INVESTIGATION OF ENERGY EFFICIENT TRAFFIC ADAPTIVE MAC LAYER PROTOCOLS FOR MULTI-HOP AD-HOC NETWORKS

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ABSTRACT

INVESTIGATION OF ENERGY EFFICIENT TRAFFIC ADAPTIVE MAC LAYER PROTOCOLS FOR MULTI-HOP AD-HOC NETWORKS

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Multi Hop Ad-Hoc Networks typically refer to interconnected sensing devices with limited processing, communication, and power capabilities. Self-organization, reliability, and energy efficiency are important issues in these networks. Energy efficient, traffic adaptive, multi-channel, and schedule based MAC Layer protocols have been studied for ad-hoc networks in this thesis.

Medium sharing problem is one of the most important topic for multi hop ad-hoc networks, especially under intensive data traffic. In recent years, traffic adaptive MAC Layer protocols are becoming more popular in these networks to solve the heavy data traffic scenarios problems. Traffic adaptive MAC Layer protocols aim low power consumption by arranging nodes' priorities with respect to nodes' traffic density. These protocols determine that which node will be transmitter and which node will be receiver and lastly which nodes will be in sleep state. In addition, these protocols should have good solutions for high throughput and low latency while they keep providing low power consumption. Besides, traffic adaptive MAC Layer protocols should handle basic problems of ad-hoc networks such as hidden terminal problem, exposed terminal problem, collisions.

Traffic Adaptive Medium Access Protocol (TRAMA), Flow-Aware Medium Access Protocol (FLAMA), and Dynamic Multi-channel Medium Access Protocol (DYNAMMA) are traffic adaptive MAC Layer protocols that have been evaluated in this study. These three protocols had been examined with only grid network topologies in the previous studies. The first aim of this work is to repeat the literature results for these protocols. Then, these protocols have been simulated for

different scenarios such as random network topologies, different transmission ranges and signal model with shadow fading.

Keywords: Multi Hop Ad-Hoc Network, MAC Layer, Topology, Traffic Adaptive, Energy Efficiency, Throughput, Latency

ÖZ

INVESTIGATION OF ENERGY EFFICIENT TRAFFIC ADAPTIVE MAC LAYER PROTOCOLS FOR MULTI-HOP AD-HOC NETWORKS

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Aralık 2017, 68 Sayfa

Çok komşulu Ad-Hoc ağları genellikle kendi aralarında bağlı, sınırlı işlem, sınırlı haberleşme ve sınırlı güç kapasitesi bulunan aygıtlardan oluşur. Böyle ağlar için kendi aralarında organize olabilme, güvenirlilik ve enerji verimliliği önemli konulardandır. Bu tez çalışmasında, çok komşulu Ad-Hoc ağları için enerji tasarruflu, trafik uyumlu, çok kanallı ve zaman çizelgeli kanal erişimi olan MAC katmanı protokolleri incelenmiştir.

Özellikle yoğun veri trafiğinde ortam paylaşımı, çok komşulu Ad-Hoc ağlarında en önemli problemlerden biridir. Son yıllarda trafik uyumlu MAC katmanı protokolleri yoğun veri trafiği sorununu çözmek için daha popüler hale gelmeye başladı. Trafik uyumlu MAC katmanı protokolleri, düğümlerin önceliğini düğümlerin veri trafik yoğunluğuna göre ayarlayarak düşük güç tüketimini amaçlar. Bu protokoller hangi düğümün verici durumunda, hangi düğümün alıcı durumunda ve hangi düğümün uyku durumunda olacağını belirler. Ayrıca bu protokoller, düşük güç tüketimi sağlarken yüksek veri hacmi ve düşük veri paketi gecikmesi için de iyi çözümlere sahip olmalıdır. Bütün bu yaklaşımlarla beraber trafik uyumlu MAC katmanı protokolleri gizli terminal, korunmasız terminal ve çarpışma problemleri gibi çok komşulu Ad-Hoc ağların temel problemlerine de çözüm getirmelidir.

Bu çalışmada, trafik uyumlu olan TRAMA, FLAMA ve DYNAMMA MAC katmanı protokolleri değerlendirilmiştir. Önceki çalışmalarda bu üç protocol sadece ızgara ağlar için incelenmiştir. Bu çalışmadaki ilk amaç bu protokollerin literatürdeki sonuçlarını tekrarlamaktır. Bundan sonra bu protokollerin performansları rastgele ağ topolojileri, farklı iletim mesafeleri ve Shadow Fading sinyal modeli gibi farklı senaryolar için simüle edilmiştir.

Anahtar Kelimeler: Çok komşulu Ad-Hoc Ağları, MAC Katmanı, Topoloji, Trafik Uyumlu, Enerji Tasarrufu, Veri Hacmi, Veri Gecikmesi

In memoriam of my beloved father,

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LIST OF ABBREVIATIONS

CDMA	: Code Division Multiple Access
CSMA	: Carrier Sense Multiple Access
CSMA/CD	: Carrier Sense Multiple Access with Collision Detection
CSMA/CA	: Carrier Sense Multiple Access with Collision Avoidance
DCF	: Distributed Coordination Function
DMAC	: Power Efficient Dynamic Medium Access Control
DYNAMMA	: Dynamic Multi-Channel Medium Access
ER-MAC	: Emergency Medium Access Control
FIFO	: First In First Out
FLAMA	: Flow-Aware Medium Access
IEEE	: The Institute of Electrical and Electronics Engineers
LLC	: Logical Link Control
MAC	: Medium Access Control
NCR	: Neighborhood-Aware Contention Resolution
OFDMA	: Orthogonal Frequency-Division Multiple Access
OSI	: Open Systems Interconnection Model
PAMAS	: Power Aware Multi-Access
SMAC	: Sensor Medium Access Control
TDMA	: Time Division Multiple Access
TMAC	: Timeout Medium Access Control
TRAMA	: Traffic Adaptive Medium Access
TRANSFORMA	: Traffic Forecasting Medium Access

CHAPTER 1

INTRODUCTION

There is not any fixed network infrastructure for multi-hop ad-hoc networks in wireless communication. The network services are provided by improvisation in these networks. Consequently, ad-hoc networks can be an ideal solution for several applications such as environmental monitoring, surveillance, and tracking.

Multi hop ad-hoc networks connect the nodes that have limited capabilities. Power is one of the main limitation for wireless sensor networks, since wireless devices need the battery power. As a result, operational lifetime of the network is directly dependent on energy efficiency maximization. In addition to energy problem, communication capability is limited in wireless sensor networks. However, improvements in the technology of physical layer provide high data rates and multiple communication channels usage.

The technological advances have been moving the fundamental challenges from physical layer to the medium access control (MAC) layer to provide high throughput and low latency. On the other hand, growing technology requires higher energy. Therefore, energy efficiency in MAC layer is critical to support better energy management.

This study focuses on evaluating three MAC layer protocols for multi hop ad-hoc networks: Traffic Adaptive Medium Access Control (TRAMA), Flow Aware Medium Access (FLAMA), and Dynamic Multi-channel Medium Access (DYNAMMA). Performances of these MAC layer protocols are simulated and compared under different scenarios (grid topologies, random topologies, different transmission ranges, and shadow fading signal model).

In this part of the thesis, MAC layer is defined and channel access control mechanisms are examined. In addition, research focus of this work is mentioned.

1.1 MEDIUM ACCESS CONTROL LAYER

Medium Access Control (MAC) is the sub-layer of the data link layer in the open system interconnection (OSI) model [1]. The OSI model pictures the components of a network system. The model is just a conceptual model of the network system. It tries to standardize the communication of nodes with standard protocols. The OSI model splits the network into seven different layers.

The layers of the OSI model is shown in Figure 1.1. This OSI model is a conceptual visualization of the network system; it does not have any functional features.

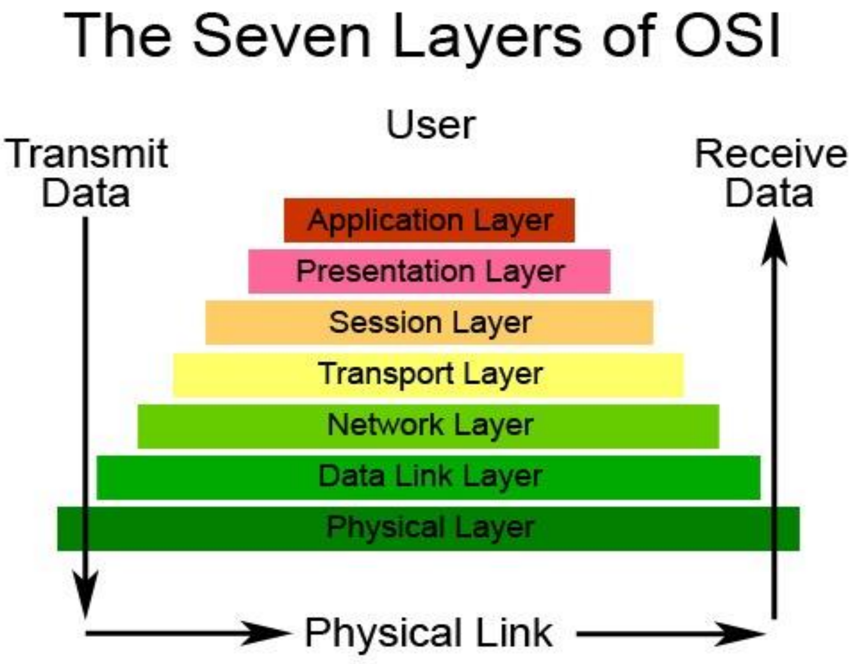


Figure 1.1: The OSI model and layers of OSI model

In the OSI model, each layer has unique important jobs. MAC layer is examined in this thesis. MAC is implemented on a hardware which is called media access controller. It is a physical interface between the physical layer of the network and logical link control sub layer which is the other sub layer of the data link layer.

Channel access control and channel addressing are the main tasks of MAC layer. MAC layer provides communication between each pair of nodes within a shared medium which they incorporate.

1.2 CHANNEL ACCESS CONTROL

Channel access control is used in telecommunications and computer networks to allow network terminals to share media capacity through a multipoint transmission medium. A channel access scheme is based on a multiplexing method, which allows several data streams or signals to share the same communication channel or physical medium.

All nodes of a network may transmit data packets in the same time slot. There will be a collision if the packets are transmitted at the same time and the physical layer becomes useless at this situation. MAC protocol is designed to prevent this circumstance.

Communication is done through a shared medium in a network. Several nodes are connected to the medium to use it together. First task of a medium access protocol is to decide which node uses the shared medium.

1.3 RESEARCH FOCUS

The focus of this research is evaluating traffic adaptive energy efficient MAC layer protocols which appeared already in the literature. This work aims: (1) to observe the performance of these protocols for different topologies, (2) to examine the benefits of multi-channel usage with in different transmission ranges, (3) and to study shadow signal model to investigate the applicability of these protocols.

Energy efficiency is one of the most important subject in wireless multi hop ad-hoc networks. Energy efficient schedule based channel access schemes are studied for these networks in this thesis. The energy efficient MAC layer protocols aim to provide high throughput and low packet delay. On the other hand, these MAC layer protocols should avoid hidden terminal, exposed terminal, direct interference, and self-interference problems which are commonly occur in ad-hoc networks. Three time scheduled MAC layer protocols, TRAMA, FLAMA, and DYNAMMA, are simulated for different scenarios such as different network topologies, different transmission ranges, and shadow fading signal model. Multiple channel access scheme is also studied and simulated for FLAMA and DYNAMMA with these scenarios to see the benefit of multiple channel usage in MAC layer. These three MAC layer protocols have been compared with respect to their efficiency, throughput, and packet delay parameters.

1.4 THESIS ORGANIZATION

The rest of the thesis is designed as follows. Chapter 2 gives background of this work and motivation. Information about energy efficiency of ad-hoc networks will be presented in Chapter 3. Detailed descriptions of MAC layer protocols TRAMA, FLAMA, and DYNAMMA had been given with their structures and algorithms in Chapter 4. After explaining the details of these MAC layer protocols, the simulation results are examined in Chapter 5. In addition, the simulation setups and assumptions are mentioned in this chapter. Finally, Chapter 6 concludes the thesis with future work suggestions.

CHAPTER 2

BACKGROUND AND MOTIVATION

This chapter includes background information about the thesis study. In the first part, the overview of multi hop ad-hoc networks is given. Secondly, wireless medium access is examined for multi hop ad-hoc networks. Basic problems of MAC Layer protocols are presented after this fundamental information is given. Finally, the main purpose of this thesis study is explained in this chapter.

2.1 MULTI HOP AD HOC NETWORKS

Multi hop ad hoc networks are a group of wireless nodes that create multi hop network without any network infrastructure or any centralized administration [2].

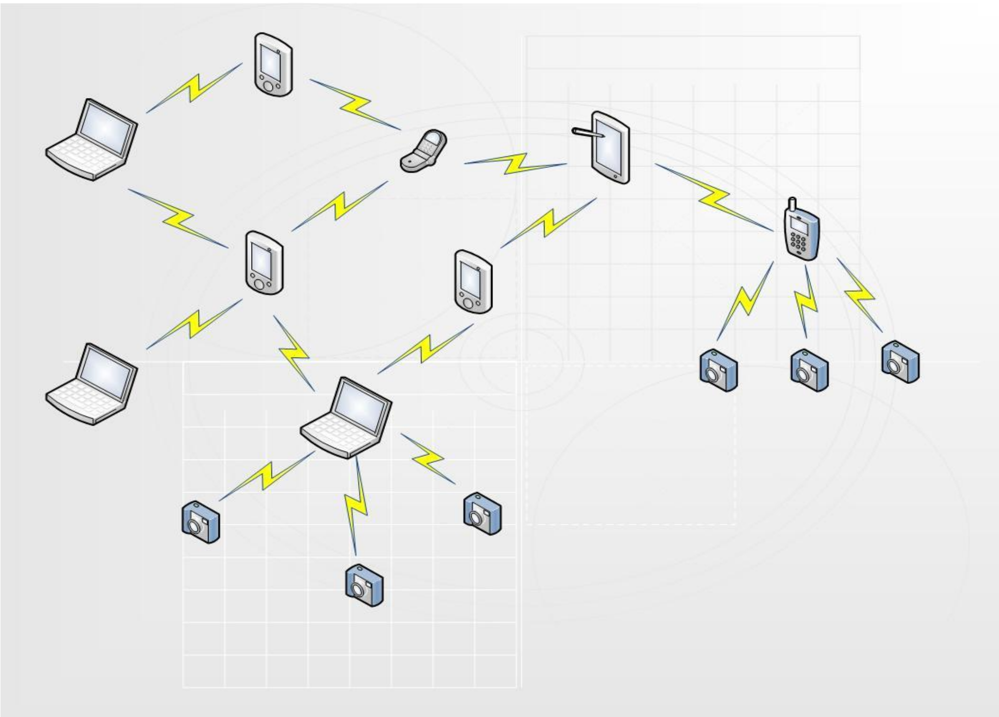


Figure 2.1. Multi Hop Ad Hoc Network

There is an example of multi hop ad-hoc network in Figure 2.1 which is a demonstration that each device in network may communicate with each other. The nodes use the same wireless medium in these networks. The nodes need to be organized themselves in a certain way and MAC Layer protocols are used for this purpose.

2.2 WIRELESS MEDIUM ACCESS FOR MULTI HOP AD-HOC NETWORK

Wireless medium should be used efficiently and fairly to share limited resources between nodes in the network. MAC layer protocols have an important role to provide this functionality in multi hop ad-hoc networks. MAC layer protocols, which are used in wireless communication, can be considered as centralized and distributed topologies as seen in Figure 2.2 [3, 4].

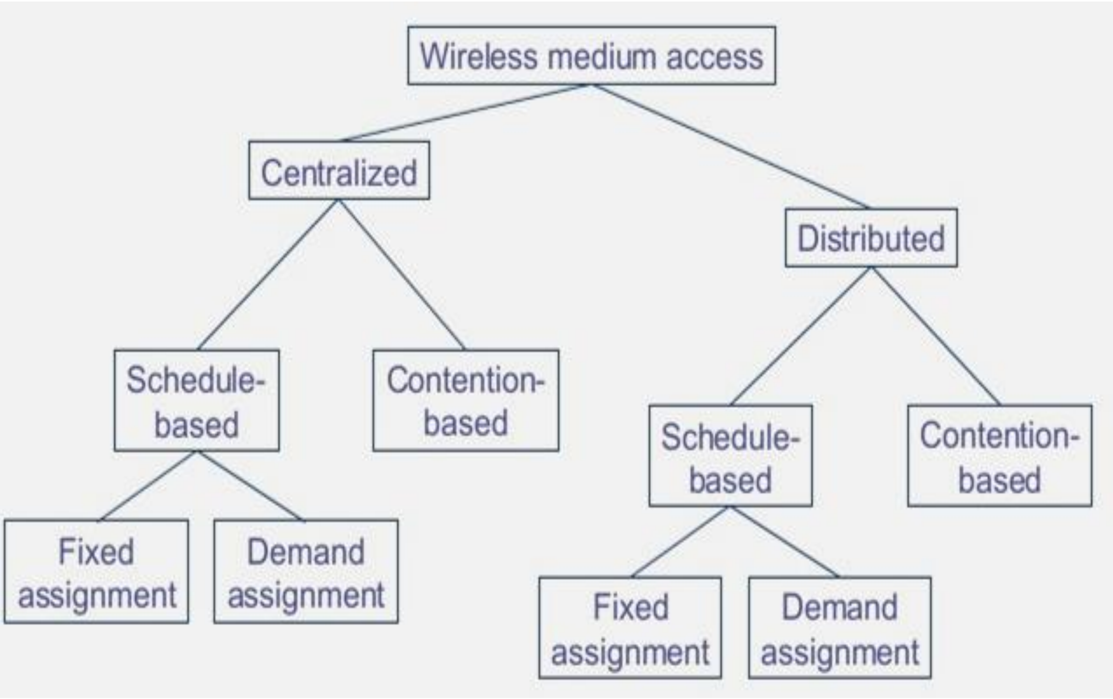


Figure 2.2. Wireless Medium Access

Centralized topologies need a center to organize which node can access to the medium in the network. In these topologies, network is collision-free and these topologies can be applied simply. On the other hand, usage of medium requires perfect synchronization from the control station. However, distributed topologies do not need any station to organize the network. Distributed topologies may be applied for non-infrastructure networks like multi hop ad-hoc networks. There are many MAC Layer protocols in literature and these networks use both for centralized and decentralized topologies. These topologies can be simply categorized as contention based and scheduled based protocols [5].

2.2.1 Contention Based Protocols

In wireless multi hop ad-hoc networks, contention-based MAC protocols are preferred because of their simplicity and ease of implementation. On the other hand, this simplicity brings some disadvantages. Contention based approach comes with the price of energy efficiency and channel utilization.

2.2.2 Scheduled Based Protocols

Scheduled based medium access specifies which nodes will use the resources. These protocols provide energy-efficiency and channel utilization unlike contention based protocols. However, scheduled based protocols come with synchronization problem. Members of the network, nodes, should be synchronized for using scheduled structure.

2.3 MAC OVERVIEW FOR MULTI HOP AD-HOC NETWORKS

The main function of MAC layer protocols is to provide medium sharing efficiently and fairly as mentioned before. The most important and simplest feature of well-designed MAC layer protocols is that they should provide collision-free communication. It means there should not be a collision when nodes communicate with each other in the network. Collision may occur commonly in two different ways in multi hop ad-hoc networks, which are called hidden terminal and exposed terminal problems [6].

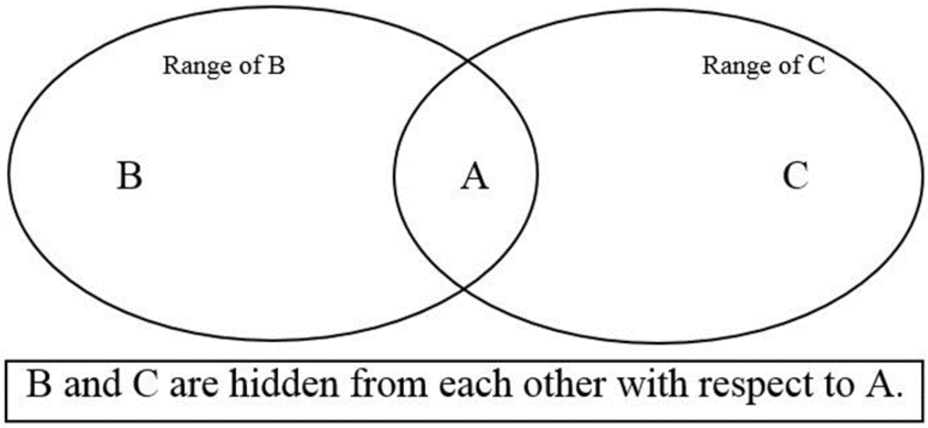


Figure 2.3. Hidden Terminal Problem

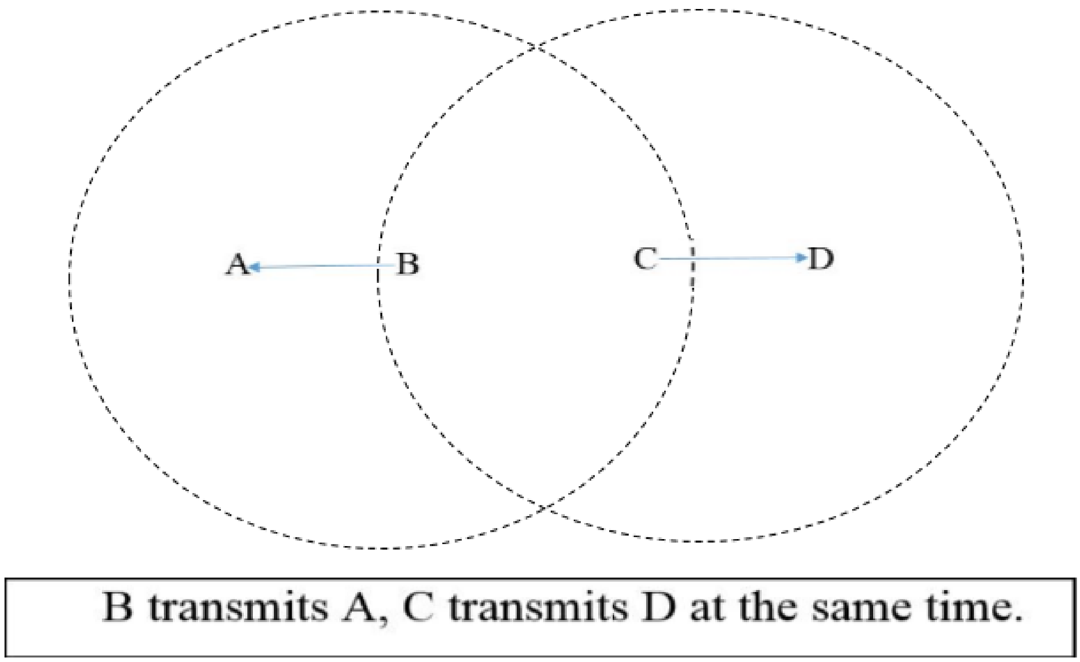


Figure 2.4. Exposed Terminal Problem

Hidden terminal problem is illustrated in Figure 2.3. In the figure when node B and node C want to communicate with node A the collision occurs and this problem is called hidden terminal problem. Demonstration of exposed terminal problem is in Figure 2.4. Nodes B and C are in the transmission range of each other in the figure. If these nodes want to communicate with nodes A and D at the same time, the collision will occur and this problem is called exposed terminal problem.

This most basic and most important problem of multi hop ad-hoc networks, collision, can be solved by deciding which nodes can be operating at the network at the same time. All nodes in the network should know their one hop and two hop neighbors to avoid collisions. At the next step, the most basic and commonly used way of collision avoidance in MAC layer protocols is mentioned.

2.3.1 Neighborhood-Aware Contention Resolution (NCR) Algorithm

The collision problem occurs when more than one node try to access the shared medium. This problem is solved by designing contention resolution algorithms.

Neighborhood-Aware Contention Resolution (NCR) offers a solution to overcome medium sharing problem [7]. The winner node or link is chosen from among a group of contenders in NCR. The contenders are made from one hop and two hop neighbors of each node in ad-hoc networks. Each node should have this information to use NCR algorithm.

M_i is named for the group of contenders against node i for the same time slot to explain the election problem. The priority of a node is very important for a time slot from the group $M_i \cup \{i\}$. The priority of a node is called by Pi. This priority is calculated with a formula which is given by 2.1.

$$Pi = Rand\ (i \oplus\ t) \oplus i \tag{2.1}$$

The $Rand(x)$ is Pseudo-Random-Generator function. The '$\oplus$' sign expresses for operation of concatenation of two operands and this process generates same output for same inputs; therefore, NCR gives a unique priority number to each node in network. Accordingly, NCR provides high utilization of network. The Pseudo Code of general NCR algorithm is given at the below and this explains NCR algorithm in detail.

The NCR algorithm is the basis to select the transmitting node for the three protocols which are TRAMA, FLAMA, and DYNAMMA studied in this thesis.

General NCR Algorithm Pseudo-Code

Procedure NCR$(i,\ t)$	
$for\ (k \in M_i \cup i)$	// For members of M_i and i
$P_k = Rand(k \oplus t) \oplus k$	// Calculate priority numbers
$if\ (P_i > P_k\ \&\ i = !k)$	// Compare the priority numbers of node i with other nodes which are in the set of $M_i \cup i$
winner node $= i$	// Winner node of contention context is determined
end if	
end for	
end procedure	

2.4 MOTIVATION

The main properties, functionalities, and structures of MAC layer protocols, which used for wireless medium access, are explained in the previous parts. Three different MAC layer protocols, TRAMA, FLAMA and DYNAMMA, are investigated in this thesis. These three protocols are scheduled-based, energy efficient, traffic adaptive, distributed and demand based protocols. FLAMA and DYNAMMA may extend to the multi-channel structure. The multi-channel structure comes with physical layer features and provides multiple communication at the same time. These protocols also must satisfy the basic properties that are mentioned in this chapter. The protocols studied in this study have already been available in the literature and the results such as throughput, energy efficiency and latency have been examined in the previous studies but the results are obtained only for grid network topologies and same transmission ranges in existing works.

First goal is to verify the previous studies in this work. Secondly, the protocols will be examined in random topologies other than the grid topology. Thus, change in their performances in random topologies can be analyzed. Then, different transmission ranges will be investigated to see the effect of multi-channel structure. It is known that if the transmission ranges change, one hop and two hop neighborhoods will be effected and when these change, the operation and the performance of the protocols under study will be different. The effect of the multi-channel structure on the performance of the protocols will also be studied in this experiment. Lastly, it is intended to explore that the effect of shadow fading signal model on performance of the protocols [8]. The effect of the physical layer on the protocols is also investigated in this last experiment.

CHAPTER 3

ENERGY EFFICIENCY IN MULTI-HOP AD-HOC NETWORKS

Wireless sensor networks are becoming more important day by day in developing communication technology. The use of multi hop ad-hoc networks in this evolving technology is examined. Energy consumption remains as an important problem for these networks with this growing technology [9]. Nodes, the members of ad-hoc networks, have limited battery life and the batteries of nodes cannot be changed. Therefore, their battery life should be as long as possible. It can be achieved by low energy consumption at nodes. In this chapter, the general overview of the energy efficient MAC protocols' concepts and energy efficiency will be mentioned.

3.1 ENERGY CONSUMPTION IN MULTI HOP AD-HOC NETWORKS

3.1.1 Reasons of Energy Waste

There are several reasons for energy waste in a network. The following effects cause energy waste in ad-hoc networks:

Collisions: If a collision occurs, it means that communication has failed and transmitter node should retransmit the packet. Therefore, retransmission process causes increase in the energy consumption.

Overhearing: If a node receives irrelevant packets which are transmitted to other nodes.

Idle Listening: One of the major reason of energy waste is idle listening. Nodes, which are neither transmitter nor receiver, always listen the channel. Listening a channel continuously consumes much energy.

3.1.2 Importance of Energy Efficiency

Physical layer brings some challenges about energy consumption. Improvements of technology in the physical layer such as high data rates and multiple RF chains require more power.

Nodes usually work with battery in multi hop ad-hoc networks and batteries of nodes usually cannot be changed when they are over [10]. Power limitation makes energy efficient MAC protocols important since operational lifetime maximization of the batteries of the nodes is critical.

In traditional methods, all nodes in the network listen the channel in whole operation time. However, these methods are not applicable to use energy more efficiently. Less energy consumption achieved by making nodes sleep if they are not in operational state with the protocols, which are studied in this thesis.

Wireless sensor networks are becoming popular with the new technologies and the usage of multi hop ad-hoc networks is increasing in the industrial applications. Therefore, energy efficient MAC protocols are very important to make longer operational lifetime by saving energy at MAC layer.

3.2 ENERGY EFFICIENT MAC PROTOCOLS

3.2.1 Related Work

Singh and Raghavendra introduces PAMAS [11] for energy efficiency to access medium. This protocol avoids overhearing among neighbor nodes to obtain energy efficieny by using out-of channel signaling. Nodes sleep periodically in the power save mode of IEEE 802.11 DCF. Tseng et al. [12] explored three sleep modes of 802.11 DCF for multi-hop networks. The S-MAC [13] has similar features to PAMAS and protocol of Tseng et al. Like the other approaches, S-MAC avoids overhearing and nodes periodically sleep. S-MAC synchronize neighboring nodes' sleep schedules. An improvement of S-MAC, T-MAC [14] protocol, adapts the duty cycle based on traffic. However, channel contention significantly increases because of synchronized listen periods. D-MAC [15] is designed to use in data gathering applications as a contention-based medium access protocol. Delay is reduced by scheduling transmissions at each hop for this protocol. However, D-MAC is designed for fixed topology and does not allow multiple data gathering trees. All of the above mentioned protocols improve energy efficiency by avoiding idle listening. On the other hand, these protocols waste energy in (1) collisions due to hidden terminals and (2) carrier-sensing. The WiMedia MAC targets UWB-based PHY [16] by defining a distributed, time slotted medium access mechanism. Periodical transmission of beacons and distributed reservations medium access scheme is used in the protocol. Reservation-based structure brings advantage for applications which require guaranteed service rates. Despite, these approaches cannot be considered with variable service rates and may also lead to fairness problems and increased overhead to create and maintain reservations.

All previously mentioned protocols are designed to work with a single channel. Given that most commercially available radios to-date provide multiple orthogonal channels, protocols should make use of this feature to schedule parallel transmissions within a two-hop neighborhood, thus improving channel utilization. The work by So and Vaidya describes a multi-channel MAC for ad hoc networks (MMAC) using a single transceiver [17]. It is a contention-based medium access protocol similar to IEEE 802.11 and it uses the ATIM window in IEEE 802.11 PSM for announcing channel switching information. In MMAC, every node must listen in a default channel during the ATIM window. Nodes negotiate channels to transmit or receive by exchanging Preferred Channel Lists (PCLs). Another recent example of a multi-channel MAC is the Slotted Seeded Channel Hopping (SSCH) [18] protocol. SSCH is an improvement over SEEDEX [19] for scheduling across multiple channels. However, both approaches do not consider energy efficiency.

3.2.2 TRAMA, FLAMA, and DYNAMMA in Energy Efficiency

TRAMA, FLAMA, and DYNAMMA are introduced to obtain energy efficiency for wireless sensor ad-hoc networks. Details of the protocols' algorithms will be mentioned at the next chapter. This section explains why these protocols are chosen among the energy efficient protocols.

TRAMA, FLAMA, and DYNAMMA have "distributed TDMA" structure which provides energy efficiency in the network. Energy efficient MAC protocols are usually designed as contention-based protocols as mentioned at the previous section. TRAMA, FLAMA, and DYNAMMA are designed with "distributed TDMA" approach to be used in ad-hoc networks to obtain energy efficiency. Therefore, these protocols have been selected for this thesis study.

There are other MAC protocols which are developed with distributed TDMA approach in the literature. Traffic Forecasting Medium Access (TRANSFORMA) is one of these protocols that is introduced for energy efficiency by forecasting traffic information in the network [20, 21]. It uses the traffic information from within the nodes with access to medium to assign timeslots. This protocol is developed to use in real time services such as live chat programs or streaming video applications [22]. Stanayah et al. propose a new MAC protocol, ER-MAC, with distributed TDMA structure [23]. This protocol provides energy efficiency in ad-hoc networks. It tackles the most important emergency response requirements, such as autonomous switching from energy-efficient normal monitoring to emergency monitoring to cope with heavy traffic, robust adaptation to changes in the topology, packet prioritization and fairness support. Although, TRANSFORMA and ER-MAC have good solutions for energy efficiency in ad-hoc networks, both protocols are not suitable the scenarios studied in this thesis. Therefore, these protocols are not included in simulations.

TRAMA, FLAMA, and DYNAMMA protocols provide good energy efficiency as mentioned in the survey of TDMA energy efficient MAC protocols of Sachin Gajjar et al [24]. These protocols also increase the network operational life time by using energy efficiently. This feature and the multichannel structure of DYNAMMA have been reviewed in the literature and it is explained that the protocols have an important place in ad-hoc networks with these benefits of the protocols [25, 26, 27]. The details of the protocols will be described at the next chapter.

CHAPTER 4

TRAFFIC ADAPTIVE ENERGY EFFICIENT MAC LAYER PROTOCOLS

Collision may occur in ad-hoc networks during data communication if there are no preventions to deal with this problem in the protocols. TRAMA, FLAMA, and DYNAMMA handle this problem by using their distributed scheduling algorithms. In this chapter, the details of TRAMA, FLAMA, and DYNAMMA MAC protocols' algorithms are mentioned to satisfy good energy savings and high performance for multi hop ad-hoc networks [28].

4.1 TRAMA

4.1.1 Structure of TRAMA

The traffic adaptive medium access (TRAMA) protocol is used to provide energy efficiency. It also maintains good throughput and acceptable delay [29]. Energy efficiency is obtained by switching nodes to sleep state to consume less energy when they are not assigned as transmitter or receiver. Collision free communication is provided by an election algorithm based on the NCR structure.

TRAMA protocol consists three main parts which are called Neighbor Protocol (NP), Schedule Exchange Protocol (SEP), and Adaptive Election Algorithm (AEA). TRAMA functionality works with these components and these main parts are explained in the next three sub-sections.

4.1.1.1 Neighbor Protocol (NP)

NP gathers two-hop neighborhood information by using signaling packets and periodically operates during random access period to ensure all nodes have the topology structure information.

4.1.1.2 Schedule Exchange Protocol (SEP)

SEP works to exchange information, which are two-hop neighborhood and schedule of nodes, among each other. SEP uses schedule packets to exchange information. These schedule packets consist transmitter and intended receiver nodes for future transmission slots.

SEP propagates information periodically. The period of SEP is called SCHEDULE_INTERVAL which is a parameter of TRAMA. SEP works in every SCHEDULE_INTERVAL. (i.e. SCHEDULE_INTERVAL=200 means SEP works for every 200 transmission slot for one time slot.)

4.1.1.3 Adaptive Election Algorithm (AEA)

AEA is the main and the most important component of TRAMA. This algorithm decides the state of nodes whether it should be in transmitter mode, receiver mode or sleep mode. The algorithm operates an election process by using schedule information that obtained by SEP and NP. It also provides that nodes, which have no data to send, to be removed from the election process to improve channel utilization. At the next section the details of AEA and the terminologies that used by AEA will be presented.

4.1.2 Algorithm of TRAMA

As mentioned before AEA is the main component of TRAMA. Pseudo code of AEA is seen at Table 4.2. Table 4.1 shows some notations and terminologies that used by AEA.

Table 4.1: Notations and Terminologies of TRAMA

N2 (u)	Set of neighbors of node u which are two-hops away.
N1 (u)	Set of neighbors of node u which are one-hop away.
CS (u)	u's Contending Set is the set of nodes in u's two-hop neighborhood such that {u U **N1**(u) U **N2**(u)}.
tx (u)	Absolute Winner is the node with the highest priority in **CS** (u).
atx (u)	Alternate Winner is the node which has highest priority among u's one-hop neighbors.
PTX (u)	The set of all nodes in {u U **N1** (u) – atx(u)} is called Possible Transmitter Set.
NEED (u)	Need Contender Set is the set of nodes in { **PTX** (u) U u} that are in need of additional transmission slots.
ntx (u)	Need Transmitter is the node with highest priority among the set of nodes **NEED** (u) containing valid synchronized schedule.

Table 4.2: AEA Pseudo-Code Description

```
Compute tx(u), atx(u) and ntx(u)
if (u = tx(u)) then
if (u:isScheduleAnnouncedForT x = TRUE) then
let u:state = TX
let u:receiver = u:reported:rxId
Transmit the packet and update the announced schedule
else if (u:giveup = TRUE) then
call HandleNeedTransmissions
endif
else if (tx(u) ϵ N1(u)) then
if (tx(u):announcedScheduleIsValid = TRUE AND tx(u):announcedGiveup = TRUE) then
call HandleNeedTransmissions
else if (tx(u):announcedScheduleIsValid = FALSE OR tx(u):announcedReceiver = u) then
let u:mode = RX
else
let u:mode = SL
Update schedule for tx(u)
endif
else
if (atx(u) hidden from tx(u) AND atx(u) ϵ PTX(u)) then
if (atx(u):announcedScheduleIsValid = TRUE AND atx(u):announcedGiveup = TRUE) then
call HandleNeedTransmissions
else if (atx(u):announcedScheduleIsValid = FALSE OR atx(u):announcedReceiver = u) then
let u:mode = RX
else
let u:mode = SL
Update schedule for atx(u)
endif
else
call HandleNeedTransmissions
endif
procedure HandleNeedTransmissions
if (ntx(u) = u) then
let u:state = TX
let u:receiver = u:reported:rxId
Transmit the packet and update the announced schedule
else if (ntx(u):announcedScheduleIsValid = FALSE jj ntx(u):announcedReceiver = u) then
let u:mode = RX
else
let u:mode = SL
Update the schedule for ntx(u)
endif
```

The terminologies above in Table 4.1 are used in AEA as seen in the description of pseudo-code of AEA in Table 4.2. AEA operates at all nodes to determine tx(u), atx(u) and ntx(u). State of a node is selected transmitter if node u has highest priority among its contending set and u has data to send. A node's state is receiver mode if it is announced as receiver by current transmitter node, otherwise its state is sleeping mode.

The transmission process starts after a node's state is decided by operating the algorithm of TRAMA. This structure and algorithm of TRAMA provides that there is no collision during communication. The algorithm is implemented in this study as already mentioned in literature.

4.2 FLAMA

4.2.1 Structure of FLAMA

The Flow Aware Medium-Access (FLAMA) is a scheduled-based energy efficient MAC protocol, which uses flow-based traffic information to decide which node in the network will access the channel [30].

FLAMA can be extended to the multi-channel applications. It is an important property to keep pace with new technologies related to physical layer. The multi-channel extension of FLAMA is called Multi-channel FLAMA (MFLAMA) [31]. MFLAMA and FLAMA use same election process algorithm. This algorithm will be presented in the next section.

4.2.2 Algorithm of FLAMA

FLAMA uses distributed election algorithm to provide collision-free communication. This algorithm operates similar with TRAMA Adaptive Election Algorithm. It decides the nodes' state; transmitter mode, receiver mode or sleep mode. It also provides that only one node can be transmitter in the two-hop neighborhood. This algorithm needs priorities of nodes and two-hop neighborhood information of nodes to operate election process. The priorities of nodes are calculated based on a pseudo-random function using node identifier, time-slot identifier and node weight, which is about node data intensity. This algorithm also obtains multiple channel communication scheduling. MFLAMA/FLAMA election algorithm’s pseudo-code is seen in Table 4.3.

Table 4.3: Pseudo-Code of MFLAMA/FLAMA

```
Compute SortedOneHop(u, t) based on descending order of node priorities.
Initialize parentAvailable = TRUE; UsedChannelList = /0; u.state =UNKNOWN;
foreach (node ∈ SortedOneHop(u, t))
if (node == u) then: Out-going flow to parent
foreach (twoHop ∈ TwoHopList(u) )
if PriorityHigh(twoHop, u) then : TwoHop higher priority
if (TXCHANNEL(u) == TXCHANNEL(twoHop) || u.parent ==twoHop.parent)
let u.state = SLEEP; break ;
endif
endif
end
if (u.state == UNKNOWN && parentAvailable && TXCHANNEL(u) ∋
UsedChannelList) then
let u.state = TX; u.txchan = TXCHANNEL(u); u.rx = parent;
else let u.state = SLEEP; break ;
end
if (node ==CHILD(u)) then : Incoming flow from child
let u.state = RX; u.rxchan = TXCHANNEL(node); u.tx = node;
else
let UsedChannelList = {UsedChannelList,TXCHANNEL(node)};
if (node == u.parent) then let parentAvailable = FALSE endif
end
if (u.state ==UNKNOWN) let u.state = SLEEP endif
```

By implementing this algorithm as described in literature, the simulations are examined and results, which are seen in Chapter 5, are obtained.

4.3 DYNAMMA

4.3.1 Structure of DYNAMMA

DYNAMMA is a MAC protocol for ad-hoc networks. It is able to adapt traffic patterns dynamically. It can operate the multi-channel with conflict free and it is also energy efficient. DYNAMMA is produced to take advantage of physical layer with new technologies such as high data rate and the multi-channel usage [32].

Time slot organization of DYNAMMA differs from TRAMA and FLAMA. Timeslot organization of the protocols can be seen in Figure 4.1. This timeslot organization brings advantage to DYNAMMA over the average packet calculations.

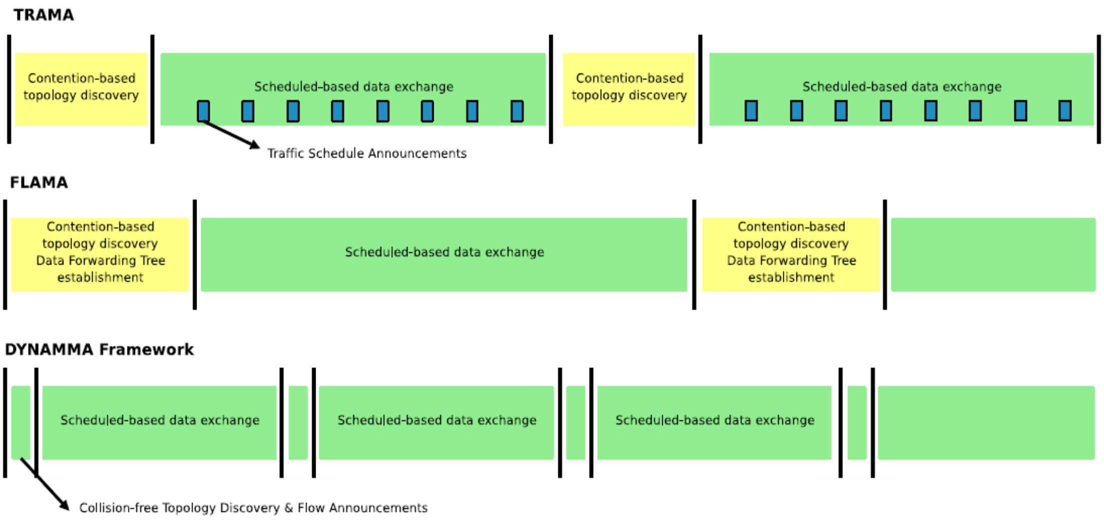


Figure 4.1. Timeslot Organization of TRAMA, FLAMA and DYNAMMA

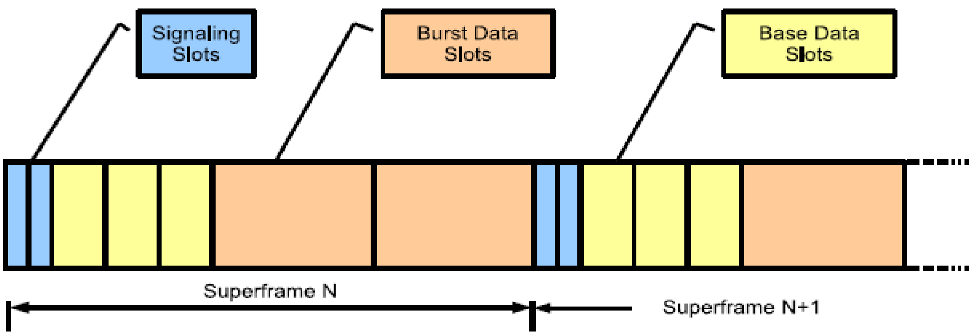


Figure 4.2. DYNAMMA's Superframe Structure

DYNAMMA has a superframe structure for the time slot organization which can be seen in Figure 4.2. This superframe structure consists signaling slots, base data slots and burst data slots. Data communication is obtained by base data slots and burst data slots and neighbor and traffic information are exchanged with signaling slots. Superframe structure and DYNAMMA notations are used to decide which node can access the channel in the network.

Traffic and neighborhood information are exchanged between nodes by using signaling slots as mentioned before. A set of one-hop data flows are modeled as traffic information in DYNAMMA. This flow data information is gathered by signaling slots. The required number of time slots for each flow differs from each other. Because of this reason, there is a classification for traffic flows. Three classes are used for classification of traffic flows depending on their data intensity on a flow in DYNAMMA. Classes are named Class 0, Class 1, and Class 2. Class 0 can contend for all time slots, Class 1 can contend 50% of all time slots and Class 1 can contend for 25% of all time slots. Some notations and terminologies that used in DYNAMMA can be seen in Table 4.4.

A flow's class is determined by using these terminologies and notations. A flow's channel access probability equals 1/NumberofContendingFlows approximately. $E_r(f)$, flow f's expected number of access slots is calculated by production of channel access probability with the slots' number in the superframe. $S_r(f)$ is defined as required access slots and it is computed based on data packets on each node queue buffer. U(f), channel utilization factor, is calculated as *U(f)* = $S_r(f)$)/ $E_r(f)$ by applying the required and expected number of slots to formulations. A flow class is determined by comparing threshold value TH_p and $U(f)$. If $U(f) > TH_0$, flow matches to Class 0, if $TH_1 < U(f) < TH_0$, flow fits to Class 1 and if $TH_2 < U(f) < TH_1$, flow belongs to Class 2 where $TH_0 = 0.95, TH_1 = 0.65,$ and $TH_2 = 0$.

DYNAMMA uses a Distributed Scheduling Algorithm to schedule the timeslot usage in the network by using these values and other terminologies in the Table 4.4.

The election process is operated with this algorithm and the details of algorithm will be presented in the next section.

Table 4.4: Notations and Terminologies of DYNAMMA

Number of channels, **M**	The available channel's total number.
One-hop Neighbors, **N1**(u)	Set of node u's neighbors which are one-hop away.
Two-hop Neighbors, **N2**(u)	Set of node u's neighbors that are two-hops away.
Active Flow Set, **AF**(u, t)	Set of all active flows which are in node u's two-hop neighborhood in timeslot t.
Required Access Slots, $S_r(f,n)$	Flow f's required number of access slots in superframe n.
Expected Access Slots, $E_r(f,n)$	Flow f's expected number of channel access slots in superframe n..
Channel Utilization Factor, $U(f,n)$	Flow f's channel utilization factor in superframe n
Channel Utilization Threshold, TH_p	Flow class p's channel utilization threshold.

4.3.2 Algorithm of DYNAMMA

DYNAMMA operates Distributed Scheduling Algorithm to establish collision free communication. Every node in the network operate the algorithm at the beginning of base or burst data slot to decide whether its state is transmitter mode, receiver mode or sleep mode. Pseudo-random function (PRF) is used for this structure. In this election process, there are some main steps at each node which is defined as follow:

- For the current timeslot t gather all active contending flows AF(u,t) which includes all outgoing flows of node u, all the outgoing flows of N1(u), all the outgoing flows of N2(u).
- Flow priorities computed as PRF(flow.srcId, flow.flowId, t, n) and the transmission channel for the flow is PRF(flow.srcId)%M.

DYNAMMA Distributed Scheduling Algorithm operates after these steps for this election process. Its pseudo code is seen in Table 4.5.

Table 4.5: Distributed Scheduling Algorithm of DYNAMMA

Compute **AF**(*u, t*) and sort **AF**(*u, t*) based on descending order of flow priorities.
Initialize *BlackListNodes* = /0; *UsedChannelList* = /0; *u.state =UNKNOWN*;
foreach (*f low* ∈ **AF**(*u*, *t*)) **begin**
if (*f low.srcId* == *u*) **then** : Outgoing flow
if (*TXCHANNEL*(*u*) _*UsedChannelList* && *f low.destId* _ *BlackListNodes*) **begin**
let *u.state* = *TX*; *u.txchan* = *TXCHANNEL*(*u*); *u.tx f low* = *f low*;
else let *u.state* = *SLEEP*;
endif
else if (*f low.destId* == *u* || *f low.destId* == *ANY DEST*) **then** : Incoming flow
if ((*TXCHANNEL*(*f low.srcId*) _*UsedChannelList*) OR
(*CONFLICTTX hidden from f low.srcId*)) **then**
if (*f low.destId* _ *BlackListNodes*) **then**
let *u.state* = *RX*;*u.rxchan* = *TXCHANNEL*(*f low.srcId*); *u.rx f low* = *f low*;
else *u.state* = *SLEEP*; **endif**
else *u.state* = *SLEEP*; **endif**
else if (*f low.srcId* ∈ **N1**(*u*)) **then** : One-hop Originated Flow
let *UsedChannelList* = *{UsedChannelList,TXCHANNEL*(*f low.srcId*)*}*;
let *BlackListNodes* = *{BlackListNodes, f low.srcId, f low.destId}*;
else : Two-hop or Three-hop Originated Flow
let *UsedChannelList* = *{UsedChannelList,TXCHANNEL*(*f low.srcId*)*}*;
let *BlackListNodes* = *{BlackListNodes, f low.destId}*;
if (*f low.srcId* _ *{***N1**(*u*),**N2**(*u*)*}*) **then** set hidden usage flag; **endif**
endif
if (*u.state* ==*UNKNOWN*) **then continue** ; **else break** ;
end

This structures and algorithm are implemented and the results are compared with literature. The other approaches like different transmission ranges, random network topologies and shadow fading signal model is investigated in this research for all protocols.

4.4 Common Features of TRAMA, FLAMA, and DYNAMMA

The details of the each protocol are explained in the previous sections. It is seen that there are many common features of the protocols as mentioned in this chapter. The election algorithms of all protocols have a structure based on NCR algorithm. Although, NCR algorithm decides the winner node among the contenders in the classical approach, the election algorithms of these protocols decide the receiver node and sleep nodes except transmitter node among two hop neighborhood.

The protocols have contention based topology discovery in the time-slot organization as demonstrated in Figure 4.1. Nodes access the medium randomly to learn one hop and two-hop neighborhood information with traffic density of two-hop neighborhood by signaling slots in this stage of time-slot organization. As a result of this, all nodes have necessary information of two-hop neighborhood to run election algorithm.

These protocols have been introduced for ad-hoc networks. Since ad-hoc networks are distributed, these protocols have also distributed structure. Therefore, protocols learn one-hop neighbor information by signaling slots which complexity is O(n) [33] and algorithms may have 2-hop neighborhood information in one loop iteration by using one-hop neighbor information. As a result, the complexity of the protocols is O(n^2). Protocols also discover topology information at the contention stages of the time slots. Thanks to this feature, protocols are robust because they can learn the changes in network structure when topology information changes. Finally, distributed networks have self-organized structures and these protocols organize the network themselves and this typical property of the distributed networks makes these protocols stable. As a consequence, it can be said that the protocols are scalable because of their complexity, stability and robustness features.

TRAMA, FLAMA, and DYNAMMA provide conflict-free communication, energy efficiency and good throughput as their common benefits. However, packet delay performance of the protocols differ from each other. The simulation setup and the results will be described in the next chapter.

CHAPTER 5

SIMULATION SETUP AND RESULTS

Simulation results of the study will be reviewed in this chapter. First, performance metrics of the study will be described. After that, simulation setup of the thesis will be referred. Thirdly, simulation results of this study and the literature results will be compared to be sure that the simulation setup of this thesis is correct. Finally, results of different scenarios such as different network topologies, different transmission ranges and shadow fading signal model will be examined.

Some assumptions are made in this thesis while simulating protocols. Firstly, it is assumed that all nodes are time synchronized perfectly in the network. The other assumption is about the antennas and it is considered that the antennas of the nodes are identical and omni-directional. Finally, it is thought that the medium has free space path loss model for all scenarios except shadow fading model. The loss of shadow fading is added to free space path loss for the shadow fading signal model scenario.

5.1 PERFORMANCE METRICS

Different performance metrics are calculated for the protocols which are evaluated in this study. All these performance metrics are used to determine the advantages and disadvantages of these protocols and compare the protocols with each other. The performance metrics' explanation are given below:

- **Average Packet Delivery Ratio:** This metric is calculated by dividing the number of received packets to the number of sent packets by averaging over all the nodes in the network. If all one-hop neighbors of a node receive a packet, it may be counted as received packet for broadcast traffic.

- **Percentage Sleep Time:** This parameter is computed by averaging the proportion of the number of sleeping slots to the number of total slots for the entire network.
- **Average Queuing Delay:** It is the average of delay time for delivered packets to the receiver.
- **Average Sleep Interval:** This is calculated by averaging the duration of sleeping intervals which means that a node is in idle state.

5.2 SIMULATION SETUP

The studies in the literature used different grid network topologies, data sizes, transmission ranges and parameters which have been specialized for each protocol. First goal of this research is to obtain similar simulation results in comparison to the literature. Secondly, the simulations are executed for random network topologies to see how the results will change. The simulations are also repeated to see the effect of the multi-channel structure for MAC layer protocols with different transmission ranges. Finally, a signal model with shadow fading is considered to see the effect of physical layer at throughput performance.

5.2.1 Simulation Setup of TRAMA for Literature Results

TRAMA is investigated for grid network topology in the literature. The network structure is shown in Figure 5.1.

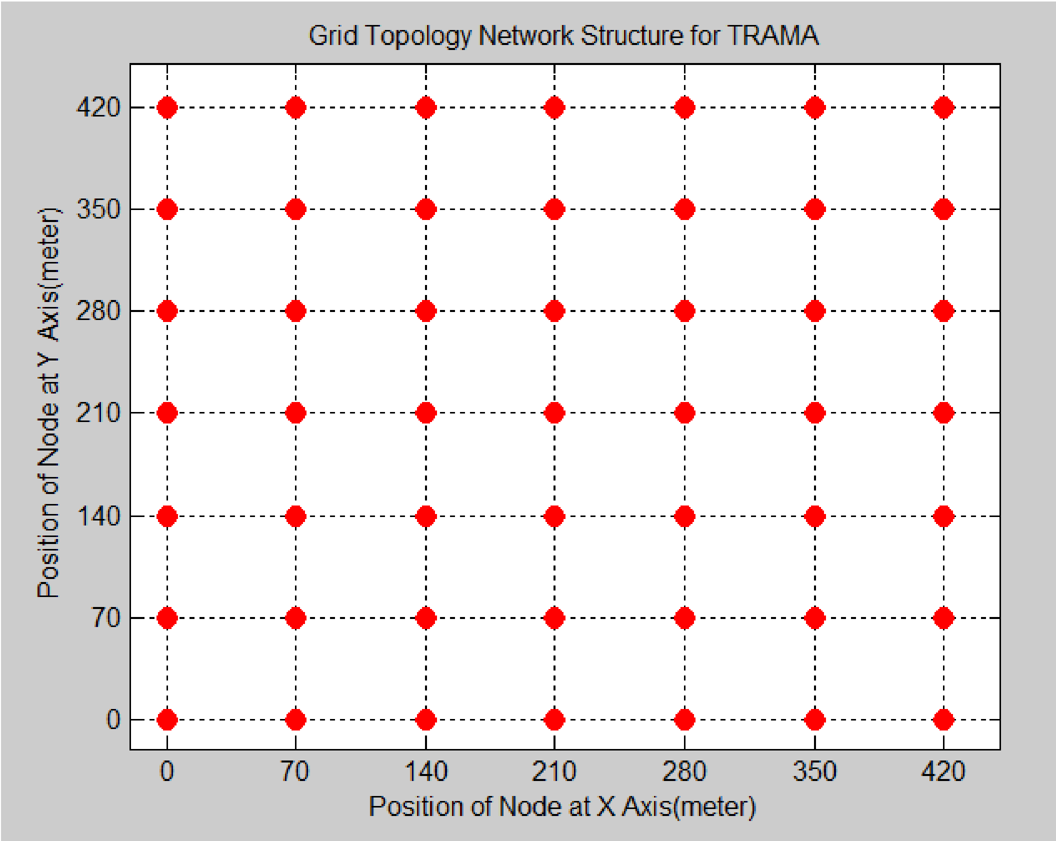


Figure 5.1. TRAMA Network Topology

The simulation has the following parameters to repeat TRAMA literature results;

- Transmission range of the nodes are 100 m.
- 512 byte data packet transmission is done. That is approximately 46 msec timeslot length.
- Simulations run for 400 seconds both unicast and broadcast transmission types.
- Synthetic broadcast traffic using Poisson arrivals. There are 12 different mean inter arrival times in simulation which are 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 1.2, 1.5, 1.8, 2, 2.5 seconds.
- SCHEDULE_INTERVAL is 100 transmission slots.

5.2.2 Simulation Setup of FLAMA and MFLAMA for Literature Results

FLAMA is investigated for grid network topology in the literature. The network structure is shown in Figure 5.2.

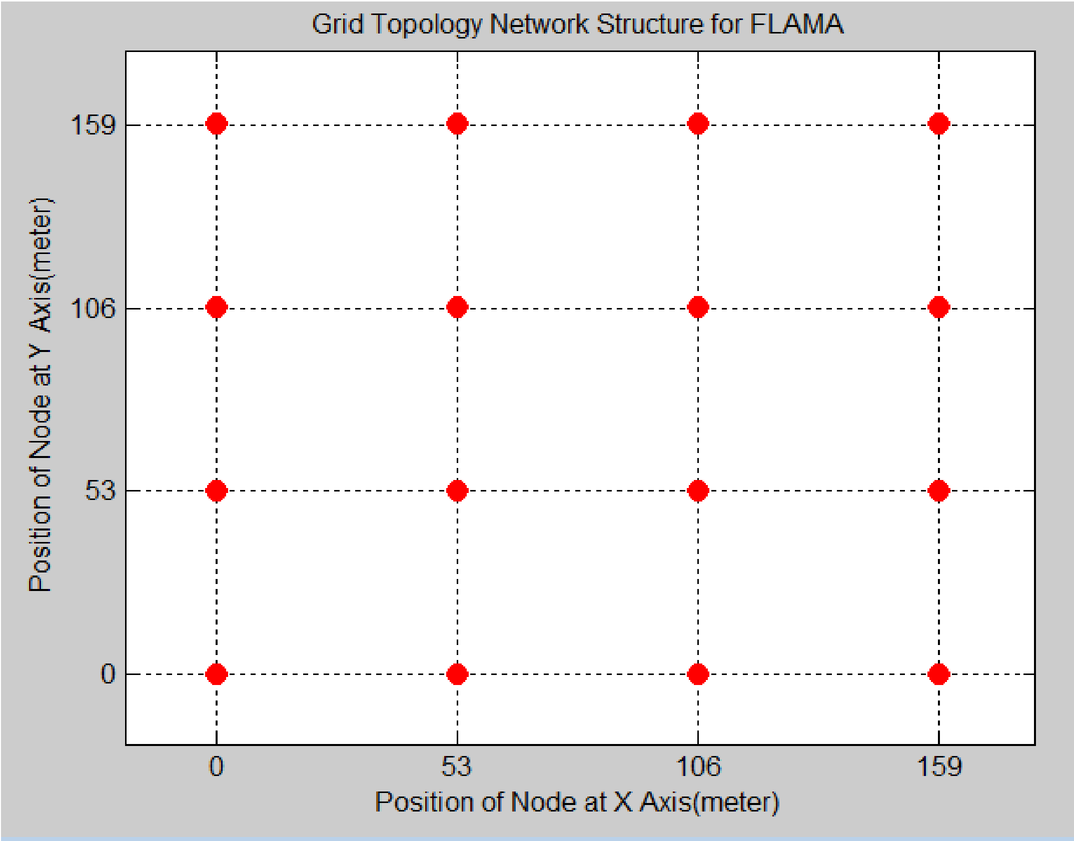


Figure 5.2. FLAMA Network Topology

The simulation has the following parameters to repeat FLAMA literature results;

- Transmission range of the nodes are 90 m.
- 128 byte data packet transmission is done. That is approximately 53 msec timeslot length.
- Simulations run for 2000 seconds.
- There are 9 different packet generation intervals which have mean inter arrival times as 2, 3, 4, 5, 6, 7, 8, 9, 10 seconds.

5.2.3 Simulation Setup of DYNAMMA for Literature Results

DYNAMMA is studied for grid network topology in the literature. The network structure is shown in Figure 5.3.

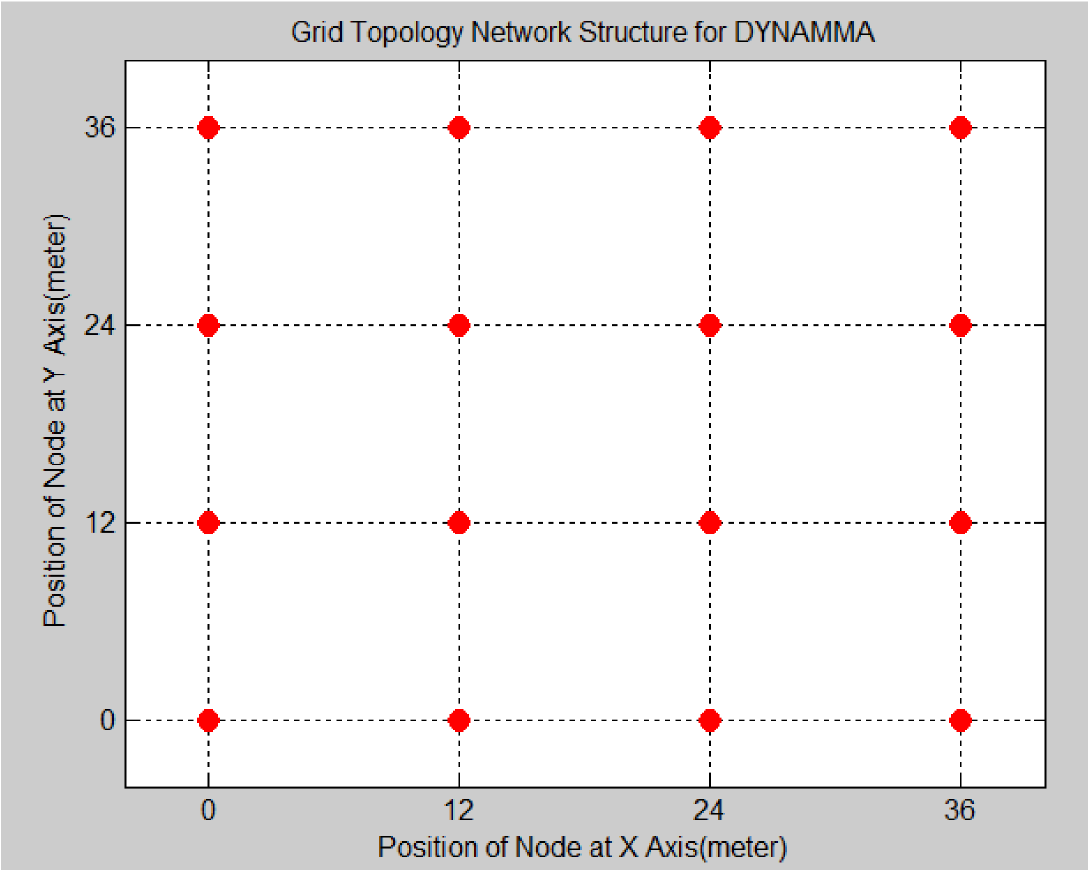


Figure 5.3. DYNAMMA Network Topology

The simulation has the following parameters to repeat DYNAMMA literature results;

- Transmission range of the nodes are 20 m.
- 4096 byte data packet transmission is done. That is approximately 638.125 µsec timeslot length for signaling slots and 1268.125 µsec for burst data slots and a DYNAMMA super frame consists 238 burst slots, 16 base slots, and 16 signaling slots.
- Simulations run for 100000 base slots approximately.
- There are 10 different packet generation intervals which have mean inter arrival times as 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 milliseconds.

TRAMA protocol is compared with DYNAMMA in literature and parameters of TRAMA is optimized for this study. TRAMA specialized parameters are as follow:

- SCHEDULE_INTERVAL is 100 transmission slots.
- 96 byte signaling packet is used. That is approximately 28.25 µsec signaling timeslot length.

- 4096 byte data transmission is done. That is approximately 630.75 µsec data timeslot length.
- Random access period is 10000 signaling slots (0.2825 sec) and repeats once in every 10000 transmission slots (6.3075 sec).

5.2.4 Simulation Setup of Protocols for Thesis Approach

As mentioned before, after getting the same results as the literature results, the simulations are done for twenty random topologies to see how the performance of the protocols will be affected. In addition, the simulations are repeated for different transmission ranges to see the effect of the multi-channel MAC layer structure. Lastly, a signal model, which has shadow fading component with free space loss, is considered to see the effect of physical layer at throughput performance.

Twenty random topologies are used to see the performance of protocols with different network topologies. Two examples of these topologies are demonstrated in Figure 5.4 and Figure 5.5. DYNAMMA, FLAMA, MFLAMA and TRAMA are compared with the simulation setup of DYNAMMA for these random networks.

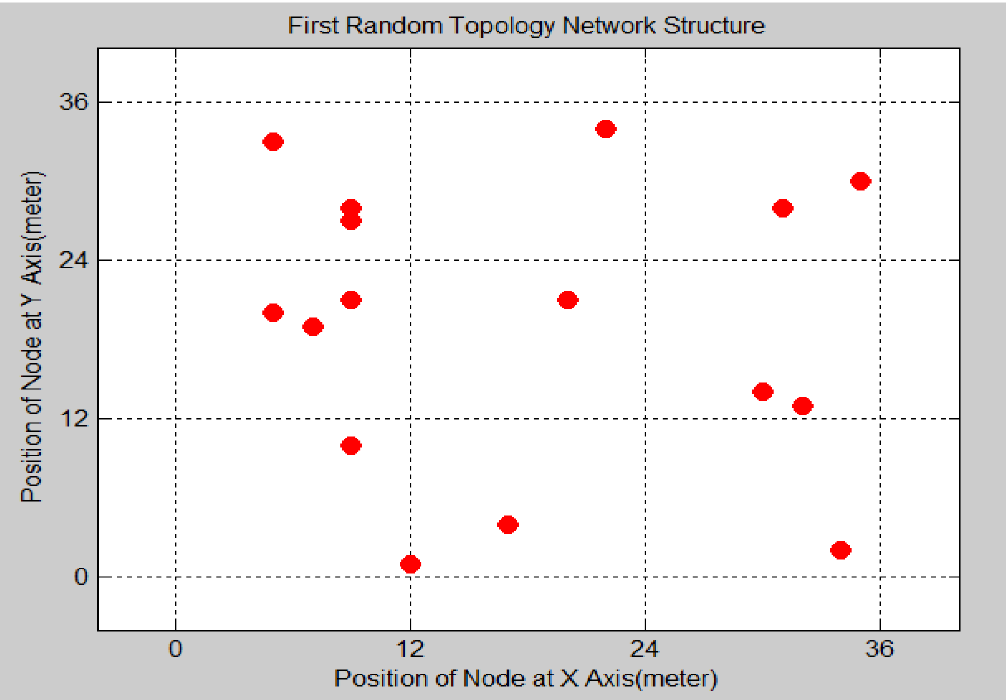


Figure 5.4. First Example of Random Network Topology

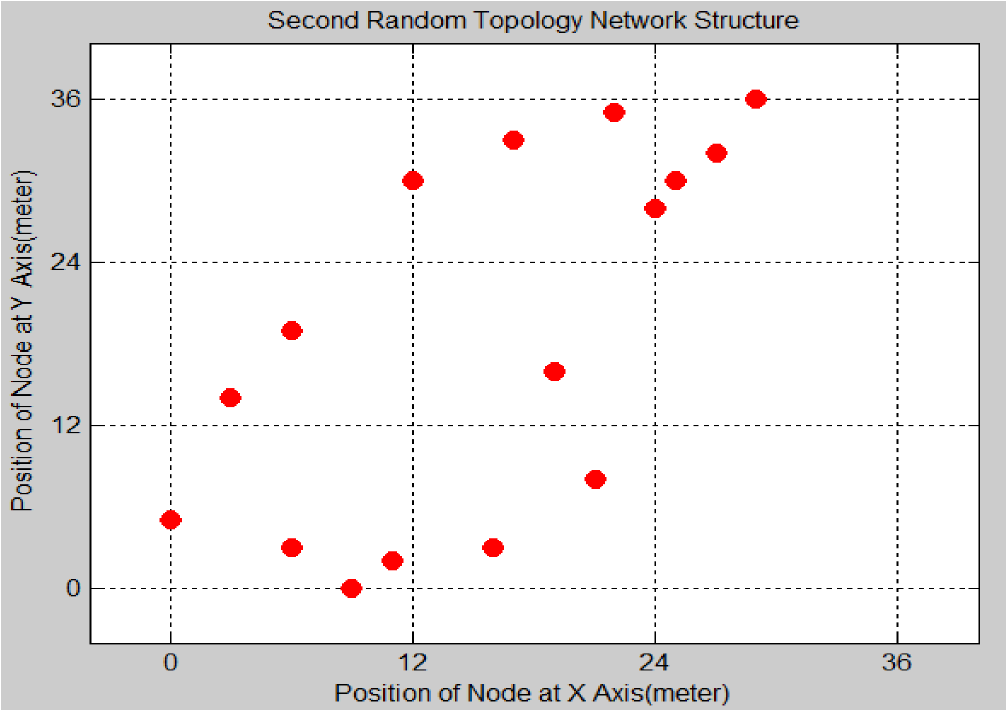


Figure 5.5. Second Example of Random Network Topology

The effect of the multi-channel MAC layer structure is investigated with DYNAMMA simulation setup and different transmission ranges which are shown in Table 5.1. FLAMA and MFLAMA are considered also with DYNAMMA simulation setup for this experiment.

Table 5.1: Transmission Ranges for Simulation

	Simulation-1	Simulation-2	Simulation-3
Transmission Range	20 meter	15 meter	35 meter

As the final experiment, a signal model is considered to see the effect of physical layer at throughput performance. This signal model contains a shadow fading component. The received signal power, P_r, is calculated as follows in Equation 5.1:

$$P_r = P_T - P_{fs} + X \qquad (5.1)$$

where P_T is transmitter signal power, P_{fs} is free space path loss and X is a random variable which is taken as shadow fading component. The random variable, X, is modeled as a lognormal random variable with zero mean and 4 dB standard deviation. Free space path loss, P_{fs}, is calculated from Friis Transmission Formula which is seen in Equation 5.2 [34]. G_t and G_r are antenna gain and these values are taken as 1. λ is the wavelength, ratio of speed of light and frequency. Frequency is set to 3.1 GHz which is taken from the literature and d is the distance between transmitter and receiver. This experiment has been done only for grid topology and two different distances exist that are equal to 12 and 18 meters in the grid topology.

$$P_{fs} = G_t \, G_r (\frac{\lambda}{4\pi d})^2 \tag{5.2}$$

When the numerical values of the Equation 5.1 are used as in literature and P_T is taken also from literature as -13.5 dBm, the new equation in dB is in Equation 5.3:

$$P_r = P_T - 42.26 + 20\log d + X_\sigma \tag{5.3}$$

Receiver threshold is taken as -81.1 dBm which is the threshold of the UWB short-range radio in the experiment . If the Received Signal Strength (RSS) is weaker than this threshold, the packet will be thought as dropped; otherwise, if the RSS is stronger than this value, the packet will be accounted successfully received. Only percentage received metric is calculated for the signal model experiment.

5.3 COMPARISON OF RESULTS WITH LITERATURE RESULTS

The first goal is to get the same results with the literature results to be sure that the simulation setup is correct in this research. The simulations had been done with Qualnet network simulator program in literature [35]. An event based time scheduled simulation program is written with C++ programing language on Windows operating system for this thesis study. Some libraries of Windows operating system are used to obtain one millisecond process interval to make simulations more sensitive about time slot lengths. The algorithm of the protocols implemented with this C++ simulation program.

5.3.1 Comparison of TRAMA

The metrics are average packet delivery ratio, percentage sleep time, average packet delay, and percentage sleep interval duration for TRAMA. These metric results had been studied for unicast and broadcast transmission in literature. Simulation results and literature results are almost same as seen in Figure 5.6, Figure 5.7, and Figure 5.8.

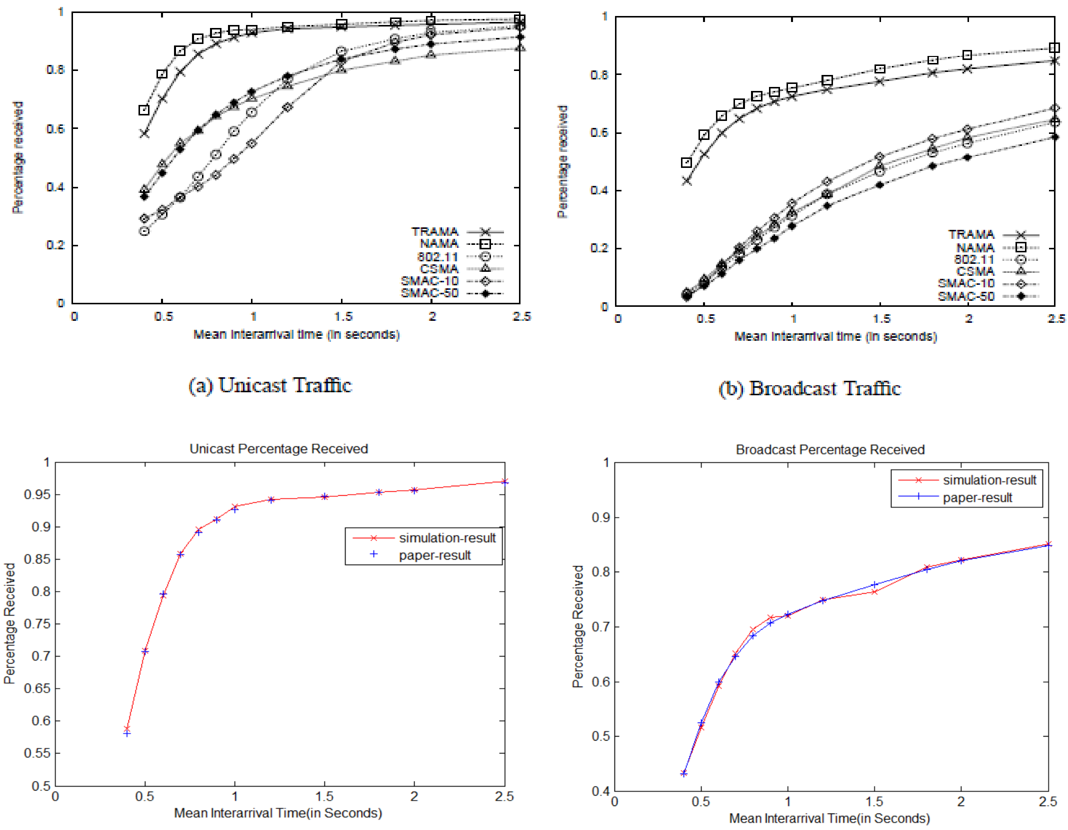
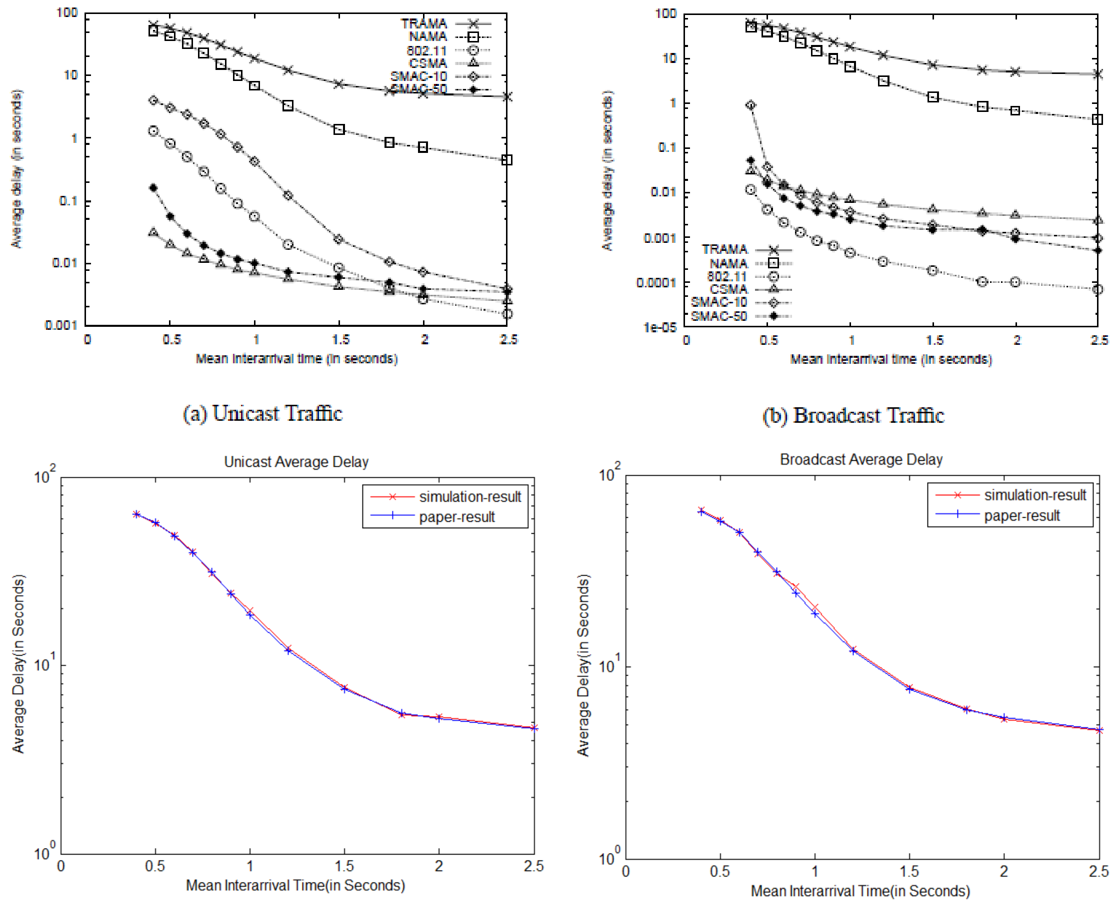


Figure 5.6. TRAMA Average Packet Delivery Ratio Comparison

Throughput of the system can be seen in Figure 5.6. Unicast traffic has better performance than broadcast traffic, since the packets must be delivered to all one hop neighbor nodes in broadcast traffic. It is also seen that the throughput increases when packet generation duration decreases. Because, less packets arrive to the nodes and queue buffer load decreases.



(a) Unicast Traffic

(b) Broadcast Traffic

Figure 5.7. TRAMA Average Packet Delay Comparison

Average delay of the system can be seen in Figure 5.7. Unicast traffic has close performance with broadcast traffic, since average delay calculations are done over the packets which received by receiver nodes successfully. Queue buffer load decreases when packet generation decreases and that leads less delays in the system.

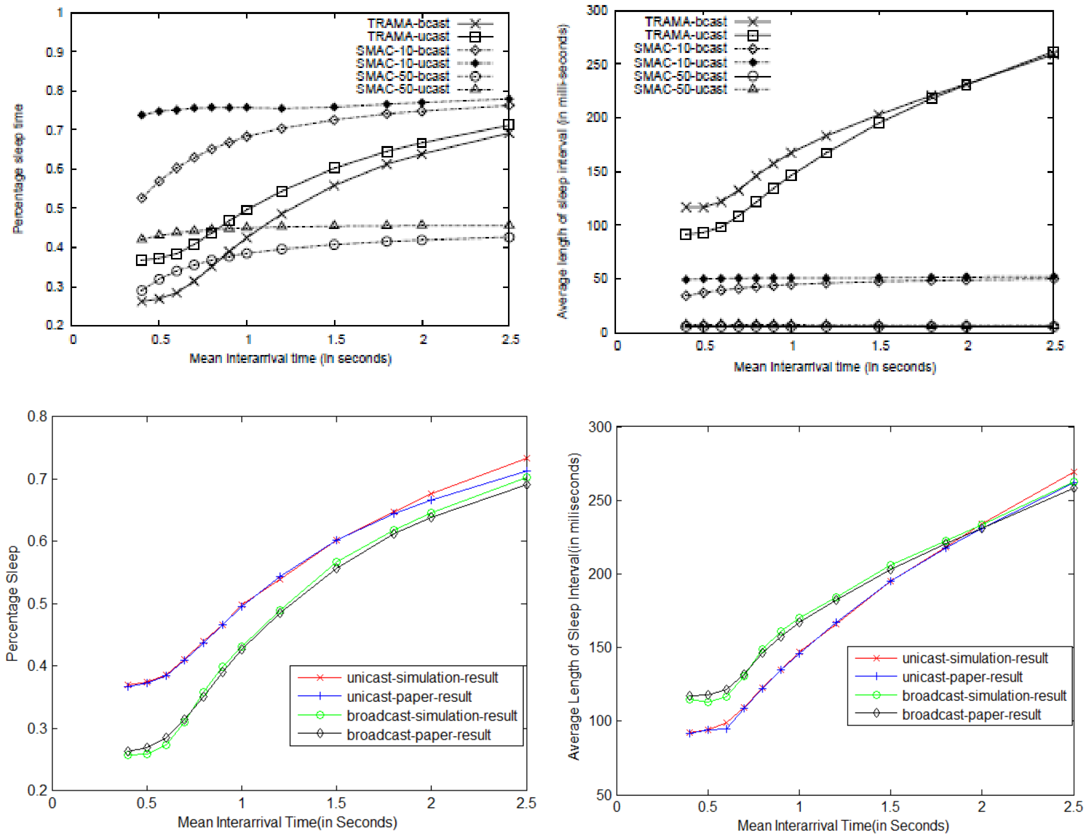


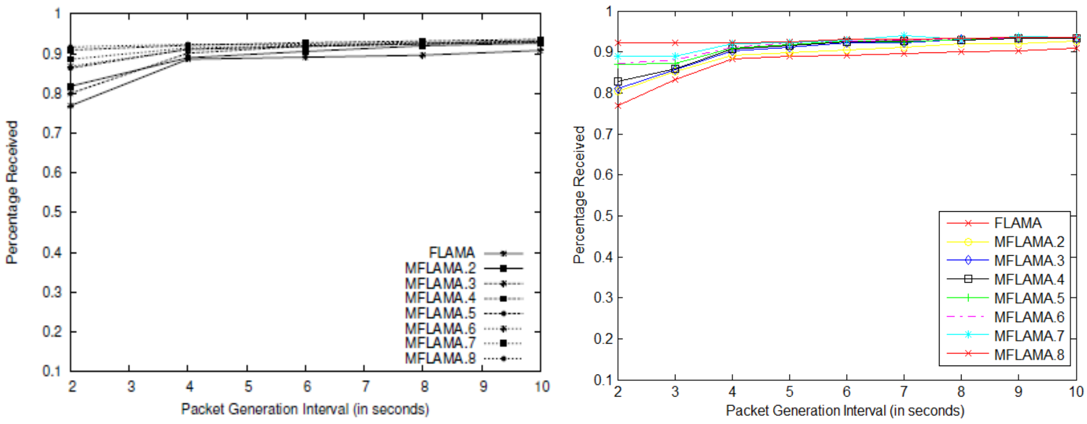
Figure 5.8. TRAMA Energy Efficiency Comparison

Energy efficiency parameters are seen in Figure 5.8. Nodes are idle when they are neither transmitter nor receiver in TRAMA protocol. As seen in Figure 5.8, unicast traffic sleep rate is higher than broadcast traffic sleep rate, since broadcast traffic has more receiver nodes when a node transmitting information to its one hop neighbors. If less packets are generated in system, the sleeping times will increase and that will provide more energy efficiency.

These results show that the simulation setup works well for TRAMA and this setup can be used in the other experiments like random topologies or different transmission ranges.

5.3.2 Comparison of FLAMA and MFLAMA

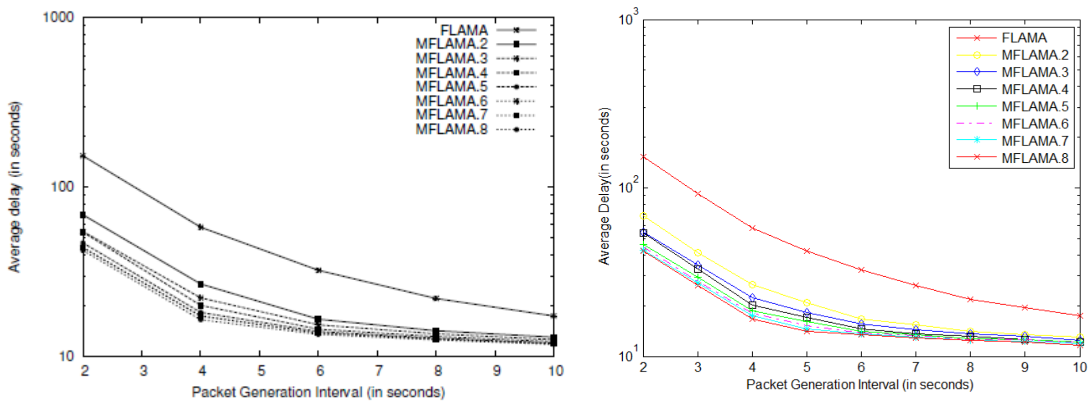
The metrics are average packet delivery ratio, average packet delay, and percentage sleep time for FLAMA. Simulation results and literature results are almost same as seen in Figure 5.9, Figure 5.10, and Figure 5.11.



(a) Paper Result (b) Simulation Result

Figure 5.9. FLAMA Average Packet Delay Comparison

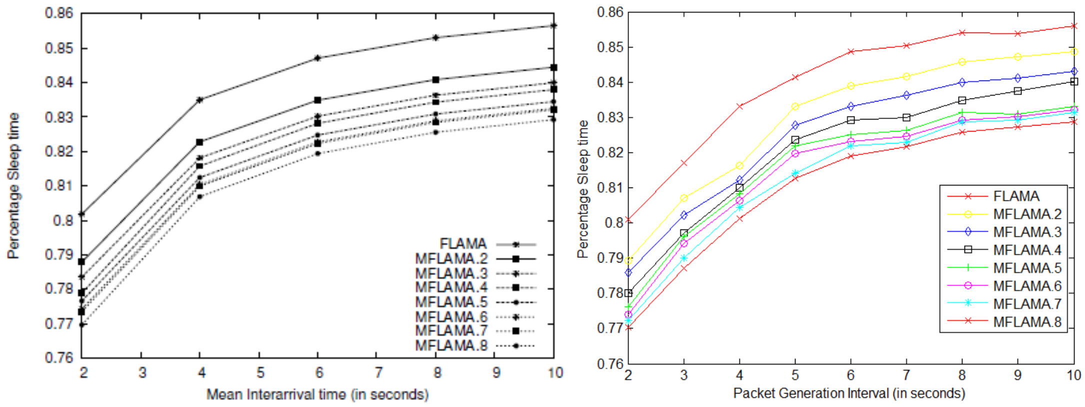
Throughput of the system can be seen for different channel numbers in Figure 5.9. It is seen that when number of orthogonal channels increases, the throughput increases too. The reason of this result is that using the multi-channel structure provides more than one transmission at the same time.



(a) Paper Result (b) Simulation Result

Figure 5.10. FLAMA Average Packet Delay Comparison

Average delay of the system can be seen for single channel and the multi-channel structure in Figure 5.10. It is seen that the multi-channel structure leads to less packet delays in queue by providing more than one transmission process in same time slot.



(a) Paper Result (b) Simulation Result

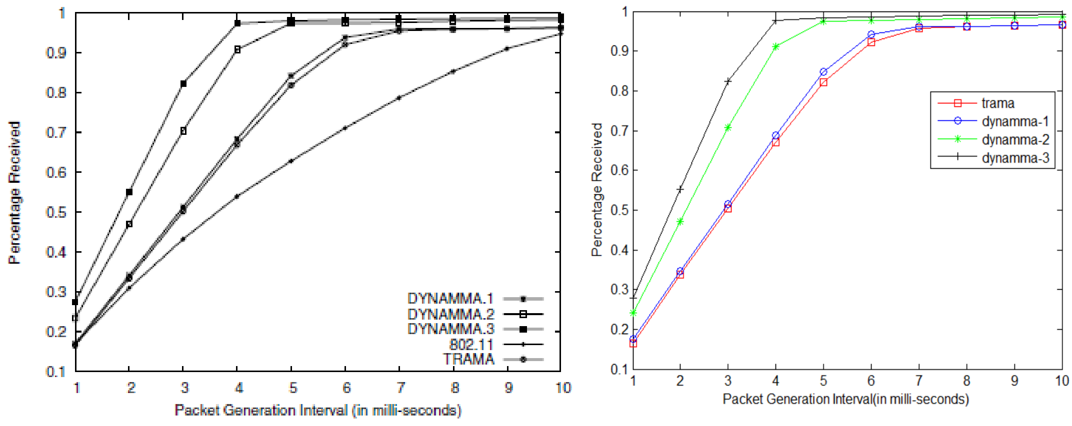
Figure 5.11. FLAMA Energy Efficiency Comparison

Percentage sleep time of nodes in the system is seen in Figure 5.11. This parameter shows the energy efficiency of FLAMA with different channel number usage. As it is seen, the sleep time decreases while the channel numbers are increasing. The energy consumption increases for the multi-channel structure since the sleep time decreases. The reason of this result is about the usage of nodes at the same time to communicate with multiple channels.

The results of FLAMA and MFLAMA show that simulation setup is working well and this simulation setup for FLAMA and MFLAMA can be used in the other experiment scenarios.

5.3.3 Comparison of DYNAMMA

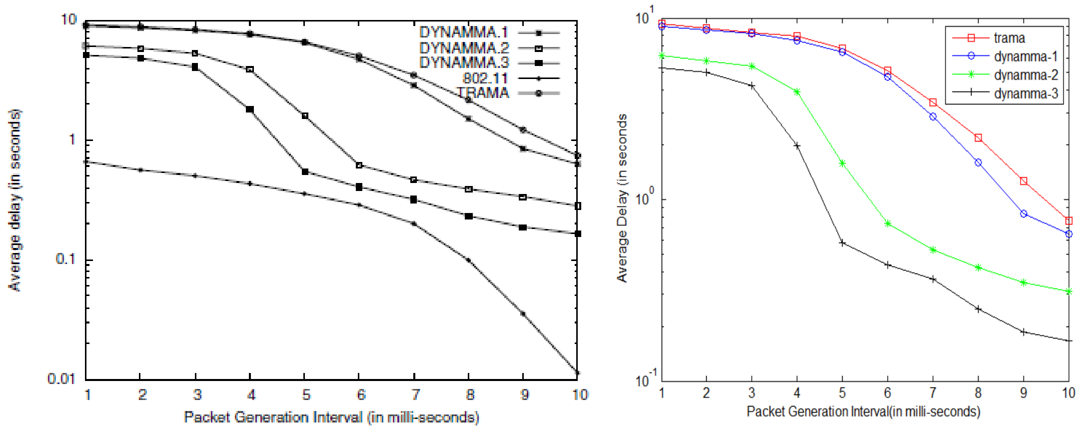
The metrics are average packet delivery ratio, average packet delay, and percentage sleep time for DYNAMMA. The simulation results and the literature results are almost same as seen in Figure 5.12, Figure 5.13, and Figure 5.14.



(a) Paper Result (b) Simulation Result

Figure 5.12. DYNAMMA Average Packet Delivery Ratio Comparison

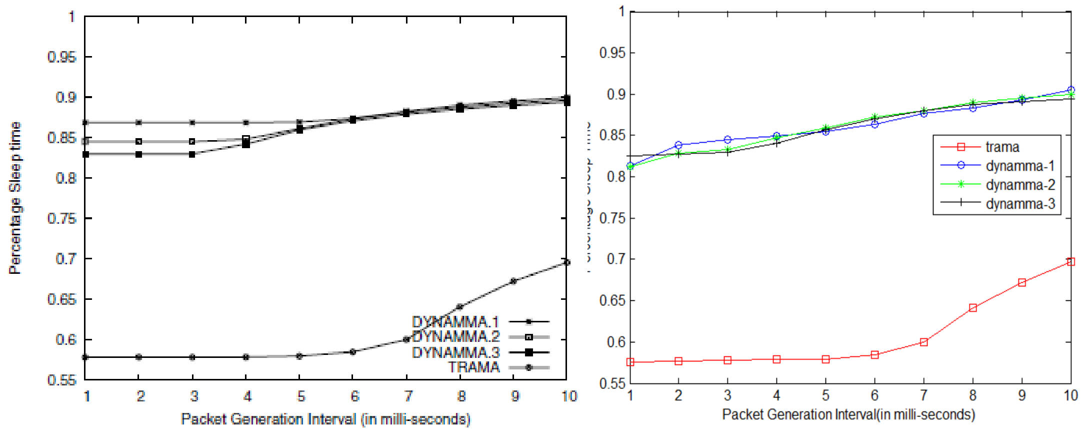
Throughput of the system can be seen for different channel numbers of DYNAMMA and TRAMA in Figure 5.12. Results of TRAMA and single channel DYNAMMA are close to each other. However, the multi-channel DYNAMMA structure has significantly good results over single channel DYNAMMA and TRAMA. This shows that using the multi-channel structure provides high throughput.



(a) Paper Result (b) Simulation Result

Figure 5.13. DYNAMMA Average Packet Delay Comparison

Average delay of the system can be seen for different channel numbers of DYNAMMA and TRAMA in Figure 5.13. Single-channel DYNAMMA and TRAMA have similar results and it is seen that the multi-channel DYNAMMA structure provides less queue delays because of more than one communication process at the same time slot.



(a) Paper Result (b) Simulation Result

Figure 5.14. DYNAMMA Energy Efficiency Comparison

Percentage sleep time of nodes in the system is seen in Figure 5.14. This parameter is used for energy efficiency. TRAMA and single channel DYNAMMA structure have significantly difference for sleep time. This difference is basicly about the protocols working scheme. In addition, the single channel structure and the multi-channel structure have close sleeping times. Superframe structure of DYNAMMA leads this result and the multi-channel structure has a disadvantage for energy efficiency.

These results show that simulation setup works correct for DYNAMMA. This simulation setup can be used for different experiments.

5.4 SIMULATION RESULTS

5.4.1 Results for Different Topologies

In this part of the study, the intention is to see the performance of TRAMA, FLAMA and DYNAMMA together with different network topologies. DYNAMMA and TRAMA had results together with the same simulation setup, which are seen in Figure 5.12, Figure 5.13, and Figure 5.14. Firstly, FLAMA is investigated with these two protocols together with the grid topology, which is seen in Figure 5.3. After that, TRAMA, FLAMA, and DYNAMMA are investigated together for twenty different random network topologies. Two examples of these random topologies are seen in Figure 5.4 and Figure 5.5. Finally, throughput, average packet delay, and percentage sleep metrics are examined for three protocols with these different network topologies. Averages of the results of random topologies are calculated and plotted in this research.

Results of the percentage received metric are illustrated in Figure 5.15 and Figure 5.16 to demonstrate the throughput performance of the protocols with grid topology and different random topologies. The outcomes of the percentage sleep time metric are given in Figure 5.17 and Figure 5.18 to investigate the energy efficiency of the protocols. The results of packet delay duration, which is related that how many seconds a packet waits in queue during transmission process, are shown in Figure 5.19 and Figure 5.20.

The throughput performances of these protocols are shown in Figure 5.15 for the grid network topology, which can be seen in Figure 5.3. As it is seen in the figure, performance of TRAMA, performance of one channel DYNAMMA, and performance of one channel FLAMA are similar to each other. The multi-channel effect for FLAMA is less than the multi-channel effect for DYNAMMA. It is about the structure of time slot organization. FLAMA is organized slot by slot and DYNAMMA has a superframe structure. That leads DYNAMMA has better results than FLAMA with the multi-channel structure. It is also seen if the packet generation decreases, the performances of the protocols will not affect so much and the similar results are occurred for the all protocols.

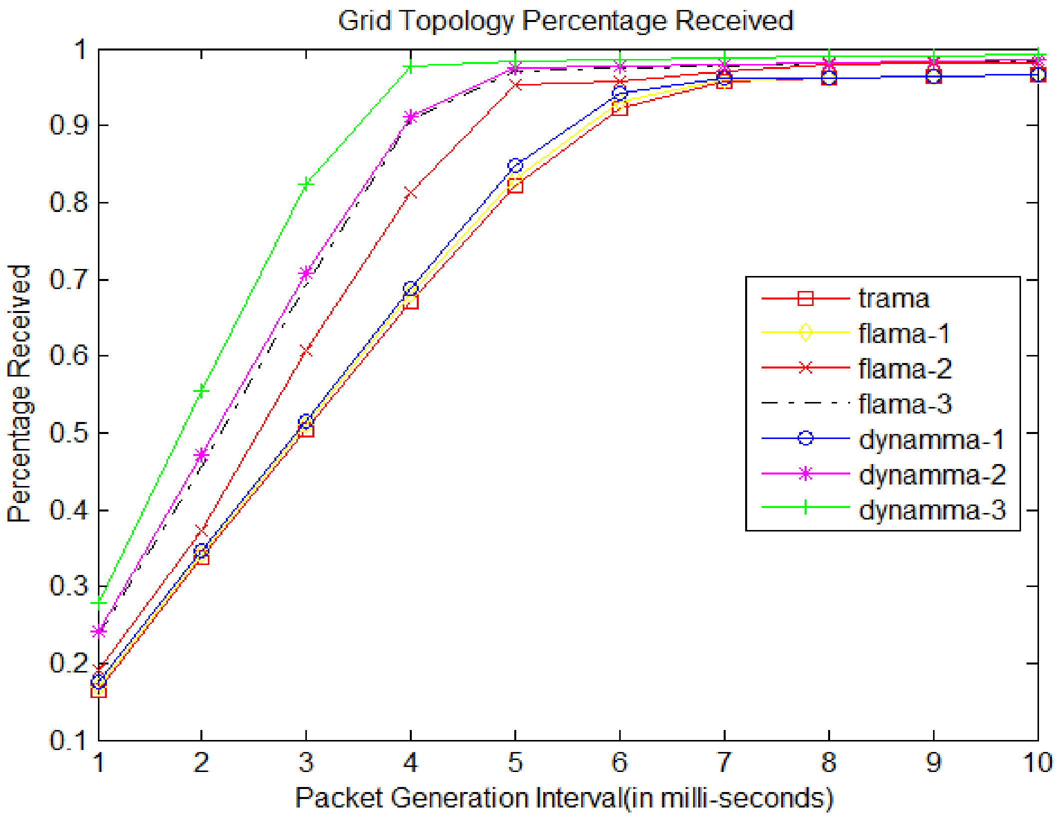


Figure 5.15. Grid Topology Percentage Received

The average results of the percentage received rates are shown in Figure 5.16 for the twenty random network topologies which the samples of topologies can be seen in Figure 5.4 and Figure 5.5. Throughput results are similar to grid topology for different random network topologies. As it is seen in Figure 5.15 and Figure 5.16 the plot regimes do not change much. Throughput performance results of the protocols show that these protocols can be considered to use for any network topology. If mobile networks were accepted as time varying random topologies, TRAMA, FLAMA and DYNAMMA would be thought to be able to work on mobile networks with these results.

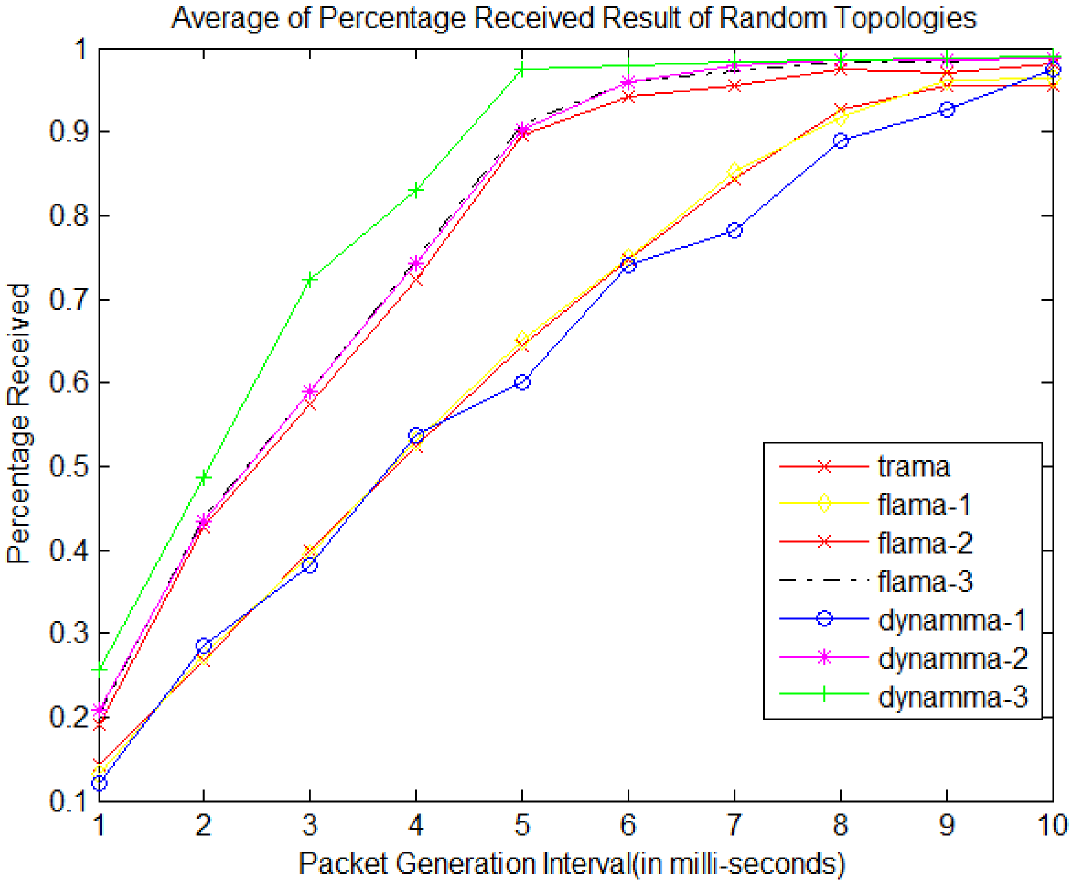


Figure 5.16. Average of Percentage Received Result of Random Topologies

The result of the percentage sleep rate of these protocols are shown in Figure 5.17 for the grid network topology which can be seen in Figure 5.3. This metric is about the energy efficiency and FLAMA has similar results with DYNAMMA. Results of TRAMA are worse than these two protocols. It is about the structure of time slot organization and operating way of the protocols. TRAMA renews itself periodically for every SCHEDULE_INTERVAL which is a parameter of TRAMA. All nodes should operate in the network to get the traffic and the scheduling information because of the renew operation. This causes much energy consumption for TRAMA compared to FLAMA and DYNAMMA.

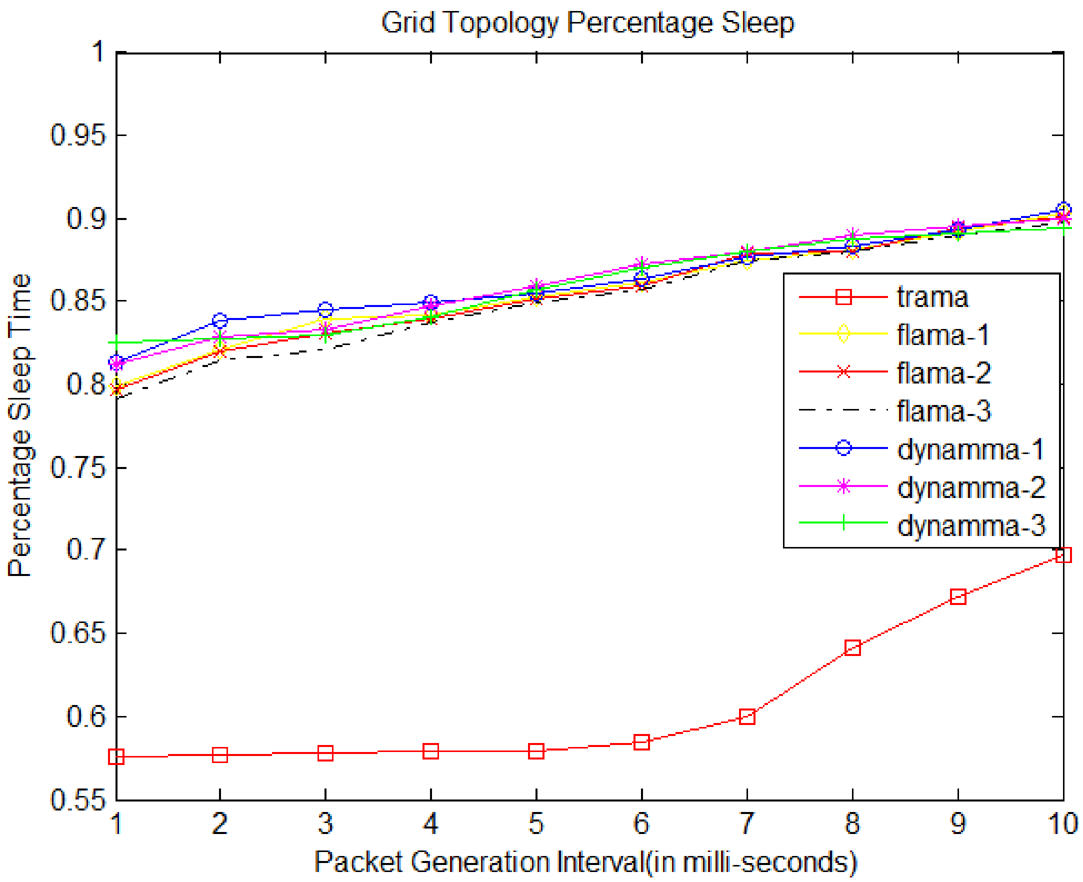


Figure 5.17. Grid Topology Percentage Sleep Time

The energy efficiency metric results of the protocols are shown in Figure 5.18 for the twenty random network topologies which two samples of the topologies can be seen in Figure 5.4 and Figure 5.5. Grid topology and random topologies have similar outcomes for percentage sleep time. Graphics are similar for the grid topology and the random topologies as seen in Figure 5.17 and Figure 5.18.

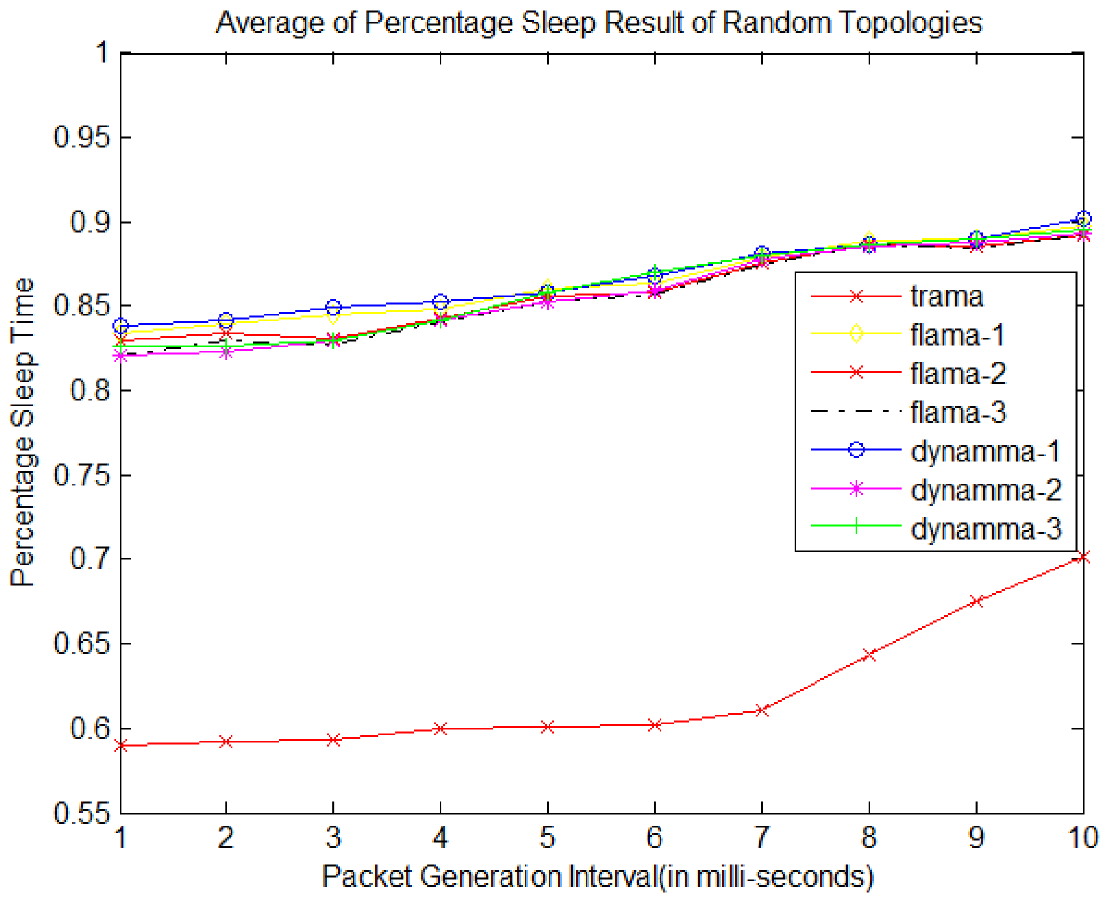


Figure 5.18. Average of Percentage Received Result of Random Topologies

Average delay of the transmitted packet results are seen in Figure 5.19 for grid topology. Effect of the multi-channel structure usage can be seen with this result. Packets will be delivered to the receiver nodes at the same time when protocols use the multi-channel structure. TRAMA, single channel FLAMA, and single channel DYNAMMA have similar results as seen in figure.

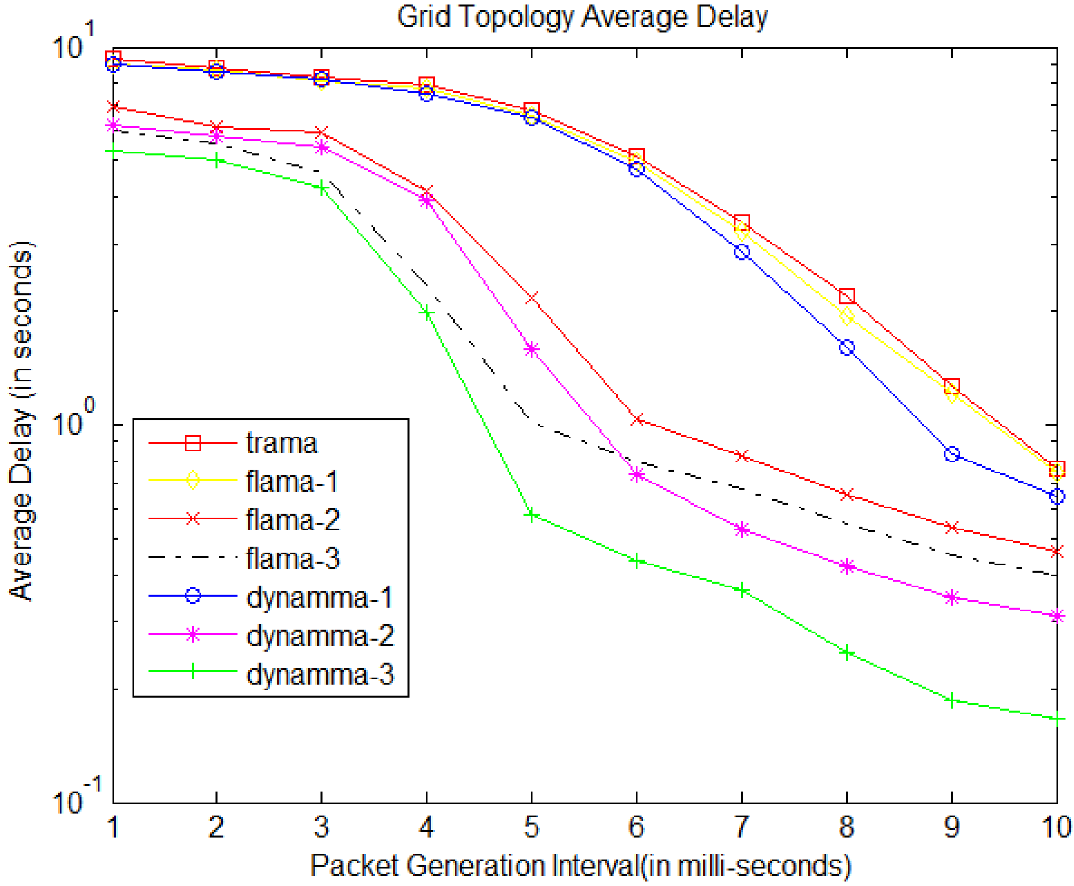


Figure 5.19. Grid Topology Average Delay

Figure 5.20 shows the waiting time of a packet in queue for the three protocols for the twenty different random network topologies. The outcome of the experiment is similar for grid and random network topologies.

It is investigated that the performance of TRAMA, FLAMA, and DYNAMMA for three different metrics that are percentage received rate, average packet delay and percentage sleep time. These results show that these three protocols can be used with different network topologies. These results also lead these protocols may be considered for mobile networks. Since the protocols have similar results with both grid topology and random topologies, it is possible that these protocols can be used in the mobile networks that may be thought as random topologies varying with time.

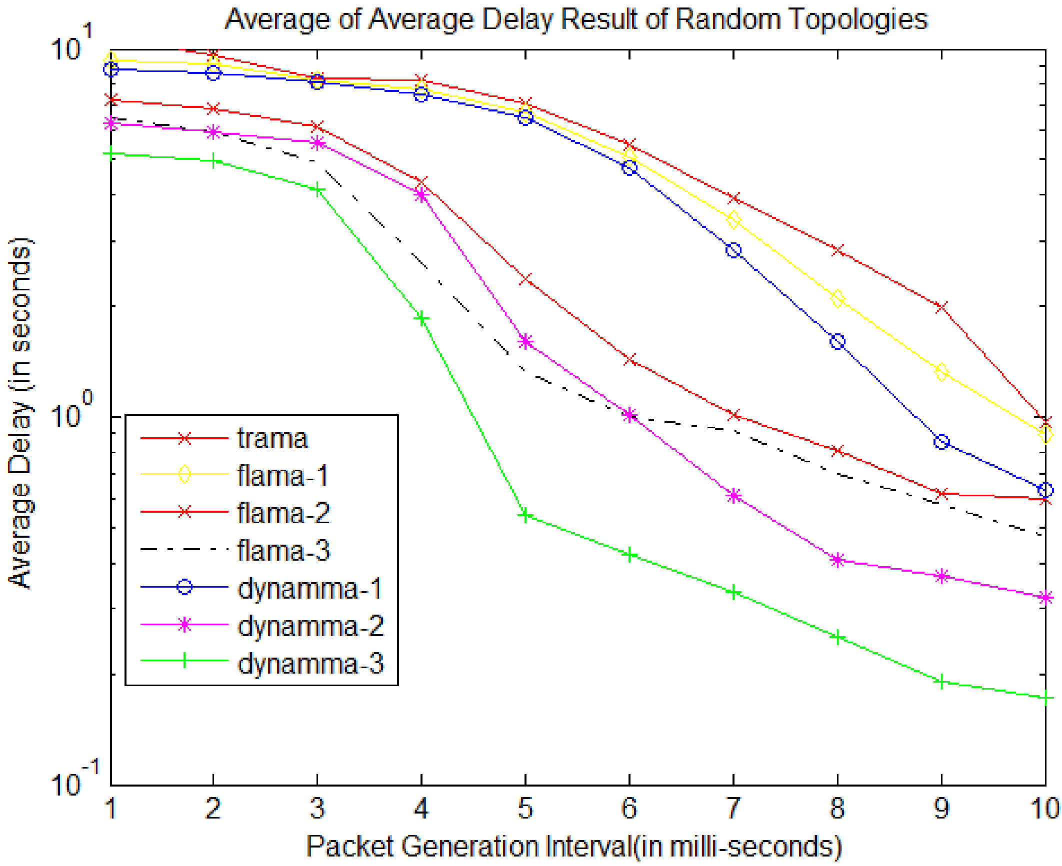


Figure 5.20. Average of Average Delay Result of Random Topologies

5.4.2 Results for Different Transmission Ranges

Performances of the protocols are investigated for different network topologies in section 5.4.1. The purpose is to see the performance of the protocols for another different scenario in this section. The changing transmission ranges of the nodes cause that one hop and two hop neighbors of the nodes will be different in this experiment.

20-meter transmission range had been used in the all experiments in this research up to this section. However, 15 meter and 35 meter transmission ranges will be used for this experiment to compare results with 20 meter transmission range. The nodes will have less one hop and two hop neighbors when arranging transmission range to 15-meter. In the opposite, number of one hop and two hop neighbors of a node will increase when 35-meter transmission range is selected for the experiment. This leads that winning probability of a timeslot for a node will change. When a node has less one hop and two hop neighbors this probability will increase and it will decrease in vice versa situation. The goal is to see the multi-channel effect in this experiment. It is expected that the multi-channel protocols, FLAMA and DYNAMMA, will have a good performance in 35-meter transmission range experiment. Because, nodes have more one hop and two hop neighbors and a node has a low winning probability to transmit its packet for this study and multi-channel structure may provide more than one transmission process in network.

The percentage received rate, throughput, is investigated in Table 5.2. The results are getting worse when transmission range increases especially for TRAMA, single channel FLAMA, and single channel DYNAMMA. Since each node competes with much one-hop neighbor nodes, the percentage received rate decreases for this experiment. The multi-channel FLAMA and DYNAMMA have better outcomes when transmission range increases compared to TRAMA and one channel FLAMA and one channel DYNAMMA. This result shows that importance of the multi-channel structure usage and in which condition the multi-channel protocols should be used.

Energy efficiency metric, percentage sleep time, is demonstrated in Table 5.3. Percentage sleep time is increasing while transmission range is decreasing. Because the nodes have less one hop neighbor nodes when transmission range is short and the nodes are more active for communication. Since there are more time slots to send packets, the nodes are either transmitter or receiver. This situation brings more energy consumption and less sleep time for nodes during experiment.

Average delay of a packet in the queue is examined in Table 5.4. The delay times are increasing when the transmission range increases. Since the nodes have less one hop neighbor nodes in short transmission ranges, the nodes have more active time slots for communication and the packets wait less time in the queue so this feature brings less delay time. In the opposite, especially for TRAMA, single channel

FLAMA, and single channel DYNAMMA have worse results and that shows benefits of multi-channel for queue delay metric.

Table 5.2: Percentage Received for Different Transmission Ranges

Protocol	**15 meter(*)**	**20 meter(*)**	**35 meter(*)**
TRAMA (3 ms)(**)	0.5488	0.5048	0.2901
FLAMA-1 (3 ms) (**)	0.5613	0.5113	0.3064
FLAMA-2 (3 ms) (**)	0.6039	0.6061	0.4972
FLAMA-3 (3 ms) (**)	0.7113	0.6931	0.6332
DYNAMMA-1 (3 ms) (**)	0.5933	0.5151	0.3132
DYNAMMA-2 (3 ms) (**)	0.7047	0.7069	0.6107
DYNAMMA-3 (3 ms) (**)	0.8238	0.8247	0.7308
Protocol	**15 meter(*)**	**20 meter(*)**	**35 meter(*)**
TRAMA (6 ms) (**)	0.9789	0.9213	0.5796
FLAMA-1 (6 ms) (**)	0.9801	0.9321	0.5921
FLAMA-2 (6 ms) (**)	0.9813	0.9577	0.8785
FLAMA-3 (6 ms) (**)	0.9856	0.9748	0.9645
DYNAMMA-1 (6 ms) (**)	0.9848	0.9420	0.6075
DYNAMMA-2 (6 ms) (**)	0.9861	0.9771	0.9699
DYNAMMA-3 (6 ms) (**)	0.9865	0.9855	0.9733
Protocol	**15 meter(*)**	**20 meter(*)**	**35 meter(*)**
TRAMA (9 ms) (**)	0.9968	0.9634	0.8741
FLAMA-1 (9 ms) (**)	0.9982	0.9641	0.9416
FLAMA-2 (9 ms) (**)	0.9979	0.9819	0.9791
FLAMA-3 (9 ms) (**)	0.9991	0.9832	0.9853
DYNAMMA-1 (9 ms) (**)	0.9998	0.9649	0.9506
DYNAMMA-2 (9 ms) (**)	0.9991	0.9843	0.9824
DYNAMMA-3 (9 ms) (**)	0.9997	0.9910	0.9896

* : Results are expressed in percentage rate.

** : 3,6, and 9 ms specify the packet generation interval times in milliseconds.

Table 5.3: Percentage Sleep Time for Different Transmission Ranges

Protocol	15 meter(*)	20 meter(*)	35 meter(*)
TRAMA (3 ms) (**)	0.5602	0.5784	0.6104
FLAMA-1 (3 ms) (**)	0.8178	0.8391	0.8419
FLAMA-2 (3 ms) (**)	0.8067	0.8307	0.8371
FLAMA-3 (3 ms) (**)	0.8013	0.8215	0.8294
DYNAMMA-1 (3 ms) (**)	0.8201	0.8447	0.8597
DYNAMMA-2 (3 ms) (**)	0.8187	0.8331	0.8455
DYNAMMA-3 (3 ms) (**)	0.8153	0.8295	0.8374
Protocol	**15 meter(*)**	**20 meter(*)**	**35 meter(*)**
TRAMA (6 ms) (**)	0.5694	0.5843	0.6232
FLAMA-1 (6 ms) (**)	0.8397	0.8619	0.8671
FLAMA-2 (6 ms) (**)	0.8316	0.8589	0.8593
FLAMA-3 (6 ms) (**)	0.8259	0.8573	0.8584
DYNAMMA-1 (6 ms) (**)	0.8414	0.8641	0.8791
DYNAMMA-2 (6 ms) (**)	0.8411	0.8723	0.8664
DYNAMMA-3 (6 ms) (**)	0.8397	0.8703	0.8583
Protocol	**15 meter(*)**	**20 meter(*)**	**35 meter(*)**
TRAMA (9 ms) (**)	0.6324	0.6723	0.7009
FLAMA-1 (9 ms) (**)	0.8798	0.8926	0.8993
FLAMA-2 (9 ms) (**)	0.8703	0.8942	0.8962
FLAMA-3 (9 ms) (**)	0.8637	0.8897	0.8916
DYNAMMA-1 (9 ms) (**)	0.8817	0.8933	0.8961
DYNAMMA-2 (9 ms) (**)	0.8821	0.8958	0.8894
DYNAMMA-3 (9 ms) (**)	0.8796	0.8913	0.8857

* : Results are expressed in percentage rate.

** : 3,6, and 9 ms specify the packet generation interval times in milliseconds.

Table 5.4: Average Delay for Different Transmission Ranges

Protocol	15 meter(*)	20 meter(*)	35 meter(*)
TRAMA (3 ms) (**)	7.7256	8.3172	9.1722
FLAMA-1 (3 ms) (**)	7.4187	8.1187	8.9187
FLAMA-2 (3 ms) (**)	5.9529	5.9152	6.4152
FLAMA-3 (3 ms) (**)	4.7135	4.6352	5.0352
DYNAMMA-1 (3 ms) (**)	6.2951	8.1887	8.8711
DYNAMMA-2 (3 ms) (**)	5.4371	5.4565	5.7431
DYNAMMA-3 (3 ms) (**)	4.3269	4.2565	4.6223
Protocol	**15 meter(*)**	**20 meter(*)**	**35 meter(*)**
TRAMA (6 ms) (**)	5.0013	5.1195	6.5364
FLAMA-1 (6 ms) (**)	4.7804	4.9784	6.1184
FLAMA-2 (6 ms) (**)	0.9971	1.0351	1.6351
FLAMA-3 (6 ms) (**)	0.7556	0.7951	1.0951
DYNAMMA-1 (6 ms) (**)	4.3663	4.7363	6.1317
DYNAMMA-2 (6 ms) (**)	0.7946	0.7351	1.0158
DYNAMMA-3 (6 ms) (**)	0.5197	0.4351	0.7363
Protocol	**15 meter(*)**	**20 meter(*)**	**35 meter(*)**
TRAMA (9 ms) (**)	1.0264	1.2615	2.1513
FLAMA-1 (9 ms) (**)	0.9674	1.2131	1.3151
FLAMA-2 (9 ms) (**)	0.5189	0.5351	0.5745
FLAMA-3 (9 ms) (**)	0.4443	0.4513	0.5139
DYNAMMA-1 (9 ms) (**)	0.6928	0.8387	1.7463
DYNAMMA-2 (9 ms) (**)	0.3651	0.3501	0.3761
DYNAMMA-3 (9 ms) (**)	0.1908	0.1861	0.2013

* : Results are expressed in seconds.

** : 3,6, and 9 ms specify the packet generation interval times in milliseconds.

The multi-channel benefits can be seen by examining these experiment outcomes. The nodes have more one hop and two hop neighbors with 35-meter transmission range so the nodes should compete with more nodes to send packet in a time slot. The efficiency and performance may be increased by using the multi-channel structure. Since FLAMA and DYNAMMA have the multi-channel specification, these two protocols are better than TRAMA for this scenario.

5.4.3 Results for Shadow Fading Signal Model

Free space path loss is the only attenuator of the transmitted signal in the previous experiments because of the assumption. A shadow fading component which is mentioned in Section 5.2.4 is added to the transmitted signal in this experiment. The goal is to see how the throughput performance of the protocols will be effected with such a signal model.

The multi-channel structure is used for FLAMA and DYNAMMA again in this experiment. It is assumed that there is no interference between the multi channels. There is only free space path loss and shadow fading in each channel by assumption.

The simulations are done for grid topology in this experiment. The simulation results are seen in Figure 5.21, Figure 5.22, and Figure 5.23 to compare protocol performances for fading and no fading scenarios. The plot regimes are similar with shadow fading model and without shadow fading model as seen in figures. The performances of the each protocol with fading and no fading situation are compared for grid topology. Performance comparison of TRAMA is in Figure 5.21. FLAMA performance results can be seen in Figure 5.22. Results of performance for DYNAMMA is in Figure 5.23. Shadow fading component attenuates the received signal as seen in the figures below and this causes that the throughput performance decreases for the all protocols.

Especially, nodes are sensitive to shadow fading attenuation in the far distances between transmitter and receiver. So, the ratio of the received packets at these nodes is effected much. The throughput performance of near nodes does not changed much compared with far distances of nodes. As a result, overall performance of the protocols decreases when considered all network members.

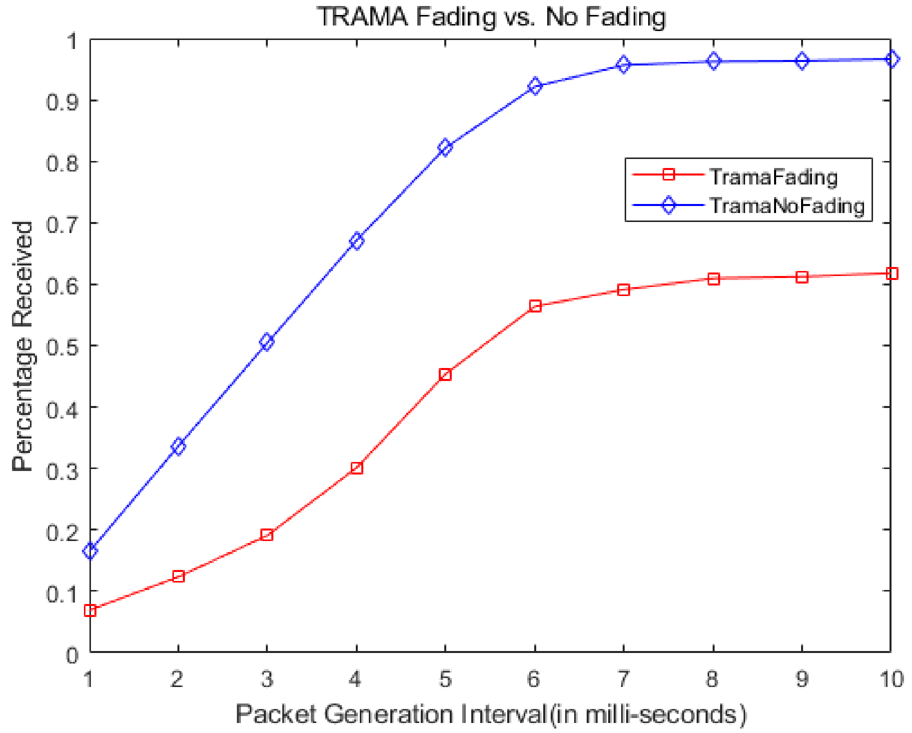


Figure 5.21. Grid Topology TRAMA Fading Vs. No Fading

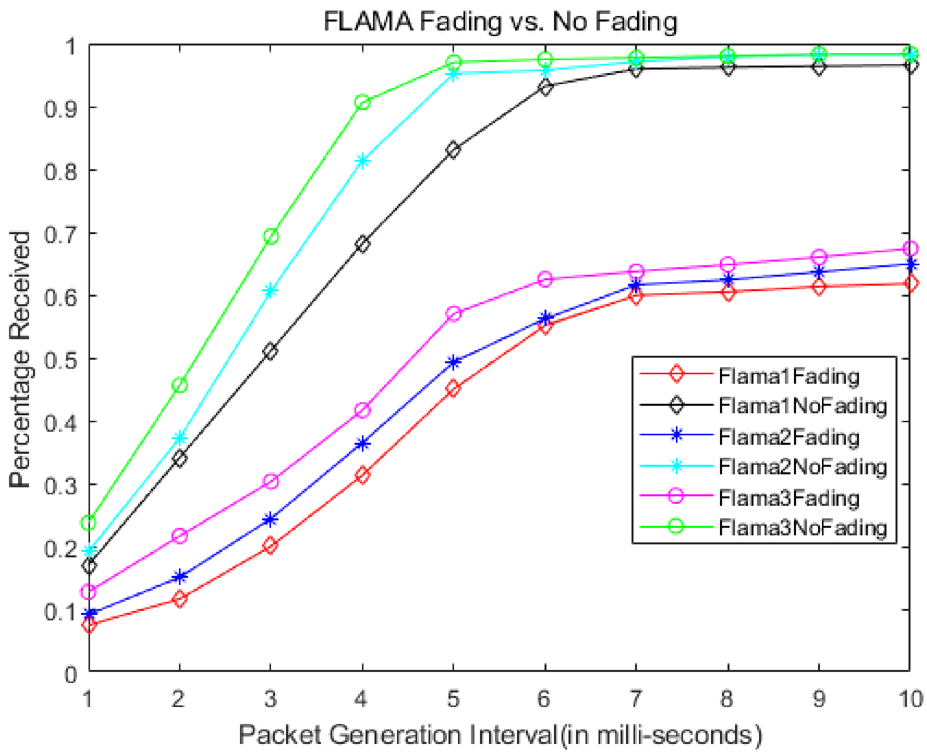


Figure 5.22. Grid Topology FLAMA Fading Vs. No Fading

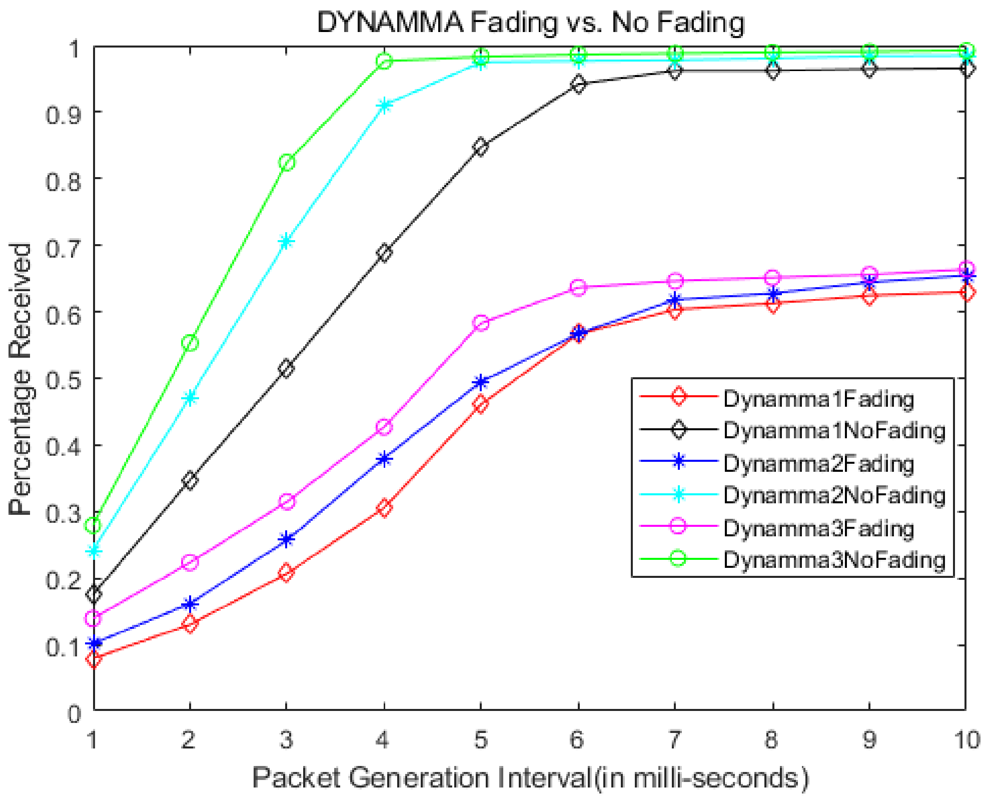


Figure 5.23. Grid Topology DYNAMMA Fading Vs. No Fading

CHAPTER 6

CONCLUSION AND FUTURE WORK

Power capacities of the devices are limited in wireless multi hop ad-hoc networks. In addition, when a battery of a device is drained, it is not usually possible to change it. The energy efficiency is an important issue for these networks due to these reasons. Schedule based energy efficient MAC layer protocols, TRAMA, FLAMA, and DYNAMMA, are evaluated for different scenarios in the thesis. A good MAC layer protocol should be able to handle common problems such as hidden terminal and exposed terminal problems. In addition, it should provide features such as good throughput and low packet delay features while obtaining energy efficiency.

First goal is to get the same literature results by building simulation setup and to make sure this simulation setup is correct. After that, three different scenarios, which are random network topologies, different simulation ranges, and shadow fading signal model are simulated for TRAMA, FLAMA, and DYNAMMA.

Another goal is to see the performance of the protocols with different topologies since only grid topology is used for the protocols in the literature. Twenty different random topologies are generated and the simulations are done over these random networks. Average of the results of random topologies is similar to grid topology structure. There are not big differences on the performance metrics and the regimes of the outcomes are very close to each other. Therefore, using these protocols is feasible in any other topologies.

In the second scenario, the purpose is to see the multi-channel effect in this research by using different transmission ranges. The neighborhood structure such as one-hop neighbor size and two-hop neighbor size will differ when the transmission range changes. Firstly, the transmission range is set shorter than the literature in the experiment. Although, TRAMA, single channel FLAMA, single channel

DYNAMMA have better throughput and less average packet delay than the literature, their percentage sleep, energy efficiency metric, is worse than literature. The nodes have less one-hop and two-hop neighbors in this structure. That leads better results for throughput and average packet delay especially for TRAMA, single channel FLAMA, and single channel DYNAMMA. On the other hand, having less one-hop and two-hop neighbors makes the nodes more active during the simulations and this comes with more power consumption and less sleep mode state. The transmission range compared to existing studies in literature is increased in the second experiment. That leads that each node will have more one-hop and two-hop neighbors. Since the size of neighborhood is increased, TRAMA, single channel FLAMA, and single channel DYNAMMA have worse results than literature from the throughput view. Energy efficiency metric, percentage sleep, is higher than literature for TRAMA, single channel FLAMA, and single channel DYNAMMA. Average delay parameter is close to the literature and there is not big difference for this metric. The multi-channel FLAMA and DYNAMMA have similar outcomes for this experiment for all metrics in this experiment. Benefit of the multi-channel structure occurs prominently at high transmission range experiment. The multi-channel FLAMA and DYNAMMA have close results to the literature results while TRAMA, single channel FLAMA, and single channel DYNAMMA have bad outcomes for this experiment.

At the last scenario, it is considered that there is a shadow fading effect on the received signal except free space path loss. Only the throughput performance is investigated with this experiment for grid topology. The outcome of the study is worse than the signal model, which has only free space path loss. The nodes fail very much especially at the far distances between transmitter and receiver.

The nodes in network are static in this research. Mobility effect on the performance of protocols can be investigated in the future. Another study can be the allocation of transmit power of the nodes. In the shadow fading signal model experiment far transmitter and receiver nodes attenuated much. MAC layer protocols decide which node will be transmitter and receiver in a time slot. Transmit power can be arranged in a range by considering the interference. For example, if transmitter is close to receiver less transmit power can be used and as opposite, if transmitter and receiver are far from each other, a higher transmit power can be used.

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