


Figure 3.9(e): Instantaneous BLER as function of $SNR_j(t)$ and CQI = 26 using Eq. (3.11) for a single node

3.6 Performance Metrics

This section details the performance metrics such as the packet throughput, packet delay, energy consumption and number of packets blocked and dropped to evaluate the performance of the proposed MAC protocol. We define m as the number of packets, N_f is the number of frames, ∝ is the blocking threshold value and N is the number of sensor nodes.

3.6.1 Average Packet Throughput

The average packet throughput is defined as the number of successful packets transmitted per node per frame. In the simulation this is obtained by

$$\bar{S} = \sum_{i=1}^{N\times N_f} \frac{m_i}{N \times N_f} \tag{3.12}$$

3.6.2 Average Packet Delay

The average packet delay of a packet is the time period from the time a packet arrives in the buffer of a node to the time it is successfully transmitted to the intended receiving node.

The average packet delay experienced by all the packets that were processed during a simulation time is obtained by

$$Delay = \sum_{i=1}^{m} \frac{d_i}{m}$$
$$\bar{D} = \sum_{j=1}^{N \times N_f} \frac{Delay_j}{N \times N_f} \tag{3.13}$$

where d is the delay of a single packet is i.e., (Packet transmission time – Packet arrival time).

3.6.3 Average Node Energy Consumption

The average energy consumption per node per frame is computed as follows: The energy spent by each node is the energy consumed in transmitting, sleep and back-off modes. Thus each term can be expressed as the average energy spent in that state multiplied by the time the node is in that state. In the simulation this is obtained by

$$\bar{E} = \frac{E_{Tx} + E_{Sleep} + E_{Back-off}}{N \times N_f} \tag{3.14}$$

where

a) E_{Tx} is the amount of energy consumed in transmit state and is given by

$$E_{Tx} = \sum_{i=1}^{I_{Tx}} T_{Tx,i} \cdot Power_{TX} \tag{3.15}$$

where T_{Tx} is the time spend in the transmit state, I_{Tx} is the number of iterations of transmit state and $Power_{TX}$ is the transmission power and is given in Table 3.2.

b) E_{Sleep} is the energy consumed in sleep state and is given by

$$E_{Sleep} = \sum_{i=1}^{I_{sleep}} T_{Sleep,i} \cdot Power_{Sleep} \tag{3.16}$$

where T_{Sleep} is the time spend in the sleep state, I_{sleep} is the number of iterations of sleep state and $Power_{Sleep}$ is the sleep power and is given in Table 3.2.

c) $E_{Back-off}$ is the energy consumed in back-off state and is given by

$$E_{Sleep} = \sum_{i=1}^{I_{Back-off}} T_{Back-off,i} \cdot Power_{Back-off} \tag{3.17}$$

where $T_{Back-off}$ is the time spend in the back-off state, $I_{Back-off}$ is the number of iterations of back-off state and $Power_{Back-off}$ is the idle power and is given in Table 3.2.

3.6.4 Number of Blocked and Dropped Packets

a) **Number of Blocked Packets**

In the simulation, when a new message arrives and the number of transmitting nodes is greater than the blocking threshold value in a current frame, this event causes the corresponding packets to be blocked. Thus, the number of blocked packets per node per frame is obtained by

$$\begin{aligned} N_{Blocked,node} &= \sum_{k=\alpha}^{N} m_k \\ \overline{N}_{Blocked} &= \sum_{i=1}^{N \times N_f} \frac{N_{Blocked,node_i}}{N \times N_f} \end{aligned} \tag{3.18}$$

b) **Number of Dropped Packets**

In the simulation, the number of packets dropped this is obtained as follows:

The number of packets dropped per node per frame is calculated by subtracting the number of packets transmitted successfully per node per frame from the number of packets generated per node per frame.

Table 3.1: CQI mapping for transport block size for TTI=2 ms (terrestrial standard) [68]

CQI Value	Modulation and Coding	Number of codes used per TTI	Bits per TTI(transport block size)	Bit rate (Kbits/s)
1	QPSK 1/3 (on each code 960 bits are sent in a TTI)	1	137	68.5
2			173	86.5
3			233	116.5
4			317	158.5
5			377	188.5
6			461	230.5
7		2	650	325
8			792	396
9			931	465.5
10		3	1262	631
11			1483	741.5
12			1742	871
13		4	2279	1139.5
14			2583	1291.5
15		5	3319	1659.5
16	16 QAM 1/3 (on each code 1920 bits are sent in a TTI)		3565	1782.5
17			4189	2094.5
18			4664	2332
19			5287	2643.5
20			5887	2943.5
21			6554	3277
22		5	7168	3584
23		7	9719	4859.5
24		8	11418	5709
25		10	14411	7205.5
26		12	17237	8618.5
27		15	21754	10877
28			23370	11685
29			24222	12111
30			25558	12779

Table 3.2: Simulation Parameters

DRMACSN MAC and No blocking scheme	
Spreading Factor	16
RTR	32 bits
DS	40 bits
Preamble	24 bits
DATA packet	128 bits
ACK	24 bits
Maximum Range	20 meters
General Parameters(DRMACSN MAC, IEEE 802.15.4 MAC and No blocking scheme)	
Number of Sensor Nodes	100
Data rate	640 kbps
IEEE 802.15.4 MAC parameters	
DATA packet	50 and 100 bytes
Maximum Range	7 meters
RADIO PARAMETERS ARE TAKEN FROM CC2420 TRANSCEIVER [69]	
Transmission power, $Power_{TX}$	48.72:62.64 mW
Receiving power, $Power_{RX}$	52.64:67.68 mW
Sleep power, $Power_{Sleep}$	0.056:1.5336 mW
Idle power, $Power_{Idle}$	1.1928: 1.5336 mW

Table 3.3: SNR Simulation parameters [59]

Parameters	Value
$N = N_0W$	2.00245.10^{-14}Watt
W	5MHZ
PATHLOSS ATTENUATION *L(t)* Near Zone ($R < 20m$) Far Zone ($R \geq 20m$) None-line of sight	(in dB) 92.92+10.96log(R) 106.48+43.85log(R) 151.32+log(R)
SHADOWING ATTENUATION *s(t)* (Gaussian variable) Mean Standard deviation	(in dB) 0 1

Table 3.4: Total number of packets generated

Arrival rate, λ (Messages/sec)	Total Packets
For ρ_S = 0.006(Messages/frame), $\lambda = \frac{\rho_S}{T_f} = \frac{0.006}{0.02}$=0.3	= Arrival rate x frame size x number of nodes x total number of frames =0.3x0.02x100x10^6 =600000
For ρ_S = 0.000125(Messages/frame), $\lambda = \frac{\rho_S}{T_f} = \frac{0.000125}{0.02}$=0.0125	= 0.0125x0.02x100x10^6 = 25000

3.7 Performance Results

This section provides example results for the DRMACSN MAC protocol. An event-driven based simulator was developed in VC++ 2008 to evaluate the performance of the DRMACSN MAC protocol for average throughput, energy consumption and delay. The concept and details of the simulator algorithm are presented in the Appendix.

3.7.1 Network Parameters

The number of packets dropped per node per frame is calculated by subtracting the number of packets generated per node per frame from the number of packets transmitted successfully per node per frame. The parameters used in the simulation are shown in Table 3.2 and are consistent with the sensor nodes' hardware [69]. Table 3.3 lists the parameters for the simulation of SNR values, which are similar to those proposed in [59].

It is assumed that 100 sensor nodes are deployed randomly in a square region of 1000m x 1000m area as shown in Figure 3.10(a). It is further assumed that each node can reach all its neighbours within its radio range where the sensor range is assumed to be limited to 20 m. Therefore, the maximum transmission range of a sensor node can be assumed as 20 m. The simulation duration is set to 1000000 frame time for all MAC protocols.

In order to validate the DRMACSN MAC protocol with the IEEE 802.15.4 MAC protocol [46-48], the same simulation parameters are used as in Table 3.2 to simulate the IEEE 802.15.4 MAC protocol in VC++ 2008.

In this thesis, the length of one frame is 20 ms for MAC protocols. The size of one packet is 128 bits and the nodes can send one packet per frame.

In Figure 3.10(b), the results for the neighbourhood information such as the channel load, K as seen by individual nodes for the DRMACSN MAC protocol are plotted. In Figure 3.10(c), the actual numbers of simultaneous transmissions on a frame for a blocking threshold value of 16 are plotted.

It is observed that the channel load is greater than the blocking threshold value on some frames. This situation arises because when the channel load is less than the threshold value on the current frame, the DRMACSN MAC protocol allows new nodes to start their messages on the next frame. If any new message arrives from newly activated nodes when the channel load, $K >= \propto$ threshold value, the DRMACSN MAC protocol blocks such nodes to avoid collisions and to reduce energy consumption.

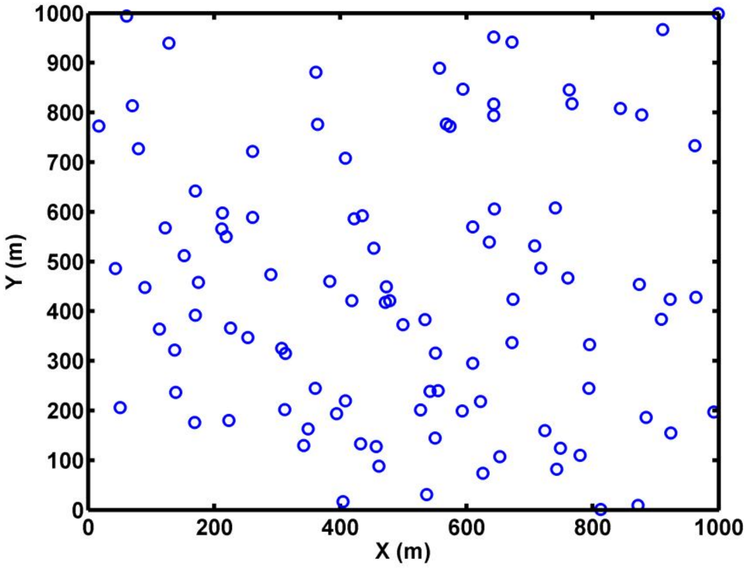


Figure 3.10(a): Sensor nodes randomly deployed

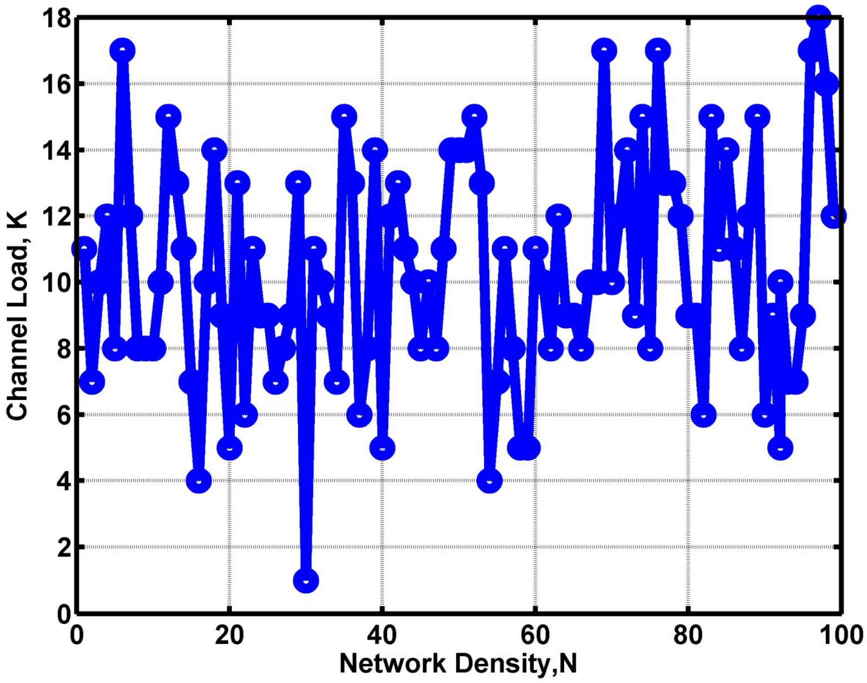


Figure 3.10(b): Channel load, K as seen by individual nodes for DRMACSN MAC protocol, ρ_S = 0.004 (Message/frame)

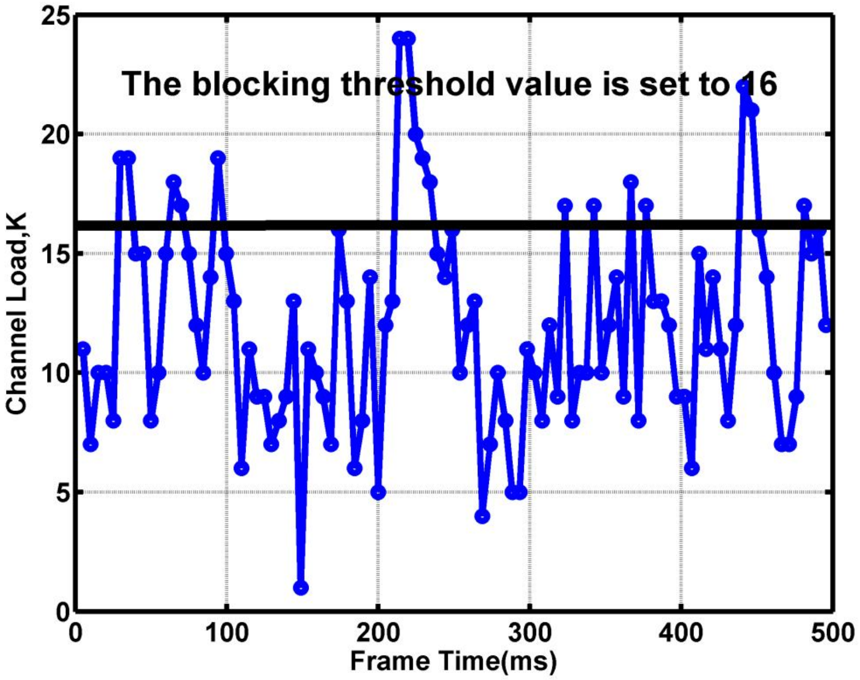


Figure 3.10(c): Actual number of simultaneous transmissions on a frame for DRMACSN MAC protocol, ρ_S = 0.004 (Message/frame)

The arrival process of messages at each node is assumed to be either a Poisson process or a Bernoulli process. It is considered that the distribution of the message length is geometric in terms of number of packets per message. The results in Figure 3.11(a) show the message distribution of the Poisson and Bernoulli arrivals for λ = {0.125 and 0.2} messages per second with mean number of packets per node per frame being 8 and 5 respectively for the duration of 250 frames. It can be observed that the curves in Figure 3.11(a) confirm that the messages generated by each node follow the geometric distribution.

Figure 3.11 (b) and (c) show the probability distribution of the packet inter-arrival times observed at a node every 5 seconds for Poisson and Bernoulli arrival processes, respectively for the duration of 10 frames. It can be seen that the curve in Figure 3.11(b) confirm that the packet inter-arrival time follows the exponential distribution for Poisson arrival processes. The result in Figure 3.11(c) confirms that the packet inter-arrival time follows the geometric distribution for Bernoulli arrival processes.

Table 3.4 shows the number of packets generated per node per frame for all three MAC protocols. The average number of packets generated per message for the duration of 250 frames is shown in Figure 3.11(d) and (e) for both arrival models.

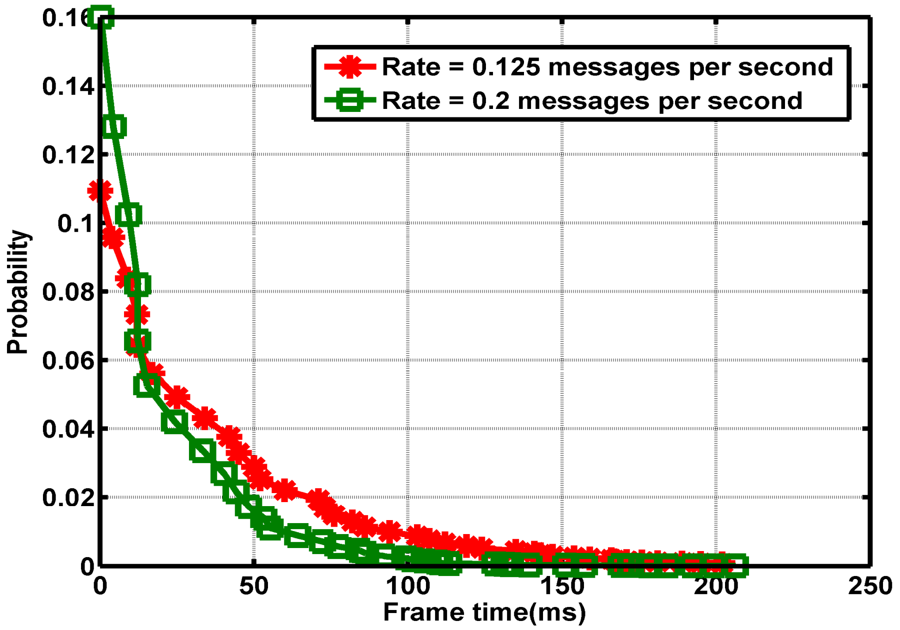
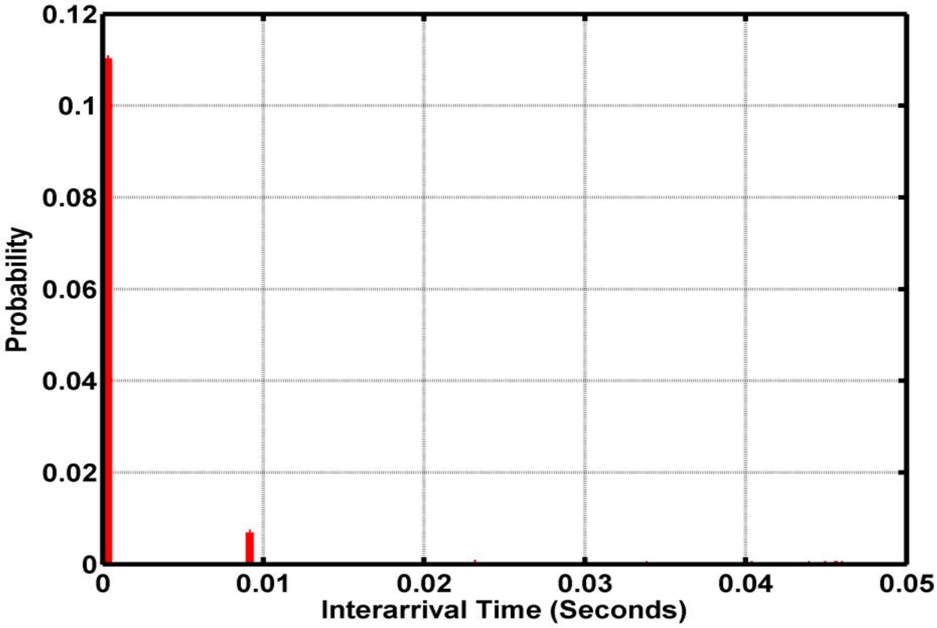
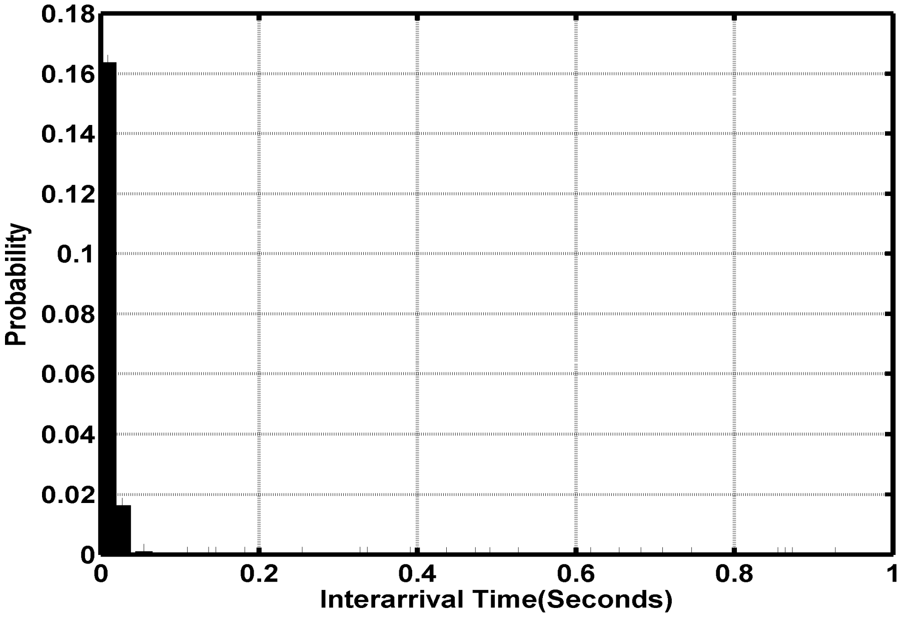


Figure 3.11(a): The probability distribution of messages for the Poisson and Bernoulli process



(b) Poisson arrivals



(c) Bernoulli arrivals

Figure 3.11(b) and (c): The probability distribution for packet inter-arrival times of the Poisson arrivals and Bernoulli arrivals

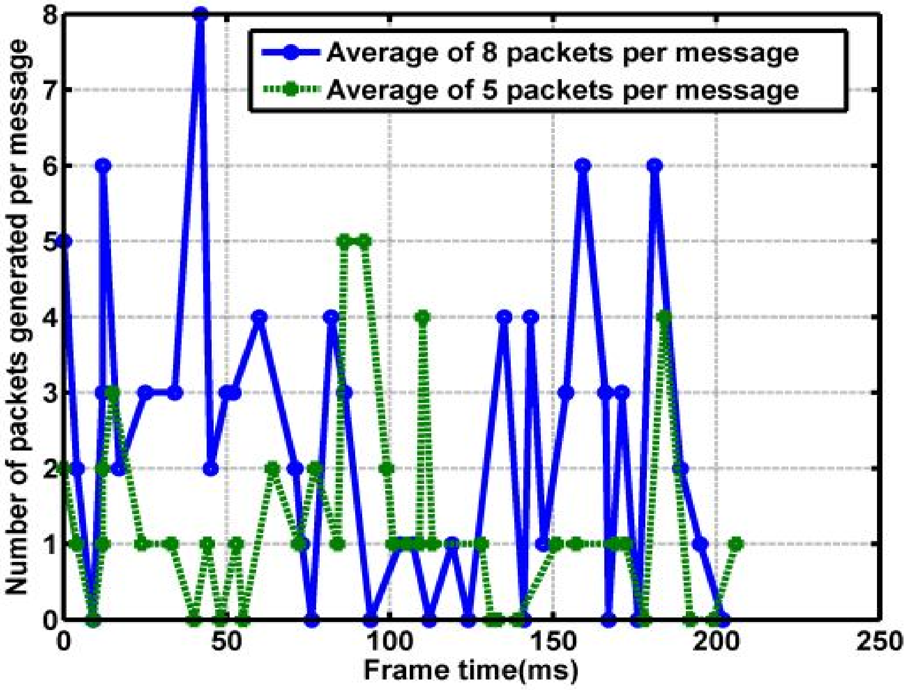


Figure 3.11(d): Average number of packets generated by a node based on the Poisson process

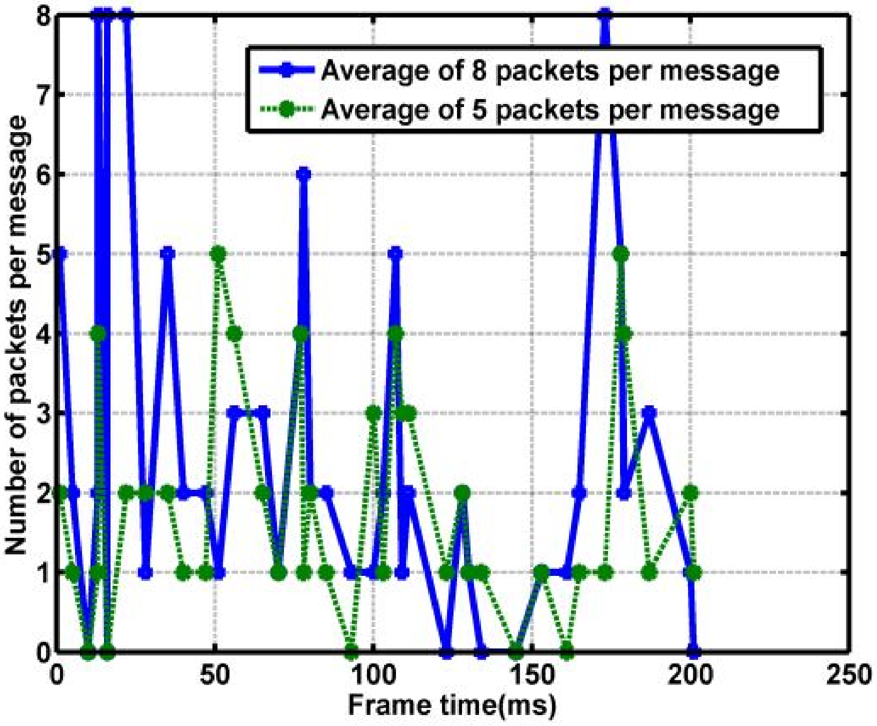


Figure 3.11(e): Average number of packets generated by a node based on the Bernoulli process

3.7.2 Performance Evaluation of the DRMACSN MAC Protocol

In order to illustrate the performance of the DRMACSN MAC protocol, the value of the blocking threshold, ∝ = {6, 12 and 16} is used. The value of blocking threshold, ∝, is fixed after testing the performance of the DRMACSN MAC protocol in the simulations as shown in Figure 3.12(a). It is clear from Figure 3.12(a) that a good throughput can be seen at ∝ =16 for the proposed MAC protocol. Furthermore, this maximum value depends on the selected value of ρ_S, the optimal value is function of ρ_S. Therefore, for simulation purposes, the maximum value of 16 is considered for ∝ . In addition, the data rates (listed in Table 3.1) are varied as per computed CQI for the DRMACSN MAC protocol to evaluate the performances for varying blocking threshold values. The results for average throughput, average energy consumption and average delay are presented in this sub-section. The effect of the variable CQI values for the DRMACSN MAC protocol on the packet throughput is also evaluated in this sub-section.

In Figure 3.12(b), several packet throughputs vs. arrival rate curves for a fixed (low, medium and high) CQI value and variable CQI values are provided. The results in Figure 3.12(b) confirm that a good throughput for the use of a fixed CQI value (low=6, medium=16 or high = 26) for DRMACSN MAC protocol is obtained.

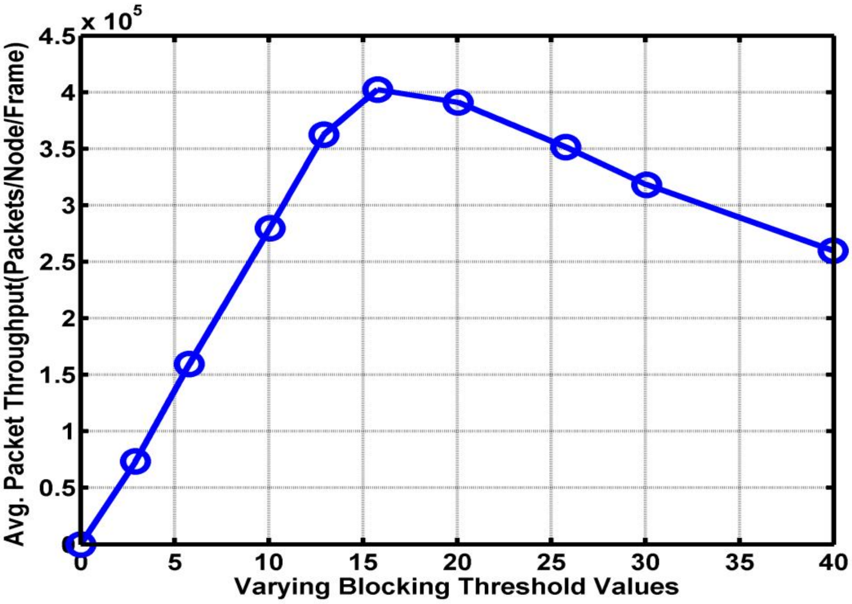


Figure 3.12(a): The average throughput vs blocking thresholds,∝ for DRMACSN MAC protocol, ρ_S = 0.004 (Message/frame), CQI = 26

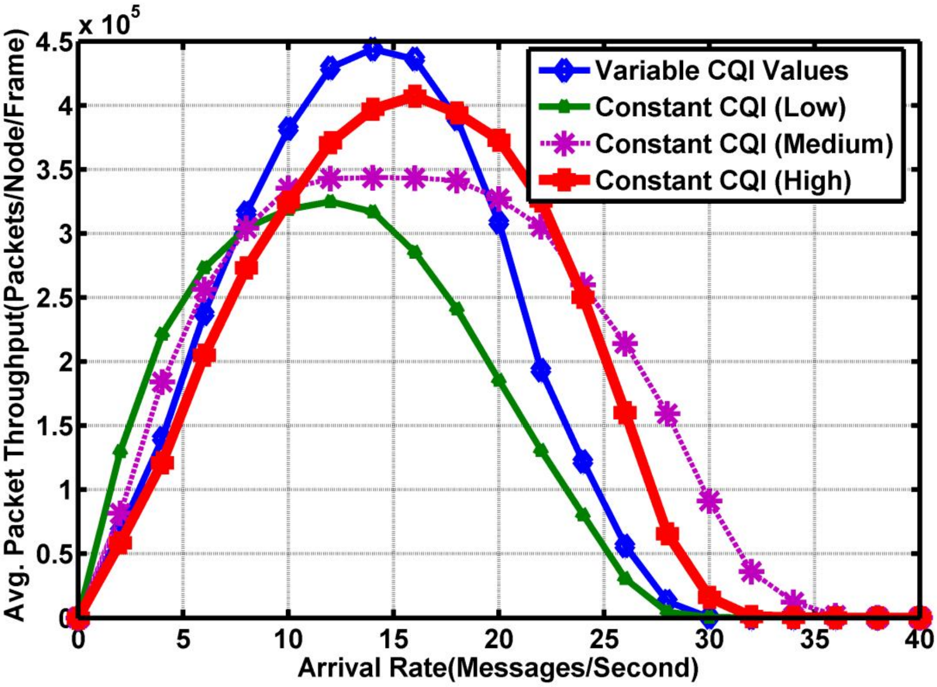


Figure 3.12(b): Effect of CQI values on the packet throughput comparison

A variable CQI value provides an optimum packet throughput compared to constant CQI values. Thus, variable CQI values are implemented in the DRMACSN MAC protocol. The result in Figure 3.12(c) show the packet throughput for a given CQI value, the blocking threshold value is set, ∝ = 12. The effect that ∝ has an on the performance of the DRMACSN MAC protocol by varying the arrival rate was examined for a given CQI value. A fixed value is considered to ∝ to obtain the optimum packet throughput in the simulation. The maximum throughput that is obtained in the simulation for that fixed ∝ value is considered as the optimum packet throughput, From Figure 3.12(d), it can be seen that, based on the optimum packet throughput, ∝ = 9 provides the best results for a load value of 12 and CQI =22. If this process is repeated for other ∝ values, it can be expected that different ∝ values will provide optimum results for different loads and CQI values respectively. If each optimum ∝ value is associated with each corresponding load value and CQI value, then the optimum packet throughput curve illustrated in Figure 3.12(d) is obtained. In order to envisage the optimum packet throughput curve (the solid line in Figure 3.12(d)), the solid line was used which maps the peak packet throughput obtained after all possible ∝ values have been considered. For purposes of clarity only odd values of ∝ were used.

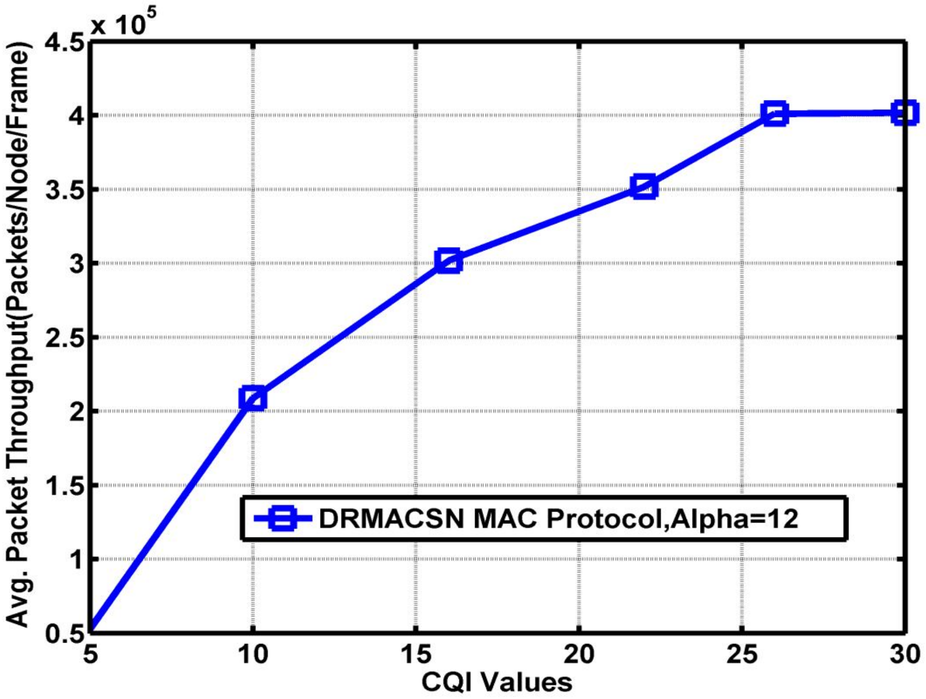


Figure 3.12(c): The average throughput vs variable CQI values for DRMACSN MAC protocol, ρ_S=0.004 (Message/frame)

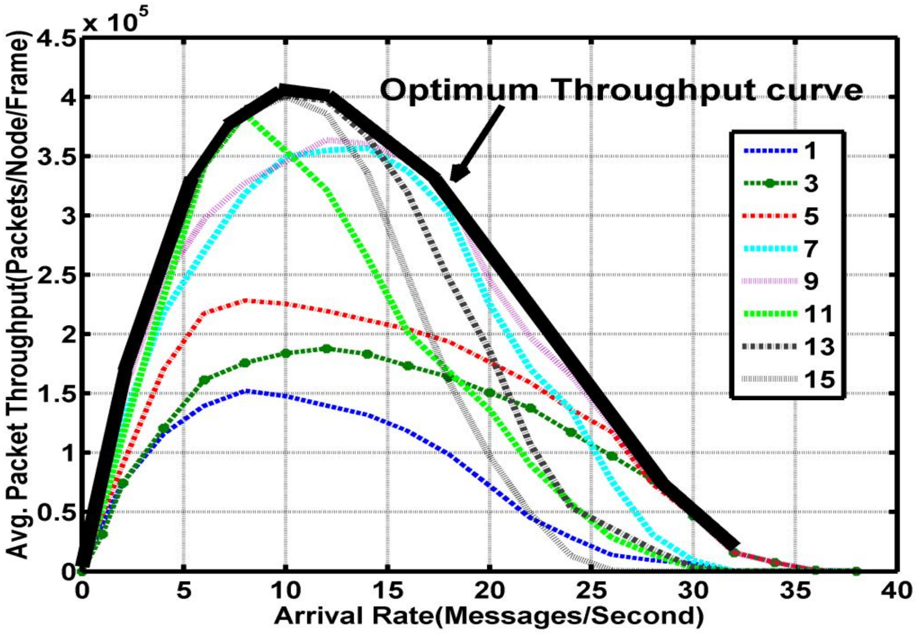


Figure 3.12(d): Optimum packet throughput curve obtained by a dynamic blocking threshold,∝

The results in Figure 3.13 show the number of packets sent per node per frame for the DRMACSN MAC protocol for various blocking threshold values versus the message arrival rate. The reason why the results for $\propto = 12$ and 16 are smaller than the results achieved for $\propto = 6$, evident in Figure 3.13 (a) and (b), is due to the fact that there will be more message blocking for $\propto = 12$ and 16 at higher loads compared to $\propto = 6$. Thus, the number of packets sent is higher for $\propto = 6$.

A. Average Packet Throughput Results

The results in Figure 3.14 show the average packet throughput of the DRMACSN MAC protocol for varying blocking threshold values for increasing arrival rate. It can be seen from Figure 3.14 that, the packet throughput of the system is good, when the load is lower. It can also be seen that the DRMACSN MAC protocol has good results for the throughput performance for lower values of the blocking threshold. In Figure 3.14, $\propto = 12$ was considered to examine the packet throughput curves.

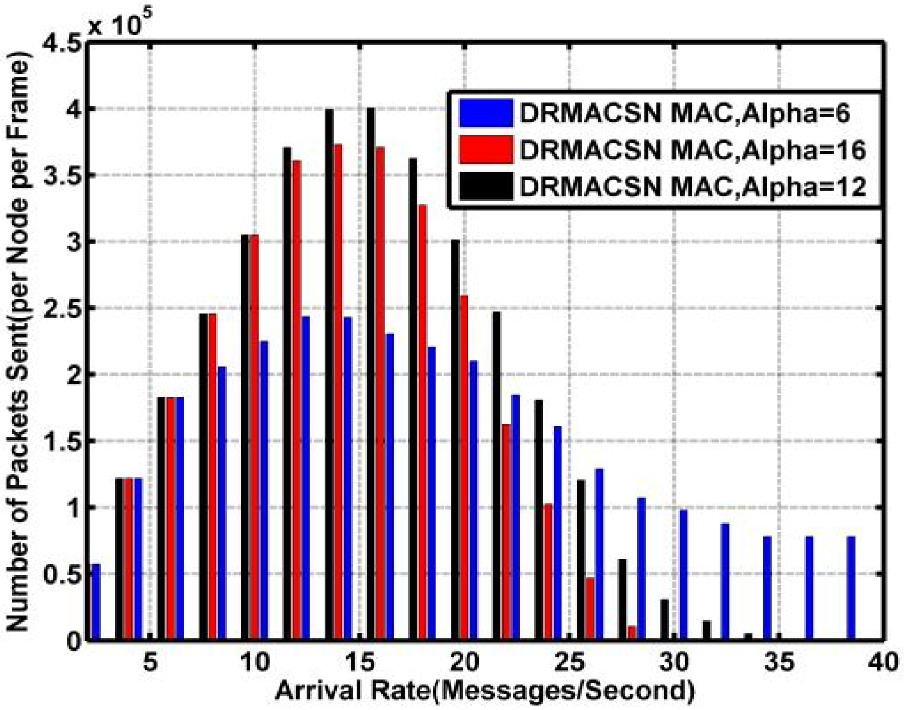


Figure 3.13: The number of packets sent per node per frame the DRMACSN MAC protocol for varying the blocking threshold values versus arrival rate

If the average data message length is $\bar{m}$ (packets/message) then it is expected that the load is approximately $G \approx \lambda = \rho_S / T_f$ (messages/frame). At very low loads (below $\lambda \leq 10$ (messages/second), the average BLER(t) is low enough to ensure that most messages are successful. This is explained by the linear region of the load/packet throughput curve in Figure 3.14 for $\lambda \leq 10$ (messages/second). As λ increases, the load increases, the average BLER(t) increases, and the fraction of messages that become corrupt start to increase. At this point, the packet throughput starts to decrease. As λ starts to approach 12 message arrivals per frame, the average load is expected to approach the threshold of α = 12 ((0.24/20ms)). At this point, it is expected that collisions start occurring and messages start to block/abort. At each abortion/blocking, the load reduces to below threshold value. For a short while after each collision there is thus a low load in which some messages are transmitting correctly with a low BLER(t). The opposite performance can be seen at higher load values. At high channel load, however, collisions become more frequent and thus, the throughput drops when the value of blocking threshold, $\propto$, is high.

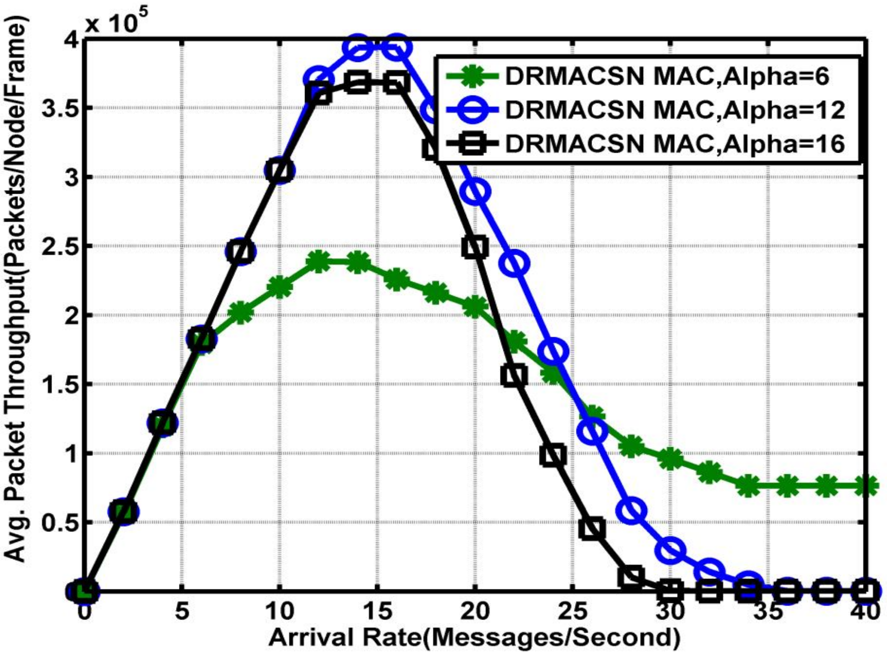


Figure 3.14: Effect of varying blocking threshold, $\propto$ = 6, 12 and 16 on the throughput as arrival rate increases for DRMACSN MAC protocol

B. Number of Packets Blocked and Dropped due to BLER(t)

This is a very important parameter to be investigated, as the packet contains valuable information which, if blocked/dropped, may adversely affect putting together the actual messages that have been sent. Thus if a packet is blocked/dropped, it needs to be re-transmitted for actual message recovery, which in turn leads to additional energy consumption in nodes. Furthermore, this is undesirable in the case of WSNs, in which the nodes are under immense constraint on energy consumption.

Figure 3.15 demonstrates the results for the number of packets blocked per node per frame for different values of the blocking threshold values for the DRMACSN MAC protocol. Figure 3.16 shows the results for the number of dropped packets due to BLER(t) per node per frame as a function of arrival rate, λ for different values of blocking threshold for the DRMACSN MAC protocol. BLER(t) = 10% was set to evaluate the number packets dropped per node per frame for the DRMACSN MAC protocol.

It is observed that the number of blocked packets for the blocking threshold value, $\propto = 6$ are higher than 12 and 16. This occurs because the blocking threshold has been set to be low and only a few simultaneous transmitting nodes are allowed to transmit their messages.

It is evident in Figure 3.15 that the number of blocked packets is almost similar at lower loads for all values of $\propto$. As load increases, the number of packets blocked is higher for lower values of $\propto$ because more number of nodes is being blocked when the blocking threshold has been set to low value.

The opposite performance can be observed from Figure 3.16, that the number of packets dropped is higher for $\propto = 16$, 12 respectively compared to lower value of $\propto = 6$. This is due to the fact that more simultaneous transmitting nodes are allowed to transmit in the channel and hence, more packets are being transmitted across the channel. However, the increase in nodes is accompanied by an increase in multiple access interference (MAI) and hence the packets have a higher probability of being in error.

C. Average Energy Consumption Results

In Figure 3.17, the results for average energy consumption per node per frame obtained through varying the blocking threshold values are compared. The result shows that the reduced energy consumption of the DRMACSN MAC protocol is obtained as it employs a channel load sensing scheme.

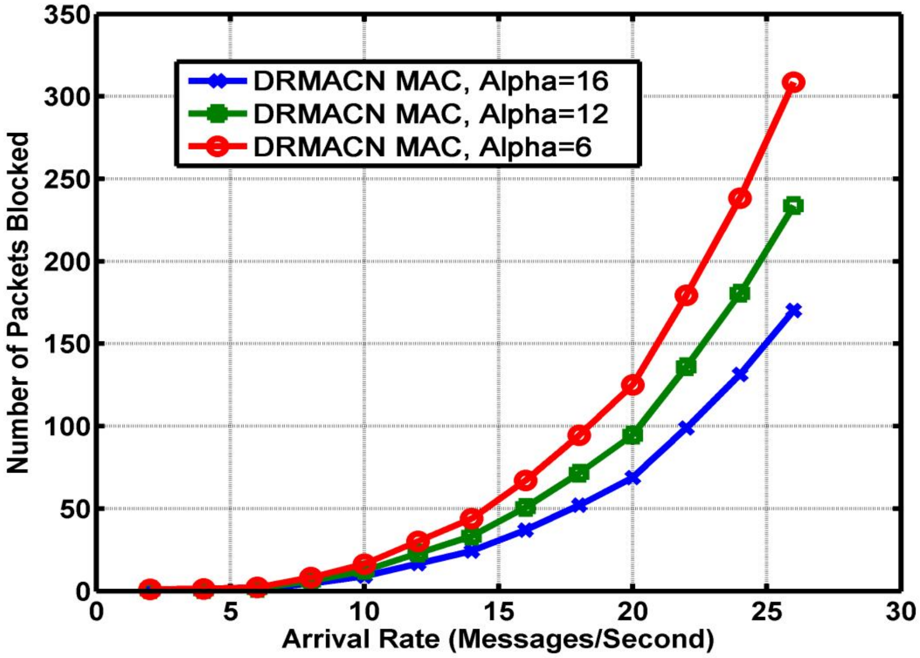


Figure 3.15: Packet blocked comparison of DRMACSN MAC protocols for varying blocking threshold values

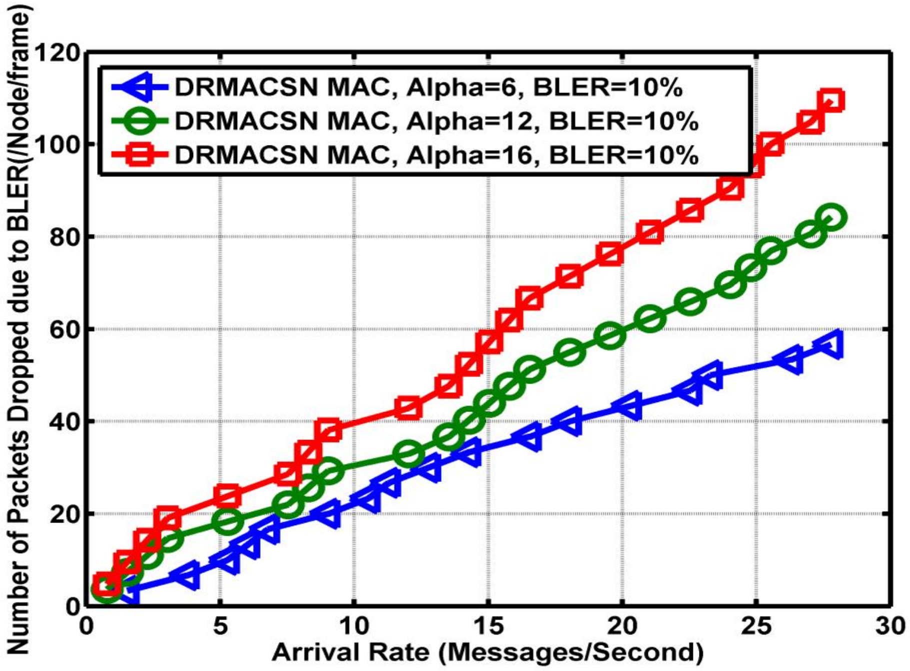


Figure 3.16: The number of packets dropped due to BLER(t) for DRMACSN MAC protocols for varying blocking threshold values

The DRMACSN MAC protocol is capable of reducing energy consumption, by using the channel sensing scheme while taking into consideration the current network status in terms of the channel load. As λ increases, the channel load decreases due to blocking of new arrivals when the blocking threshold is set, this leads to constant energy consumption in the network. This is in correspondence to the reduced throughputs obtained at higher loads for all values of $\propto$. It can be seen from Figure 3.17 that the expected energy consumption is higher at lower loads for higher values of $\propto = 16$ and 12, compared to a lower value $\propto = 6$. This is due to the fact that a few re-transmissions of packets occurring can be expected for $\propto = 6$ due to less collisions. Therefore, this leads to achieve low energy consumption for lower values of $\propto$. It can be shown in Figure 3.17 that energy consumption is constant for higher loads because no other nodes are allowed to transmit after blocking threshold is set and the system capacity is reached. Therefore, this feature also allows the proposed MAC protocol to save energy in the network. Comparison of the protocol with channel load sensing and that without channel load sensing shows that reduced energy consumption is obtained if channel load sensing in employed.

D. Average Packet Delay Results

Figure 3.18 shows the average packet delay versus arrival rate for various values of blocking threshold $\propto$. From Figure 3.18, it can be seen that, at low traffic rates, the delay is the same for all values of $\propto$. This is in correspondence to the same throughputs obtained at lower loads for all values of $\propto$. At higher load values, lower values of $\propto$ provide significantly lower delays. As λ increases, when the blocking threshold is set, only admitted nodes are allowed to transmit their packets and newly arrived nodes are blocked. These nodes will enter into the back-off mode, this results in increasing delay. In addition, when the node’s packets gets dropped due to BLER(t), these packets needs to be re-transmitted, this component also adds additional delay at higher loads for higher values of blocking threshold values. Thus, at higher load values, a substantial increment in the delay can be observed for higher blocking threshold values. It can be seen from Figure 3.18 that the expected delay increases at higher loads for $\propto = 16$, whereas for $\propto = 6$ the delay is much lower, this even occurs for higher loads.

3.7.3 Comparision of DRMACSN MAC with other MAC Protocols

In this section, the performance of the proposed DRMACSN MAC protocol is validated by comparing it with the IEEE 802.15.4 MAC protocol [46-48] and MAC without a blocking scheme. The protocols in [46-48] are considered to validate the performance of the protocols since the IEEE 802.15.4 standard was designed to support WSN constraints. Note that the DRMACSN MAC protocol and IEEE 802.15.4 are compared at a parity of system bandwidth. The simulation of the IEEE 802.15.4 MAC protocol [46-48] was studied and the results verified in the custom built event-driven simulator in VC++ 2008 for the throughput, delay and energy consumption.

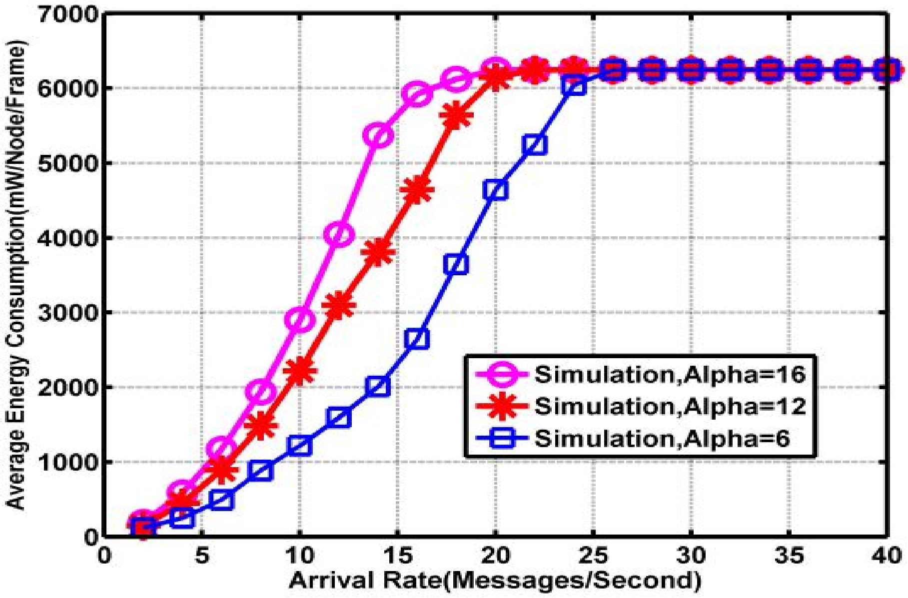


Figure 3.17: The average energy consumption of DRMAC MAC for increasing arrival rate, blocking threshold, ∝ = 6, 12 and 16

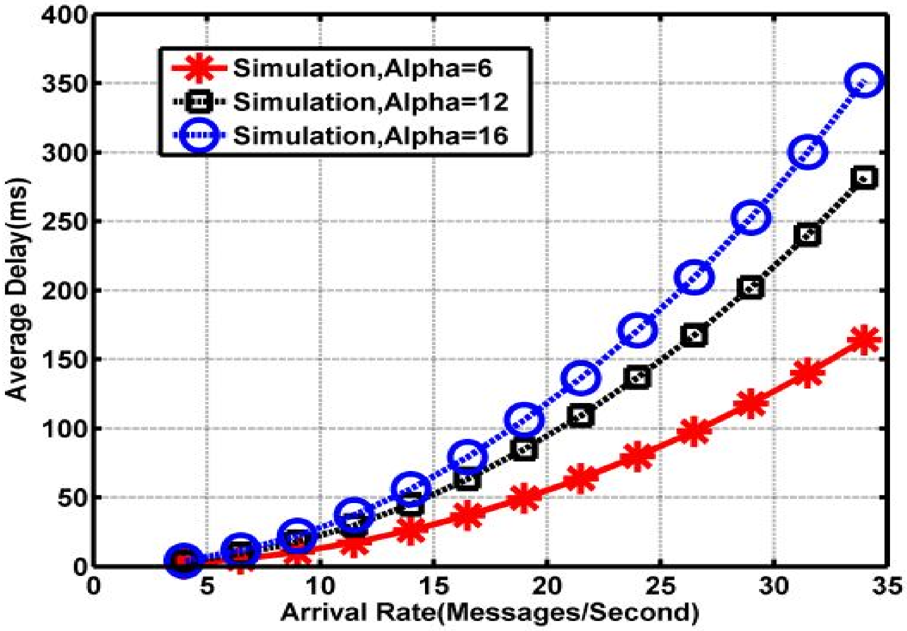


Figure 3.18: Effect of varying blocking threshold, ∝ = 6,12 and 16 on the average delay versus arrival rate for DRMACSN MAC protocol

The results of each simulation were internally consistent, i.e., the number of packets generated was equal to the number of packets generated for the DRMACSN MAC protocol. However, the results of the simulations, shown in Figures 3.19(a) and (b), in fact, match the previously reported studies of these protocols [48] for the throughput and energy consumption.

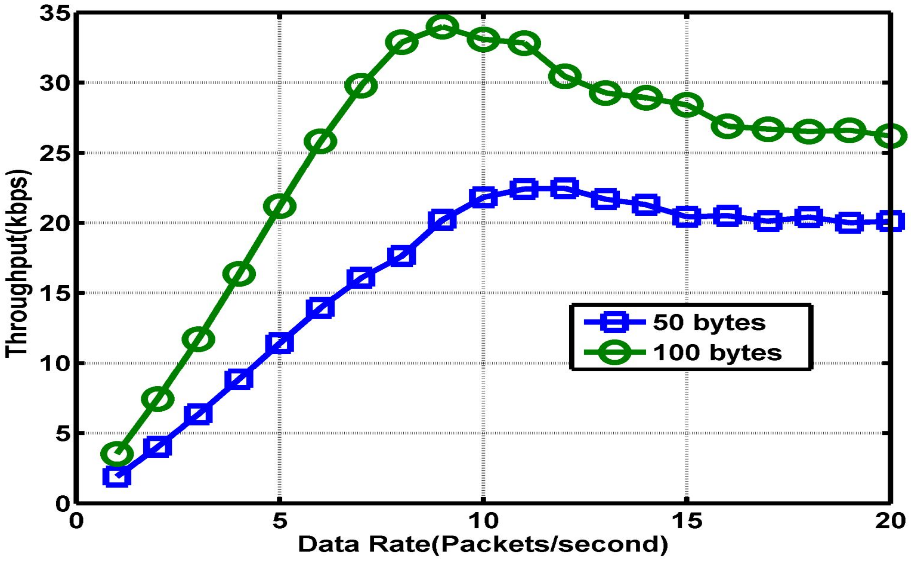


Figure 3.19(a): The throughput of IEEE 802.15.4 MAC protocol

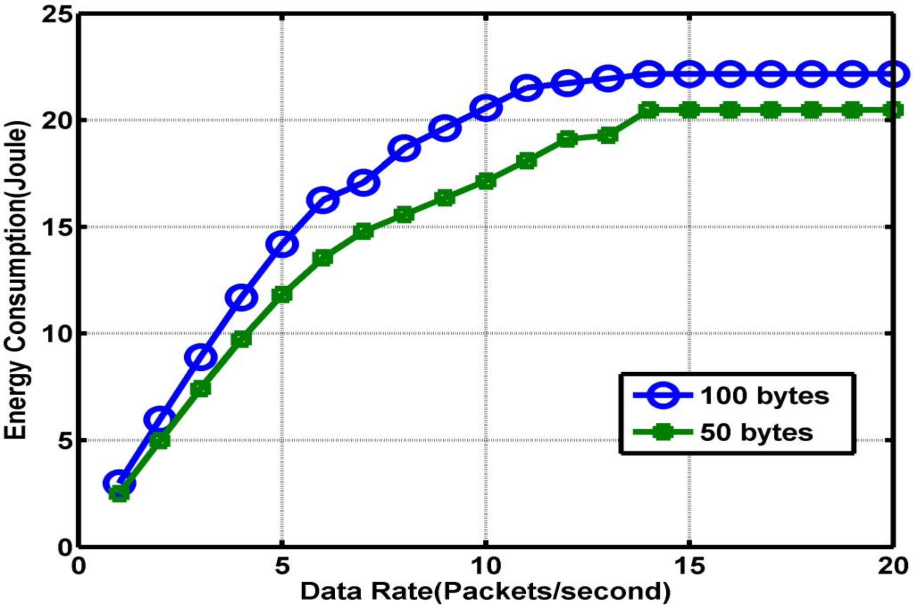


Figure 3.19(b): Energy consumption of IEEE 802.15.4 MAC protocol

A. Packet Throughput Results

Figure 3.20 shows a comparison of the number of packets sent per node per frame versus arrival rate by all three MAC protocols. The results confirm that the DRMACSN MAC protocol achieves high packet transmission success due to the channel load sensing technique. When the channel status is good, the DRMACSN MAC protocol allows the nodes to transmit more packets compared to other MAC protocols. Thus, it achieves higher successful transmission of packets compared to IEEE 802.15.4 MAC and no blocking scheme protocols.

Figure 3.21 shows the comparison of the DRMACSN MAC protocol’s packet throughput with the MAC without a blocking scheme and the IEEE 802.15.4 MAC protocol for increasing arrival rate. All curves in Figure 3.21 are obtained for the same set of network parameters as outlined in Table 3-2. Results in Figure 3.21 show that a good throughput can be achieved with the DRMACSN MAC protocol compared to no blocking scheme and IEEE 802.15.4 MAC protocol developed for WSNs.

As can be seen in Figure 3.21, the throughput of all MAC protocols is increases linearly with the increase of traffic load when the channel load is low. The packet throughput starts to decrease when the channel load is high. In a higher traffic scenario, the throughput of no blocking is scheme is low due to the fact that many concurrent transmissions are allowed in the network without knowing the channel status. The consequence is that more and more packets are damaged due to collisions.

When the channel load is high, the DRMACSN MAC protocol has a better throughput than the IEEE 802.15.4 MAC and no blocking scheme. Because of the reservation scheme and channel load sensing scheme, the DRMACSN MAC protocol can handle the load-bottleneck problem and can support good packet throughput. When the traffic load of 16 (messages/second) is reached, only few messages are successfully transmitted by the IEEE 802.15.4 MAC. On the other hand, this confirms that IEEE 802.15.4 MAC protocol is designed for low traffic purposes.

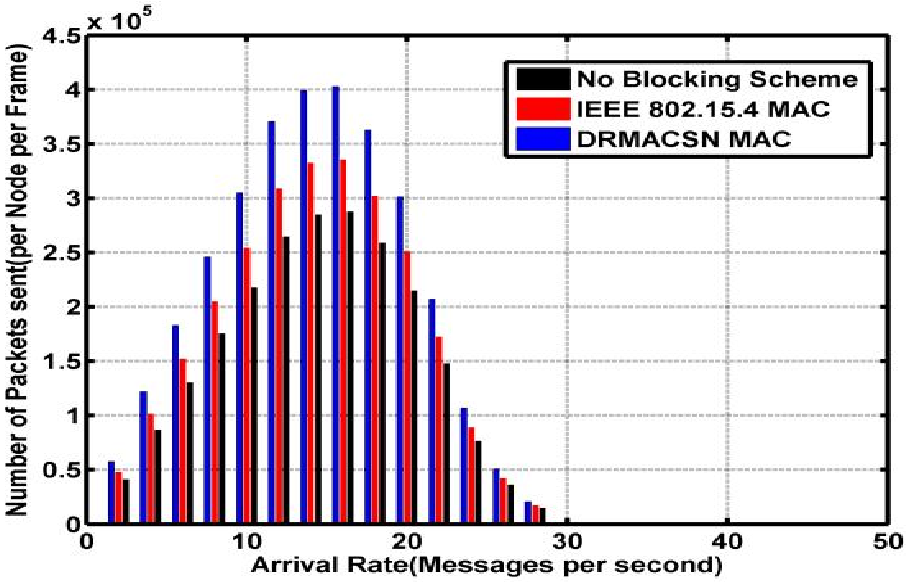


Figure 3.20: Comparison of DRMACSN MAC protocol's number of packets sent with no blocking scheme and IEEE 802.15.4 MAC as function of arrival rate

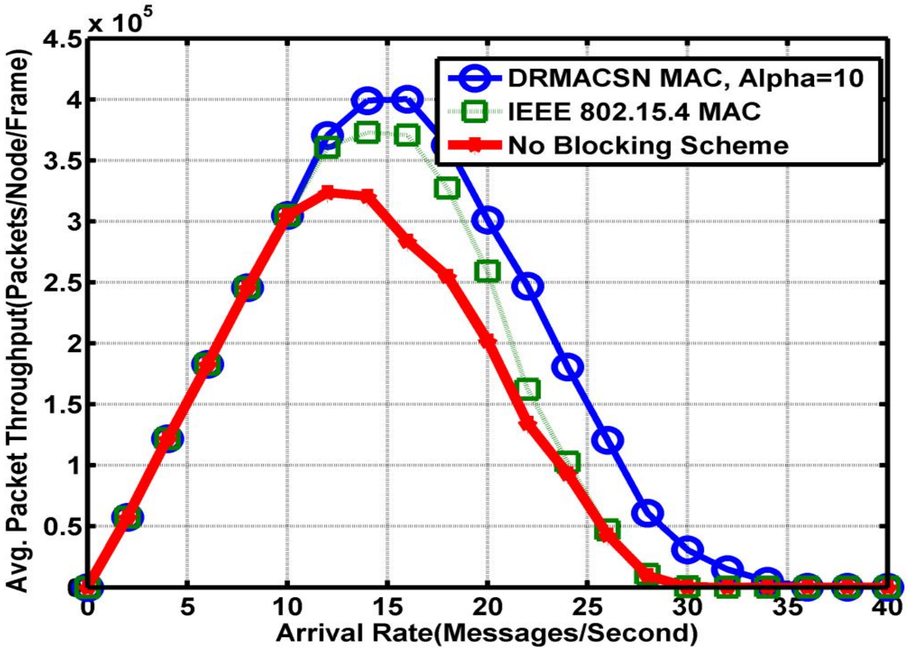


Figure 3.21: Comparison of DRMACSN MAC protocol's throughput with no blocking scheme and IEEE 802.15.4 MAC as function of arrival rate

B. Energy Consumption Comparison

Figure 3.22 illustrates the average energy consumption of the MAC protocols. It can be seen from Figure 3.22 that the no blocking scheme consumes the largest amount of energy in all traffic load scenarios. The DRMACSN MAC protocol's energy consumption is low because when the blocking threshold is set the DRMACSN MAC protocol blocks new arrivals; therefore, the energy consumption is reduced in the network.

It is also observed that the energy consumption increases at higher loads because the DRMACSN MAC protocol allows admitted nodes to continue their transmission when the channel status is good. Thus, the DRMACSN MAC protocol has the best energy saving property, and far out-performs IEEE 802.15.4 MAC and MAC with the no load sensing technique. It is clear from Figure 3.22 that the energy consumption by all MAC protocols becomes constant when the system reaches its maximum capacity.

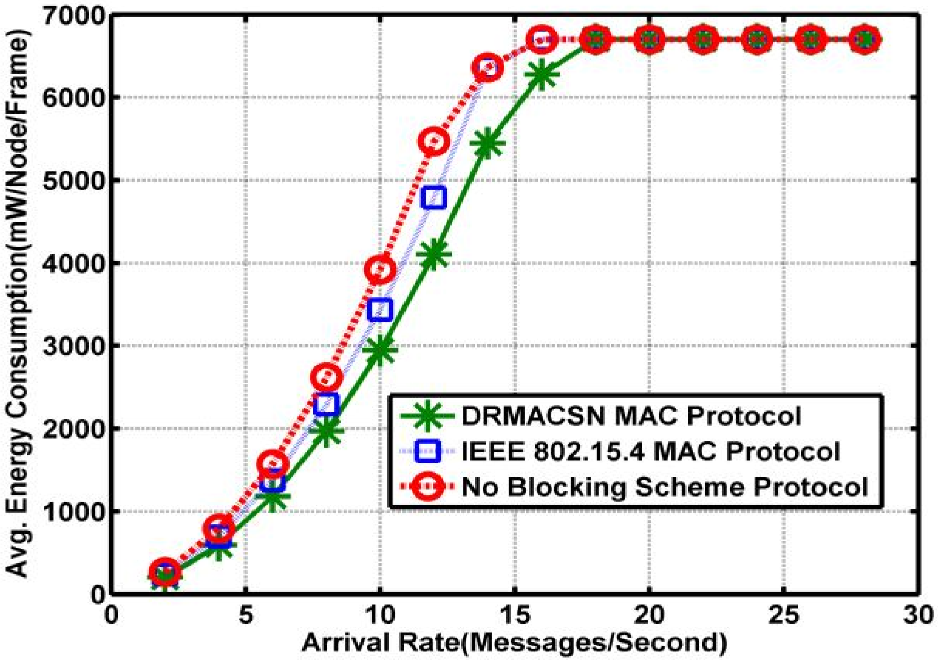


Figure 3.22:Comparison of DRMACSN MAC protocol's average energy Consumption with no blocking scheme and IEEE 802.15.4 MAC

C. Packet Delay Results Comparison

The performance of the average packet delay of the DRMACSN MAC with the IEEE 802.15.4 MAC and no blocking scheme is compared in Figure 3.23 as the arrival rate increases. As can be seen from Figure 3.23, the delay is the same for all schemes in low traffic conditions and at higher load values. On the other hand, the DRMACSN MAC protocol reduces the delay compared to the IEEE 802.15.4 MAC and no blocking scheme because the intermediate nodes in the path are awake to relay the received packets to the next destination node in the DRMACSN MAC protocol.

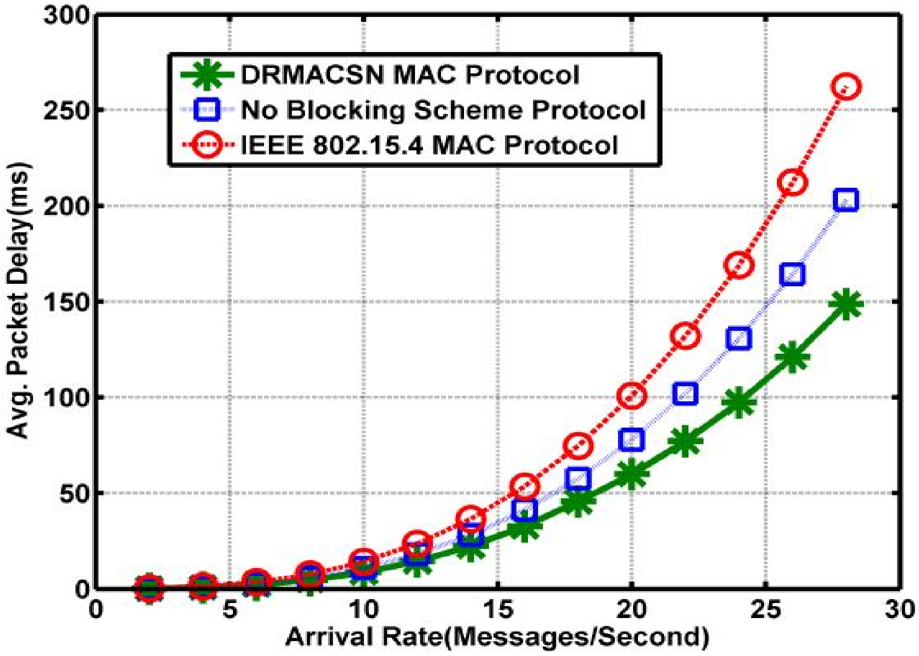


Figure 3.23:Comparison of average delay for DRMACSN MAC protocol, No Blocking Scheme and IEEE 802.15.4 MAC

3.8 Summary

In this chapter, a distributed MAC protocol based on DS-CDMA for WSNs has been proposed. It employs a channel load sensing technique to improve throughput by minimizing delay and energy consumption. The simulation results for energy consumption, throughput and delay for the proposed MAC protocol have been presented.

The results show that a significant increase in the performance of the system in terms of improved throughput and reduced energy consumption and delay can be obtained by implementing the channel load sensing technique.

The simulation results of the DRMACSN MAC protocol were compared with the IEEE 802.15.4 MAC and MAC with no channel load sensing scheme for energy consumption, throughput and delay. Simulation results have revealed that the proposed MAC protocol can achieve good performance in all traffic load conditions.

Finally, the simulation results have shown that the proposed MAC protocol out-performs IEEE 802.15.4 MAC with regard to the number of packets sent, packet throughput and energy consumption.

Chapter 4

Throughput and Energy Analysis of Distributed DS-CDMA based MAC protocol for Wireless Sensor Networks

4.1 Introduction

This chapter presents the throughput and energy analysis of the DRMACSN MAC protocol for DS-CDMA based WSNs. To reiterate, the DRMACSN protocol presented in Chapter 3 is a distributed and receiver-oriented protocol that employs a channel load sensing technique to improve the throughput and energy efficiency in the network. In this chapter, an analytical model based on the homogeneous Markov chain model (HMC) that is used to evaluate the performance of the DRMACSN MAC protocol is presented. Most of the MAC protocols designed for WSNs have taken a pragmatic or experimental approach, without presenting an analytical model to provide insight on how the protocols perform. Only a few recent works have attempted to model and analyse some of the MAC protocols in [70-72]. There are a few analytical works using Markov models to analyse the behaviour of a single node or WSN [73-75]. There have also been many studies to investigate the performance of the IEEE 802.15.4 MAC for WSNs with a view to analysing the throughput, delay and energy consumption through the discrete Markov chain model [76-82].

In [70], the authors analysed the performance of the DMAC [19] protocol for WSNs under both CBR traffic and stochastic traffic following a Poisson process. The stochastic traffic model is modelled as a discrete-time Markov chain (DTMC) and analytical results were obtained using numerical methods. The work in [70] analysed the average delay and energy consumption at a single source node under both traffic models. The authors in [70] assumed that the random delay, which will be introduced by contention, is the same for all slots. Then further assumed that the energy consumption is the same for all sending and receiving of data; however sending slots and receiving slots may consume different amounts of energy. The consistency between the analytical results and the simulation results in [70] confirm that the analytical approach can be applied as a complementary tool for performance analysis of the DMAC [19] protocol.

An analytical model that describes the behaviour of SMAC [10, 11] with a finite queue capacity is proposed in [71]. The work in [71] focused on throughput analysis of SMAC with a finite queue capacity with or without re-transmissions. The proposed model in [71] assumes that each node has an independent packet arrival process and has a finite FIFO queue. Additionally, the work in [71] also assumes that the channel is ideal, all nodes are well synchronized and a data packet can be transmitted within one cycle. The proposed model in [71] was also used to optimize the parameters of SMAC viz. queue capacity and contention window size for a given network and traffic load so that the maximum throughput could be achieved for a given duty cycle. Furthermore, the proposed model can also be used to arbitrate the trade-off between throughput and network lifetime by choosing approaches of SMAC [10, 11] duty cycles. The throughput of SMAC [10, 11] obtained from the proposed model and the results in [71] are validated by using comprehensive simulations.

In [72], the authors proposed a Markov model to analyse the throughput of XMAC [25] which is an asynchronous duty-cycles MAC for WSNs under various network conditions. The proposed model in [72] assumes that each node has an independent packet arrival process and the channel is ideal (no fading, no capture effect and no hidden nodes), one data packet being transmitted/received per cycle at each node. Additionally, every node has a constant probability of transmitting a data packet regardless of any node’s queue length. The simulations in [72] show that the proposed analytical models provide throughput values that closely match the simulation results under various network conditions. The results in [72] confirm that the throughput obtained from the proposed analytical model matches the simulation results of SMAC [10, 11] within 5%.

The work done in [73] considers a WSN where nodes send their data to a sink by using multi-hop transmissions. It was assumed that the nodes alternatively switch between sleep and transmit mode. While in sleep mode, nodes consume less power but they cannot send/receive data. The Markov model proposed in [73] is to study the network performance in terms of energy, capacity and delay consumption as the sensor changes from sleep/active mode. The behaviour of a single sensor node as well as the dynamics of the entire network was modelled in [73] by using a DTMC model, in which the time is slotted according to the data transmission time. Then it was extended to include the channel contention among nodes and data routing through the network. The analytical expressions for the average transfer delay, network energy consumption per unit slot are derived in [73]. The performance of the model was validated by comparing the analytical results with simulation results to show the accuracy of the model.

In [74], the authors predict the sensor energy consumption using a Markov chain for a single node and the network energy status was derived via simulation. The construction of an energy map using a probabilistic and statistical prediction-based approach, which aids in reducing energy consumption of a WSN, was studied in [74]. A probabilistic model based on Markov chains was used to model each sensor node. The modes of operation of a node are represented by the states of a Markov chain and the random variables represent the probability of staying in each state for a certain length of time. The authors in [74] found that each node tries to estimate the amount of energy that it will be spending in the near future and it sends this information along with its available energy to the monitoring node in the prediction-based energy map scheme. The authors in [74] present a statistical model in which the energy level is represented by a time series using the autoregressive integrated moving average (ARIMA) model to make the predictions. A node sends only its available energy to a monitoring node in the energy dissipation model. Simulations were conducted to compare the proposed schemes. The simulations' results in [74] indicate that the prediction-based approached are more energy efficient and more scalable with respect to the number of sensing events.

An analytical framework was developed in [75] to evaluate the transient behaviour of a WSN in which sensor nodes implement the energy-saving scheme of active/idle states. It is considered that a generic sensor node can perform four fundamental functions viz., sensing the environment, sending/receiving data units and listening to the channel. The proposed model in [75] captures the behaviour of the battery life of each sensor and evaluates the distribution of the lifetime of all sensors in the network. A DTMC model is used in [75] to obtain the behaviour of a generic sensor node. It is further considered that the duration of a time slot is assumed to be equal to the time needed to transmit a data packet. Expressions for some of the performance measures, such as network capacity, average delivery delay, network energy consumption per time slot and network lifetime, were derived.

The authors in [76] developed analytical models based on the discrete time Markov chain for fixed and exponential back-off windows to analyse the energy efficiency issues in WSNs that consider the channel access procedure of IEEE 802.15.4 by taking a fixed number of backlogged nodes. The conditions for the success and failure status of the channel access scheme in the IEEE 802.15.4 CSMA-CA standard is based on its two clear channel assessments (CCAs). Channel access is considered to be successful when both CCAs of a node are successful and a node starts its transmissions. However, if a busy channel is reported at the first CCA, a value of back-off exponential (BE) is incremented by one; a node will retry until it reaches its maximum retry limit. Otherwise the process terminates due to a channel access failure and the packet may be rejected. However, this has been modified in [76] and assumed that the packet is not rejected in a single channel access failure attempt.

The work done in [77], compared the theoretical results with the simulation results to confirm that energy consumption is increased when the contention window size and the network density is increased in WSNs. It was observed that energy consumption is less in a WSN when adapting an exponential contention window rather than a fixed one. It was suggested in [77] that the exponential contention window scheme is also useful in a WSN where the sensors were deployed in a remote monitoring region and replacement or recharging of batteries is not possible. When the WSN network population and traffic loads are known, the effective energy consumption in a WSN can be achieved by using fixed contention windows.

The work done in [78] proposes the performance evaluation of IEEE 802.15.4 for WSN applications by considering a peer-to-peer topology. The analytical work done in [78] consists of models for CSMA/CA mechanism and MAC operations specified by IEEE 802.15.4. The network formed in a beacon-enabled, cluster-tree topology was used to analyse the IEEE 802.15.4 for WSN. The performance of a device and a coordinator are analysed in terms of the average power consumption and throughput. The results were validated with the simulation results obtained from the WSN simulator.

In [79], the performance of an IEEE 802.15.4 WSN for event detection application was studied. The author in [79] considered a single-hop network topology such that all nodes can communicate directly with the central coordinator. It was assumed that all nodes in [79] operate according to the un-slotted IEEE 802.15.4 mode; however, this can be extended to a slotted mode. The transient analysis is carried out when k sensor nodes detect the event and attempt to send their report to a central controller. The proposed model in [79] provides a detailed evolution of the system, taking into account some events that are difficult to capture by simulation. An efficient solution algorithm was derived in [79], by exploiting the properties of WSNs, to reduce the complexity of the model. The authors derived the delay distribution of each report delivery as well as the probability that m out of k reports reach the central controller within a given time constraint. The results in [79] show that the probability of small delays in report delivery increases as the number of sensors grows up to a certain value, after which the opposite behaviour can be seen in the results. The model can also be used to determine the number of sensors covering the area of interest which allows the system to meet both the specified time deadline and the required reliability level.

A novel analytical framework that combines the theory of DTMCs and classical queuing theory to model the behaviour of the MAC in IEEE 802.15.4 wireless networks is proposed in [80]. The work in [80] considers two scenarios: firstly, the network where the nodes communicate directly to the coordinator (the final sink), and secondly, a cluster-tree scenario where the source nodes communicate to the coordinator through a series of relay nodes, that forward the received packets and do not generate traffic on their own. The network performance in terms of aggregated network throughput and packet delivery delay was evaluated.

The work done in [81] proposed to characterize both the sensors' behaviour and the channel status using a Markov chain model. The proposed model was used to derive the average system performance, in terms of throughput and energy consumption. In [81], the radio was allowed to enter a shutdown state between transmissions, which has been shown to be a very effective means to reduce energy consumption in WSNs for a very wide range of traffic rates when the traffic is predominantly uplink. Furthermore, the proposed work initializes the contention window length to one showing improved throughput and reduced energy consumption when MAC level acknowledgements are not used.

In [82], the authors proposed a novel analytical model by considering a non-beacon-enabled WSN for the IEEE 802.15.4 MAC protocol, where a star topology was established. The work done in [82] considered IEEE 802.15.4 sensor nodes simultaneously generating reports to be sent to a sink node through single-hop transmissions. The work in [82] assumes that the nodes are all synchronized, owing to the query being sent by the sink node and starting the back-off algorithm all at the same time for the transmission of their packets. The ideal channel conditions (no hidden node problem) are assumed in [82]. Further, the work assumes that probabilities that a node succeeds in accessing the channel, that a node successfully transmits a packet, and that the sink receives a packet have been evaluated. The message delay is derived by considering that there are no acknowledgements. This implies that the messages are lost due to collision when two sensors are considered and the initial contention window was set to seven in [82].

The analytical models proposed in [70-82] consider either the node behaviour or the network behaviour to analyse the performance of WSNs. Notwithstanding a few models proposed in [70-82] that consider both scenarios for WSNs, as far as is known, there is no analytical model which considers both scenarios along with CDMA in WSNs. In this chapter an analytical model to analyse the performance of the DRMACSN MAC protocol is presented. This chapter provides comparison results for the throughput and the energy consumption of the proposed MAC protocol through simulations and analysis.

The remainder of this chapter is organized as follows: Section 4.2 presents the state transition diagram, assumptions and distribution of the length of the re-transmitted packets for the proposed MAC protocol. In Section 4.3, the state transition probabilities are determined. Following this, Section 4.4 presents the performance measures such as the average throughput and average energy consumption of the proposed MAC protocol. Section 4.5 presents the performance evaluation of the DRMACSN protocol. The concluding remarks of this contribution are presented in Section 4.6. The contents of this chapter, in part, are to be submitted as a journal paper to the IEEE Transactions on Mobile Computing.

4.2 DRMACSN MAC State Transition Diagram and Assumptions

In this section, the state transition diagram to analyse the performance of DRMACSN MAC protocol is discussed. The state transition diagram for a sensor node is depicted in Figure 4-1. The states for the state transition diagram are: Sleep State (SS), Transmit State (Tx), and Back-off State (BS). A node will be in a sleep state when it does not have data in its buffer to transmit. The node continues to stay in the sleep state for a random period of time. When messages start to arrive and the sleep timer expires, the node enters into the active state if the channel load $K < \propto$. The node starts sending messages continuously until the buffer is empty. When there are no messages in its buffer, the node enters into a sleep state to conserve its energy. The node enters into a back-off state from sleep state when the channel load, K, exceeds the blocking threshold, $\propto$. A node continues to be in the back-off state when K is greater than α and the back-off time has not expired, i.e. $T < T_{Back-off}$. Otherwise a node leaves the back-off state and enters into the Tx state to transmit/receive packets.

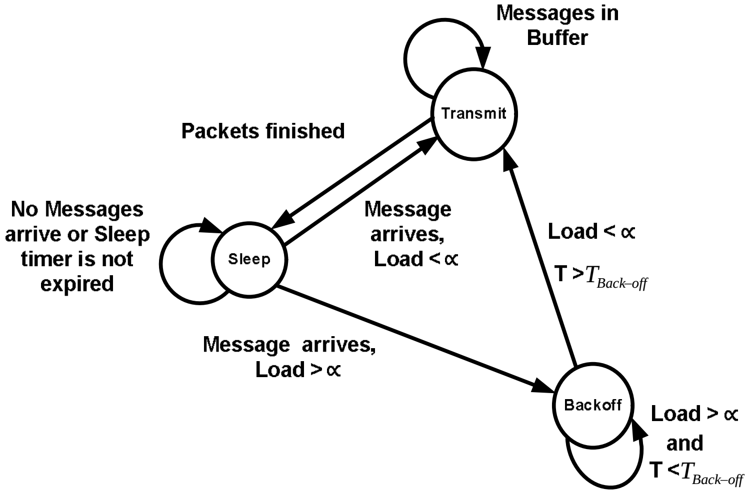


Figure 4.1: State Diagram of Sensor Node

In this section, the assumptions made in order to simplify the analysis are presented. The following population model is presented.

Let s represent the number of nodes in the sleep state. Let b represent the number of nodes in the backlogged state. Let x represent the number of nodes in the transmit state. Therefore, the total number of nodes is equal to

$$N = s + b + x \tag{4.1}$$

We also define $\bar{n}_s$, $\bar{n}_b$ and $\bar{n}_x$ as the expected steady state sub-population sizes.

A WSN that has a finite number of nodes is considered. It is assumed that the messages can arrive in sleep, back-off and transmit state in the proposed MAC protocol. It is further assumed that the CQI value is constant in this analysis and that whenever the channel load $K \geq \alpha$ (Blocking threshold), no new node is admitted. This is slightly different from simulation. In addition, it is assumed that the distribution of re-transmitted packets is geometric with mean length $\frac{1}{\mu_R}$. This assumption is verified through the simulation in Section 4.2.1.

The finite number of nodes is divided into three sub-populations as follows:

a) **Sleep** nodes: It is assumed that the sleep state time is a geometric random variable where in each frame there is a probability of $\frac{1}{\mu_s}$ that the sleep time terminates, $\bar{T}_S = \frac{1}{\mu_s}$.

Further, it is assumed that there are arrivals of new messages in the sleep state. The length of new messages is assumed to be geometrically distributed with mean length $\bar{m}$ packets. This geometric distribution for new message lengths is defined as $P(M)$.

b) **Back-off** nodes: It is assumed that the back-off time is geometrically distributed with mean $\bar{T}_B = {\mu_B}^{-1}$. In this thesis, it is also considered that there are arrivals of new messages while nodes are in the back-off state. The same distribution of new arrivals as in the sleep state is assumed.

c) **Transmit** nodes: these are nodes in transmit state that is in the process of transmitting messages that are in the buffer. The duration of transmit state, T_x, is computed as follows

$$T_x = (\text{Total number of packets transmitted}) \times T_f$$

$$T_x = k.\, T_f \tag{4.2}$$

Thus, the overall message termination rate, μ_x is equal to,

$$\mu_x = \frac{1}{T_x} = \frac{1}{k.\, T_f} \tag{4.3}$$

In this thesis, it is assumed that there are arrivals of new messages while nodes are transmitting messages. It is also assumed that the distribution of new arrivals in transmit sate also follows the same distribution as in sleep state.

4.2.1 Distribution of the Length of Re-transmitted Packets

The computation of the distribution of the lengths of re-transmitted packets $P_R(M)$ is complicated [54]. Since the proposed MAC uses SR-ARQ to notify the lost packets only to the sender, i.e. each time a message is unsuccessful, only the lost packets in the original message are re-transmitted, and this means that unsuccessful messages are broken down into smaller messages. These smaller messages will then be re-transmitted later. Further, the smaller messages will have a higher probability of success than the re-transmission of the original messages since they are shorter. Therefore, It is assumed that this scheme simplifies the problem significantly and allows an accurate approximation for $P_R(M)$, namely: the distribution of the length of re-transmitted packets, $P_R(M)$ appears to be similar to the geometric distribution with mean length, $\overline{m}_R$. This assumption was verified and justified in previous works [54, 83].

In order to justify this assumption, simulation results are produced (refer to Figures 4.2(a), (b) and (c)) for three classes of loads (low, medium and high). Figures 4.2(a)-(c) illustrate the simulation results for the proposed MAC protocol with arbitrary parameters of the distribution of new messages and re-transmitted packets of original message length respectively. These results also include the combined message length distribution, which incorporates the old messages, (messages at beginning of the T_x state), new messages and re-transmitted packets of the message. In order to evaluate the geometric distribution assumption effectively, the three classes of loads (low, medium and high) were considered.

a) A very low load is considered in Figure 4.2(a), where the probability of nodes (in any of three states) generating a message is low, $\rho_s = 0.000125$ (Messages/frame), In this case, the average carried load is very low and the probability of packet success is almost 100 percent and thus, the number of nodes in the back-off state is very low. Further, since most messages are being generated by sleep and transmit state nodes, it is expected that the combined message length distribution is equal to the new message length. Further, the mean length of re-transmitted packets is expected to be low as the message success probability is very high at low loads and also, there is no blocking in this case. Thus, the result in Figure 4.2(a) proves this to be true. the average length of retransmitted messages

b) A medium load, $\rho_s = 0.0025$ (Messages/frame) is considered in Figure 4.2(b), the average length of re-transmitted messages, $\overline{m}_R$ = 3 packets/message. It can be observed that the contribution of messages from the back-off node is considerably greater. It can be seen from Figure 4.2(b) that the mean of re-transmitted packets length distribution is still less than that of the mean of new messages. Thus, the mean of combined messages lies between these two.

c) Figure 4.2(c) shows the result for the high offered load, $\rho_s = 0.005$ (Messages/frame), the average length of re-transmitted messages, $\overline{m}_R$ = 3 packets/message, which results in a poor system throughput and thus the system will have most of the re-transmission of packets in this case.

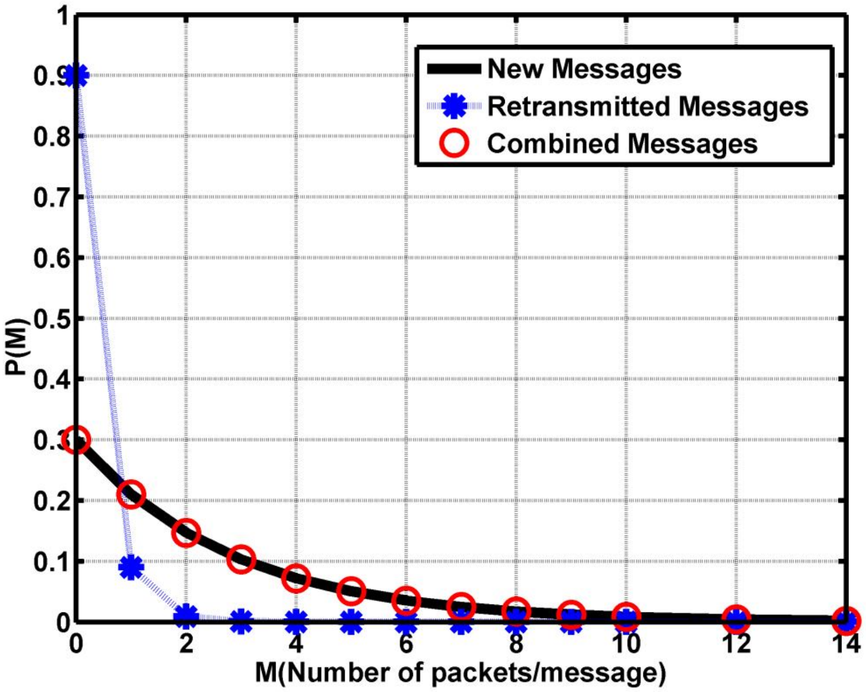


Figure 4.2(a): Simulation results showing that the distribution of retransmitted messages is approximately geometric for a low load value, $N = 100$, ρ_S = 0.00025, ρ_R = 0.005, $\bar{m} = 5$

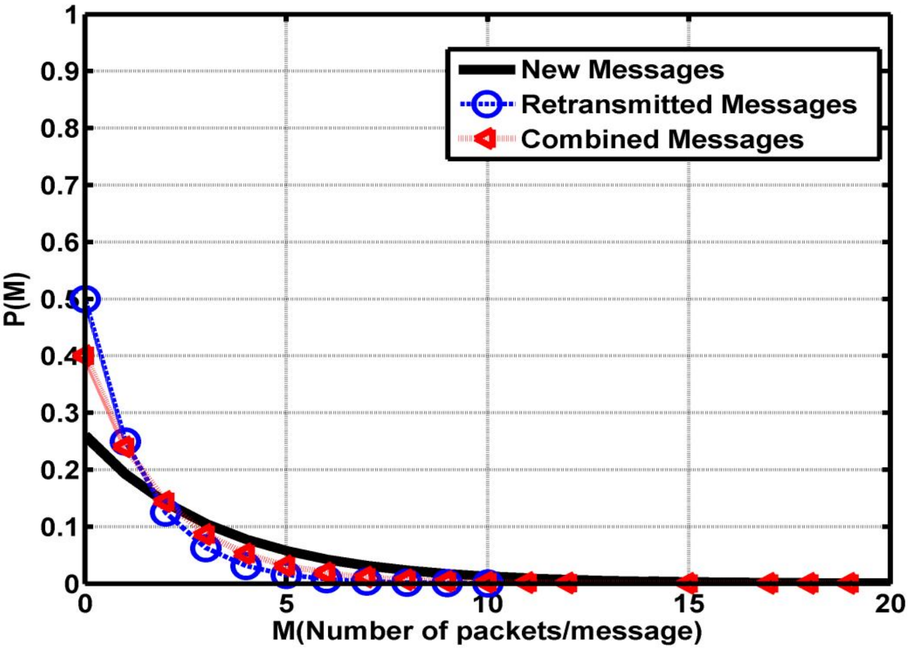


Figure 4.2(b): Simulation results showing that the distribution of retransmitted messages is approximately geometric for a medium load value, N = 100, ρ_S = 0.0025, ρ_R = 0.0066, $\bar{m} = 5$ and $\bar{m}_R$ = 3

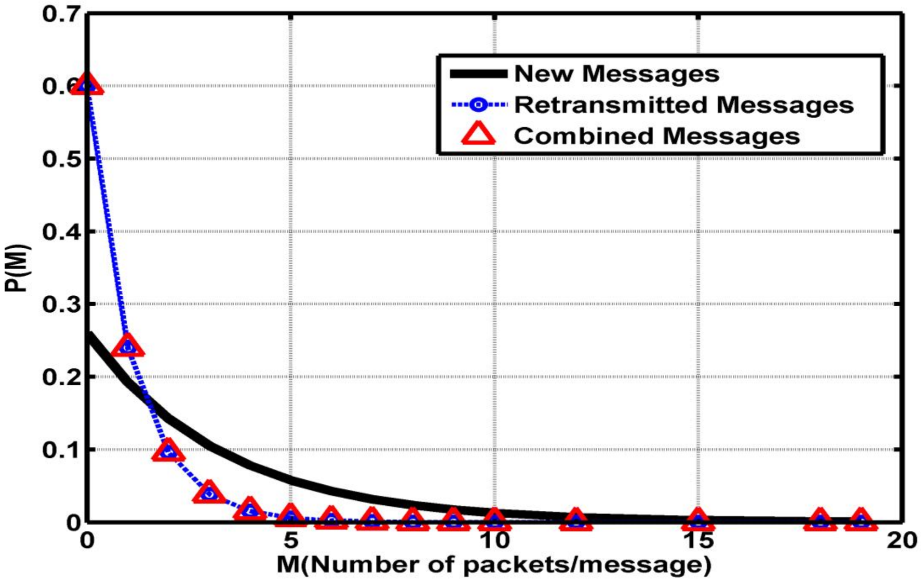


Figure 4.2(c): Simulation results showing that the distribution of retransmitted messages is approximately geometric for a high load value, N = 100, ρ_S = 0.0066, ρ_R = 0.0066, $\bar{m}$ = 5 and $\bar{m}_R$ = 3

4.3 DRMACSN MAC Protocol Analysis

In this subsection, the homogenous Markov chain model to analyse the performance of the proposed MAC protocol is presented and expressions for the packet throughput and energy consumption are derived. The Markov analysis follows the work performed in [54] due to the similar operation of a data admission control scheme. In order to simplify the analysis, the blocking threshold, α, is used as the maximum capacity in this analysis. The state changes on a frame-by-frame basis and it will be represented as a memory-less process [54]. It is considered that the number of messages arriving in the current frame is completely independent of the network status. Figure 4.3 shows the Markov chain for the DRMACSN MAC protocol.

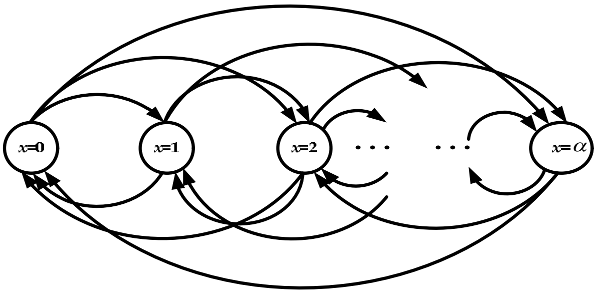


Figure 4.3: Markov chain for DRMACSN MAC protocol

The state of the network, x is defined as the number of transmitting nodes in a current frame and $\mathrm{X(j)}$ is the steady state probability of being in state, $x = j$. The entire process for x can be obtained from the information in the current frame and the previous frame, therefore, a simple Markov chain can be used to represent this process. The term π_{ij} is defined as the state transition probability of moving from the current state $x = i$ in frame, f to the next state $x = j$ in frame, $f + 1$. The elements of π_{ij} can be structured as the following state transition matrix, P

$$\mathrm{P} = \begin{bmatrix} \pi_{00} & \pi_{10} & \cdots & \pi_{\alpha 0} \\ \pi_{01} & \pi_{11} & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ \pi_{0\alpha} & \pi_{1\alpha} & \vdots & \pi_{\alpha\alpha} \end{bmatrix} \tag{4.4}$$

The elements of P are computed in Section 4.4.

Let $f_A(y|i)$ be the probability that y nodes change their state to transmit state given that i nodes are transmitting in the current frame f and $f_T(y|i)$ be the probability that y nodes terminate from the transmit state given that i nodes are transmitting in the same frame f. The following probabilities are defined:

$$\begin{aligned} f_A(y|i) &= b(N-i, y, \mu_s) \\ f_T(y|i) &= b(i, y, \mu_x) \end{aligned} \tag{4.5}$$

For ease of notation we will drop the nodes that are transmitting in the current frame, i, but with the understanding $f_A(y) = b(N-i, y, \mu_s)$ and $f_T(y) = b(i, y, \mu_x)$ for a given i. Denoting the binomial distribution with parameters m, M and ξ as

$$b(m, M, \xi) \triangleq \binom{M}{m} \xi^m (1-\xi)^{M-m} \tag{4.6}$$

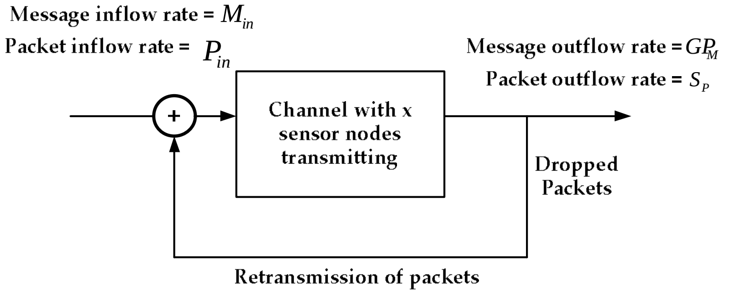


Figure 4.4: The system information flow model for the proposed system [83, 84]

4.3.1 The System Information Flow Model

Figure 4.4 illustrates the flow model for messages and packets into and out of the network along with the different population subsets for the three states [83, 84].

a) **Message input flow** : The message input flow in a cycle is simply equal to the new offered message load, i.e. message input flow, $\mathrm{M_{in}}$

$$\mathrm{M_{in}} = \rho_S \cdot \mathrm{N} \cdot [\mathrm{T_s} + \mathrm{T_b} + \mathrm{T_x}] \tag{4.7}$$

b) **The packet input flow** is simply the message input flow multiplied by the expected number of packets, i.e.

$$P_{in} = \rho_S \cdot \mathrm{N} \cdot \,\overline{m}\, \cdot [\mathrm{T_s} + \mathrm{T_b} + \mathrm{T_x}] \tag{4.8}$$

4.4 Computation of Steady State Probabilities

Given that there are N nodes in the system, the transmission of messages only comes from x nodes. Consider that i transmitting nodes in the current frame, f, moves to j transmitting nodes in the next frame, $f + 1$. The following three types of transitions can be defined.

a) If the number of nodes i in the frame f is less than or equal to $\propto$, then new nodes will move to transmit state. Among the i sensor nodes in transmit state, c nodes terminate transmission with a probability μ_x, where c is a random variable within in the range $(i - j) \leq c \leq i$. The number of new messages that arrive into the channel is $j - i + c$ where the probability of this occurrence is $f_A(j - i + c)$. The probability of this event is given by

$$\sum_{c=0}^{i} f_A(j - i + c) f_T(c), \qquad i \leq \propto, j \geq i \tag{4.9}$$

b) If $i \leq \alpha$ and $j \leq i$, then there will be blocking of some nodes. This case can result from the event that $(i - j)$ nodes terminate normally with probability, μ_x so that the channel load can return to j. The probability of this event is given by

$$\sum_{c=i-j}^{i} f_A(j - i + c) f_T(c), \qquad i \leq \propto, j \leq i \tag{4.10}$$

c) If $i \leq \alpha$ and $j \leq i$, then there will be blocking of some nodes. This case can result from the event that $(i-j)$ nodes terminate normally with probability, μ_x. The probability of this event is given by

$$f_T((i-j)), \quad i \geq \propto, j \leq i \tag{4.11}$$

Considering the above events, the state transition probability, π_{ij} can be obtained as follows

$$\pi_{ij} = \begin{cases} \sum_{c=0}^{i} f_A(j-i+c)\, f_T(c), & i \leq \propto, j \geq i \\ \sum_{c=i-j}^{i} f_A(j-i+c)\, f_T(c), & i \leq \propto, j \leq i \\ f_T((i-j)), & i \geq \propto, j \leq i \\ 0 & otherwise \end{cases} \tag{4.12}$$

The following equations can be solved simultaneously to determine the steady state probabilities.

$$\mathrm{X(j)} = \sum_{i=0}^{\propto} \mathrm{X(i)}\pi_{ij} \quad \text{and} \quad \sum_{j=0}^{\propto} \mathrm{X(j)} = 1 \tag{4.13}$$

The following approaches [85, 86] can be used to calculate the steady state probabilities, $X(j)$.

a) Iterative numerical methods such as Gauss-seidel, Jacobi iterations, etc.
b) Eigenvector corresponding to a unity Eigen-value.

In this work, the Eigenvector approach to find $X(j)$ is used in MATLAB.

4.5 Performance Measures

In this section, the performance measures such as the packet throughput and the energy consumption of the proposed MAC protocol are derived.

4.5.1 Average Packet Throughput

The packet throughput is the number of successful packets per node per frame and it is obtained as follows.

The packet throughput of the proposed MAC protocol, S, given that j nodes are transmitting is given by(the derivation is given in Appendix A-2)

$$S|j \text{ nodes transmitting} = \sum_{i=0}^{j} \binom{j}{j-i} (j-i) P_{SP}^{j-i}(j) \cdot (1 - P_{SP}(j))^{i} \tag{4.14}$$

where $P_{SP}(j)$ is the probability of packet success and is computed using Eq. 4.31in Section 4.6 of this chapter.

The average packet throughput per node per frame, S_p or $S_p(\bar{m}, \overline{T}_x)$ for the proposed MAC protocol is given by

$$S_p = \sum_{j=0}^{\propto} \sum_{i=0}^{j} \binom{j}{j-i} (j-i) P_{SP}^{j-i}(j) \cdot (1 - P_{SP}(j))^{i} \cdot X(j) \tag{4.15}$$

The message output flow is simply equal to message throughput, which is the fraction of load, G that is successfully transmitted across the channel per frame and is given by

$$M_{out} = (\rho_S \cdot N \cdot [\overline{T}_s + \overline{T}_b + \overline{T}_x] + G_R \overline{T}_x) \cdot P_M \tag{4.16}$$
$$M_{out} = G \cdot P_M$$

where G_R is the total number of retransmitted packets per message and given by

$$G_R = \rho_S (1 - P_M) \tag{4.17}$$

where P_M is message successful probability and is computed using Eq. 4.36 in Section 4.7 of this chapter.

The following packet flow equations can also be used to obtain the value of unknown variables, $\overline{T}_x$ and $\bar{m}$:

$$P_{in} = P_{out}$$

$$\rho_S \cdot N \cdot \bar{m} \cdot [\overline{T}_s + \overline{T}_b + \overline{T}_x] = S_p \tag{4.18}$$

After simplifying Eq. (4.17), the following approximation expressions are obtained to find the values of $\overline{T}_x$ and $\bar{m}$:

$$\overline{T}_x = \left| \frac{S_p - \rho_S N \bar{m} [\overline{T}_s + \overline{T}_b]}{\rho_S N \bar{m}} \right| \tag{4.19}$$
$$\bar{m} = \frac{S_p}{\rho_S \cdot N \cdot [\overline{T}_s + \overline{T}_b + \overline{T}_x]}$$

Eq. (4.19) are still contains unknown variables, S_p, $\bar{T}_x$, and $\bar{m}$. The system of three equations, Eq. (4.19) and (4.15) are solved to get the value for $\bar{T}_x$ and $\bar{m}$.

4.5.2 Average Energy Consumption

The energy consumption is an important performance measure since power is the critical factor in WSNs [87]. The average energy consumption of the proposed system per node per frame, $\bar{E}$, can be divided into three contributions**.** The first one is the energy spent in the transmit state to transmit the packets, E_{Tx}. The second one is the energy spent in the back-off state, $E_{Back-off}$. The third one is the energy spent in the sleep state, E_{Sleep}. The power consumption of nodes is shown in Table 3-2 of Chapter 3.

Let $L_{Preamble}$, L_{RTR}, L_{DS}, L_{DATA} and L_{ACK} be the length of the preamble, RTR, DS, DATA and ACK packets.

The average energy consumption per node per frame, $\bar{E}$ is obtained as follows.

$$\begin{aligned}\bar{E} = &\sum_{x=1}^{N} x \cdot X(x) \cdot (E_{Tx}) \\ &+ \sum_{b=1}^{N-x} \sum_{s=1}^{N-x-b} (s \cdot X(N-x-b) \cdot E_{Sleep}) \cdot (b \cdot X(N-x) \\ &\cdot (E_{Back-off}))\end{aligned} \tag{4.20}$$

where E_{Tx}, $E_{Back-off}$ and E_{Sleep} is the energy consumed in the aforementioned states i.e., transmitting, sleep, and back-off state and are computed as follows:

4.5.2.1 Energy Consumption in Transmit State

In the proposed MAC, a node spends energy when it is transmitting its message or forwarding the packets sent by other nodes to the next node on the route or to a destination. The energy consumption for transmission of any packets, $E_{Tx}^{PacketType}$ is the sum of the amount of energy consumed in successful transmission of packets such as Preamble, RTR, DS, DATA, and ACK. The total amount of energy consumed by a node for the transmission of packets is given by

$$E_{Tx} = \left(\theta + E_{Tx}^{PacketType} + \Delta\right)$$

(4.21)

$$E_{Tx}^{PacketType} = \bar{T}_{Tx} \cdot \left(\left[\left(\left(E_{Tx}^{Preamble} + E_{Tx}^{RTR}\right) + E_{Tx}^{DATA} \right) + \left(E_{Tx}^{DSRTRNBR}\right) + E_{Tx}^{ACK}\right] + NU_{TX}\right) \tag{4.22}$$

In Eq. (4.21) and (4.22), the notation is as follows.

a) $\bar{T}_{Tx}$ is the total time spent in transmit state, equal to $\frac{1}{\mu_x}$.

b) θ represents the switching energy from sleep to transmit state, Δ represents the switching energy from transmit to sleep state [88].

c) NU_{TX} is the amount of energy consumed by the nodes while transmitting the network update information.

$$NU_{TX} = \left[\left(\frac{L_{NRT}}{R_b}\right) \cdot (Power_{TX})\right] \tag{4.23}$$

d) $E_{Tx}^{Preamble}$ is the energy consumed when the source node transmits the preamble request to the receiver node.

$$E_{Tx}^{Preamble} = \left[\left(\frac{L_{Preamble}}{R_b}\right) \cdot (Power_{TX})\right] \tag{4.24}$$

e) E_{Tx}^{RTR} is the energy consumed when receiver node transmits the RTR reply back to source node

$$E_{Tx}^{RTR} = \left[\left(\frac{L_{RTR}}{R_b}\right) \cdot (Power_{TX})\right] \tag{4.25}$$

f) In the proposed MAC, the energy consumed when the source and receiver nodes send DS and RTR packets respectively to their neighbour nodes to inform about the current transmissions

$$E_{Tx}^{DSRTRNBR} = \left(\left(\frac{[L_{RTR} + L_{DS}]}{R_b}\right) \cdot (Power_{TX})\right) \tag{4.26}$$

g) The energy consumed by a sensor node for the transmission of the data packets successfully.

$$E_{Tx}^{DATA} = k \cdot \left[\left(\frac{L_{DATA}}{R_b}\right) \cdot (Power_{TX})\right] \tag{4.27}$$

h) The energy consumed by receiver node to transmit the ACK packet to source node,

$$E_{Tx}^{ACK} = \left[\left(\frac{L_{ACK}}{R_b}\right) \cdot (Power_{TX})\right]$$

(4.28)

4.5.2.2 Energy Consumption in Back-off State

When the node is in the back-off state, it spends energy checking the channel status and receiving new messages. The energy consumed in the back-off mode is given by

$$E_{Back-off} = \omega + (\overline{T}_B \times \mathrm{Power}_{\mathrm{Back-off}}) \tag{4.29}$$

where ω represents the switching energy from back-off state to transmit state. $\mathrm{Power}_{\mathrm{Back-off}}$ is the amount of energy consumed per unit of time by a sensor node in the back-off state and $\overline{T}_B$ is the duration of a back-off state.

4.5.2.3 Energy Consumption in Sleep State

It is the energy consumed when a node is in the sleep state. The energy dissipated by a node when it is not transmitting but receiving new messages is

$$E_{Sleep} = \delta + \left(\overline{T}_S \times \mathrm{Power}_{\mathrm{Sleep}}\right) \tag{4.30}$$

where $\mathrm{Power}_{\mathrm{Sleep}}$ is the amount of energy consumed per unit time by a sensor node in the sleep state. δ represents the switching energy from sleep state to back-off state, $\overline{T}_S$ is sleep time of a node.

4.6 Computation of the Packet Success Probability

The probability of success, P_{SP}, given that j other nodes is conditioned on the fact that all L bits received correctly. The BLER is a block error rate which is expected to be a function of the SNR and the CQI where CQI is a constant and SNR is a random quantity which is given by Eq. 3.4 in Section 3.5.2 of Chapter 3. As a simplification, a semi analysed approach has been taken and an average SNR from simulator has been used in this work.

The expression for the probability of packet success is given by [67]:

$$BLER_j(t) = f(SNR_j(t), CQI_j(j)) \tag{4.31}$$

$$\mathrm{P}_{\mathrm{SP}}(j) = \left(1 - BLER_j(t)\right)^L \tag{4.32}$$

4.7 Computation of the Message Success Probability

A message is defined to be successfully transmitted if all packets have been transmitted correctly. $P_m(\mathrm{j})$ is defined as the probability of success of the first m packets of a message, given that the m^{th}packet sees j other nodes. The probability of success of the first packet in the message is conditioned on the fact that the message is not blocked and all bits are received correctly. The success probability of a message containing m packets is the probability that all m packets are successful, and is given by

$$P_1(\mathrm{j}) = \mathrm{X}(\mathrm{j}) \cdot (1 - P_B(j)) \cdot \mathrm{P_{SP}}(j) \qquad m = 1, j < \alpha \tag{4.33}$$

The Eq. (4.33) is solved recursively to compute the probability of the entire message's success.

$$P_m(\mathrm{j}) = \sum_{i=1}^{\alpha} P_{m-1}(j) \cdot \pi_{ij}^{PS} \qquad m > 1, j < \alpha \tag{4.34}$$

where $\mathrm{P_{SP}}(j)$ is given in Eq. (4.31) and $P_B(j)$ is given in Eq. (4. 36) and as in Eq. (4.11), π_{ij}^{PS} represents the probability that the m^{th}reference packet is successfully transmitted given that it sees the system state change from i to j. The probability of the reference packet's success is incorporated into π_{ij}^{PS} by including the probability of packet success term, $P_{SP}(\cdot)$.

$$\pi_{ij}^{PS} = \begin{cases} \sum_{c=0}^{i} f_A(j-i+c)\, f_T(c)\mathrm{P_{SP}}(j), & i \leq \propto, j \geq i \\ \sum_{c=i-j}^{i} f_A(j-i+c)\, f_T(c)\mathrm{P_{SP}}(j), & i \leq \propto, j \leq i \\ f_T(i-j)\mathrm{P_{SP}}(j), & i \geq \propto, j \leq i \\ 0 & otherwise \end{cases} \tag{4.35}$$

The overall average message success probability, P_M is found by averaging over all possible message lengths and is given by

$$P_M = \sum_{l=0}^{\propto} P_m(l) \cdot P_M(l) \tag{4.36}$$

4.8 Computation of the Message Blocking Probability

The message blocking probability, $P_B(j)$, is determined by considering the probability of a reference message being blocked. In the proposed work, the event that causes a new message to be blocked occurs when a new message arrives and the number of transmitting nodes is greater than the blocking threshold, α in a current frame in state, i. The blocking probability is then given by

$$P_B(j) = \sum_{k=\propto}^{N} X(k) \tag{4.37}$$

4.9 Stability analysis

The Stability definition: "A system is said to be stable if its load line intersects the equilibrium contour in exactly one place otherwise the system is said to be unstable" [84]. A direct approach to solve the pair of simultaneous equilibrium equations is to plot message and packet curves in the $(\bar{n}_b, \bar{m}_R)$ [54, 83, 84]. In Figure 4.5 (a), (b) and (c) shows the example of equilibrium contours in the $(\bar{n}_b, \bar{m}_R)$ plane for a system with $N = 100$, massage arrival rates, ρ_S = {0.005, 0.0025, 0.000125} messages per frame. It can be observed that from Figure 4.5 (a), (b) and (c), the system has only one intersection point between the message and packet flow curves. Thus, these single points' intersection shows that the proposed MAC protocol has stability.

4.10 Performance Results

This section provides the comparison results obtained from the analytical model with simulation results for the DRMACSN MAC protocol. The set of equations discussed earlier were solved numerically using MATLAB. In order to evaluate the performance measures of the proposed MAC protocol, the same environments that have been presented in Chapter 3 are considered. The simulations' parameters presented in Chapter 3 are also used in this analysis with the following exception: The value of ρ_S is varied to present different load values to the network. It is considered that the data message arrival follows a Poisson process with a rate parameter, λ (Messages/second). The length of data messages is assumed to conform to a geometric distribution.

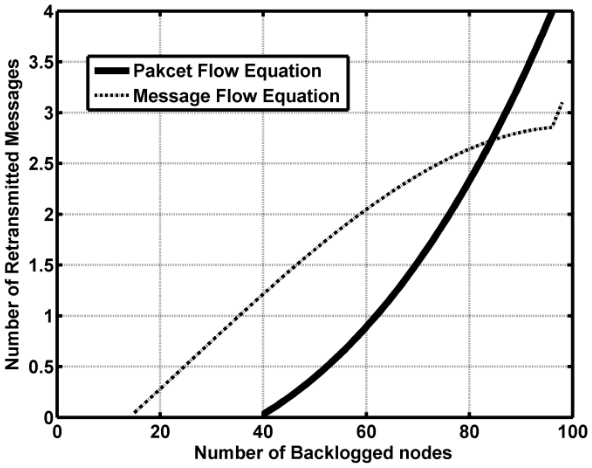


Figure 4.5(a): Message and packet flow contours for some of the equilibrium solution of the proposed MAC protocol, ∝=16, ρ_s = 0.005 messages/frame.

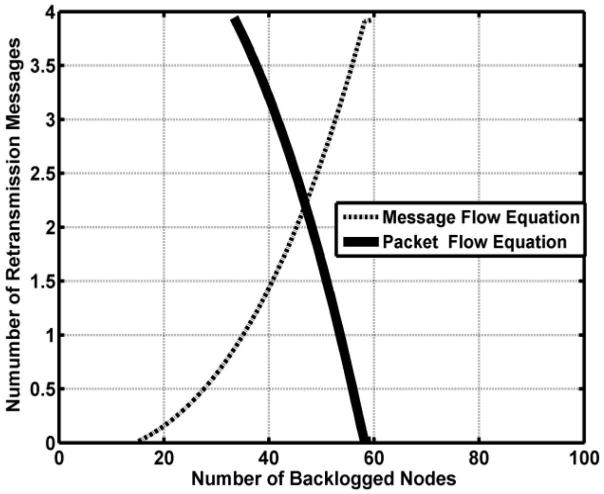


Figure 4.5(b): Message and packet flow contours for some of the equilibrium solution of the proposed MAC protocol, ∝= 16,ρ_s = 0.0025 messages/frame.

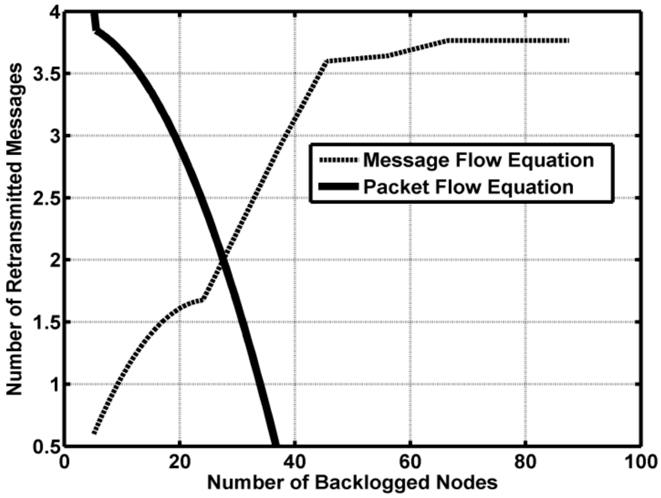


Figure 4.5(c): Message and packet flow contours for some of the equilibrium solution of the proposed MAC protocol, $\propto=16, \rho_s =$ 0.000125 messages/frame.

Figure 4.6 shows the analytical and simulation results of constant CQI values to compare the effect of CQI values on the packet throughput. It can be seen that an optimum throughput can be obtained using variable CQI values. However, the results also show that the DRMACSN MAC protocol can achieve a good throughput via a constant CQI value. This result justifies why a constant CQI value was used to validate the performance of the DRMACSN MAC protocol.

The results of message throughput and packet throughputs are compared in Figure 4.7. For network parameters ($\overline{m}$ = 5 packets/message), it is expected the packet throughput to be five times the message throughput for all possible load values. The results in Figure 4.7 verify this.

Figure 4.8 shows the analytical and simulation results for the average packet throughput of the proposed MAC protocol under the various values of blocking threshold, $\propto$ for increasing arrival rates, λ (CQI = 26 for both simulation and analysis). The curves plotted for the packet throughput for the DRMACSN MAC protocol as computed using Eq. (4.15) of Chapter 4 in Figure 4.8. The results in Figure 4.8 show that a proposed MAC protocol provides good throughput performance for lower channel load values. However, a lower throughput performance is obtained at higher load values.

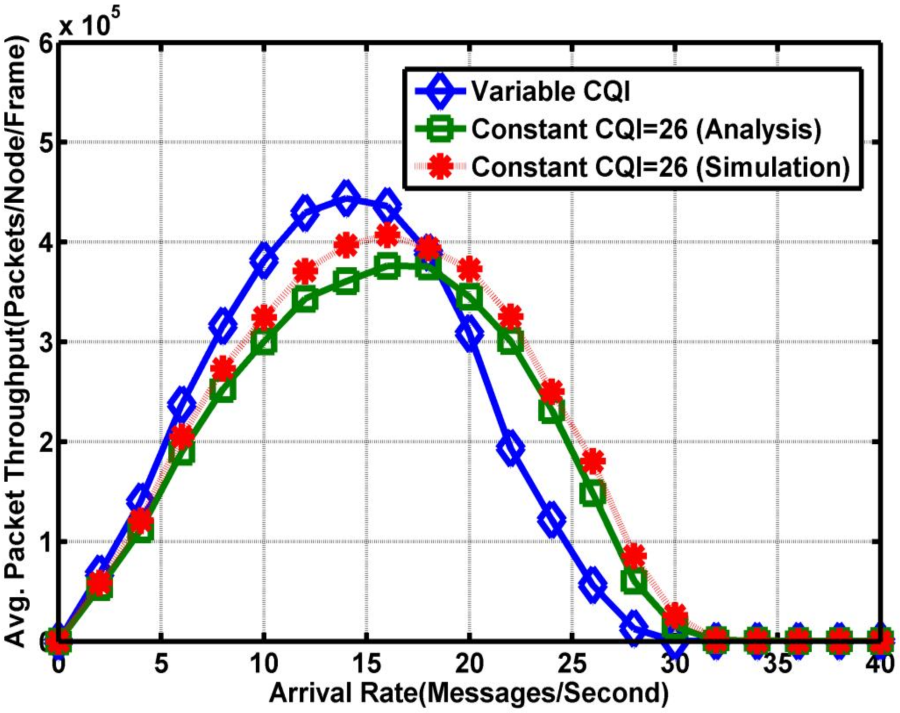


Figure 4.6: Comparison of effect of CQI values on the packet throughput

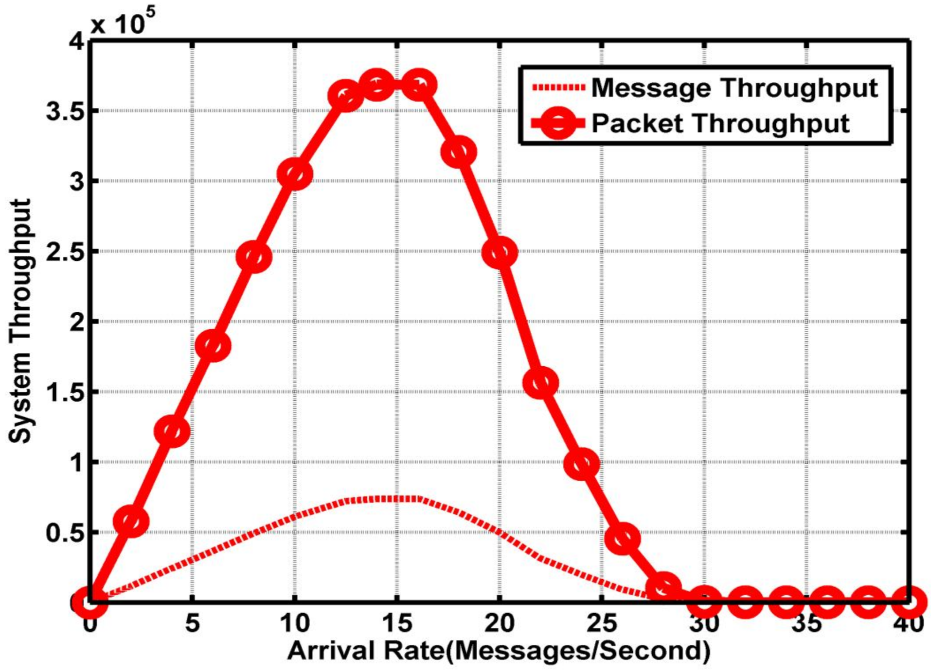


Figure 4.7: Comparison of message and packet throughputs for DRMACSN MAC protocol, $\bar{m}$ = 5 Packets/message

The analysis and the simulation results confirm that there will be very few collisions at low channel loads. In the proposed MAC protocol, all the transmitting nodes have their reserved mini-slot for the transmission of the data packets, and only those nodes have a chance of transmitting in the beginning of the *DATA* slot. This helps the proposed protocol to minimize the collisions at low channel loads, thus improving the throughput of the system.

Figure 4.9 shows the average energy consumed by node per frame as the arrival rate increases. In Figure 4.9 curves plotted for the analysis results for the energy consumption as computed Eq. (4.20) of Chapter 4 for the DRMACSN MAC protocol. The energy consumption is the same for all blocking threshold values in lower channel loads. After some frames, the energy consumption increases at higher loads because the proposed MAC protocol allows admitted nodes to continue their transmission when the channel status is good.

The results in Figure 4.9 confirm that the energy consumption of the DRMACSN MAC protocol is slightly lower for higher blocking threshold value, α = 12 as compared to blocking threshold value, α = 16 because when blocking occurs new nodes are not allowed to transmit their packets.

It can be seen from Figure 4.9 that energy consumption is constant at the higher loads. This behaviour can be explained as follows. When the traffic load increases, the system reaches its maximum capacity. Additionally, an interesting property of DRMACSN MAC protocol is that no new nodes are allowed to transmit when blocking occurs, only the admitted nodes are transmitting, which leads to less energy being consumed in the transmission of data packets. Thus, this feature allows the proposed MAC protocol to save energy in the network and maintain constant energy consumption at higher loads.

These results also confirm that the energy consumption of the DRMACSN MAC protocol is lower as it employs the channel load sensing scheme to conserve the energy of the nodes.

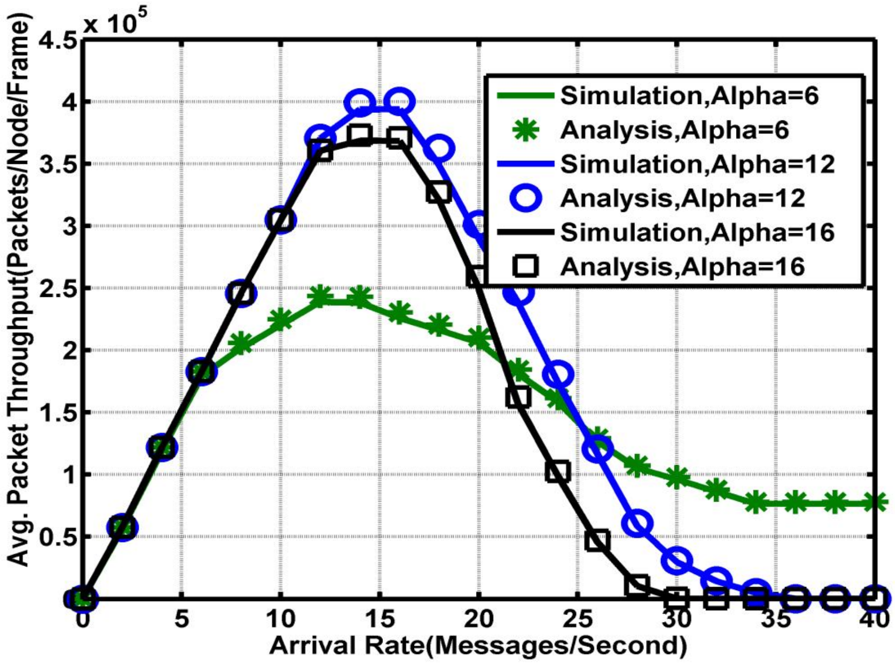


Figure 4.8: Effect of blocking threshold, ∝ =6, 12, and 16 on the packet throughput as traffic rate increases for DRMACSN MAC protocol, ρ_S = 0.004 (Message/frame), CQI = 26

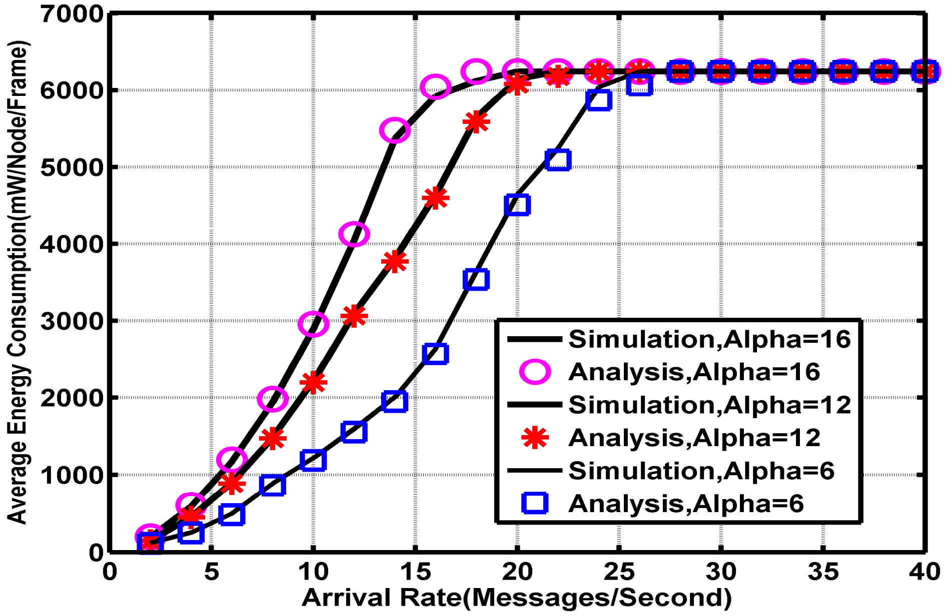


Figure 4.9: Average energy consumption versus traffic rate, the blocking threshold values are, ∝ = 6, 12 and 16 for DRMACSN MAC protocol, ρ_S = 0.004 (Message/frame), CQI=26

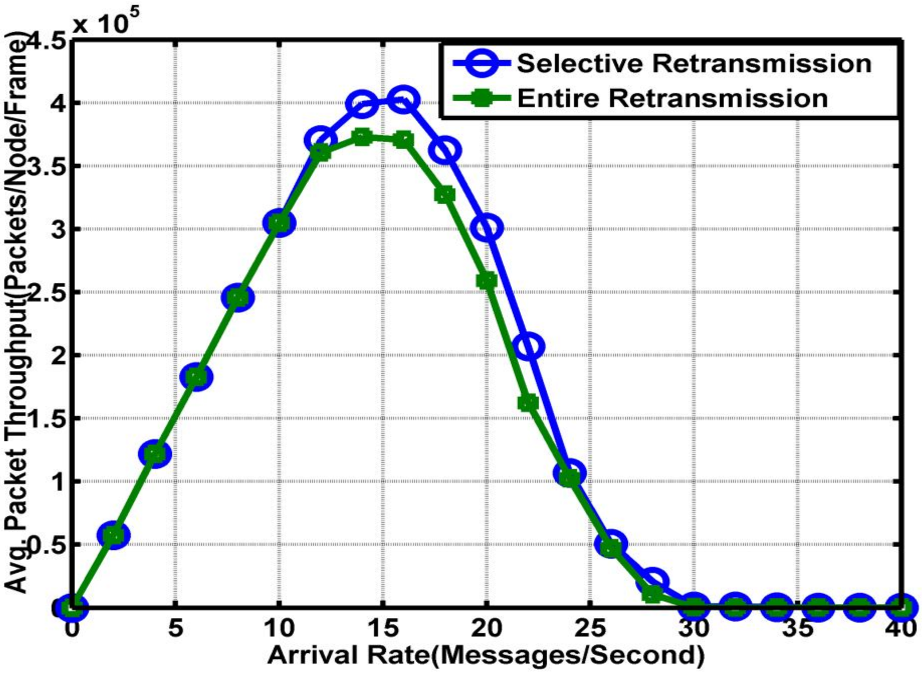


Figure 4.10: Average throughput comparison of selective retransmission of the proposed MAC and retransmission of entire message for arrival rate

We examined the throughput and energy consumption performance of the proposed MAC protocol for retransmission of lost packets. The performance is compared with the system which re-transmits the entire messages in Figure 4.10 and 4.11. As can be observed in results of Figure 4.10, a significant increase in packet throughput can be achieved for the proposed MAC protocol as compared to the system which re-transmits the entire messages.

A comparison performance of the energy consumption for the proposed MAC protocol for re-transmission of packets is compared with the system which re-transmits entire messages in Figure 4.11. The results show that significant energy can be saved in the proposed MAC protocol as it re-transmits only the corrupted or lost packets in the reference message. Thus, the proposed MAC protocol achieves good node lifetime.

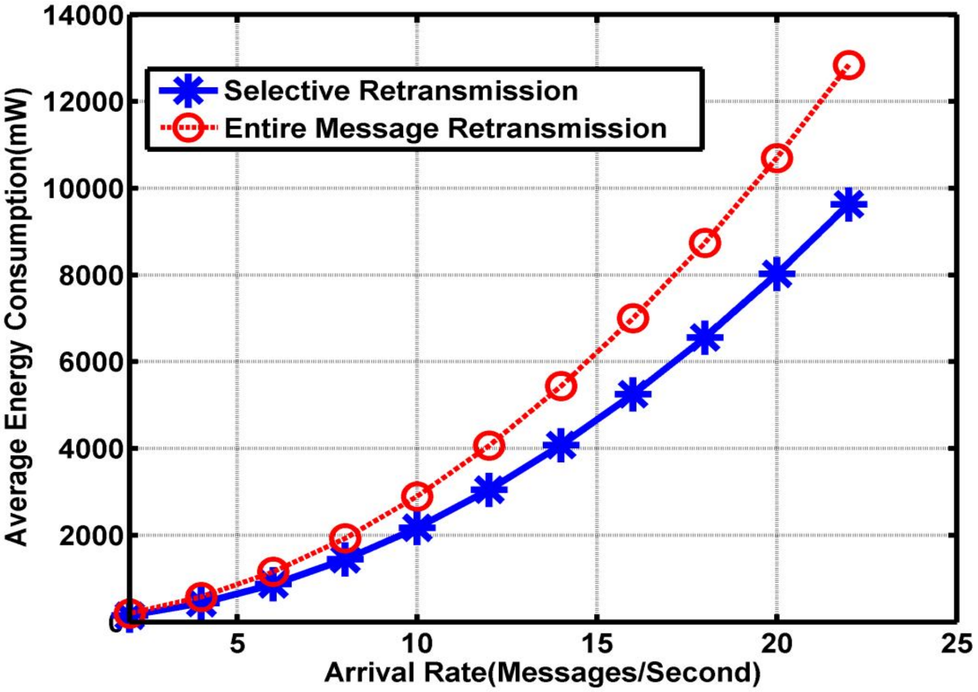


Figure 4.11: Average energy consumption comparison of selective retransmission of the proposed MAC protocol and retransmission of entire message

4.11 Summary

In this chapter, a novel analytical model is proposed to analyse the performance of the DRMACSN MAC protocol based on DS-CDMA for WSNs. The proposed model combines the node behaviour, network behaviour and CDMA to evaluate the performance of the DRMACSN MAC protocol. In this model, the arrival process as a Poisson process was considered. The length of data messages was assumed to conform to a geometric distribution. The selective-repeat re-transmission scheme was incorporated in the proposed model to reduce energy consumption.

To save energy, sensor nodes switch between three operational modes: sleep, back-off and transmit mode. While in sleep mode, nodes consume lower energy, wait for the arrival of new messages. When messages arrive and a random sleep timer expires, a node enters the transmit mode if the channel load is less than the threshold value, otherwise it enters a back-off state for a random time. While a node is in back-off mode, it will have arrival of new messages. When the channel load is less than the blocking threshold value and random back-off timer has expired, the node enters the transmit mode.

While the node is in the transmit mode, it starts transmitting messages until its buffer is empty. A node will also have arrival of new messages in transmit mode. When there are no messages in its buffer, a node enters a sleep mode to save energy. The node energy model was developed to investigate of energy consumption as the sensor nodes dynamics in sleep/back-off/transmitting mode vary.

The second part of this chapter was devoted to presenting the derivation of an accurate statistical analysis, using a DTMC modelling approach of the performance of the DRMACSN MAC protocol. Expressions to predict the expected data packet throughputs and the expected energy consumption measurements were derived. Expressions for predicting the data message blocking and successful probabilities were also derived.

The third part of this chapter presented results for the proposed model as obtained from the derived Markov model and a custom built event-driven simulator for an arbitrary set of network parameters. The simulation and the analytical results confirm that system performance in terms of improved throughput and reduced energy consumption can be achieved through the use of the channel load blocking scheme.

In addition, the results show a substantial decrease in energy consumption when the variable blocking threshold is implemented. An interesting property of the proposed protocol is that the sensor nodes check the channel status before proceeding to send any of the packets such as preamble, RTR and DATA. This improves the probability of success of those nodes transmitting before the overload condition is reached. Furthermore, the proposed MAC protocol aborts or drops the sensor nodes, which arrive to cause a channel overload condition.

The results presented also show that a significant improvement can be achieved by re-transmitting only the corrupted packets in a message rather than re-transmitting the entire message regardless of the number of corrupt packets in the message. Thus, significant energy conservation as well as improved throughput can be achieved for the proposed MAC protocol while re-transmitting only corrupted or lost packets in the reference message.

Chapter 5

Queuing Analysis of DRMACSN: Distributed DS-CDMA based MAC protocol for Wireless Sensor Networks

5.1 Introduction

This chapter presents the queuing analysis of the DRMACSN MAC protocol for DS-CDMA-based WSNs. To reiterate the DRMACSN MAC protocol presented in Chapter 3 is a distributed and receiver-oriented protocol that employs a channel load blocking scheme to reduce packet delay in the network. The significant challenge in WSNs is to conserve energy by minimizing packet delays, collisions and re-transmission of messages. In order to minimize energy consumption in a WSN, the sensor node enters the sleep mode whenever communication is not required or when there are no data packets in its buffer to transmit, and will wake up as soon as the random timer expires. In order to understand the factors that influence the packet delay in a WSN, an accurate analytical model is required. There have been few works in the literature that studied the delay analysis using queuing models in WSNs [89-97].

In [89], the authors have developed a discrete-time $Geom/G/1$ multiple vacation queuing model to capture the working principle of the sleep/wakeup protocol. In the work done in [89], a sleep/wakeup protocol is considered in IEEE 802.15.4, where the node will enter the sleep mode whenever communication is not required and will wake up as soon as a new data frame is ready. In their system, a steady state system model is proposed to analyse the energy consumption. The work in [89] considers the average latency and average energy consumption as the main metric to analyse the system performance. The sleep stage is considered as the first vacation period, and the listening stage as another vacation period [89]. It is assumed that both vacation periods have a fixed time length. The message lengths are assumed to be geometrically distributed. The transmission time of a data frame is assumed to be an independent and identically distributed random variable. The PGFs of the service time, the number of data frames arrived at beginning of the setup time and the busy time period are derived. In this work, the queue length and waiting time are derived but the impact of MAC on the queuing length and energy consumption of individual sensor nodes is not considered.

The work in [90] studied the $M/G/1/K$ vacation model to capture the individual sensor node activities in the network. A beacon-enabled IEEE 802.15.4 WSN was analysed by modelling the network reliability (i.e., the mean number of packets received by the coordinator) as the function of the activity management policy and MAC layer parameters in [90]. The network coordinator monitors the throughput and adjusts the probability with which individual nodes go to sleep after finishing the transmission of data packets. In [90], each sensor node collects the sensed data even when in the sleep mode. Each node attempts to transmit the packets in its buffer while in active mode. The node goes into sleep mode when the buffer is empty for a random period of time. The authors then derived the analytical expressions for the network reliability and the probability distribution of the sensors' inactive time as the function of the activity management policy and the MAC layer parameters. The authors also determined the probability distribution parameter of the sensor inactive time as the function of the required reliability and MAC layer parameters. The analysis work in [90] considered the network reliability as a complex function of the network and traffic parameters such as MAC operational algorithms and its parameters. The main problem in [90] is that the activity management policy is centralized and the computation is performed by the network coordinator.

In [91], the authors developed a novel power saving scheme based on the N-policy $M/M/1$ queuing theory for WSNs. The topology used in [91] contains the sink node in the centre, and M concentric circles, each containing nodes along its circumference. The work in [91] considered that sensor nodes closer to a sink node have a larger forwarding traffic burden than nodes further away from the sink node. These nodes consume more energy than nodes far away from the sink. This leads to the lifetime of a WSN to deteriorate because of uneven energy consumption patterns. The authors in [91] used the queue threshold N to control the total average times of turning on the transmitting functions of a node for the buffered data packets. In [91], when a node has queued up N packets, it triggers its transmitting function of radio and starts the transmission process for the queued packets in a burst. The arrival process is assumed as a Poisson process with a rate λ in [91]. The authors derived analytical expressions for the number of packets in a node when the radio server is in idle, busy and under N-policy. The authors have tried to balance the energy expenditure through tuning the optimal N value for nodes in the innermost ring. In order to validate the results of the proposed design scheme, simulations in NS-2 are performed. The simulation results confirm that 23% of network lifetime can be prolonged due to saving energy in the innermost rings. The problem in [91] is that the method to optimize N policy as a function of network density or channel load is not considered.

The authors in [92] theoretically analysed the queue-based power saving technique to reduce power consumption for sensor nodes. In order to synchronize wakeup patterns of the networked sensors, an M/G/1 queue with server vacations model was proposed in [92]. In addition, an optimal queue number was estimated that minimizes power consumption in sensor nodes by controlling the average times of turning on the transmitting function of the sensor node for the buffered data packets. The model used in [92] puts the sensor nodes in a sleep mode from time to time to reduce energy consumption. The proposed model, which schedules the nodes for turning on and off their radios, was called the wakeup patterns. This approach can be classified into two categories: synchronous and asynchronous. In synchronous wakeup patterns, every node has exactly the same wakeup and sleep times and exchanges the packets during the common wakeup periods. In the asynchronous pattern, the nodes can have different wakeup and sleep times. Thus, nodes have an extra mechanism to awake or determine the length of wakeup periods. In [92], the authors proposed a framework to analyse synchronous wakeup patterns.

An analytical model is developed in [93] to analyse the performance of TDMA based MAC protocols for WSNs. The model proposed in [93] characterised the queuing delays associated with the MAC layer as well as the energy consumed at MAC layer. The system was modelled as an M/G/1 queue with general service time distribution with both polling and vacations in [93]. The polling TDMA based MAC with sleep and wakeup cycles was considered to derive the average packet delays and the rate of energy consumption of sensor nodes in [93]. The simulation results are used to validate the analytical model to show that polling TDMA with sleep and wakeup cycle achieves lower delays as well as reduced energy consumption.

The analytical model in [94] was developed for multi-hop WSNs with the SMAC protocol [10, 11], which can take the node’s active/sleep and contention back-off mechanism into account. Each node was modelled as a finite single server queue. Further, the state of each node was modelled as a two dimensional continuous-time Markov chain (CTMC) in [94]. It was considered that each node can generate data packets and also relay data packets to other nodes as a router. The work in [94] assumed that each node generates packets according to a Poisson process. All the packets enter the finite buffer of the node and wait for transmission under the first-in-first-out (FIFO) discipline without prioritization. The network performances in terms of Quality of Service (QoS) such as packet loss, average packet delay as well as average power consumption were derived in [94].

The authors in [95] proposed a finite queuing model of synchronous patterns in contention-based WSNs. The work was focused on the analysis of network performance assuming that the active/sleep dynamics of a node are independent. The work done in [95] investigated the impact of sleep/active duty cycle, node buffer size and time scale on the network performance and explored the trade-off between power efficiency and QoS requirements in WSNs. In [95], it was assumed that a node in active state generates packets according to a Poisson process. The states of a node were modelled using a continuous Markov chain model (CTMC) and derived the expressions for average packet loss rate, average packet delay and average power consumption. The simulation results show that the accuracy of the proposed model was validated as the results matched well to provide strong insight into the design of synchronous patterns in contention-based WSNs. The problem in [95] is that the relay node’s packets will be delayed due to the channel contention; however, the authors did not discuss the solution to this problem in this work.

In [96], the authors proposed a new evaluation method to analyse the packet buffer capacity of nodes using M/M/1/N queuing when it is in good working condition. The work in [96] considered that the packet buffer capacity corresponds to the length of waiting queue and nodes were blocked when the length of waiting queue had reached the maximum. In order to evaluate the congestion situation in [96], the effective arrival and transfer rates were computed in the model, and holding nodes were added to the network model to expand the queuing network model. The blocking probability and system performance indicator of each node were computed using an approximate iterative algorithm in [96]. The important parameters, such as queuing delays, packets dropped when nodes were blocked due to the length of waiting queue reaching the maximum, are not considered in [96].

The work in [97] developed a discrete-time queuing model with a setup to describe the working principle of the power management mode of WSNs. In [97], some of the performance measures in terms of the average response time of data frames, the handover ratio and the average energy consumption were presented. The work in [97] considers the power management mode of IEEE 802.15.4 to reduce energy consumption of sensor nodes. The work in [97] considered that when the source nodes have a data frame to send, both the source and destination nodes are in active period, otherwise both nodes will be in sleep mode to reduce energy consumption. Analytical expressions for the queue length, waiting time, busy period and the average energy consumption were derived.

However, the analytical models proposed in the literature [89, 91, 92, 95 - 97] only considered the dynamics of the sensor nodes and did not consider the effect of MAC for queuing and delay analysis in the WSN. Furthermore, an increase of queuing delays causes energy waste, throughput reduction, increase in collisions and re-transmissions at the MAC layer, and leads to the decrease of node lifetime.

This chapter is organized as follows. Section 5.2 presents the traffic models, assumptions and message arrival processes in the proposed system for the DRMACSN MAC protocol. In Section 5.3, the performance measures are presented. Section 5.4 presents the stationary queue length and delay analysis of DRMACSN MAC protocol. Section 5.5 presents and discusses the results of the analysis. Finally, Section 5.6 concludes the chapter. The contents of this chapter, in part, are to be submitted as a journal paper to IET WSN.

5.2 Traffic Model Description and Assumptions

In this section, the traffic model issues and assumptions for the proposed MAC protocol are discussed. The discrete-time $Geom/G/1$ and $M/G/1$ queuing models are modelled to analyse the delay performances of the DRMACSN MAC protocol.

The following assumptions are made to simplify the analysis:

i. It is considered that the CQI value is constant for the analysis for the DRMACSN MAC protocol.
ii. It is assumed that whenever the channel load, $K \geq \alpha$ (Blocking threshold), there will be no new node admitted into the channel. This is slightly different from simulation.

Figure 5.1 shows the message arrival process in the system. The embedding points are defined as the time points at which either the departure of a message [98] or the vacation period is ended in the DRMACSN MAC protocol. In this thesis, the embedding points are shown in transmit state in the Figure 5.1. It is assumed that the nodes in sleep state may have arrivals of new messages which follows the Bernoulli distribution with probability, ρ_S (messages/frame) or Poisson distribution with rate λ (messages/second) and the time spent in sleep is geometrically distributed with mean, $\bar{T}_S = \frac{1}{\mu_S}$ and that each back-off node also has new arrivals of new messages which follows the Bernoulli or Poisson distribution. It is assumed that the back-off time is geometrically distributed with a mean, $\bar{T}_B = \frac{1}{\mu_B}$. The mean time in transmit state depends on the messages in the buffer and assume its means time, $\bar{T}_x = \frac{1}{\mu_x}$.

It is considered that the nodes take the vacation when there are no packets in their buffer and sleep and back-off timer is not expired in the DRMACSN MAC protocol. Furthermore, it is assumed that the vacation time, V is equal to $T_S + T_B$ in the proposed system.

The total number of messages in transmit state is equal to the number of messages at the beginning of transmit state, L_x^{beg} (refer to Figure 5-1) and the number of retransmitted packets of the original message, L_x^{beg}, and the arrivals of new message in transmit state, L_x^{new} and the number of retransmitted packets of new message, L_x^{new} during the time duration T_x.

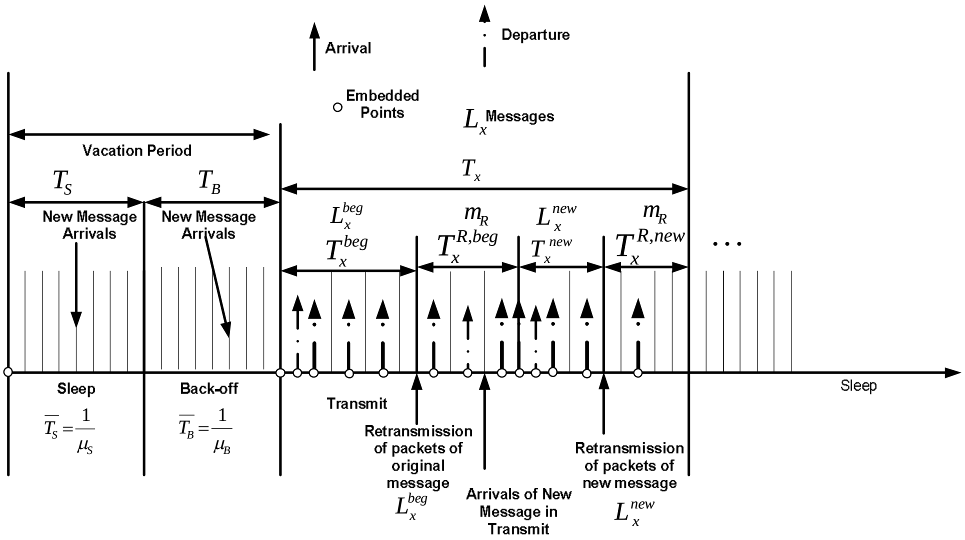


Figure 5.1: Message arrival process in the proposed system

Thus, the total messages, L_x in the time duration, T_x is,

$$L_x = L_x^{beg} + L_x^{R,beg} + L_x^{new} + L_x^{R,new} \tag{5.1}$$

The corresponding total time, T_x is thus computed as

$$T_x = T_x^{beg} + T_x^{R,beg} + T_x^{new} + T_x^{R,new}$$

$$T_x = \sum_{j=1}^{L_x^{beg}} m_{new} \cdot T_f + \sum_{j=1}^{L_x^{beg}} m_r \cdot T_f + \sum_{j=1}^{L_x^{new}} m_{new} \cdot T_f + \sum_{j=1}^{L_x^{new}} m_r \cdot T_f \tag{5.2}$$

The PGF of T_x is computed as

$$G_{T_x}(z) = G_{L_x^{Beg}}\left(G_{m_{new}}(z)\right) \cdot G_{L_x^{Beg}}\left(G_{m_r}(z)\right) \cdot G_{L_x^{new}}\left(G_{m_{new}}(z)\right) \cdot G_{L_x^{new}}\left(G_{m_r}(z)\right) \tag{5.3}$$

The average value of T_x can be computed as follows

$$E(T_x) = \left[E(L_x^{Beg})\right] \cdot [E(m_{new})] + \left[E(L_x^{Beg})\right] \cdot [E(m_r)] + [E(L_x^{new})] \cdot [E(m_{new})] + [E(L_x^{new})] \cdot [E(m_r)] \tag{5.4}$$

5.3 Performance Analysis

5.3.1 Computation of the Duration of Sleep and Back-off State

It is assumed that the time duration of sleep state, T_S is geometrically distributed and the PGF of T_S is computed as

$$G_{T_S}(z) = \frac{\mu_s z}{1-(1-\mu_s)z} \tag{5.5}$$

The moments of T_S are simply calculated as follows,

$$\text{The mean of } T_S,\ E(T_S) = \frac{1}{\mu_s} \tag{5.6}$$

Similarly, it is also assumed that the duration of the back-off state, $\mathrm{T_B}$ is geometrically distributed with μ_B . The PGF of the back-off state and the moments of T_B are calculated as follows

$$G_{T_B}(z) = \frac{\mu_B \mathrm{z}}{1-(1-\mu_B)z} \tag{5.7}$$

$$\text{The mean of } T_B,\ E(T_B) = \frac{1}{\mu_B} \tag{5.8}$$

5.3.2 Number of the Messages Arriving at the Beginning of the Transmit State

It is assumed that arrivals of new messages in sleep state follow a Bernoulli process (Model 1) with a probability ρ_S or a Poisson process (Model 2) with a rate, λ. The length of the message (in packets) is assumed to be geometrically distributed.

5.3.2.1 Model 1: Bernoulli Process

In this model, the arrivals of new messages follow the Bernoulli process with probability ρ_S. A Bernoulli random variable X indicates an arrival or lack of arrival of a message during a frame time (i.e., $X = 0$ or 1). Since the sleep state time consists of such $N_{slots,S}$ frames, which is geometric random variable and the random variable S_n is the sum of such independent random variables. That is,

$$S_n = \sum_{j=0}^{N_{slots,S}} \mathrm{X}_j \tag{5.9}$$

Eq. (5.9) is a compound random variable [99, 100]. The PGF of S_n is given by

$$G_{new,S_n}(z) = G_{N_{slots,S}}(G_{\mathrm{X}_j}(z)) \tag{5.10}$$

where $G_{N_{slots,S}}$ is the PGF of $N_{slots,S}$ and is computed using Eq. (5.11).

$$G_{N_{slots,S}}(z) = \frac{\mu_s z}{1-(1-\mu_s)z} \tag{5.11}$$

and

$G_{X_j}(z)$ is the PGF of independent random variables, X_j.

$$G_{X_j}(z) = (1-\rho_S) + \rho_S z \tag{5.12}$$

Substituting Eq.(5.15) and (5.12) in (5.10), the compound distribution of S_n is given by

$$G_{new,S_n}(z) = \frac{\mu_s - \mu_s\rho_S + \mu_s\rho_S z}{\mu_s - \mu_s\rho_S + \mu_s\rho_S z + \rho_S[1-z]} \tag{5.13}$$

Differentiating Eq. (5.13) with respect to z at z=1, the expected value of S_n is obtained as follows [99, 100] (the derivation is given in Appendix A-3).

$$E(S_n) = \frac{\rho_S}{\mu_s} \tag{5.14}$$

Similarly, the arrivals of new messages in the back-off state during a frame time T_B follows a Bernoulli distribution with probability ρ_S. Since the back-off state consists of $N_{slots,B}$ frame times, the arrival random variable B_n is the sum of such independent RVs. $G_{new,B_n}(z)$ is the PGF of B_n in Back-off state and is given by

$$G_{new,B_n}(z) = G_{N_{slots,B}}(G_{X_j}(z)) \tag{5.15}$$

where $G_{X_j}(z)$ is the PGF of independent random variables, X_j and is computed in Eq. (5.10). $G_{N_{slots,B}}$ is the PGF of $N_{slots,B}$, which equal to the PGF of T_B, computed using Eq. (5.7).

$$G_{N_{slots,B}} = \frac{\mu_B z}{1-(1-\mu_B)z} \tag{5.16}$$

The computation of the compound distribution and the expected value of B_n follow the same method used in the derivation of Eq. (5.13).

$$G_{new,B_n}(z) = \frac{\mu_B - \mu_B\rho_S + \mu_B\rho_S z}{\mu_B - \mu_B\rho_S + \mu_B\rho_S z + \rho_S[1-z]} \tag{5.17}$$

$$E(B_n) = \frac{\rho_S}{\mu_B} \tag{5.18}$$

5.3.2.2 Model 2: Poisson Process

In this model, the arrival of new messages follows the Poisson process with a rate, λ (messages/second). It is assumed that the message lengths are geometrically distributed. Hence, the random variable S_n represents the number of messages arriving in the sleep state during a frame time and is defined as,

$$S_n = \sum_{j=0}^{N_{slot,S}} K_j \qquad (5.19)$$

$$K_j \sim Poisson(\lambda)$$

The PGF of S_n is given by

$$G_{new,S_n}(z) = G_{N_{slots,S}}(G_{\mathrm{K}_j}(z)) \qquad (5.20)$$

where $G_{N_{slots,S}}$ is the PGF of $N_{slots,S}$, which is computed using Eq. (5.11) and $G_{\mathrm{K}_j}(z)$ is the PGF of independent random variables, K_j and is given by

$$G_{K_j}(z) = e^{\lambda(z-1)} \qquad (5.21)$$

Substituting Eq. (5.11) and (5. 21) in (5.20), the compound distribution of S_n is given by

$$G_{N_{slots,S}}(z) = \frac{\mu_S e^{\lambda\,(z-1)}}{1 - e^{\lambda(z-1)} + \mu_S e^{\lambda\,(z-1)}} \qquad (5.22)$$

Differentiating Eq. (5.22) with respect to z at z=1, the expected value of S_n is obtained as follows (the derivation is given in Appendix A-5)

$$E(S_n) = \frac{\lambda}{\mu_S} \qquad (5.23)$$

Similarly, nodes will have the arrivals of new messages in the back-off state duration frame time T_B and is Poisson distributed with a rate, λ . Hence, the random variable B_n representing the number of message arrivals in back-off state is,

$$B_n = \sum_{j=0}^{N_{slot,B}} K_j \qquad (5.24)$$

$$K_j \sim Poisson(\lambda) \qquad (5.25)$$

The PGF of the new message with arbitrary message length distribution is given by

$$G_{new,B_n}(z) = G_{N_{slots,B}}(G_{K_j}(z)) \tag{5.26}$$

The PGF of B_n is given by

$$G_{new,B_n}(z) = G_{N_{slots,B}}(G_{\mathrm{K}_j}(z)) \tag{5.27}$$

where $G_{N_{slots,B}}$ is the PGF of $N_{slots,B}$, computed using Eq. (5.7) and $G_{\mathrm{K}_j}(z)$ is the PGF of independent random variables, K_j and is given by

$$G_{K_j}(z) = e^{\lambda\,(z-1)} \tag{5.28}$$

The computations of the compound distribution and the expected value of B_n follow the same method used in the derivation of Eq. (5.22).

$$G_{N_{slots,B}}(z) = \frac{\mu_B e^{\lambda\,(z-1)}}{1 - e^{\lambda\,(z-1)} + \mu_B e^{\lambda\,(z-1)}} \tag{5.29}$$

$$E(B_n) = \frac{\lambda}{\mu_B} \tag{5.30}$$

The total number of messages at the beginning of the transmit state is computed as

$$L_x^{Beg} = \begin{cases} S_n & \text{if the node does not go into backoff state} \\ S_n + B_n & \text{if the node goes into backoff state} \end{cases} \tag{5.31}$$

The PGF of L_x^{Beg} is computed as

$$G_{L_x^{Beg}}(z) = G_{new,S}(z)Prob(Y) + G_{new,S}(z)G_{new,B}(z)Prob(\bar{Y}) \tag{5.32}$$

$$E\left(L_x^{beg}\right) = \frac{\rho_S}{\mu_S}Prob(Y) + \frac{\rho_S}{\mu_S}\frac{\rho_S}{\mu_B}Prob(\bar{Y}) \tag{5.33}$$

where $Prob(Y) = Prob(K < \propto)$, $Prob(\bar{Y}) = Prob(K > \propto) = 1 - \sum_{j=0}^{\alpha} X(j)$ and $X(j)$ is computed using Eq. (4.13) of Chapter 4.

5.3.3 Computation of Probability Distribution of the Number of Packets in a Message

Let the variable m_{new} represent the number of packets in a message. It is assumed that the length of the new message is to be a geometrically distributed random variable with mean $1/\mu_{p,new}$. The PGF of $m_{j,new}$ is defined as

$$G_{m_{new}}(z) = \frac{\mu_{p,new} z}{1 - (1 - \mu_{p,new})z} \tag{5.34}$$

$$E(m_{new}) = \frac{1}{\mu_{p,new}} \tag{5.35}$$

5.3.4 Computation of Arrivals of New Messages in the Transmit State

It is considered that nodes will have arrivals of new messages during time, T_x, which follows either a Bernoulli process or a Poisson process with a geometrically distributed message length. Hence, the random variable, L_x^{new} represents the number of message arrivals in the transmit state during time T_x, and is given by

a) Bernoulli process

$$L_x^{new} = \sum_{j=0}^{N_{slots,x}} X_j \tag{5.36}$$

The PGF of L_x^{new} is defined as

$$G_{L_x^{new}}(z) = G_{N_{slots,x}}(G_{X_j}(z)) \tag{5.37}$$

where

$$G_{N_{slots,x}}(z) = \frac{\mu_x z}{1 - (1 - \mu_x)z} \tag{5.38}$$

$$G_{X_j}(z) = (1 - \rho_S) + \rho_S z \tag{5.39}$$

Substituting Eq. (5.44) and (5.45) in Eq. (5.43), the compound distribution of $G_{new,B_n}(z)$ can be computed as

$$G_{L_x^{new}}(z) = \frac{\mu_x - \mu_x\rho_S + \mu_x\rho_S z}{\mu_x - \mu_x\rho_S + \mu_x\rho_S z + \rho_S[1 - z]} \tag{5.40}$$

The expected value of L_x^{new} can be computed as

$$E(L_x^{new}) = \frac{\rho_S}{\mu_x} \tag{5.41}$$

b) Poisson process

For Poisson process, the $G_{L_x^{new}}(z)$ can be computed as follows

$$G_{L_x^{new}}(z) = \frac{\mu_x e^{\lambda\,(z-1)}}{1 - e^{\lambda\,(z-1)} + \mu_x e^{\lambda\,(z-1)}} \tag{5.42}$$

$$E(L_x^{new}) = \frac{\lambda}{\mu_x} \tag{5.43}$$

5.3.5 Computation of Probability Distribution of the Number of Re-transmitted Packets of the Message

The variable m_r represents the number of re-transmitted packets of the message during time, T_x. It is assumed that the length of re-transmitted packets follows the geometric distribution with mean $\frac{1}{\mu_r}$. The PGF of $m_{j,R}$ is defined as

$$G_{m_r}(z) = \frac{\mu_r z}{1 - (1 - \mu_{Rr})z} \tag{5.44}$$

$$E(m_r) = \frac{1}{\mu_r} \tag{5.45}$$

The distribution of number of re-transmitted packets in the beginning of the transmit, L_x^{beg} is given by

$$L_x^{R,beg} = \sum_{j=0}^{L_x^{beg}} m_{j,r} \tag{5.45(a)}$$

$$\mathrm{E}(L_x^{R,beg}) = E\left(L_x^{beg}\right) \cdot \frac{1}{\mu_r} \tag{5.45(b)}$$

where $E\left(L_x^{beg}\right)$ is computed using Eq. 5.33.

5.4 Queue Length and Delay Analysis

This section describes the waiting time and the average packet delay for the Bernoulli and Poisson process for the DRMACSN MAC protocol. The $Geom/G/1$ and M/G/1 vacation models are used to model the queuing behaviour of the DRMACSN MAC protocol.

5.4.1 Bernoulli Process

Let L^{+} be the queue length in the $Geom/G/1$ queue. This can be decomposed into two independent random variables,

$$L^{+} = L + L_d \tag{5.46}$$

where L is the queue length in a classical $Geom/G/1$ queue[98,101]. The PGF of L is

$$G_L(z) = \frac{(1-\rho)(1-z)S[1-\lambda(1-z)]}{S[1-\lambda(1-z)]-z} \tag{5.47}$$

From, Eq. (5.47), applying L' Hospital's rule [98] twice, the expected value of L can be obtained as follows

$$E[L] = \rho + \frac{\lambda^2}{2(1-\rho)}E(S(S-1)) \tag{5.48}$$

where $S = \frac{1}{\mu_x}$, $\rho = \frac{\lambda}{\mu_x}$, $\lambda = \frac{\rho_S}{T_S}$ (message/frame) and $E(S(S-1) or\ S^{(2)}$ is the second moment of S, $E(S) = \frac{dS(z)}{dz}|z = 1$ or $S^{(1)}(z)$, $E\big(S(S-1)\big)=\frac{dS^{(1)}(z)}{dz}|z = 1$.

The additional queue length L_d is due to the number of messages that have arrived during a sleep and back-off state (or due to vacation effect) and the PGF of L_d is given by [98, 101]

$$G_{L_d}(z) = \frac{1-L_x^{Beg}(z)}{E(L_x^{Beg})(1-z)} \tag{5.49}$$

Differentiating Eq. (5.49) and then, applying L' Hospital's rule [98] once to the result, the expected value of L_d is computed as (the derivation is given in Appendix A-3)

$$E(L_d) = \frac{E(L_x^{Beg}(L_x^{Beg}-1))}{2E(L_x^{Beg})} \tag{5.50}$$

where $E(L_x^{Beg})$ is the first moment (or mean) of $L_x^{Beg}(z)$, $E(L_x^{Beg}) = \frac{dL_x^{Beg}(z)}{dz}|z = 1$ or $L_x^{Beg^{(1)}}(z)$ and $E(L_x^{Beg}(L_x^{Beg}-1))$ is the second moment of $L_x^{Beg}(z)$, and $E\left(L_x^{Beg}\left(L_x^{Beg}-1\right)\right) = \frac{dL_x^{Beg^{(1)}}(z)}{dz}|z = 1$.

Combining Eq.(5.48) and (5.50), one can get the average value of $E(L^{+})$ of L^{+} by

$$E(L^{+}) = \rho + \frac{\lambda^{2}}{2(1-\rho)}E(S(S-1)) + \frac{E(L_x^{Beg}(L_x^{Beg}-1))}{2E(L_x^{Beg})} \tag{5.51}$$

The stationary waiting time W can be decomposed into the sum of two independent random variables, i.e., $W = W_L + W_d$, where W_L is the waiting time of a messages for a classical $Geom/G/1$ queuing model [98, 101, 102], W_d is the waiting time of messages arriving at the beginning of the transmit state. Thus, the PGF of W_L is given as follows

$$G_{W_L}(z) = \frac{(1-\rho)(1-z)}{(1-z)-\rho_s(1-S(z))} \tag{5.52}$$

Differentiating Eq. (5.52) with respect to z at z =1, the expected value of W_L can be obtained as follows

$$E(W_L) = \frac{\lambda}{2(1-\rho)}E(S(S-1)) \tag{5.53}$$

The PGF of W_d is given by

$$G_{W_d}(z) = \frac{1-v(z)}{E(V)(1-z)} \tag{5.54}$$

where $v(z) = T_S(z) + T_B(z)$.

Differentiating Eq. (5.54) with respect to z at z=1, then, applying L' Hospital's rule [98] once, the expected value of W_d can be obtained as follows

$$E(W_d) = \frac{E(V(V-1))}{2E(V)} \tag{5.55}$$

where $E(V)$ is the first moment (or mean) of $v(z)$, $E(V) = \frac{dv(z)}{dz}|z = 1$ or $V^{(1)}(z)$ and $E(V(V-1))$ is the second moment of $v(z)$, and $E\big(V(V-1)\big) = V^{(1)}(z)|z = 1$.

The average value of W can be obtained by combining Eq. (5.54) and (5.55) as follows

$$\mathrm{E(W)} = \frac{\lambda}{2(1-\rho)}E(S(S-1)) + \frac{E(V(V-1))}{2E(V)} \tag{5.53}$$

The average packet delay can be computed using Little's law [103] for the proposed MAC as follows:

$$\overline{D} = \frac{E(L^{+})}{S_P} \tag{5.56}$$

where S_p is the average packet throughput derived in Chapter 4, Eq. (4.15).

5.4.2 Poisson Process

Let L^{+} be the queuing length in the $M/G/1$ queue, can be decomposed into two independent random variables,

$$L^{+} = L + L_d \tag{5.57}$$

where L is the queue length in a classical $M/G/1$ queue [98, 101, 102]. The PGF of L is

$$G_L(z) = \frac{(1-\rho)(1-z)S(\lambda(1-z))}{S(\lambda(1-z))-z} \tag{5.58}$$

Differentiating Eq. (5.58) with respect to z at z=1, we can obtain the expected value of L as follows

$$E[L] = \rho + \frac{\lambda^2 S^{(2)}}{2(1-\rho)} \tag{5.59}$$

where $S = \frac{1}{\mu_x}$, λ = messages/second and $\rho = \frac{\lambda}{\mu_x}$.

The additional queue length L_d is due to the number of messages arriving during the sleep and back-off state and the PGF of L_d is given by [101](the derivation are given in Appendix A-4).

$$G_{L_d}(z) = \frac{1 - L_x^{Beg}(z)}{E(L_x^{Beg})(1-z)} \tag{5.60}$$

Differentiating Eq. (5.60) with respect to z and then, applying L' Hospital's rule [98] once, the expected value, $E(L_d)$ can be computed as [101]

$$E(L_d) \ = \ \frac{\lambda E(L_x^{Beg}(L_x^{Beg}-1))}{2E(L_x^{Beg})} \tag{5.61}$$

Combining Eq. (5.59) and (5.61), the average value of $E(L^+)$ of L^+ can be obtained by

$$E(L^+) \ = \ \rho + \frac{\lambda^2 S^{(2)}}{2(1-\rho)} + \frac{\lambda E(L_x^{Beg}(L_x^{Beg}-1))}{2E(L_x^{Beg})} \tag{5.62}$$

The stationary waiting time, W can be decomposed into the sum of two independent random variables, i.e., $W = W_L + W_d$, where W_L is the waiting time of a messages for a $M/G/1$ queuing model [98, 101,102], W_d is the waiting time of messages arriving at the beginning of the transmit state [98]. Thus, the LST of $W_L$is given as follows

$$W_L{}^*(s) \ = \frac{(1-\ \rho)s}{s-\lambda(1-\ S^*(s))} \tag{5.63}$$

Differentiating Eq. (5.63) with respect to z and then, applying L' Hospital's rule [98] once, the expected value, E(W_L) can be obtained as follows

$$E(W_L) = \frac{\lambda S^{(2)}}{2(1-\rho)} \tag{5.64}$$

The LST of $W_d$is given by

$$W_d{}^*(s) = \frac{1-v^*(s)}{E(V)s} \tag{5.65}$$

Differentiating Eq. (5.65) with respect to z at z=1, then, applying L' Hospital's rule [98] once, the expected value of W_d can be obtained as follows

$$E(W_d) = \frac{E(V(V-1))}{2E(V)} \tag{5.66}$$

The average value of W can be obtained as follows

$$\text{E(W)} = \frac{\lambda S^{(2)}}{2(1-\rho)} + \frac{E(V(V-1))}{2E(V)} \tag{5.67}$$

The average packet delay can be computed using Little’s law [103] for the proposed MAC as follows:

$$\overline{D} = \frac{E(L^{+})}{S_P} \tag{5.68}$$

where S_p is the average packet throughput derived in Chapter 4, Eq. (4.15).

5.5 Performance Results

In this section, the average delay performances for the proposed MAC protocol obtained through the analysis and simulations are presented. In order to evaluate the performance measures of the proposed MAC protocol, the same environments that are presented in Chapter 3 are considered. The simulations parameters presented in Chapter 3 are also used in this analysis with the following exception: The value of ρ_S is varied to present different load values to the network. Table 5.1 shows the known and unknown variables used for the proposed MAC analysis. The set of equations discussed earlier were solved numerically using MATLAB. This was carried out iteratively as follows. Referring to Figure 5.2, we start with the initial values of iteration counter and input variables ρ_S, μ_b, μ_S, T_S, T_B, μ_r and μ_{pnew}. We compute $E(m_{new})$ from Eq. 5.35, $E(m_r)$ from Eq. 5.45, $E(L_x^{new})$ from 5.41 (Bernoulli process) and 5.43 (for Poisson process), $E(S_n)$ from 5.14 (Bernoulli) and 5.23 (Poisson), $E(B_n)$ from 5.18 (Bernoulli) and 5.30 (Poisson**)**. Then, we compute the total messages in transmit state**,** L_x using Eq. 5.1. The value of T_x is computed using Eq. 5.4, the number of messages at the beginning of transmit state is computed using Eq. 5.33. We then estimate the first moment and second moment of V, S, and L_x^{beg}. The mean queue length is estimated from Eq. 5.51 (Bernoulli) and 5.62(Poisson). The mean waiting time is estimated using Eq. 5.53 (Bernoulli) and 5.67(Poisson). Finally, we compute the average packet delay using Eq. 5.56 (Bernoulli) and 5.68 (Poisson).

Table 5.1: List of known and unknown variables

Known variables	Unknown variables
ρ_S, μ_b, μ_S, T_S, T_B, μ_r and μ_{pnew}	T_X, μ_x and L_x^{Beg}

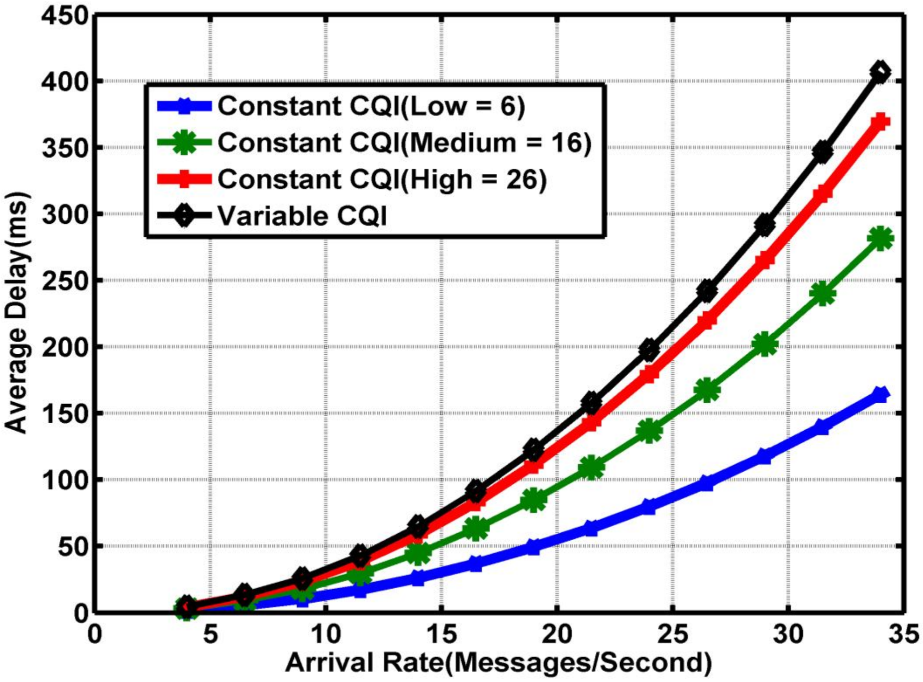


Figure 5.2(a): Comparison of effect of CQI values on average delays for Poisson process

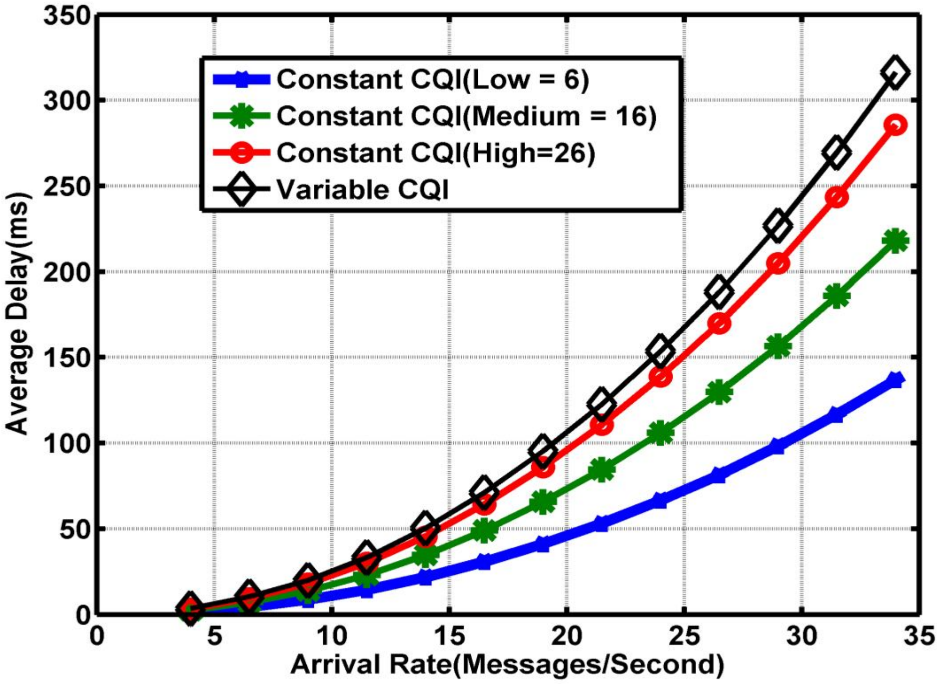


Figure 5.2(b): Comparison of effect of CQI values on average delays for Bernoulli process

Figures 5.2 (a) and (b) show the effect of CQI values on the average packet delays for DRMACSN MAC protocol for both Poisson and Bernoulli process respectively. It is assumed that a constant CQI {=26} is used to evaluate the performances of the DRMACSN MAC protocol in Section 5.2 of this chapter.

The results in Figures 5.2 (a) and (b) are used to justify the assumption i) in section 5.2. It can be seen that the delay increases more quickly for the variable CQI values and the constant CQI value (High = 26) than lower constant CQI value (Medium = 16 or Low = 6). The reason for this behaviour is that when the channel load is greater than the threshold value, the nodes are blocked in the proposed MAC protocol. Thus, these nodes will be entered into the back-off mode for a random period of time. This introduces some delay in the system. It is clear from the results that the constant CQI (High, Medium or Low) values provided lower delays in the proposed MAC protocol.

In Figure 5.3 (a), the curves plotted for the delay results for the DRMACSN MAC protocol were computed using Eq. 5.68 for arrival rate for Poisson process. Eq. 5.56 was used to plot curves in Figure 5.3 (b) for Bernoulli process. As can be seen from Figures 5.3 (a) and (b), the delay is high for $\propto = 16$ (high value) at low traffic load values due to more transmitting nodes being allowed to transmit the messages when channel status is good.

As the blocking threshold value increases, only fewer nodes will be allowed to transmit their packets and the other remaining nodes will enter the vacation period. Therefore, at higher load values, a substantial increase in the delay can be observed for $\propto = 16$ (high value) compared to the lower blocking threshold values in the DRMACSN MAC protocol. Thus, at higher load values, a substantial decrease in the delay can be observed (almost 50% of the delay is reduced) for lower blocking threshold values.

Figures 5.4 (a) and (b) show the average delay versus the average throughput for Bernoulli and Poisson process for arrival rate for the proposed MAC protocol. The results in Figures 5.4 (a) and (b) show that, for higher delays, the network with the lowest blocking threshold provides higher overall average packet throughput.

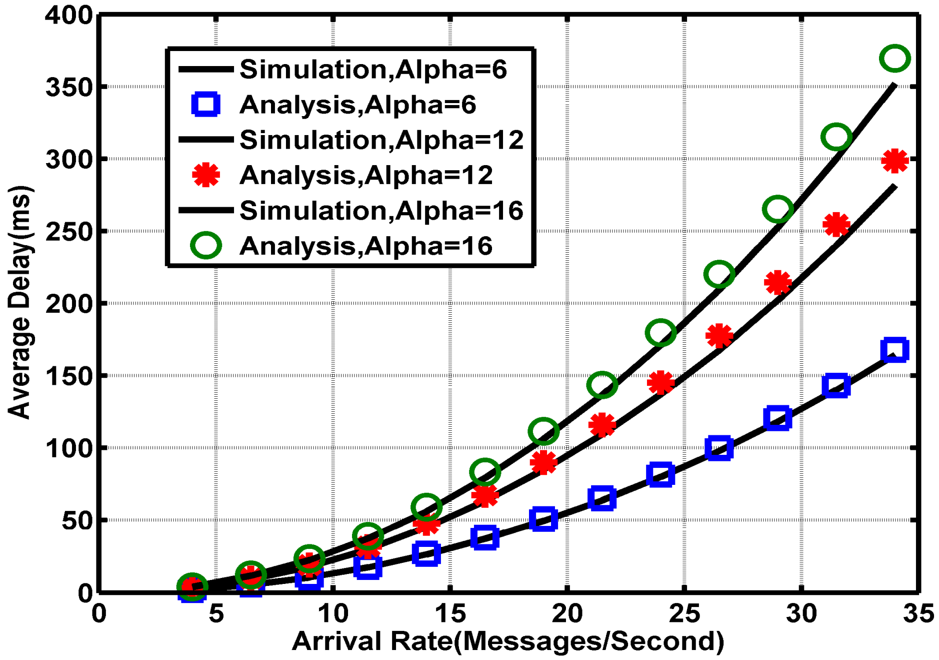


Figure 5.3(a): Effect of varying blocking threshold, ∝ = 6, 12 and 16 on the average delay versus arrival rate, Poisson process, ρ_S = 0.004 (Message/frame), CQI=26

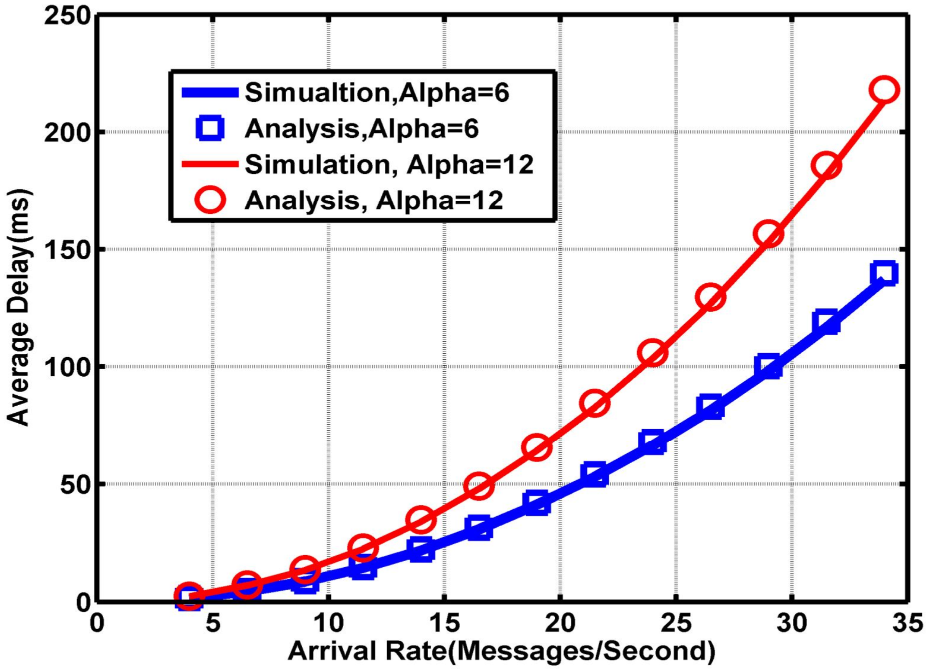


Figure 5.3(b): Effect of varying blocking threshold, ∝ = 6 and 12 on the average delay versus arrival rate, Bernoulli process, ρ_S = 0.004 (Message/frame), CQI=26

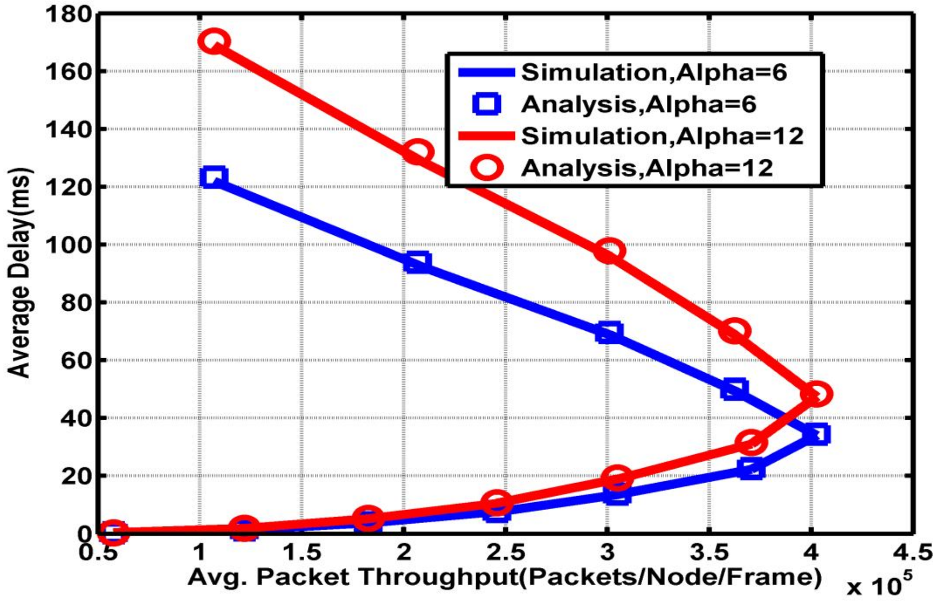


Figure 5.4(a): Effect of varying blocking threshold, $\propto$ =6 and 12 on the average delay versus average packet throughput for DRMACSN MAC protocol for Bernoulli process, ρ_S = 0.004 (Message/frame), CQI=26

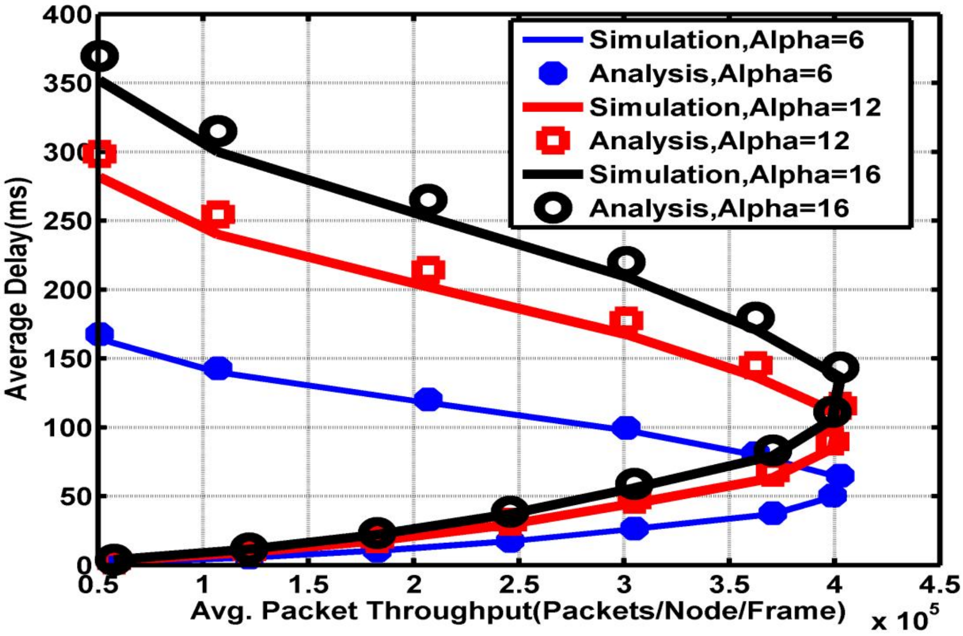


Figure 5.4(b): Effect of varying blocking threshold, $\propto$ = 6, 12 and 16 on the average delay versus average packet throughput for DRMACSN MAC protocol for Poisson arrival process, ρ_S = 0.004 (Message/frame), CQI=26

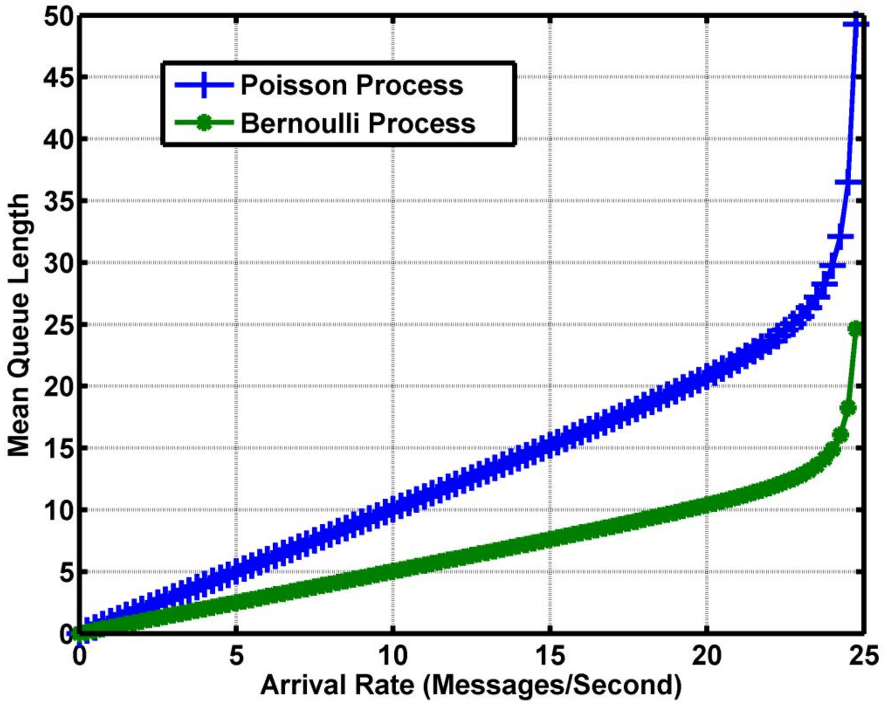


Figure 5.5: Mean queue length, $E(L^{+})$ versus arrival rate for DRMACSN MAC

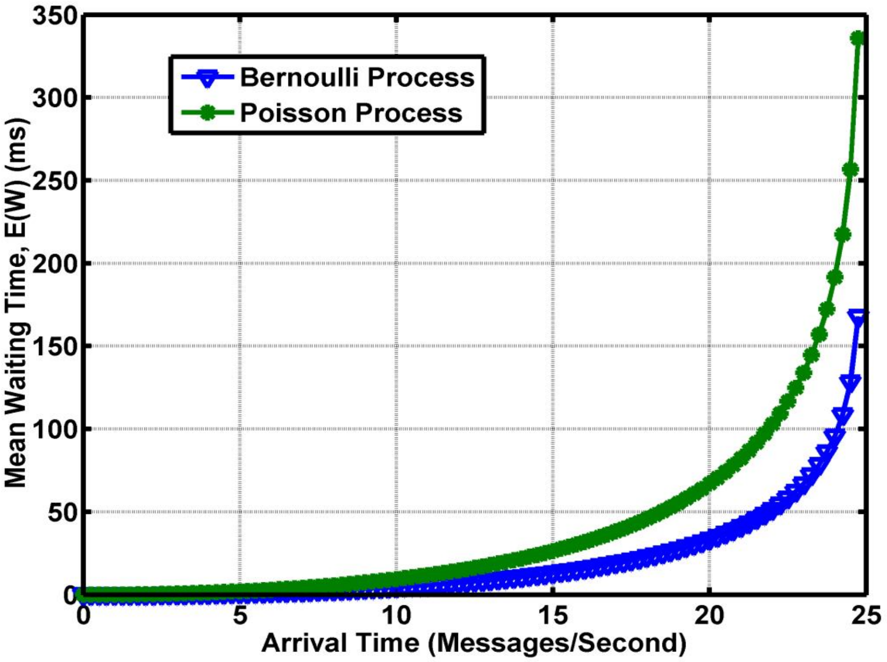


Figure 5.6: Mean waiting time, $E(W)$ versus arrival rate for DRMACSN MAC

Figures 5.5 show the mean queue length, $E(L^{+})$ as a function of arrival rate for both arrival processes (Bernoulli and Poisson). The results were computed using Eq. 5.51 and 5.53 for both arrival processes.

It is observed that when load increases, $E(L^{+})$ increases as well; for both arrival processes. It can also be observed from the results that the larger load is the higher the possibility that there will be message arriving during the transmit state as well as in the vacation state (i.e., sleep and back-off state).

Figures 5.6 shows how the mean waiting time, E(W) changes with the load for the Poisson and Bernoulli process arrival models. The results were computed using Eq. 5.62 and 5.67 for both arrival processes. From Figures 5.6, it can be seen that when load increases, E(W) increases as well. It is also further observed that the greater load is, the higher the possibility that there will be messages arriving during the vacation state (i.e., sleep and back-off state), the mean waiting time will be greater. In Figure 5.7, the simulation results for throughput and delay to verify the stability limit is shown. The result shows that stability limit of the DRMACSN MAC protocol at channel load 17 messages/second.

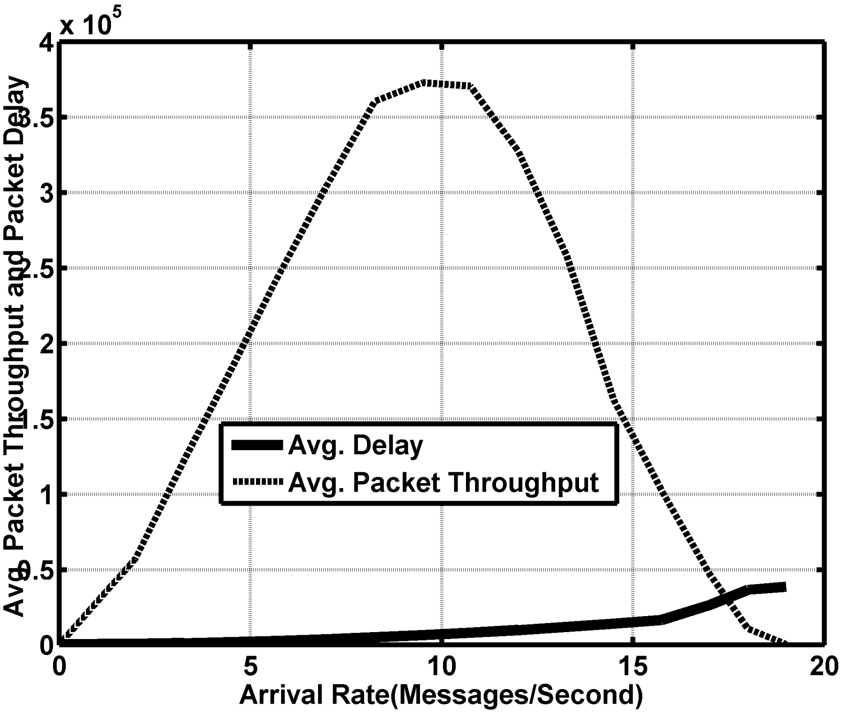


Figure 5.7: Stability verification of the DRMACSN MAC protocol

5.6 Summary

In this chapter, the behaviour of the DRMACSN MAC protocol based on DS-CDMA for WSNs was modelled using the discrete-time $Geom/G/1$ and $M/G/1$ multiple vacation queuing models.

The traffic model based on the Bernoulli and Poisson process is discussed in section 5.2. The PGF of duration of Sleep, Back-off and Transmit state respectively were determined. The PGF of number of new message arrivals in each state for each traffic model were derived. The PGF of the total number of messages at the beginning of transmit state, L_x^{Beg}, the message length (in packets) and the number of re-transmitted packets has been determined for the proposed MAC protocol.

In section 5.4, the queue length and packet delay for the Bernoulli and Poisson process was discussed to obtain expressions for the performance measurements for the DRMACSN MAC protocol. The queue length and the waiting time were decomposed into two independent random variables for both models. The PGF of the queue length and the waiting time random variables were derived. The expression for the average packet delay was derived to evaluate the delay performance of the DRMACSN MAC protocol.

The third part of this chapter presented results for both traffic models as obtained from the proposed queuing models. The analysis is accurate and the results from the proposed queuing models and simulator corresponded well for the average packet delay, thus validating the proposed analytical approach. It has been shown that the proposed MAC protocol achieves a reduced packet delay through the use of the channel load blocking scheme.

Chapter 6

Conclusions

6.1 Summary and Conclusion

In this thesis, the topic of developing an energy efficient medium access control for WSNs was examined. A new MAC protocol is based on a distributed, receiver–oriented and reservation-based scheme for WSNs was presented. A detailed simulation and analysis model was used to evaluate the performance of the proposed MAC protocol has been provided.

A literature survey of the MAC protocols for WSN was presented in Chapter 2 of this thesis. Chapter 2 compared the different MAC protocols for WSNs. The majority of the MAC designs were based on CSMA or TDMA for WSNs. The comparison was shown by taking the type of scheme used, advantages and disadvantages.

In Chapter 3, a distributed MAC protocol based on DS-CDMA for WSNs was presented. An interesting property of the proposed protocol was that the receiver and sender sensor nodes check the channel load before proceeding to send RTR/DATA packets after receiving preamble/RTR packets from the sender sensor node respectively. This led to an improvement in the probability of success for those nodes transmitting before the overload condition.

The channel sensing scheme has been proposed to abort or drop the sensor nodes, which arrive to cause a channel overload condition, increasing the probability of success of those nodes that were already transmitting before the overload was increased. The proposed MAC protocol computes the SNR values at every frame. The shadowing component was modelled as the correlated lognormal random variable. A novel variable CQI was proposed and implemented to achieve good performance in the proposed MAC protocol. A variable SNR and a constant value of CQI were used to compute BLER. A higher BLER was observed for higher values of blocking threshold values compared to the smaller values of threshold because a higher number of simultaneous transmitting nodes were allowed to transmit at higher rates.

Chapter 6: Conclusions

The effect of varying CQI and constant CQI values on the average packet throughput has been studied. It has been concluded that a variable CQI gives an optimum packet throughput for the proposed MAC protocol. An optimum packet throughput has also been studied using variable blocking threshold values for the proposed MAC protocol. It has also been shown that each blocking threshold value would provide an optimum packet throughput for different loads for a given CQI value. Through simulations, it has been shown that the value of the blocking threshold should be chosen carefully to reflect the optimum overall packet throughput. It can be concluded that the blocking threshold should be variable and dependent on the expected data message arrival rate. When the channel load is low, the frequency of collisions is low; the value of blocking threshold should be large (minimal blocking) whereas the frequency of collisions is high for high loads, the value of blocking threshold should be lower (increases blocking). This novel implementation of variable CQI values and in conjunction with a load dependent blocking threshold, α was shown to be far superior to the existing MAC protocols for WSNs which employ either blocking or the collision detection scheme.

The results from a custom-built software simulator were provided for the number of packets sent, average packet throughput, average energy consumption and average packet delay for the proposed MAC protocol. It has been shown that the number of blocked packets were higher for lower values of blocking threshold values due to a fewer nodes being allowed to transmit for lower threshold values compared to higher blocking threshold values. It has also been observed that the number of dropped packets due to BLER is higher for higher values of blocking threshold values because the number of simultaneous transmitting nodes is high for higher blocking threshold values. Thus, the frequency of collisions is high for higher threshold values compared to the lower threshold values in the proposed MAC protocol. It has been shown that a significant increase in the performance of the system in terms of improved packet throughput and reduced energy consumption and packet delay can be obtained by implementing a channel load blocking scheme the proposed MAC protocol.

The simulation results of the DRMACSN MAC protocol were compared with the IEEE 802.15.4 MAC and MAC with no channel load sensing scheme for energy consumption, throughput and delay. Simulation results have revealed that the DRMACSN MAC protocol can achieve good performance in all traffic load conditions. Finally, the simulation results have shown that the proposed MAC protocol out-performs IEEE 802.15.4 MAC with regard to the number of packets sent, packet throughput and energy consumption.

Chapter 6: Conclusions

In Chapter 4, a novel analytical model was proposed to analyse the performance of the DRMACSN MAC protocol based on DS-CDMA for WSNs. The proposed model combines the node behaviour, network behaviour and characteristics of the CDMA system to evaluate the performance of the DRMACSN MAC protocol. A Poisson process as the arrival process in the proposed model was considered. The length of data messages was assumed to conform to a geometric distribution. The selective-repeat re-transmission scheme was incorporated in the proposed model to reduce energy consumption. This re-transmission scheme allowed us to make some simplifying assumptions regarding the distribution of the length of re-transmitted packets in the network, namely that it is approximately geometric in nature. A node energy model was derived to investigate the energy consumption as the sensor nodes dynamics in sleep/back-off/transmit mode vary.

A Markov analysis of the DRMACSN MAC protocol was derived and presented, the outputs of which provided predicted measurements such as the expected data packet throughputs and the expected energy consumption measurements, the data message blocking and the successful probabilities. Analytical performance measurements were then obtained for typical imaginary data network scenarios with a variable data rate, mean data packet length of 128 bits and a mean message length of five packets. For comparison, results from a custom built event-driven simulator for the WSN were also provided. The analysis is accurate and analytical and simulation results matched closely, thus validating the proposed Markov analysis and analytical approach.

The result presented shows that a significant improvement can be achieved by re-transmitting only the corrupted packets in a message rather than re-transmitting the entire message regardless of the number of corrupt packets in the message. Thus, significant energy conservation as well as improved throughput can be achieved for the proposed MAC while re-transmitting only corrupted or lost packets in the reference message.

The packet delay behaviour of the proposed MAC protocol was modelled using discrete-time $Geom/G/1$ and $M/G/1$ multiple vacation queuing models in Chapter 5. The traffic model based on the Bernoulli and Poisson process were analysed in this chapter. The queuing analysis measurements were obtained for the DRMACSN MAC protocol for the Bernoulli and Poisson processes. The PGFs of the duration of the aforementioned states (i.e., sleep, back-off and transmit) respectively were determined. The PGF of the number of new message arrivals in each state for each traffic model was derived. The total number of messages at the beginning of transmit state, L_x^{Beg} has been derived. The PGF of L_x^{Beg} and the message length (in packets and the number of re-transmitted packets were derived for the proposed MAC protocol.

Analytical performance measurements were obtained for the DRMACSN MAC protocol for both traffic models. The mean queuing length, mean waiting time and average packet delay were derived to evaluate the packet delay performance of the DRMACSN MAC protocol. The analysis is accurate. Analytical and simulation results match very closely, thus validating the proposed queuing model and analytical approach. It has been shown that the packet delay is low for low loads because the frequency of blocking and dropping of nodes is low for both arrival processes. The packet delay is high for higher loads, because the frequency of blocking and dropping of nodes is high. It was shown that the mean queue length increases due to a higher possibility of messages arriving during the transmit state as well as in the vacation state at higher loads for both arrival processes. It was also shown that the mean waiting time of packets increases due to a higher possibility of messages arriving during the vacation state at higher loads for both arrival processes.

It has also been shown that a substantial decrease in the delay can be observed for lower threshold values. In addition, the results confirm that system performance in terms of reduced delay can be achieved through the use of the channel load blocking scheme.

6.2 Future Work

Finally, to conclude this thesis, a possible extension and/or further topics of study for this research work are proposed.

a) In Chapter 3, the distributed MAC protocol for WSNs assumed that the source node has multiple paths to its desired destination node. As a possible extension, development of an appropriate routing algorithm that determines suitable routes from source nodes can be considered.

b) The nodes spend some extra energy and experiences delays while updating CQI values. As a possible extension to this work, analyzing these parameters while updating CQI values by considering the feedback signal can also be considered.

c) Similarly, the derivation of an expression to predict the optimal value of $\propto$ based on network parameters, the offered load etc can also be considered.

d) The use of cooperative diversity techniques to predict the optimal helper or relay node based on the channel status to maximize the network lifetime by minimizing the energy consumption in the network can be considered.

e) Extension of the proposed MAC protocol to incorporate other multi-media traffic such as voice and video. In doing this, the performances of the proposed MAC for various traffic types under more stringent QoS requirements can be evaluated.

Appendix

A-1: Functional Specification of Event Driven Simulator

In this appendix, the DRMACSN MAC protocol implementation will be discussed.

A-1.1 Sensor Node Stack

In this subsection, the modules of the architecture are briefly discussed.

a) **Application Layer Module**

The application layer module is the simple module at the highest level of the hierarchy of the sensor node which simulates the behaviours of the application layer for the proposed design. This module communicates with the Network module to schedule the transmission of messages.

b) **Network Layer Module**

The network layer module is the simple module receives application layer messages from the Application layer module**.** In the proposed work, it is assumed that routing information is available to the proposed MAC protocol. Non-redundant nodes are generated in the neighbour list to conserve energy. Based on this assumption, a routing table is generated, which contains path information after calculating the neighbour nodes for each node in the network.

c) **MAC Layer Module**

The MAC layer module provides the interface between the physical layer and the routing layer. It has the basic functionality of media access and the functionality of this module is described in greater detail for DRMACSN MAC protocol implementation. Each node executes the five processes: 1) Main process 2) Transmitter process 3) Receiver process 4) Sleep process 5) Back-off process.

d) The physical layer module is responsible for transmitting the packets to the receiver node. The power manager is used to update the available battery information at the nodes when the physical Module transmits or receives the packets. Furthermore, the physical layer module can be in one of the two states, sleep and active mode respectively. In order to model the wireless characteristics of the proposed system as a two-state Markov chain model is considered.

The main process is essentially an events router, which receives events from events generation module and routes them to the appropriate processes. The following processes to implement these processes are briefly discussed.

a. **Sleep Process**: A node will be in a sleep state when a node does not have data in its buffer to transmit. The node continues to stay in the sleep state for a random period of time. When messages start to arrive and the sleep timer expires, then, the node enters into transmit state if the channel load, $K < \propto$.

b. **Back-off Process:** A node enters into a back-off mode from sleep state when the channel load, K exceeds the blocking threshold, $\propto$. Node continues to be in the back-off mode when K is greater than α or the back-off time has not expired, i.e., $T < T_{Back-off}$. It is also considered that there will be arrivals of new messages in the back-off state. Otherwise a node leaves the back-off mode and enters into the Tx/Rx state to transmit/receive packets.

c. **Transmitter Process**: A node enters into the transmit state from the sleep state when the sleep timer has expired and new message arrives and the channel load is less than the blocking threshold, $\propto$, $K < \propto$. The node starts sending DATA packets continuously until the buffer is empty. When there are no packets in its buffer and there are no arrivals of new messages, the node enters into a sleep mode to conserve its energy. The transmitter process initiates process setup by issuing a preamble packet to the receiver. If the receiver responds with a RTR packet, the transmitter process sends DS packets to its neighbours to get network status updated and then, transmits the data packets to its receiver node, waits for the ACK from the receiver node.

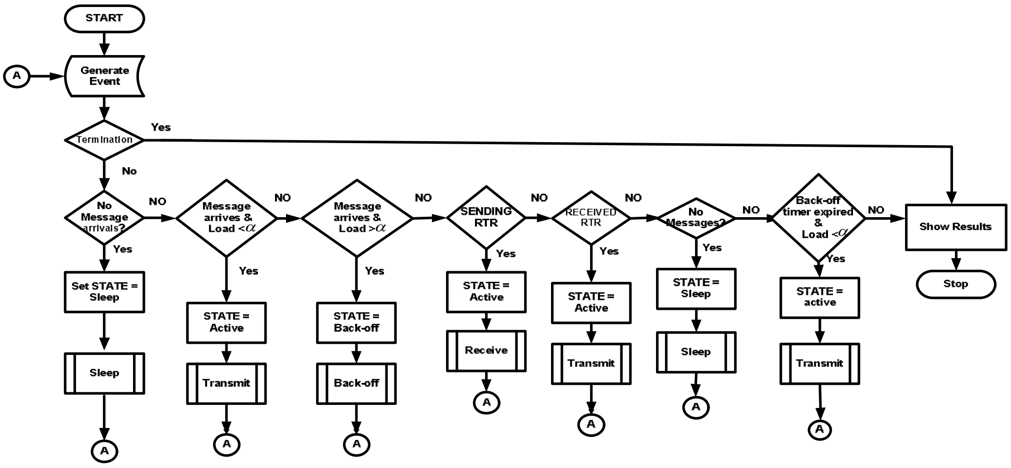


Figure A.1: Flow diagram for the MAIN process.

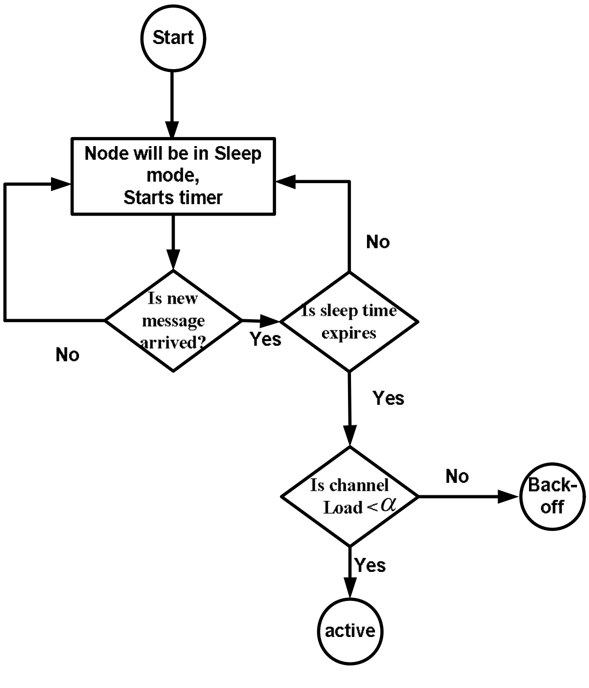


Figure A.2: Flow diagram for sleep process

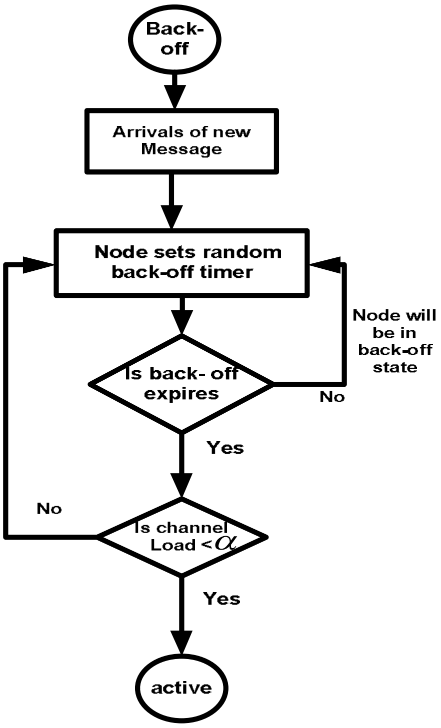


Figure A.3: Flow diagram for back-off process

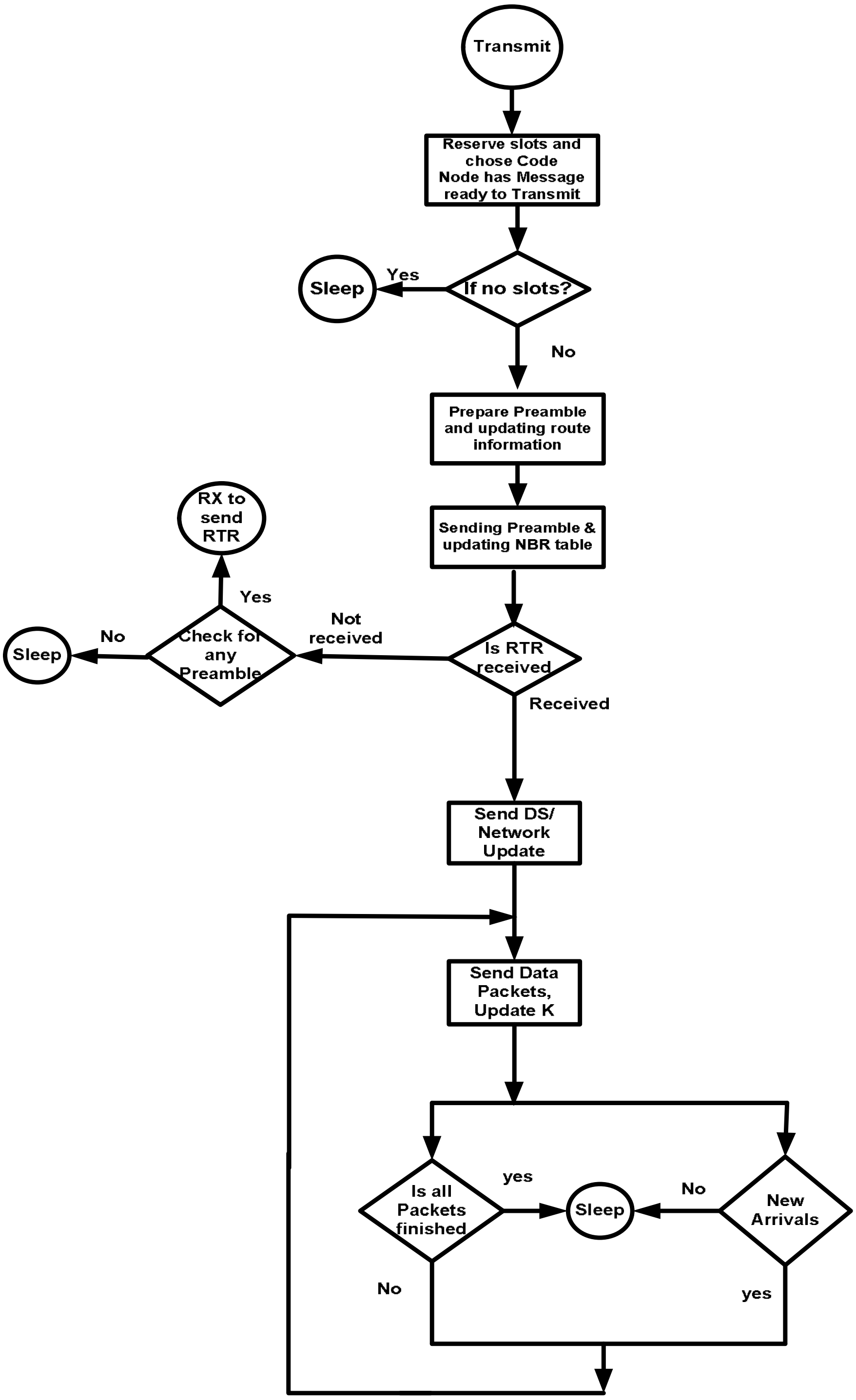


Figure A.4: Flow diagram for the transmitter process

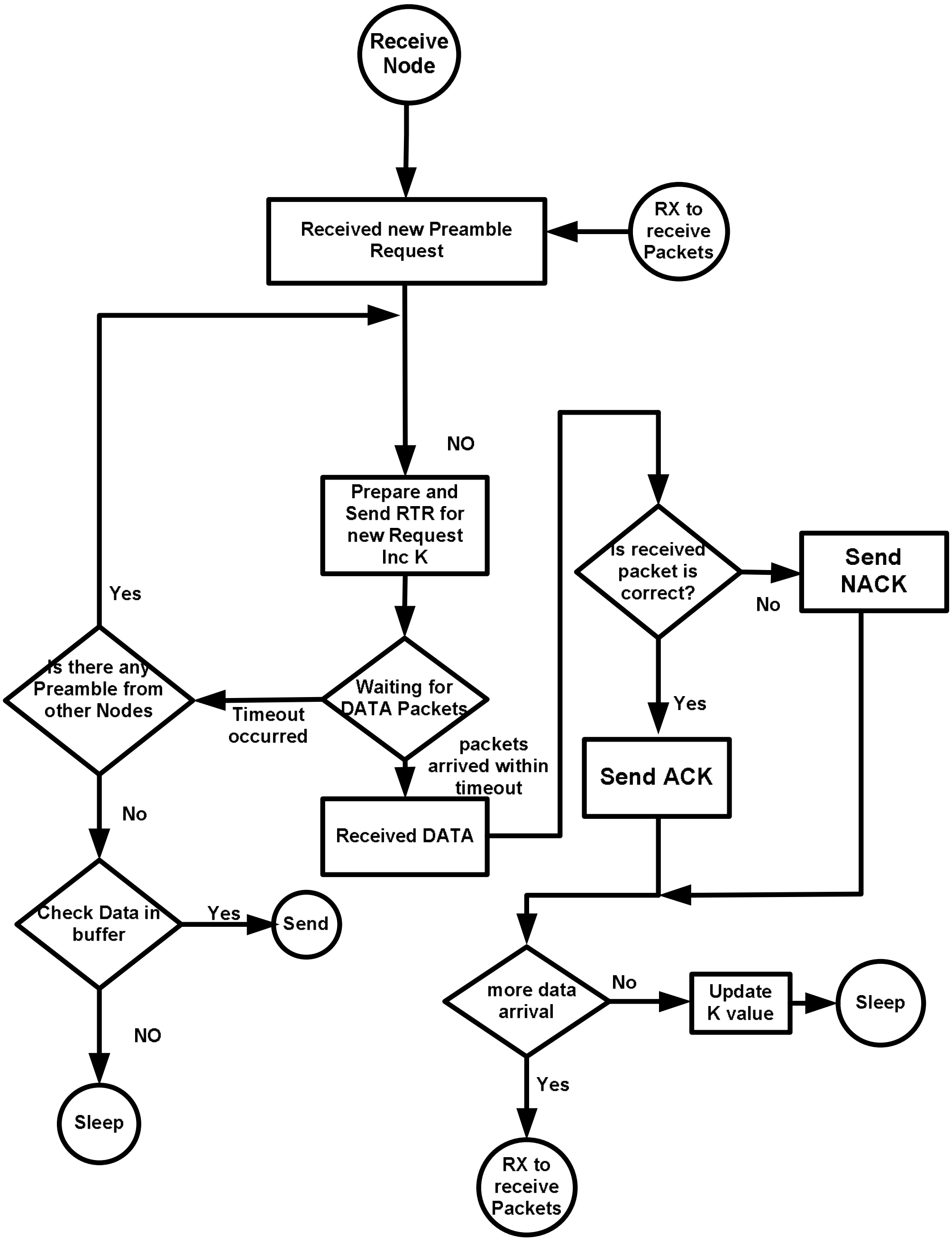


Figure A.5: Flow diagram for receiver process

A-2: Derivation of the packet throughput of the proposed MAC protocol

The probability of success of a single node is

$$S|1\text{ node is transmitting} = 1.(\mathrm{P_{SP}}(1)) \qquad \text{(A-2-1)}$$

where $\mathrm{P_{SP}}(\mathrm{j})$ is the probability of packet success and is computed using Eq. 4.31in Section 4.6 of chapter 4.

The probability of success of two nodes is

$$S|2\text{ nodes are transmitting} = 2.(\mathrm{P_{SP}}(2)^2) + 1.\mathrm{P_{SP}}(2).(1-\mathrm{P_{SP}}(2)) \qquad \text{(A-3-2)}$$

The probability of success of three nodes is

$$S|3\text{ nodes are transmitting} = 3.(\mathrm{P_{SP}}(3)^3) + \binom{3}{2}2.(\mathrm{P_{SP}}(3)^2) + (1-\mathrm{P_{SP}}(3))\text{or}\binom{3}{1}1.\mathrm{P_{SP}}(3).(1-\mathrm{P_{SP}}(3))^2 \qquad \text{(A-2-3)}$$

Thus, the packet throughput of the proposed MAC protocol, S, given that j nodes are transmitting is given by

$$S|j\text{ nodes transmitting} = \sum_{\mathrm{i}=0}^{\mathrm{j}}\binom{\mathrm{j}}{\mathrm{j}-\mathrm{i}}(\mathrm{j}-\mathrm{i})\mathrm{P_{SP}^{j-i}}(\mathrm{j})\cdot(1-\mathrm{P_{SP}}(\mathrm{j}))^{\mathrm{i}} \qquad \text{(A-2-4)}$$

A-3: Finding the expected value of S_n for Bernoulli process

$$G_{new,S_n}(z) = \frac{\mu_s - \mu_s\rho_S + \mu_s\rho_S z}{\mu_s - \mu_s\rho_S + \mu_s\rho_S z + \rho_S[1-z]} \qquad \text{A-3-1}$$

Differentiating $G_{new,S_n}(z)$ with respect to z and using the quotient rule, we get the following

$$\frac{(\mu_s - \mu_s\rho_S + \mu_s\rho_S z + \rho_S[1-z])\cdot[\mu_s\rho_S] - (\mu_s - \mu_s\rho_S + \mu_s\rho_S z)[\mu_s\rho_S - \rho_S]}{(\mu_s - \mu_s\rho_S + \mu_s\rho_S z + \rho_S[1-z])^2} \qquad \text{A-3-2}$$

After simplifying Eq. (A-3-2), we get the following

$$\frac{\mu_s \rho_S}{(\mu_s - \mu_s \rho_S + \mu_s \rho_S z + \rho_S[1 - z])^2} \tag{A-3-3}$$

After simplifying the denominator by substituting Z=1, we get the following

$$\frac{\mu_s \rho_S}{(\mu_s)^2} \tag{A-3-4}$$

Finally, we obtain the mean of $E(S_n)$ as the following

$$\frac{\rho_S}{\mu_s} \tag{A-3-5}$$

A-4: Finding the expected value of S_n for Poisson process

$$G_{N_{slots,S}}(z) = \frac{\mu_S e^{\lambda\,(z-1)}}{1 - e^{\lambda(z-1)} + \mu_S e^{\lambda\,(z-1)}} \tag{A-4-1}$$

Differentiating $G_{N_{slots,S}}(z)$ with respect to z and using the quotient rule, the product rule and the chain rule, we get the following

$$\frac{\left(1 - e^{\lambda(z-1)} + \mu_S e^{\lambda\,(z-1)}\right) \cdot\ e^{\lambda\,(z-1)} - \left(\mu_S e^{\lambda\,(z-1)}\right)\left[e^{\lambda\,(z-1)}\lambda + e^{\lambda\,(z-1)}\right]}{(1 - e^{\lambda(z-1)} + \mu_S e^{\lambda\,(z-1)})^2} \tag{A-4-2}$$

After simplifying Eq. (A-4-2), we get the following

$$\frac{\mu_S\left[e^{\lambda\,(z-1)}\right]^2 \lambda}{(1 - e^{\lambda(z-1)} + \mu_S e^{\lambda\,(z-1)})^2} \tag{A-4-3}$$

After simplifying the denominator by substituting Z=1, we get the following

$$\frac{\mu_S \lambda}{{\mu_S}^2} \tag{A-4-4}$$

Finally, we obtain the mean of $E(S_n)$ as the following

$$\frac{\lambda}{\mu_S} \tag{A-4-5}$$

A-5: Finding the expected value of $G_{L_d}(z)$ for Bernoulli and Poisson process

$$G_{L_d}(z) = \frac{1 - L_x^{Beg}(z)}{E(L_x^{Beg})(1-z)} \qquad \text{A-5-1}$$

Differentiating $G_{N_{slots,S}}(z)$ with respect to z and we get the following

$$\frac{1}{E(L_x^{Beg})}\frac{(1-z)E\left(L_x^{Beg}\right) - \left(1 - L_x^{Beg}(z)\right)}{(1-z)^2} \qquad \text{A-5-2}$$

After applying the L’ Hospital’s rule [98] to Eq. (A-5-2), we get the following

$$\frac{1}{E(L_x^{Beg})}\frac{(1-z)E\left(L_x^{Beg}\left(L_x^{Beg}-1\right)\right) + E\left(L_x^{Beg}\right) - E(L_x^{Beg})}{2(1-z)} \qquad \text{A-5-3}$$

After simplifying Eq. (A-5-3), we get the following

$$E(L_d) = \frac{E\left(L_x^{Beg}\left(L_x^{Beg}-1\right)\right)}{2E(L_x^{Beg})} \qquad \text{A-5-4}$$

where $E(L_x^{Beg})$ and $E\left(L_x^{Beg}\left(L_x^{Beg}-1\right)\right)$ are the first and second order derivatives of L_x^{Beg}.

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