EVALUATION OF PRIORITY DEPENDENT AND TIME SCHEDULED MAC LAYER PROTOCOLS FOR AD-HOC NETWORKS

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EVALUATION OF PRIORITY DEPENDENT AND TIME SCHEDULED MAC LAYER PROTOCOLS FOR AD-HOC NETWORKS

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ABSTRACT

EVALUATION OF PRIORITY DEPENDENT AND TIME SCHEDULED MAC LAYER PROTOCOLS FOR AD-HOC NETWORKS

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Ad-hoc networks have very unique features, such as dynamic topologies, relatively limited bandwidth and wireless signal propagation schemes, which present various challenges for wireless communication. In this thesis, control mechanisms for channel access scheduling and topology in ad-hoc networks are evaluated, which utilize the information from two-hop neighborhood to cope with the communication difficulties in ad-hoc networks.

Channel assignment is one of the most important topics for ad-hoc networks. Channel assignment problem can be studied using various technologies, such as time division, frequency division and code division multiple access. TDMA usage in ad-hoc networks appeals significant scientific curiosity recently.

TDMA based MAC layer protocols are constructed to take hidden terminal, direct interference and self-interference problems into consideration as well. Ad-hoc networks suffer from these challenging problems. In this thesis a solution -priority dependent and time scheduled media access control (MAC) layer protocol for ad-hoc networks is evaluated to solve these problems.

The priority dependent and time scheduled MAC layer protocol for ad-hoc networks is composed of three protocols which are node activation, link activation and pair wise link activation. In these algorithms contentions are resolved before channel access by means of the priority numbers and spread codes assigned to nodes/links randomly. Details about application of these three MAC layer protocols are presented as parts of the solution. After achieving the simulation results, these MAC layer algorithms are compared in terms of their throughput and delay performance in two different node situations; static and mobile.

Keywords: Ad-Hoc Network, MAC Layer, TDMA Scheduling, Mobility, Node Activation, Link Activation

ÖZ

AD-HOC NETWORKLER İÇİN ÖNCELİK TEMELLİ VE ZAMAN AYIRIMLI MAC KATMANI PROTOKOLLERİNİN DEĞERLENDİRMESİ

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Kablosuz iletişim açısından zorlukları temsil eden dinamik topolojiler, göreceli olarak limitli bant genişlikleri ve kablosuz sinyal iletimi ad-hoc ağlara özgün vasıflardır. Bu tez kapsamında, ad-hoc ağlarda iletişimin zorlukları ile başa çıkabilmek için iki sekmeli komşuluk bilgisi sağlayan kanal erişim planı için kontrol mekanizmaları ve topoloji kontrolü değerlendirilmiştir.

Kanal ataması ad-hoc ağlarda en büyük zorluklardan bir tanesidir. Kanal atama problemi üzerinde TDMA, FDMA veya OFDMA gibi değişik teknolojiler kullanılarak çalışılabilmektedir. Ad-hoc ağlarda TDMA kullanımı yeni bir başlıktır ve bu konudaki araştırmalar artarak devam etmektedir.

TDMA tabanlı bu MAC protokolleri gizli terminal, doğrudan engelleme ve kendi kendine engelleme problemlerini çözebilecek şekilde tasarlanmalıdır. Ad-hoc ağlar bu problemlerin sıkıntılarını yaşar ve bu problemler üstünden gelmesi mücadele gerektiren sorunlardır. Bu tez ile bu sorunları çözebilecek çözümler - ad-hoc ağlar için öncelik temelli ve zaman ayırımlı MAC katmanı protokolü- değerlendirilmiştir.

Ad-hoc ağlar için öncelik temelli ve zaman ayırımlı MAC katmanı protokolü ağ elemanı aktifleştirmeli, bağlantı aktifleştirmeli ve ikili bağlantı aktifleştirmeli olmak üzere üç protokolden meydana gelir. Bu algoritmalarda mücadeleler ağ elemanlarına veya bağlantılara rastgele olarak atanan önceliklere ve dağıtık kodlara göre kanal erişiminden önce çözümlenir. Çözüm yöntemimizi oluşturan üç adet MAC katmanı algoritmaları ile ilgili uygulama detayları verilmektedir. Simülasyon sonuçlarının elde edilmesinin ardından bu protokoller hareketli ve sabit senaryolarda verimlilik ve gecikme açısından karşılaştırılmıştır.

Anahtar Kelimeler: Amaca Özgün Ağlar, Ortam Erişim Kontrolü, TDMA Programlama, Hareketlilik, Düğüm Aktivasyonu, Bağlantı Aktivasyonu

To my family,

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LIST OF ABBREVIATIONS

OSI	: Open Systems Interconnection Model
MAC	: Medium Access Control
LLC	: Logical Link Control
NCR	: Neighborhood-Aware Contention Resolution
NAMA	: Node Activation Multiple Access
LAMA	: Link Activation Multiple Access
PAMA	: Pairwise Link Activation Multiple Access
FIFO	: First In First Out
KB	: Kilobyte
TDMA	: Time Division Multiple Access
CDMA	: Code Division Multiple Access
OFDMA	: Orthogonal Frequency-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
IEEE	: The Institute of Electrical and Electronics Engineers
SDMA	: Space-Division Multiple Access
GPS	: Global Positioning System
DSSS	: Direct Sequence Spread Spectrum
SMS	: Static Multihop Scenario
MMS	: Mobile Multihop Scenario
FCS	: Fully Connected Scenario
ALOHA	: Additive Links On-line Hawaii Area
STDMA	: Spatial Time Division Multiple Access
FPRP	: Five Phase Reservation Protocol
TRAMA	: Traffic Adaptive Medium Access

CHAPTER 1

INTRODUCTION

In ad-hoc networks, channel access schemes are examined under two major channel access schemes; schedule based and contention based. Contention based scheme is easy to manage, since it does not need any pre-coordination; while, schedule based scheme needs pre-scheduling of shared medium before transmissions start. From another aspect, fairness in contention based schemes is difficult to assure. Conversely fairness and collision freeness are advantages of schedule based schemes.

This study is focused on evaluating three medium access control (MAC) layer protocols: node activation multiple access (NAMA), link activation multiple access (LAMA) and pairwise link activation multiple access (PAMA). Under different scenarios (mobile nodes, static nodes, different topologies and different transmission ranges) and network topologies, performances of these MAC layer protocols are computed and compared.

In this part of thesis, MAC layer is defined and channel access control mechanisms are examined. Also, contributions of this work to the available literature are mentioned.

1.1 MEDIUM ACCESS CONTROL

The open systems interconnection model (OSI) model pictures the components of a network system. The model does not operate any function; it is just a conceptual model of the network system. Its aim is to standardize the communication of nodes with standard protocols. This model splits into some layers which assemble the communication system. The original OSI model is composed of seven layers.

An OSI model is a standardization of communication of nodes with defined protocols. In Figure 1.1, the components of a network system is depicted. Note that this OSI model is not appointed to a task but is a conceptual visualization of the network system. Similar to the original OSI model comprising seven layers, OSI models can be splitted to the several layers to assemble a communication system.

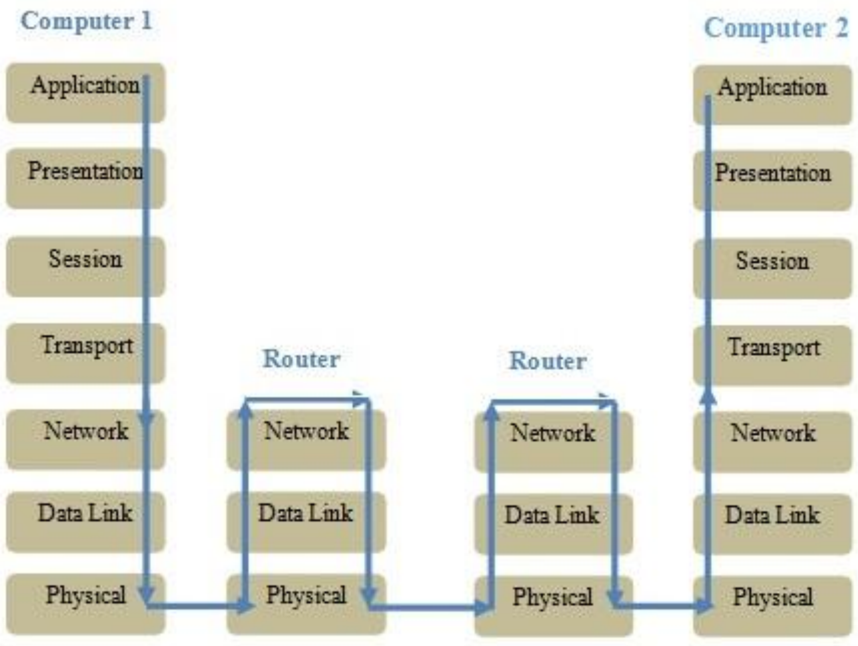

Figure 1.1: The OSI model and communication of two nodes over routers

All of the layers have important tasks in the OSI model, but throughout this thesis, MAC layer, which is a sublayer of data link layer, is examined.

The major tasks of MAC layer are channel access control and addressing. It provides communication between each pair of nodes/terminals within a shared medium which they incorporate.

MAC is implemented on a hardware which is called media access controller. It is a physical interface between logical link control sublayer which is the other sublayer of data link layer and the physical layer of the network.

1.2 CHANNEL ACCESS CONTROL MECHANISMS

Several nodes/terminals communicate each other through a shared medium. They are connected to the medium to use it collectively.

All nodes/terminals belong to a network are capable of transmitting data frames in the same time slot. Under such a circumstance, all packets involved in a collision may drop and the physical layer becomes impractical for that contention context. This is an undesired situation to be avoided as a prerequisite in MAC protocol design.

Multiple access protocols coordinate the access of nodes/terminals to the shared medium. This allows multiple nodes/terminals to use the same physical channel. Some of the shared channels are hub networks, bus networks, ring networks, shared wireless (wavelan), satellite and point-to-point networks.

Common multiple access protocols are time division multiple access (TDMA), code division multiple access (CDMA), orthogonal frequency division multiple access (OFDMA), carrier sense multiple access with collision avoidance (CSMA/CA) and slotted additive links on-line hawaii area (Slotted ALOHA).

1.3 CONTRIBUTIONS

Studies in this thesis focus on evaluating the schedule based channel access schemes for ad-hoc networks. Channel access simulation can be examined under two category; simulations with fully connected nodes and not fully connected (multihop) nodes. If nodes are fully connected to each other, then only one winner may exist for a contention context. For multihop network case, the MAC protocols should allow multiple nodes to content for a contention context and assign multiple winners in that contention context. In order to achieve this aim, three MAC layer protocols are evaluated, which are suitable for multihop ad-hoc networks. These MAC layer protocols also try to avoid hidden terminal, direct interference and self-interference problems which are frequently encountered in multihop ad-hoc networks. In order to cope with these problems, time scheduling is used in the algorithms. Every node should be identifiable and each of them should know its one and two hop neighbors identifiers in time scheduling construction. Nodes/terminals broadcast messages containing this information to ensure time scheduling. Evaluated MAC layer algorithms are executed for fully connected scenario (FCS), static multihop scenario (SMS) and mobile multihop scenario (MMS) and throughput and total delay of the network are compared.

1.4 THESIS ORGANIZATION

The rest of the thesis is designed as follows. Chapter 2 gives a detailed literature survey. A number of medium access methods, contention resolution algorithm and performance criterions of ad-hoc network system are given in Chapter 3. In Chapter 4 after explaining time division method in channel access schemes, detailed descriptions of MAC layer protocols NAMA, LAMA, PAMA are stated with their algorithms. Chapter 5 includes the implementation of the proposed MAC layer protocols design. Also mobility model used in MMS is mentioned in this chapter. Design of the simulation setup, simulation requirements and simulation results are other topics of this chapter. Finally, Chapter 6 concludes the thesis with future work suggestions.

CHAPTER 2

LITERATURE SURVEY

This chapter contains a general overview of the basic concepts about the thesis study. First of all, problems of implemented MAC layer protocols in ad-hoc networks are examined. In the second part, time division scheme in multihop ad-hoc networks is evaluated. Following the explanation of the priority dependent protocols in ad-hoc networks, node activation and link activation multiple access methods for ad-hoc networks are presented. Once and for all, mobility effect on network performance is analyzed.

2.1 DIFFICULTIES OF DESIGNING MAC LAYER PROTOCOLS IN AD-HOC NETWORKS

Various studies have been conducted on problems of MAC protocols for ad-hoc networks [1-3]. Hassanein, *et.al*, proposes a mobile point coordinator for peer-to-peer ad-hoc MAC protocols where the standard implements only Distributed Coordination Function (DCF) due to lacking central authority in the environment. Maintaining the backward compatibility with DCF, they tried to achieve quality of service and priority access for real time traffic in ad-hoc wireless environment. In simulations, their proposal results in lower average delay and discard ratio compared to DCF in real time data, in expense of a larger average delay time in non-real time data [1].

Gupta, *et.al*, investigated the fairness problems in distributed ad-hoc MAC protocols. The exponential backoff mechanism, resulting into more collisions and backoff delays for middle nodes in a network spanning multiple interference domains, is a common issue in MAC protocols. By decreasing the backoff delay upon collision or failure to send the data, they have proposed a different backoff mechanism to achieve a fairer mechanism. Impatient Backoff Algorithm, as the authors name their method, provided stable and fair outcomes and comparable mean throughputs, in the performed Markov analysis [2].

Another study is about interference and power control issues to enhance efficiency and applicability of the ad-hoc MAC protocols. Yeh, concentrated on interference-aware multiple access (IAMA) schemes for multihop wireless LANs to solve additive interference for channels in use for data and control messages. With no rely on hardware of measurement of signal strength; IAMA can also be the solution for variable-power heterogeneous hidden/exposed terminal problems [3].

The problems mentioned above are solved with the MAC layer protocols evaluated in this thesis through scheduling amog contenders.

2.2 TIME DIVISION IN MULTIHOP NETWORKS

Multihop time division multiple access based ad-hoc networks are studied extensively as well [4-6]. Li *et.al,* proposes a multihop dynamic channel assignment (MDCA) scheme for TDMA multihop cellular networks which uses interference information in surrounding cells in channel assignments to the cells. Sequential and packing-based channel searching are investigated. The results propose MDCA significantly improves system capacity and provides alleviation for call blocking in hot-spot cells [4].

Wei Li *et.al,* presents another dynamic slot assignment protocol for ad-hoc networks. With dynamic change of frame length and transmission schedule, the method proposed controls the excessive increase of unassigned slots. The method also allows transmitters to choose the slots among unassigned ones in its neighborhood to coordinate the announcement and confirmation of the assignment within the neighborhood and detect and resolve the conflicting assignments due to mobility of the nodes. The authors claim is collision free transmissions. They analyzed frame formats and slot assignments. The simulation results show dramatic improvement in average throughput compared to 802.11 protocols [5].

Besides, Li *et.al*, studies fixed channel assignment too, in contrast to the above mentioned dynamic channel assignment. They investigated application of characteristics of the hierarchical architecture and clustering for channel assignment. With help of virtual microcells, for uplink transmission, they propose a fixed channel assignment. For performance analysis a Markov chain model is utilized. The model is validated with simulations. Their results presents a reduction in the call blocking probability compared to conventional single hop cellular system FCA scheme. The result depicts increase in spectrum efficiency without increasing infrastructure costs [6].

Throughout the studies presented in this thesis, fixed channel assignment method has been applied.

2.3 PRIORITY DEPENDENT PROTOCOLS

One of the main studies referenced in this thesis belongs to Bao *et.al*. He presented three types of collision free channel access protocols for ad-hoc networks: node activation multiple access (NAMA), link activation multiple access (LAMA) and pairwise link activation multiple access (PAMA). With the identifiers to its neighbors one or two hops away given, each node elects one or multiple winners for channel access in a given contention text. Their methods show fair and capable to achieve maximum channel bandwidth. The authors analyzed delay and throughput characteristics of the contention resolution algorithms and with simulation compared their performances [7].

2.4 MAC PROTOCOLS USING NODE ACTIVATION METHOD

Using node activation in multiple channel access schemes takes an important role for this study.

Scheduling in node activation envelops an important academic interest [8-10]. Du, *et.al,* proposes a history based scheduling protocol for collision-free channel access in ad-hoc networks. In place of conventional distributed scheduling schemes based on node activation, the authors benefit from history of activity of each node to gain higher channel utilization. They prioritize each node according to the utilization of adjacent two nods. To overcome synchronization problem in history record, a node without assignment transmits a dummy packet. The results show that, throughput and delay characteristics of the proposed method is superior compared to NAMA protocol [8].

Yang, *et.al,* proposed as node activation with polling access protocol for collision free channel access in ad-hoc networks. Benefiting from the identifiers of the nodes in two hop neighborhood, each node elects a transmitting node for each time slot. The proposed method uses the network effectively by saving time slots for nodes with no packet to transmit and complements the election of nodes with polling and carrier sensing, compared to well-known topology dependent transmission scheduling schemes. The authors compare the performance of their collision free transmission protocol with conventional ones [9].

Su, *et.al,* studies topology-transparent node activation transmission scheduling protocols for multihop TDMA ad-hoc networks. In sense of node mobility, quality of service provisioning for each node is considered. The authors base their method on theory of block designs, and with mathematical properties of the design, conflict free transmission slots for each node is attained. The results are shown to be maximizing the minimum system throughput compared to existing methods [10].

2.5 MAC PROTOCOLS USING LINK ACTIVATION METHOD

Related to link activation, academic studies have concentrated on multiple channel access in ad-hoc networks [11-14]. He, *et.al,* studied on wireless networks with transmitters and receivers sharing a common channel. With their novel setup in which transmitters have cooperative data transmission and receivers have interference cancellation capabilities, they observed the maximum link activation. To achieve maximum number of compatible links with adjustment on proper interference cancellation patterns and transmitters to jointly transmit, they worked on the link activation problem and proved the complexity of the problem theoretically. The results showed the benefit of jointly deploying and interference cancellation [11].

Madany, *et.al,* reviews some real-world deployments with their attributes. Furthermore, in simulation environment, characteristics to differentiate mobility models with different attributes are studied [12].

Abdulwahid, *et.al*, proposed a Scheduled-Links Multicast Routing based on mobility prediction to overcome the challenge of dynamic changes in network topology due to node movement in one to many ends communication in mobile ad-hoc networks. The algorithm also reduces energy consumption effect due to mobility parameters in route construction and maintenance processes with reliability and quality of service requirements taken into consideration. The algorithm constructs multiple scheduled paths between multicast sources and receivers, and multiple loop-free and node-disjoint paths, for discovery. Their results depict high performance of their method compared to other similar topologies [13].

Su, *et.al,* studied topology-independent link activation transmission scheduling, for mobile code-division ad-hoc networks. The authors consider an interference model capturing the difference between transmission and interference ranges and proposes an approach quality of service provisioned conflict free transmission slots in each frame for each communication link. The results demonstrate the advantage of their proposal. They also present a topology-independent link activation scheduling framework based on group-divisible designs. The design objectives include maximization of the minimum system throughput and minimization of the schedule frame length. The design is depicted to be outperforming compared to the known methods [14].

2.6 EFFECT OF MOBILITY MODEL ON NETWORK PERFORMANCE

Another study is about effect of mobility model used on performance of ad-hoc networks. Pan, *et.al*, proposed a restricted random mobility model which tries to solve the deadlock of throughput versus delay performance of mobile nodes. Global mobility models assume nodes travel around the whole network area. Throughput and delay results show that there is a contradiction; low delay and low throughput or high delay and high throughput. They claim their restricted random mobility model helps to overcome this problem. This new multihop relay scheme gives upper and lower bounds of node throughput capacity and expected end-end delay. The trade-offs between throughput and delay performances of mobile nodes are also shown with this study. [15]

CHAPTER 3

WIRELESS MEDIUM ACCESS

Wireless communications are becoming one of the most growing interest in communication technology. Ad-hoc networks attract attention in this technology which are mostly examined under multihop and distributed category. This category brings some challenges to design well-adjusted MAC protocols which adapt to wireless networks.

3.1 WIRELESS MEDIUM ACCESS

MAC protocols have an important function in sharing the limited source between multiple nodes/terminals to schedule packet transmissions fairly and efficiently. Wireless MAC protocols can be observed under two categories: centralized and distributed topologies.

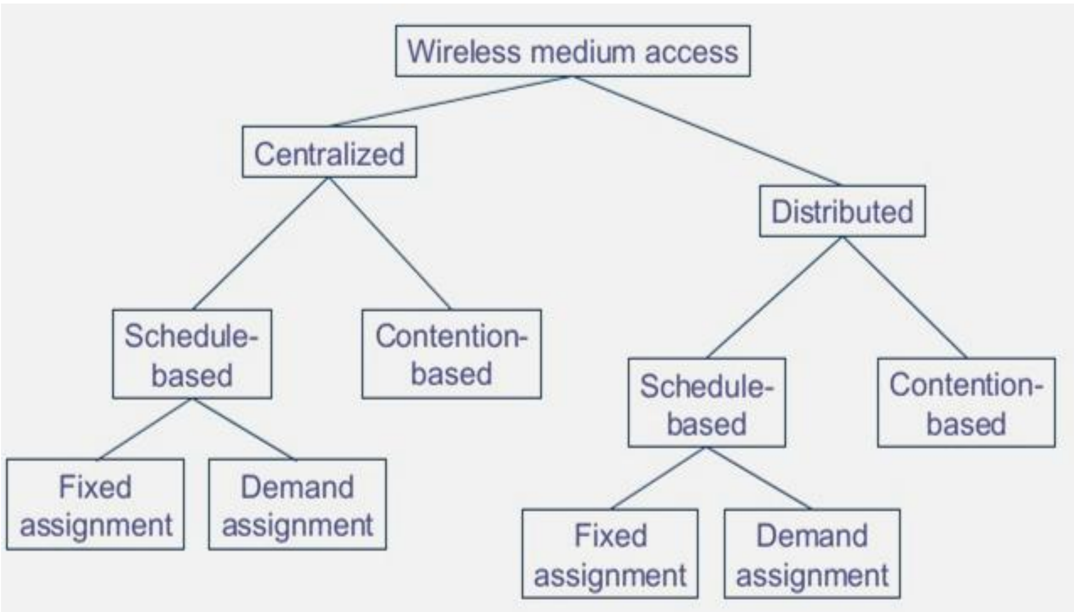

Figure 3.1: Wireless medium access methods

Centralized medium access methods need a central station which controls nodes' accesses to the medium. This type of methods has advantages and disadvantages. The main advantage is their collision-free nature. Also these algorithms are simple to apply. However, requirement of a central control station to sync the channel usages of the nodes is a main drawback. Furthermore, without a priori size information, their direct application to a network is limited. Cellular systems may be a good example to this type of networks. The central controller in these systems syncs the traffic by collecting the demands from the nodes and makes decisions about allocation of shared resource between these nodes.

On the other hand, distributed medium access methods do not need any central control station. They are appropriate for non-infrastructure networks such as mobile ad-hoc networks where access decision to shared resource is made by nodes themselves. Efficient and fair resource sharing in each local network is requested.

Centralized and distributed protocols both have schedule based and contention based subgroups. Shared resource may be assigned to nodes either fixed manner or demand manner. In schedule based MAC, it is scheduled that which node may use which shared resource. Packet collision is not a problem for this type of MAC layer protocols while time synchronization is a very important requirement. TDMA, FDMA, CDMA are some of schedule based medium access protocols. On the other hand, contention based MAC does not require any schedule. Although it is susceptible to packet loss, efficiency can be improved by using time slots which would not be used in schedule based protocols. In this type of MAC, access to resource is usually determined randomly. ALOHA, CSMA are examples of contention based medium access protocols.

Table 3.1: Channel access protocols

CHANNEL ACCESS POLİCY	
Contention Based	ALOHA, CSMA, CSMA/CD, CSMA/CA

Schedule Based	TDMA, FDMA, CDMA, Polling, Reservation

Under distributed topologies, contention-based multiple access schemes are generally chosen since sharing the channel between nodes is difficult. Although they have advantages of better efficiency and ease, they also have more important problems. They cause packet loss, waste the shared resource and use channel unfair. In the case of administrating the control channel between contenders and scheduling the shared resource, these problems would be solved. In this thesis, TDMA usage (distributed TDMA) to solve contentions is studied more than other protocols.

3.2 CONTENTION RESOLUTION with NEIGHBORHOOD-AWARE CONTENTION RESOLUTION (NCR)

Shared mediums are used by multiple nodes/terminals. A situation that more than one node/terminal would like to use the medium at the same time may occur and contention starts at this point. Contention resolution algorithms are designed to overcome this problem.

During contention multiple nodes are expected to use the same medium in the same contention context. The contention context may be a time slot or a frequency band or something else depending on the MAC layer protocol design.

There are several contention resolution algorithms, e.g. NCR, to propose a solution to this contention context sharing problem. In NCR, the winner node/link is chosen for every contention context among a group of contenders. NCR algorithm needs the contender group information to resolve this contention. In ad-hoc networks, contender group includes one hop and two hop neighbors of each node. Ad-hoc networks satisfy this neighborhood information to NCR algorithm. Each node broadcast the identifiers of the nodes in its one neighborhood. NCR algorithm identifies contention context by their identifiers. For instance, in time division multiple access schemes this identifier may be time slot number or for frequency division multiple access schemes identifier may be the starting frequency of the frequency band.

To summarize the election problem between the contenders, we name the group of contenders against node i which contend for the same contention context as M_i. In TDMA scheme, the contention context is time slot. For a time slot number, the prioritization of member nodes of the group $M_i \cup \{i\}$ is very crucial. This election should be fair between contenders. (3.1) gives a formula to set the priority for node i in time slot t, denoted by Pi.

$$Pi = Rand\ (\ i \oplus\ t) \oplus i \tag{3.1}$$

The $Rand(x)$ function in the above equation generates a Pseudo-random number from a preset range. The '$\oplus$' sign substitute for operation of concatenation of two operands. If $Rand(x)$ function generates same random number for different entities, other concatenation operation with entity identifier satisfies the uniqueness of priorities. With these unique priority number assignments, collisions are aimed to be avoided.

Algorithm 1 NCR 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

6: *end if*

7: *end for*

8: *end procedure*

According to the algorithm above, NCR calculates the priority number of each node, k, in the group of $M_i \cup i$. In step 4, priorities of all nodes in M_i are compared with priority of node i. If node i is the node with highest priority then it is assigned as the winner node of this contention. Since the time slot number changes as each time slot passes, the priority number of each contender changes as well. So randomization of priority numbers at each time slot can be guaranteed.

From probabilistic approach, probability of node i of winning the contention can be computed with the equation below which is denoted as q_i. Since priorities are assigned randomly, each node have probability to win the contention and use the shared time slot.

$$q_i = \frac{1}{|M_i \cup i|} \tag{3.2}$$

3.3 PERFORMANCE CRITERIA OF CONTENTION RESOLUTION

3.3.1 Delay of a Network System

Network delay affects the performance of the network system significantly. For communication systems, delay which a packet is exposed to can be considered as the time passes while packet travels from transmitter node to receiver node. Current developments in network technologies reduce delays into order of microseconds.

In our study, M/G/1 queuing model where arrivals of the packets are calculated based on a Poisson process is used. The packets are served in accordance with first-in-first-out (FIFO) rule. Each client experiences this delay with respect to their priorities and packet arrival rates.

3.3.2 Throughput of a Network System

Throughput of a system is calculated as the rate of the delivered data at the network terminals. But in communication networks, throughput is considered as the rate of successfully delivered message through a channel. In communication network throughput is measures in bits per second (bps) or packets/slot, which the measuring unit in this study as well.

In NCR, collision is completely avoided in the system due to assignment of unique priorities to each nodes/terminals. Shared resource can serve maximum load up to channel capacity. From this point of view, in this study, the throughput or the system throughput is defined as the sum of the data rate delivered to the network terminals.

$$S = \sum_{j=1}^{k} \min\,(\lambda_{k,} q_k) \tag{3.3}$$

In (3.3), q_k is the channel access probability of node k, and λ_k is the packet arrival rate at node k. System throughput S is calculated as the sum of minimum of arrival packet rates and channel access probabilities of all individual nodes in the shared resource.

CHAPTER 4

CHANNEL ACCESS PROTOCOLS

In ad-hoc networks, in a time slot, a contention is possible between the nodes two hops away from each other. In Figure 4.1, there is a demonstration about two hop neighborhood relations in ad-hoc networks. Circle around the node which is named as Tx, symbolizes effective transmission range of that node. Only the nodes two hop away from the node labeled as TX (transmitter) may transmit while transmitter is using the channel.

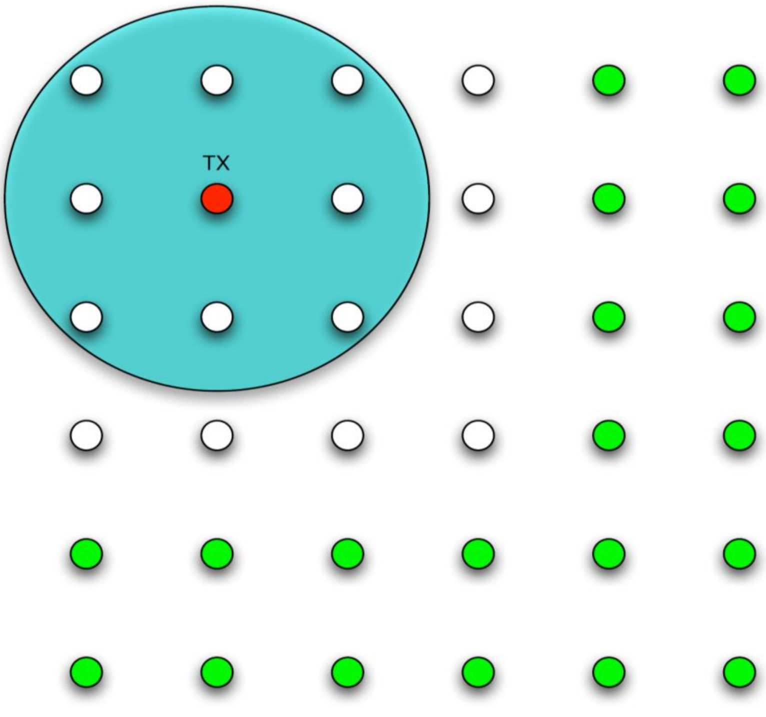

Figure 4.1: Two hop neighborhood relation

A time slot can be reused by different nodes in the network at the same time. If these nodes are within their two hop neighborhood then hidden or exposed terminal problem may occur. This problem may lead to channel interference and initiate collisions.

Requirement for a collision-free transmission for each node is transmitting data if unless the other nodes in two hop neighborhood is transmitting data at that time. This requirement is the main reason for the demand of contender information in NCR algorithm. As mentioned earlier, contenders broadcast neighborhood information to their two hop neighbors; hence, this demand is satisfied.

Based on NCR and time-division multiple access scheme, three multiple access protocols are proposed in the literature, which are NAMA, LAMA and PAMA.

4.1 TIME DIVISION IN CHANNEL ACCESS PROTOCOLS

The structure of time division is demonstrated in Figure 3.2. Parts in this structure are formed by multiple time slots. Sections are formed by multiple parts and a block consists of multiple sections. A block is defined as the longest time unit in the time schedule plan. Current time slot number, current part number and current section numbers are calculated through (4.1) – (4.3).

$$t' = t \, mod \, T_p \tag{4.1}$$

$$p' = (t/T_p) \, mod \, P_s \tag{4.2}$$

$$\mathrm{s}' = ((\mathrm{t}/\mathrm{T_p})\mathrm{xP_s}) \text{ mod } \mathrm{S_b} \tag{4.3}$$

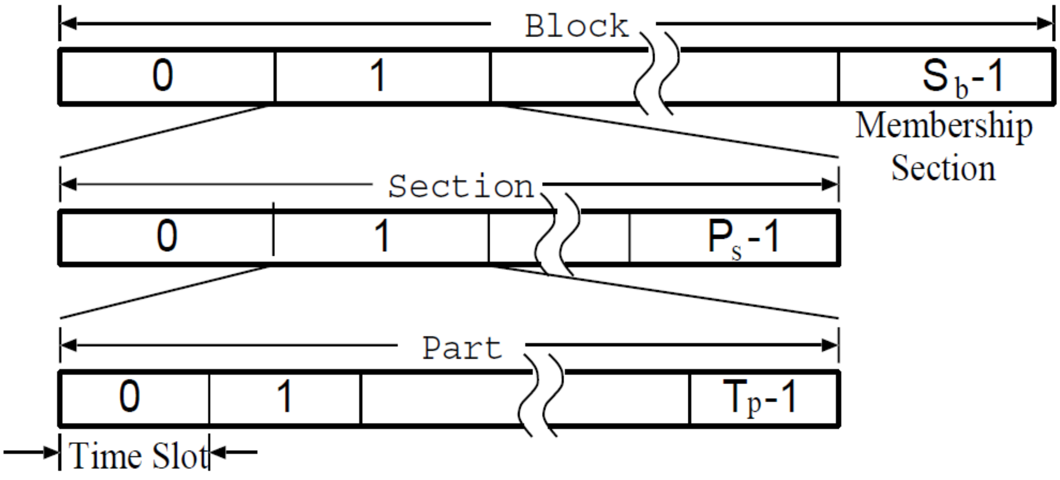

Figure 4.2: Timing structure in NAMA

In the simulations time slot number in a part is $Tp = 6$, and the number of parts within a section is $Ps = 3$ values are used.

As it is been depicted in Figure 4.2, the section at the end of a block is called as membership section. This section is constructed with the time slots containing the sender ID and part number to be used in the next blocks. The time slot of a membership section demonstrated in Figure 4.3.

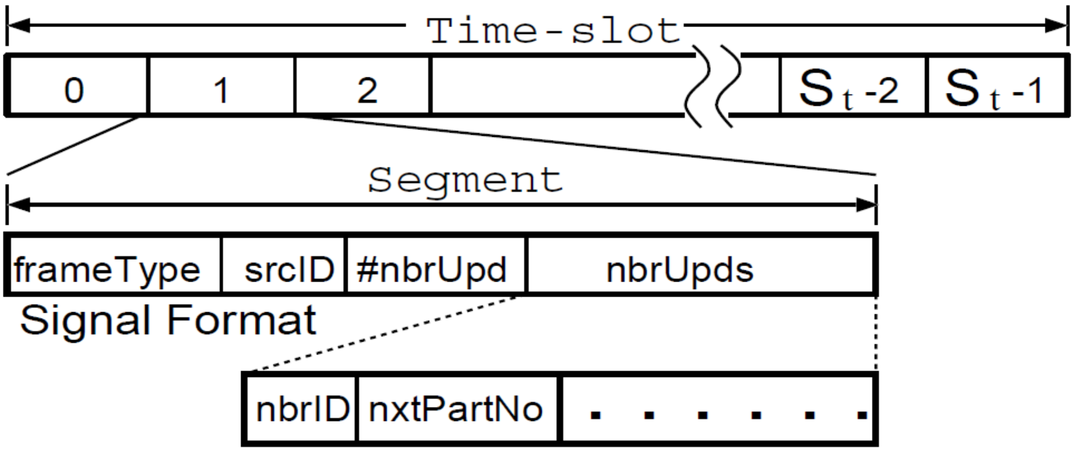

Figure 4.3: Time slot context

In the evaluated three algorithms, this time division method is used. By using this method one hop neighbors of each node could know neighbors (by membership section) and broadcast its one hop neighbor identification numbers. So, two hop neighborhood relations become constituted. Two-hop neighborhood information helps to avoid hidden terminal and exposed terminal problems.

Time synchronization of nodes is not covered in this study. However there are some methods to achieve synchronization. One of these methods is using GPS signals. Another method is attaching timestamp information attained from real-time clock.to data packets

4.2 NAMA

4.2.1 Description of NAMA

In NAMA protocol it is required that a transmission from a node to its one hop neighbor should be satisfied without any collision. When a node reaches the channel, the neighbors of this node within two hop distance should not transmit any data. For this reason, the contender group M_i of node i is the union of one-hop and two-hop neighbors of node i, which is $N_i^1 \cup N_i^2 - \{i\}$ where N_i^1 and N_i^2 symbolize one hop and two hop neighbors of node i respectively.

As soon as node i wins the contention in the relevant time slot, it is able to transmit to its one hop neighbors successfully without any collision within its two-hop neighborhood. Therefore, NAMA can be called collision-free multiple access scheme.

4.2.2 Algorithm of NAMA

Algorithm 2 NAMA Pseudo Code

1. Calculate the current part number p'according to (3.1) - (3.3)
2. Exit if p' $!=$ p_i is true.

3. Calculate the priority p_i^t using Algorithm 1 step 3.
4. Appoint node i to time slot $t_i\ != \ p_i^t modT_p$.
5. Calculate the current time slot number t'in current part number p'using (3.1) - (3.3)
6. If $t_i\ != \ t'$ is true, then go to Step 10.
7. Calculate the sequence of contending neighbors

$$M_i = \{k|k \in N_i^1 \cup N_i^2\ and\ p_k = \ p'and\ (p_k^t modT_p) = t'\}$$

   where p_k^t is the priority obtained from Algorithm 1 step 3 for k, and p_k is the part number chosen by node k.
8. Exit if Algorithm 1 step 4 does not hold for node i.
9. Get the common channel in current time slot t and exit.
10. Exit if

$$\exists k, k \in N_i^1 \cup N_i^2 and p_k = \ p'and\ (p_k^t modT_p) = t'$$

11. The set of contending neighbors of node i now becomes:

$$M_i = \{k|k \in N_i^1 \cup N_i^2 and p_k = \ p'\}$$

   Calculate another priority number p_k^t:

$$p_k^t = Rand(k \oplus t \oplus t') \oplus k, \qquad k \in M_i \cup \{i\}$$

12. Exit if

$$\exists j, j \in M_i, p_i^{t'} < p_j^{t'}$$

13. Get the channel in time slot t.

The Pseudo Code above describes NAMA [7]. Thanks to this algorithm, when node i is activated, data transmissions can be successfully received by its entire one-hop neighborhood. Because, only node i is able to transmit within its two-hop neighborhood. Hence, NAMA has collision free broadcast capability, and does not need to use code-division method.

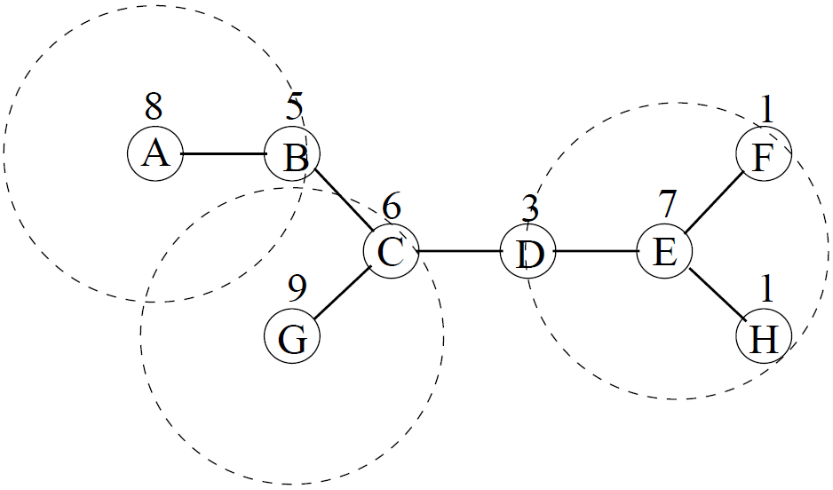

Figure 4.4: An example of NAMA operation

Figure 4.4 gives an example about NAMA operation in a multihop network. The lines between nodes show one-hop neighborhood relationship. The circles which are drowned for nodes A, G, E, points out the effective transmission ranges of these nodes. The numbers placed beside each node represent node priorities for the related time slot. According to NAMA algorithm, A, G and E nodes are able to transmit in the same time slot, since their priorities are the highest among all the contenders.

4.3 LAMA

4.3.1 Description of LAMA

As a time slotted multiple access scheme, LAMA protocol is similar to NAMA protocol. LAMA implements code division method with direct sequence spread spectrum (DSSS) in addition to NCR.

In LAMA protocol, identifier numbers are assigned to each nodes and these nodes has transceivers that can transmit and send some data using DSSS through a group of spreading codes. Nodes work in half duplex mode, in other words they can either transmit or receive packet at the same time.

Code assignment is usually used to decrease the packet collisions in the algorithms. In LAMA, receiver-oriented code assignment is applied. DSSS codes are assigned to receiver nodes and these codes are proper for unicast transmission.

In our study we use a set of pseudo noise codes generated in the algorithm as another division method. The set of pseudo noise codes is symbolized with $C_{pn} = \{c^k\}$, where c^k indicated the points in k unit codes. These codes are assigned to receiver nodes with (4.4). In this equation, c_i is the code of receiver node i assigned with a random selection from a set of pseudo noise codes.

$$c_i = c^k, k = Rand(i)\ mod\ |C_{pn}| \tag{4.4}$$

Since the set has finite number of elements to be assigned to the nodes, more than one node may have the same code. $n_{i,c}^{1}$ is the notation of the one hop neighbors of node i to which code c is assigned to. In LAMA the aim is to determine whether node i may activate a link using code c and send packets to its one hop neighbors in $n_{i,c}^{1}$ within time slot t.

The group of contenders of node i is composed of one hop neighbors and one-hop neighbors of the nodes in $n_{i,c}^{1}$, as shown in the following formula:

$$M_i = N_i^1 \cup N_j^1 - \{i\} \; where \;\; j \in \; n_{i,c}^{1} \tag{4-5}$$

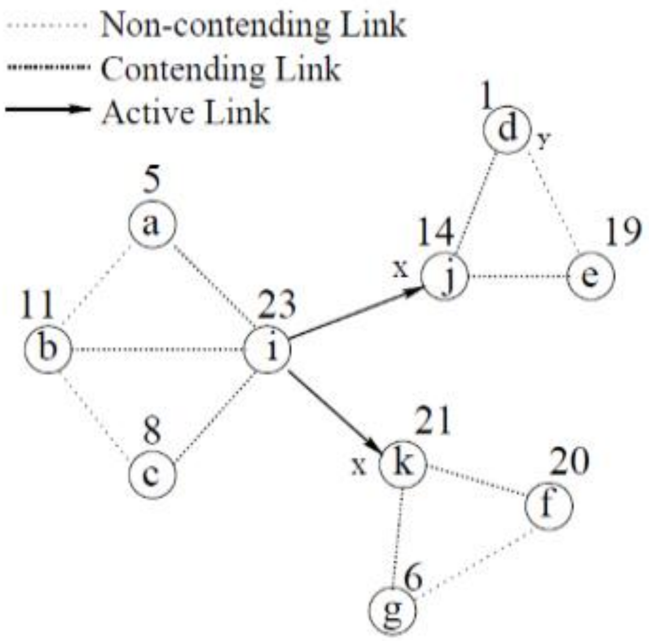

Figure 4.5: LAMA Operation

A scenario about LAMA operation is exhibited in Figure 4.5. The numbers assigned to nodes represent their priority numbers. Also code x is the spreading code of nodes 21 and 14. Since their spreading codes are same then transmission from code x is determined due to priority numbers of receiver nodes.

Node i itself has the highest priority number within its one hop neighbors. So, if it wants to transmit a frame to node j or to node k then it can choose either *(i,j)* or *(i,k)* links. At the same time slot *(e,d)* link may be activated too since code of node d is different than code of node j or node k.

4.3.1 Algorithm of LAMA

Algorithm 3 LAMA Pseudo Code

1. Calculate the priority p_k^t of every node $k \in M_i \cup \{i\}$ using Algorithm 1 step 3.
2. If *NCR*$(i,\ t)$ results $winner\ node\ = i$, then activate link $(i,j), j \in n_{i,c}^1$ in time slot t.

In the first step of LAMA algorithm, priorities of each node in the contender group of node i are calculated. After that, NCR algorithm runs and selects the winner node of the contention. If it concludes that node i is the winner node then link (i,j) will be activated.

4.4 PAMA

4.4.1 Description of PAMA

PAMA differs from NAMA since the priorities are calculated and assigned to links instead nodes. It is known that codes are assigned to receiver nodes in LAMA but in PAMA algorithm codes are assigned to pairwise links of a transmitter receiver pair. These codes recalculated at each time-slot, so that the contentions become variable for different time slots.

In PAMA links are chosen as the winner of the contention with respect to their priority i.e. among incident links PAMA selects the link with highest priority as the winner node.

4.4.2 Algorithm of PAMA

Algorithm 4 PAMA Pseudo Code

1. Get the priority $p_{x,y}^{t}$ of every link $(x,y) \in M_{(u,v)} \cup \{(u,v)\}$ using (4.6).

$$p_{(x,y)}^{t} = Rand(x \oplus y \oplus t) \oplus x \oplus y \quad (4.6)$$

2. Exit if (4.7) is not satisfied.

$$\forall (x,y) \in M_{(u,v)}, p_{(u,v)}^{t} > p_{x,y}^{t} \quad (4.7)$$

3. Get the priority of each two-hop neighbor of node u, that is:

$$\mathrm{p_k^t = Rand(k \oplus t) \oplus k, k \in N_u^2} \quad (4.8)$$

4. Get the code assignment $\mathrm{c_k}$ on node k, k $\in \mathrm{N_u^2}$ using (4.9)

$$c_u = c^k, k = Rand(\mathrm{u} \oplus t) \oplus u\ mod\ |C_{pn}| \quad (4.9)$$

5. Activate link $(u;\ v)$ in time slot t if:

$$\forall(k) \in N_u^2 \; and \;\; c_u = c^k, p_u^t > p_k^t \qquad (4.10)$$

In the algorithm above, priorities of incident links of (u, v) are calculated. If (u, v) link has the highest priority among its contenders then priorities of each two hop neighbors of u are calculated. After that code is assigned to directional links in time slot t according to (4.9), link (u, v) is activated if its priority is the highest priority within two hop neighbors who have same code with link (u, v).

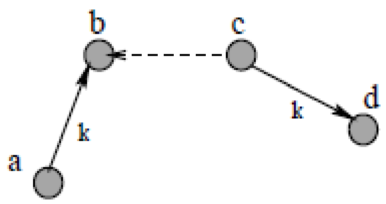

Figure 4.6: Link Vector

In Figure 4.6, a possible network scenario is presented. In this topology, node a wants to transmit data to node b while node c wants to transmit data to node b and node d. If link (a, b) and (c, d) are activated at the same time, then a collision may occur since these links have same code. Besides, PAMA algorithm assigns unique priority numbers to each links and checks the codes and priorities of contending links. So, PAMA algorithm can easily avoid the hidden terminal problem.

CHAPTER 5

SIMULATION WORK

5.1 ASSUMPTIONS

In this study, a number of assumptions are made. First of all, each node in the network is considered to satisfy time synchronization, and to know the time slot boundaries. Similarly, all of the contenders have knowledge about time slot number t. In a time slot duration, a full-scope data packet can be transmitted. Time slots enumerated starting from zero.

Medium is considered to be free-space i.e. there is no obstacle, so signal is not exposed to diffraction or reflection. Note that if the medium was not considered as free-space model, the routing of the packages would change; yet, it is out of the scope of this study; hence, the simulations will still be valid.

The antennas of nodes are assumed to be the same and omni-directional. If antennas were directional and/or different from each other, simulation results could be different from those will be presented.

5.2 MOBILITY MODEL

A mobile node is a node whose position and point of attachment to the network may change with time. As node moves within the network area, it requires new network connections to be made. This extra effort results in higher power consumption and a greater lag in the communication. Static nodes do not experience these disadvantages. Yet, current requirements to connect internet from anywhere advocates mobile nodes.

Mobility model describes the movement of nodes with their location, acceleration and velocity which are changing over time. Mobility of nodes play a considerable role in performance of MAC layer protocol, so emulating this pattern as real as possible is of cruicial importance.

The mobility model for the nodes is chosen from some alternative mobility models: Brownian motion model, Manhattan mobility model, random waypoint model. In this study, random waypoint model which is simple and feasible model for mobile ad-hoc networks is chosen. In this model, two directional motion, speed and acceleration of the nodes are randomly determined. There is an illustration of this model in Figure 5.1 which shows motions of 15 nodes in a region.

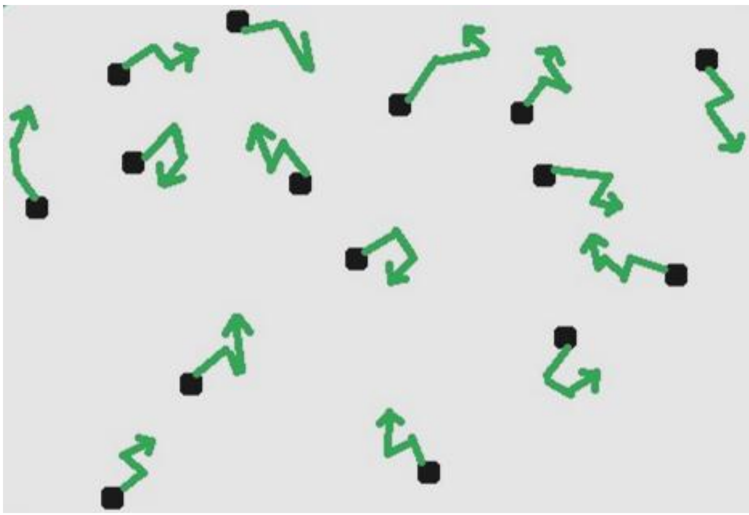

Figure 5.1: Mobility Model

5.3 SIMULATION DESIGN

The development environment used to implement these algorithms is Microsoft Visual Studio. Software of NAMA, LAMA and PAMA algorithms are evaluated over three scenarios. Simulations are performed in the static and mobile topologies.

First of the scenarios is designed for fully connected 5and 10 nodes. In the Figure 5.2, fully connected scenario (FCS) with 5 nodes is shown. The dashed lines in the figure indicate the connection between two nodes. Note that, all of the nodes are in the transmission range of each other which means every node can transmit and receive packets from another.

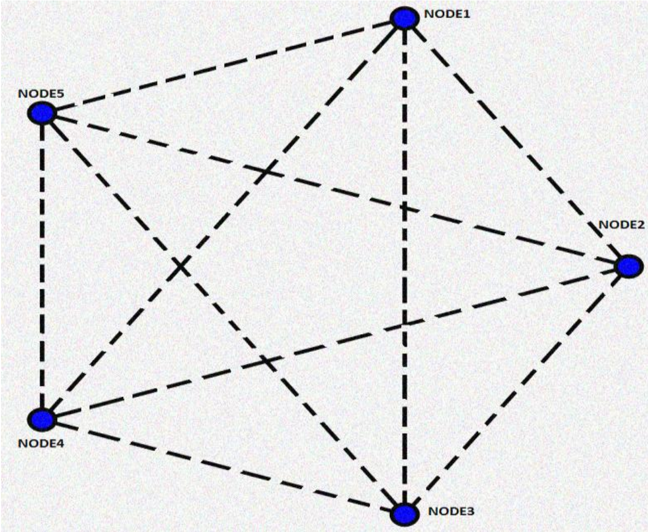

Figure 5.2: Fully Connected Scenario for 5 nodes

Figure 5.3 shows the connection topology of multihop connection scenario and dashed lines in the figure indicate the connection between two nodes. If two nodes have no dashed line inbetween them, they are not in the transmission range of each other.

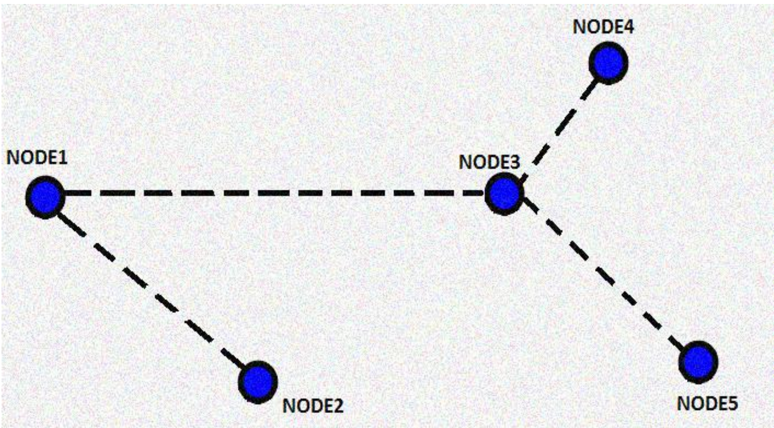

Figure 5.3: Multihop Scenario Topology for 5 nodes

For the SMS case, network area is chosen as 1000m by 1000m. 100 nodes are placed randomly to this region. To get more realistic results, this region is not enlarged to include transmission ranges of all nodes i.e. when a node is at the coordinate of 900m to 900m and transmission range of it is 200m then some effective transmission area of the node is idled.

MMS is the third scenario which is composed of 100 mobile nodes within an area of 1000m by 1000m. As in SMS test field, 1000m by 1000m network area and infinite plane is simulated as the test field.

In MMS and SMS scenarios, the transmission ranges of the nodes are set to 200m and 300 m, respectively, providing us a contention level and topology change for different cases.

Time slot duration is taken 10ms. A section ($Tp(6)\ x\ Ps(3)$) length is 180ms. For SMS and MMS case, 30 different pseudo noise codes are used.

Table 5.1: Simulation constraints

	Node Number	Time Slot Number	Simulation Duration	Node Type	Connection
FCS	5 and 10 nodes	100000	1000 secs	Static	All nodes are connected
SMS	100 nodes	50000	500 secs	Static	Transmission range of 100m and 300m
MMS	100 nodes	50000	500 secs	Mobile	Transmission range of 100m and 300m

5.4 SIMULATION RESULTS

In this section simulation results are given in the three scenarios mentioned before. First of all, throughput and delay results of FCS for 5 and 10 connected nodes are demonstrated. After that throughput and delay characteristic of static and mobile network of 100 nodes are presented for their transmission ranges of 100m and 300m. Finally comparison of SMS and MMS scenarios is depicted.

Figure 5.4 and Figure 5.5 shows the throughput results of three MAC layer protocols. As expected, under the channel capacity, throughput of the protocols shows a linear increase. When the capacity of the channel exceeded, throughput became stable. Also it is detected that PAMA has higher throughput than others. PAMA algorithm is based on scheduling of link activation. The capability of multiple links being allowed to be activated at the same time, enhances the channel capacity of PAMA.

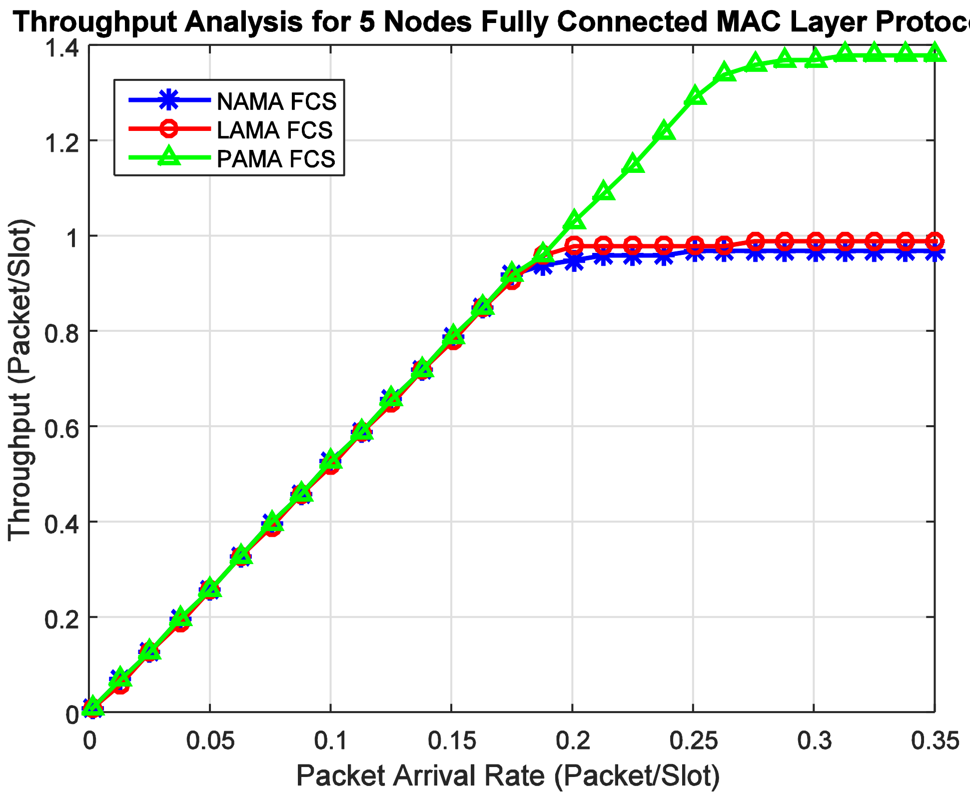

Figure 5.4: Throughput analysis for 5 nodes FCS

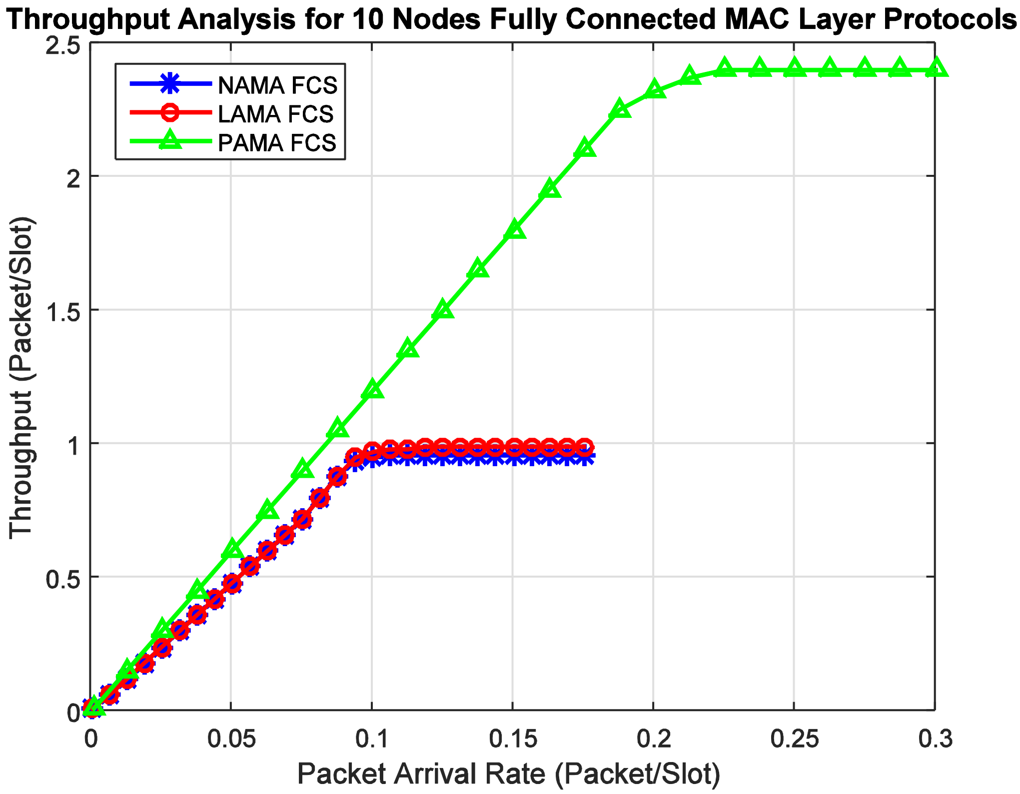

Figure 5.5: Throughput analysis for 10 nodes FCS

Figure 5.6 and Figure 5.7 demonstrate that LAMA and NAMA protocols exhibit approximately same characteristics since the channel capacity and throughput of these protocols are the same. In PAMA packets are exposed to higher starting delays than others since the number of contender links for each time slot is more than the number of nodes. As it is known, heavy load correspond to higher packet arrival rate. As PAMA has higher capacity, it is able to sustain heavier loads and presents a better delay performance under heavy loads.

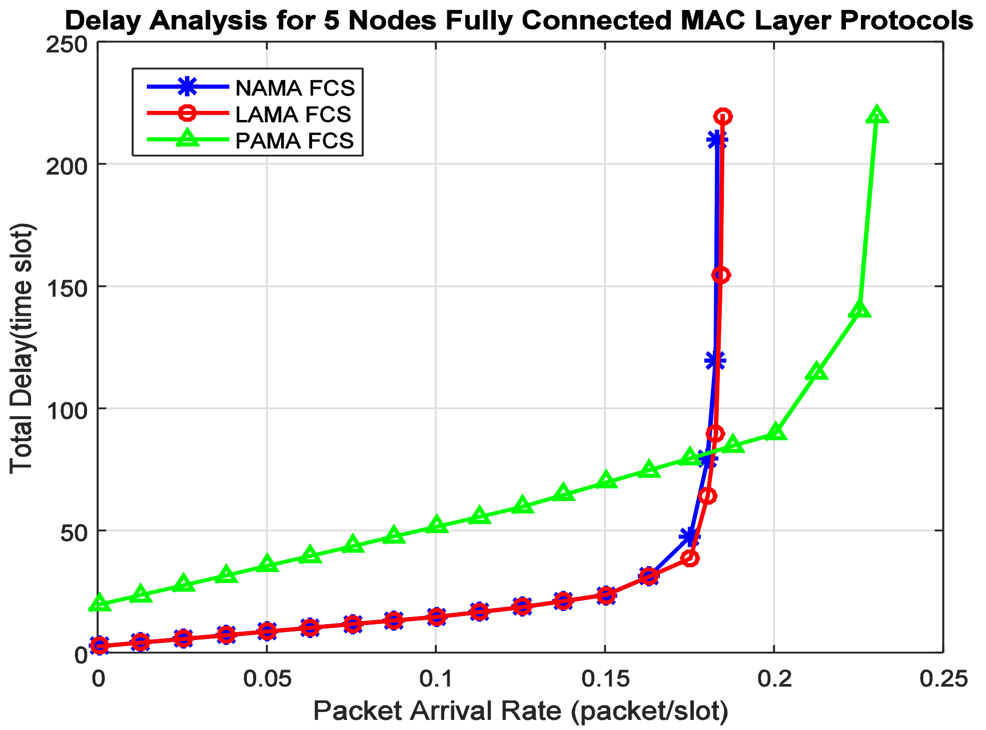

Figure 5.6: Delay analysis for 5 nodes FCS

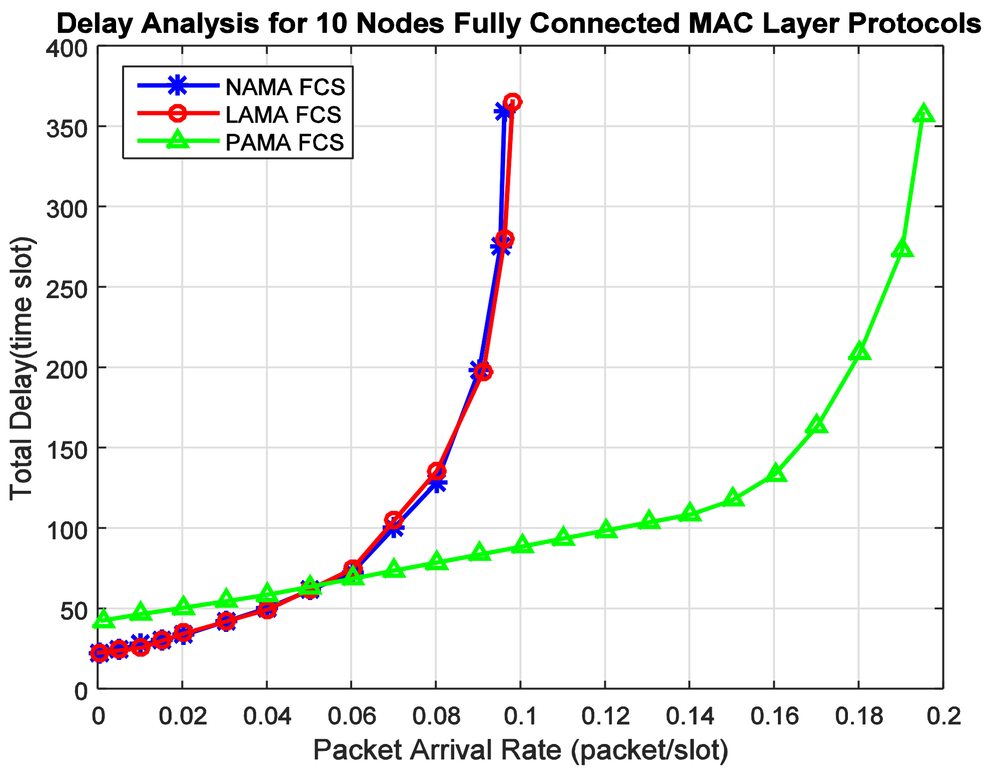

Figure 5.7: Delay analysis for 10 node FCS

Throughput analysis for multi-hop network scenario is simulated for 100 nodes and for their changing transmission ranges; 100m, 300m. Figure 5.8 and Figure 5.9 show the advantage of code division of LAMA and PAMA over NAMA.

In PAMA links are chosen according to their priorities resulting into a bidirectional packet delivery. But in LAMA a link chosen whose node has the highest priority which means only the chosen node from that link can send packets. Hence, a higher throughput can achieved with PAMA compared to LAMA.

Also effect of transmission range on SMS can be observed by examining these figures. While throughput value for 100m transmission range reaches steady state at ~18 packets/slot, for 300m transmission range this value decreases to ~5.5 packets/slot.

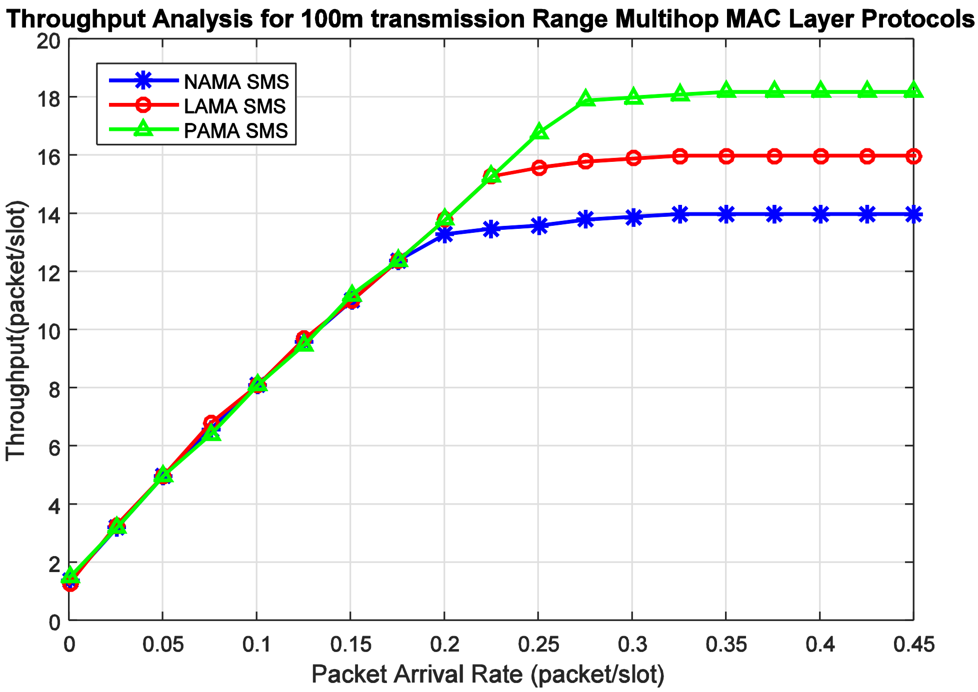

Figure 5.8: Throughput of SMS for transmission range 100m

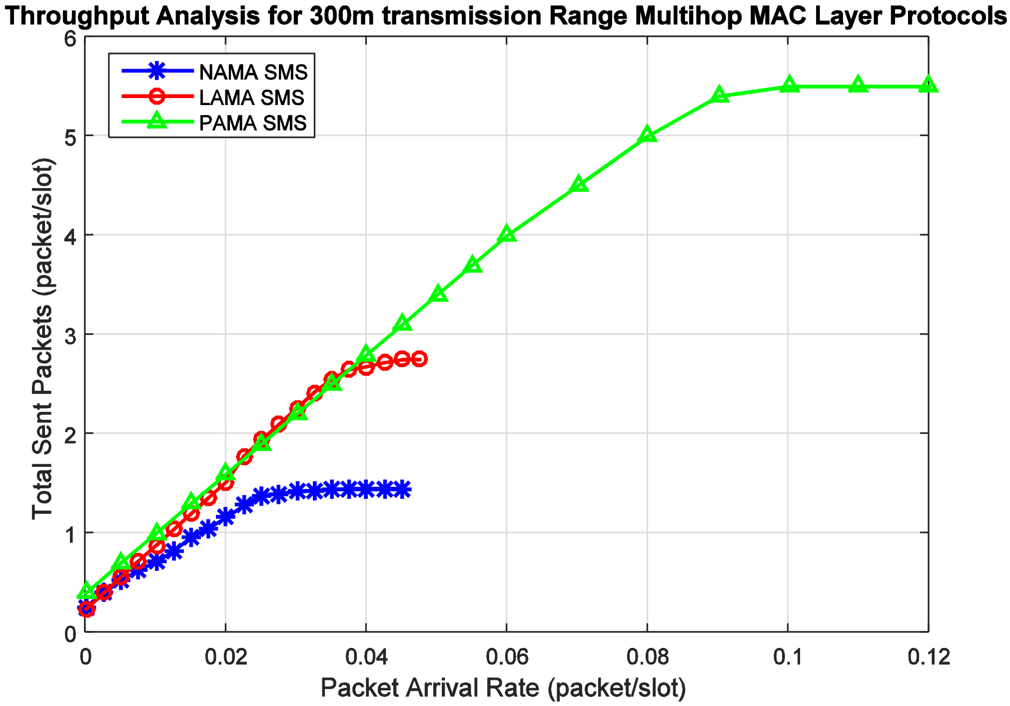

Figure 5.9: Throughput of SMS for transmission range 300m

As in FCS, PAMA has higher delays at the starting point. Delay characteristics of the protocols are shown in Figure 5.10 and Figure 5.11. Delay level of PAMA protocol increases slower with respect to the corresponding increase in LAMA and NAMA. Hence, PAMA has a higher channel capacity and spatial reuse.

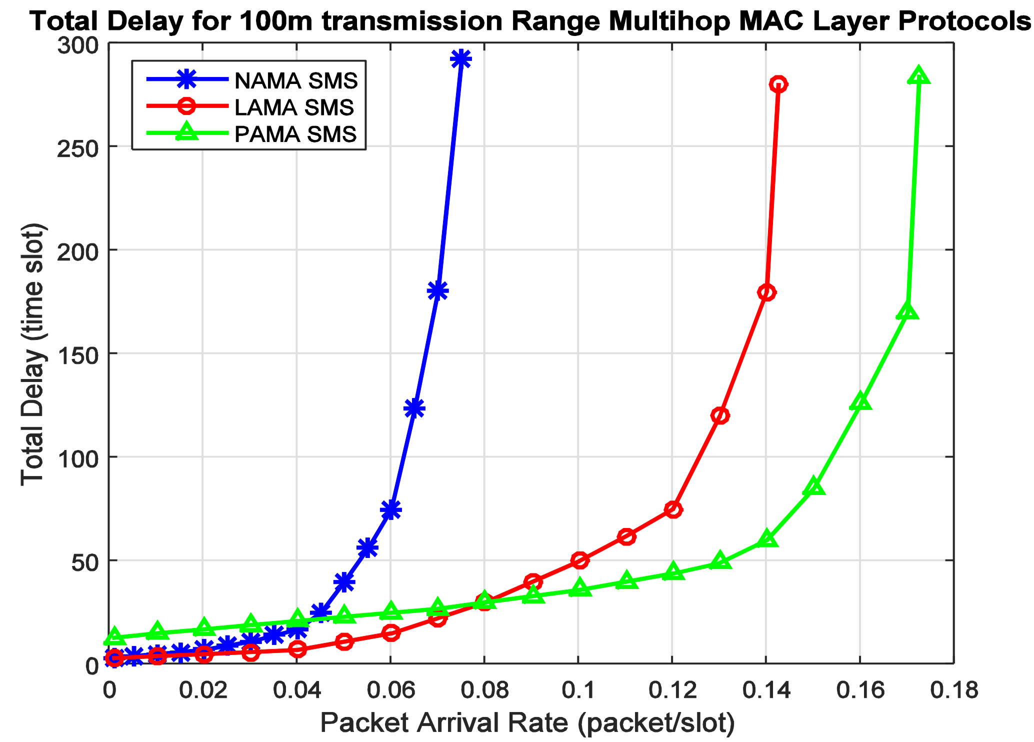

Figure 5.10: Delay of SMS for transmission range 100m

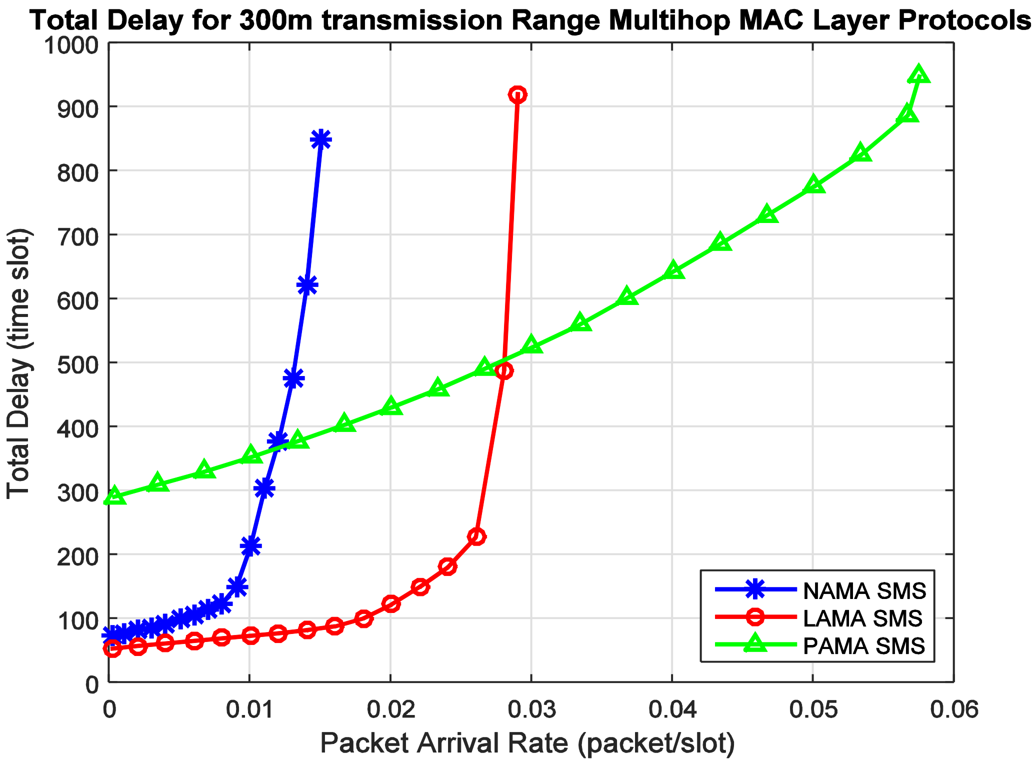

Figure 5.11: Delay of SMS for transmission range 300m

Figure 5.12 and Figure 5.13 show the throughput performances and Figure 5.14 – Figure 5.15 show delay performances of the MAC layer protocols while the nodes are mobile. The transmission ranges are 100m and 300m in the figures.

It is observed that, a shorter transmission range results into a higher throughput and a smaller delay since longer transmission range will cause more neighborhood which escalates competition. If the competition gets challenging, more nodes will start to compete for a time slot ending up with a higher delay and a smaller throughput.

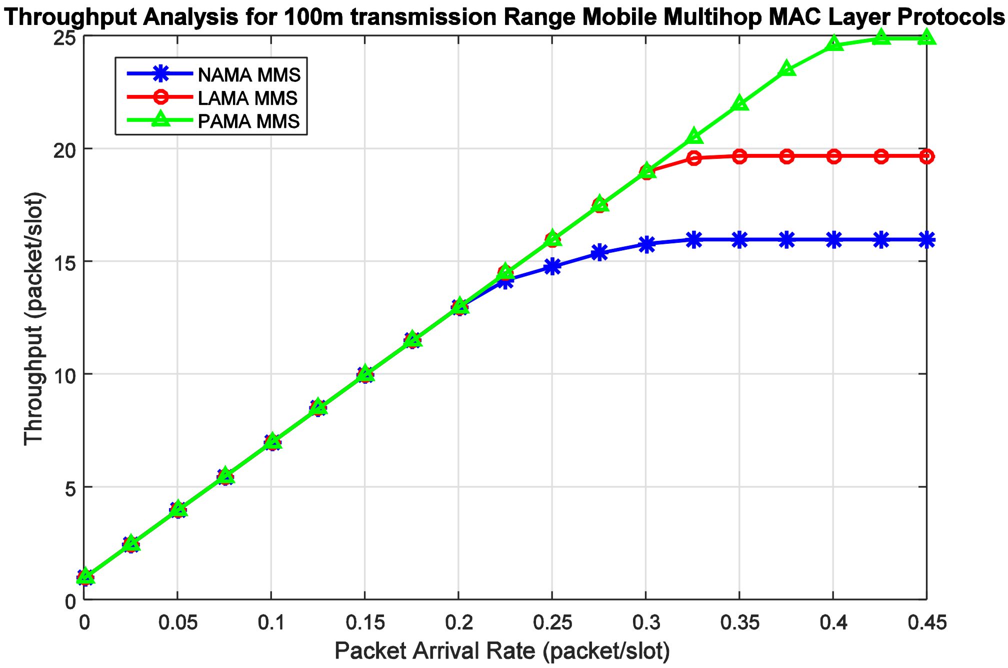

Figure 5.12: Throughput of MMS for transmission range 100m

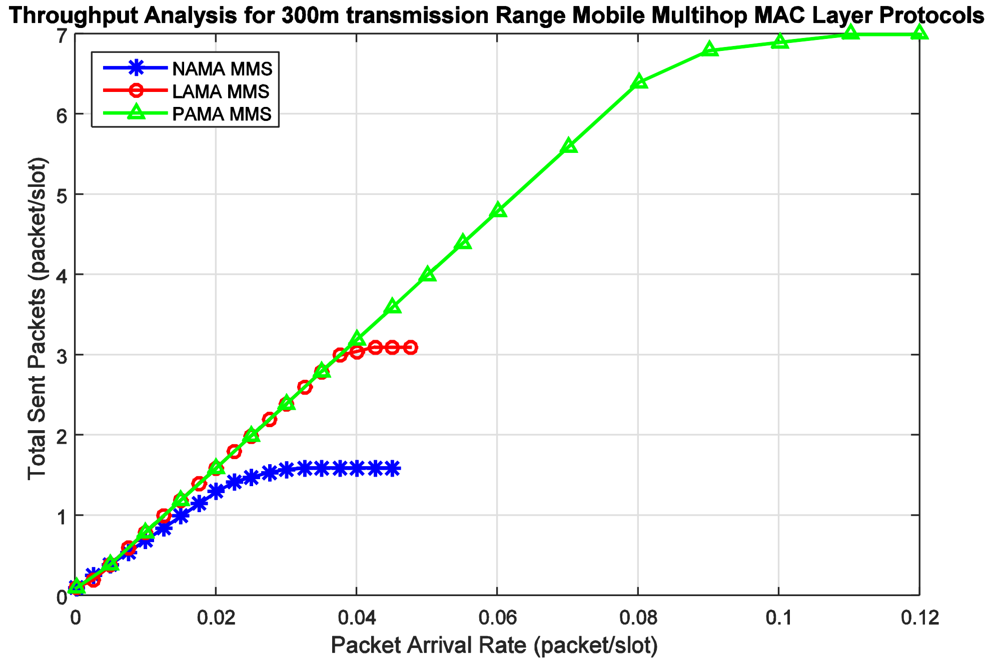

Figure 5.13: Throughput of MMS for transmission range 300m

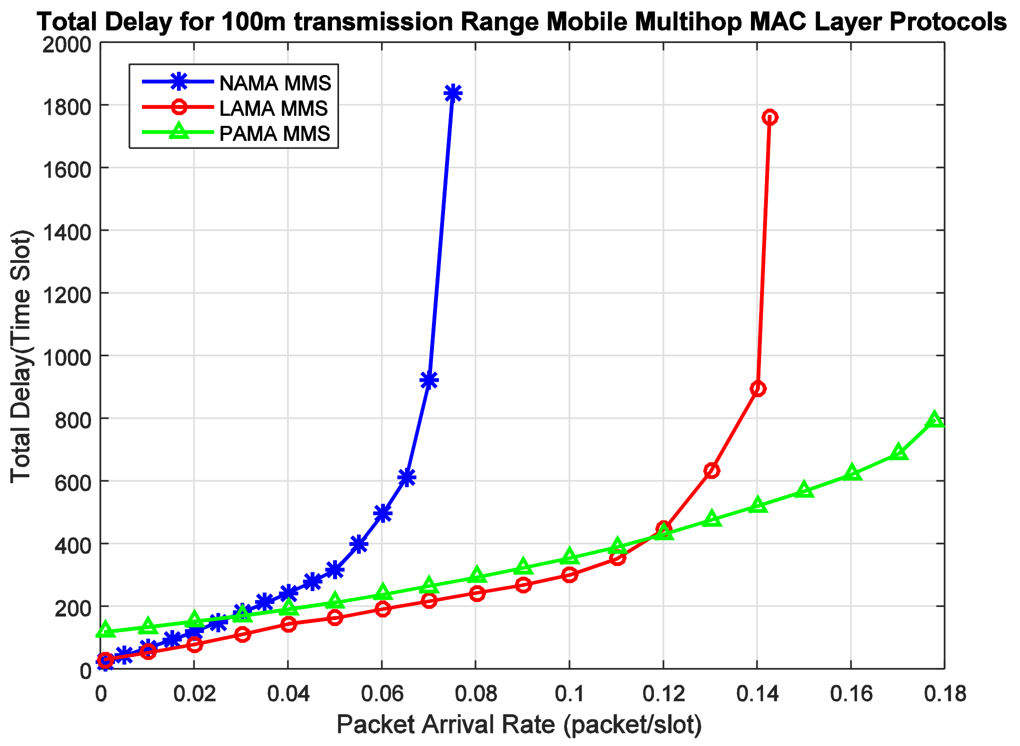

Figure 5.14: Delay analysis of MMS for transmission range 100m

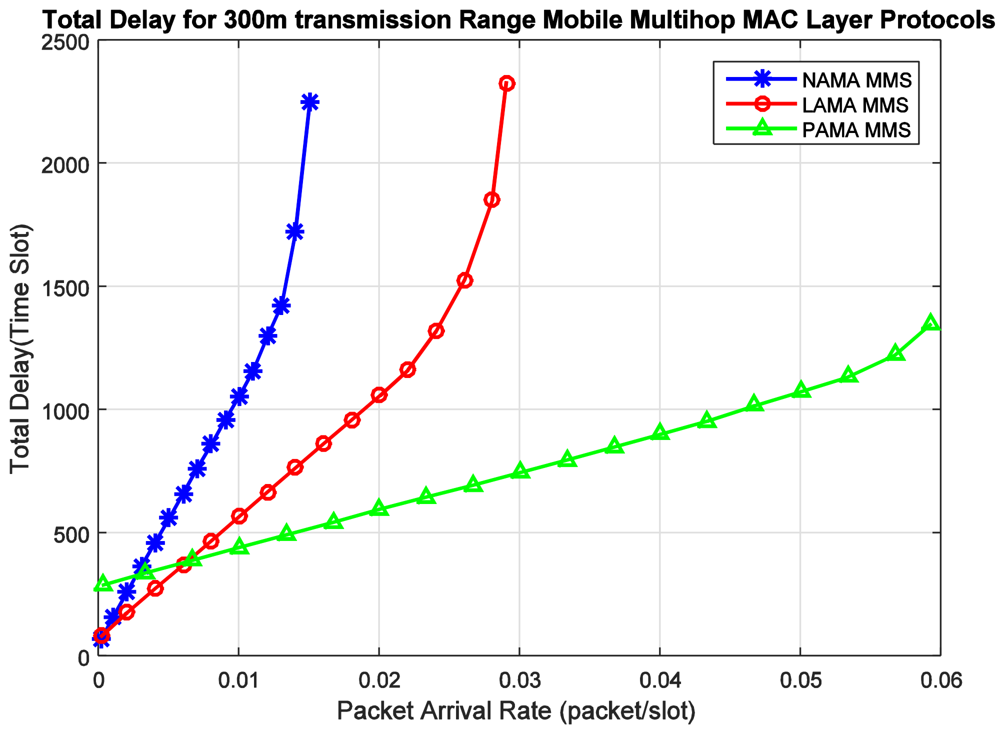

Figure 5.15: Delay analysis of MMS for transmission range 300m

Figure 5.16 and Figure 5.17 show the throughput performance comparisons between SMS and MMS; while, Figure 5.18 and Figure 5.19 show the delay performance comparison between them.

Throughput results can be evaluated in two sections: low and high packet arrival rates. In low packet arrival rate case, multi-hop scenario gives better results than mobile scenario. FIFO queues are not filled fully in this situation. Contention is low in general and mobility brings some extra effort to set up neighborhood relation repetitively at each time slot which increases delay and decreases throughput. As arrival packet ratio increases, MMS intercepts SMS performance and exceeds it at the end. Main reason causing this result is, in SMS, nodes may stacked into smaller region, positions of which are randomly assigned, and this increases contention for that region and decreases throughput performance of whole system.

Looking delay performance comparison, for all packet arrival rates, the delay observed in SMS is lower than those in MMS. Time to establish neighborhood relation at every time slot; increases delay level in MMS remarkably.

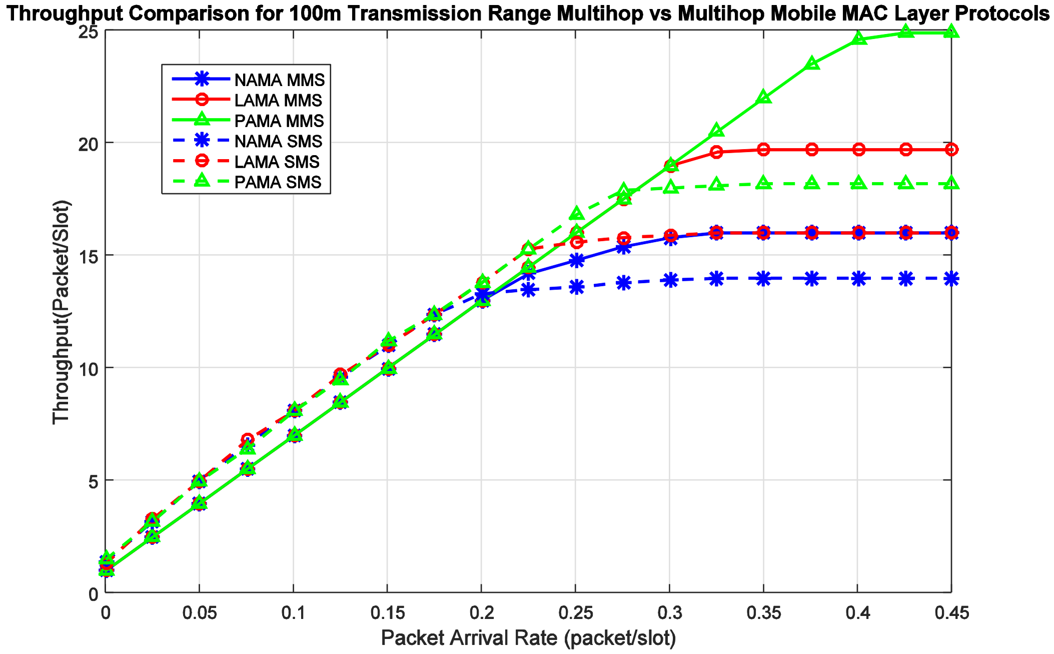

Figure 5.16: Throughput comparison of SMS vs MMS for 100m transmission range

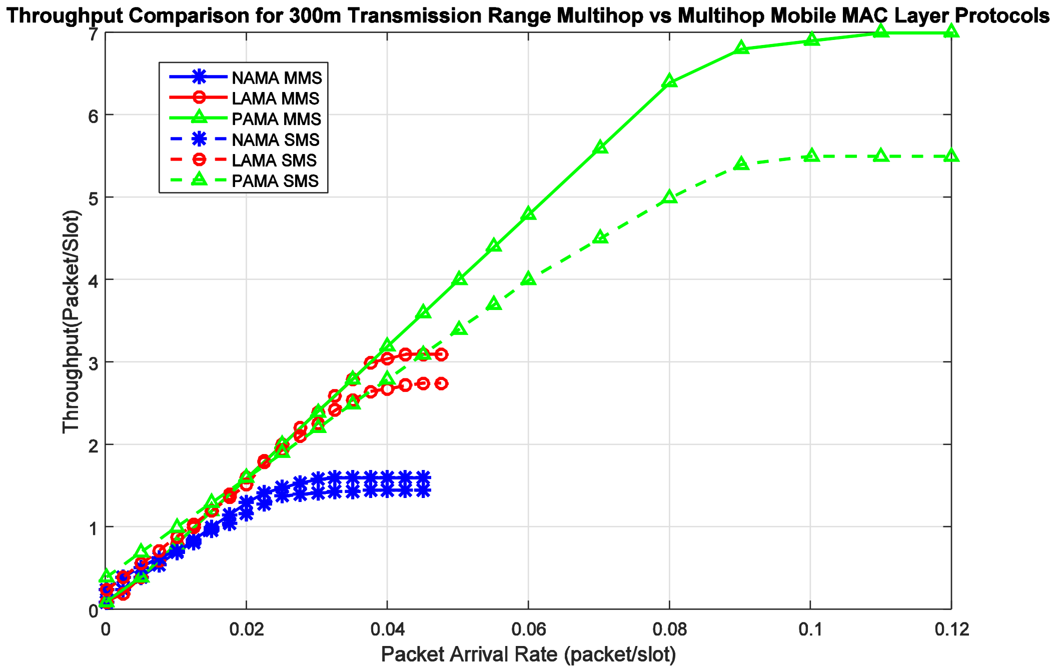

Figure 5.17: Throughput comparison of SMS vs MMS for 300m transmission range

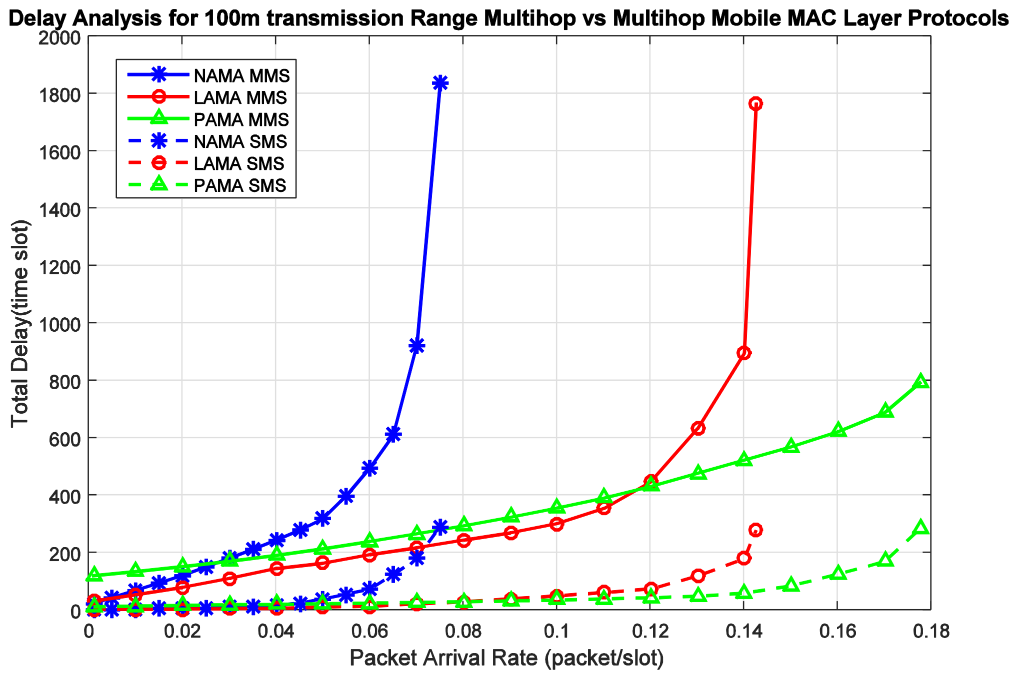

Figure 5.18: Delay comparison of SMS vs MMS for 100m transmission range

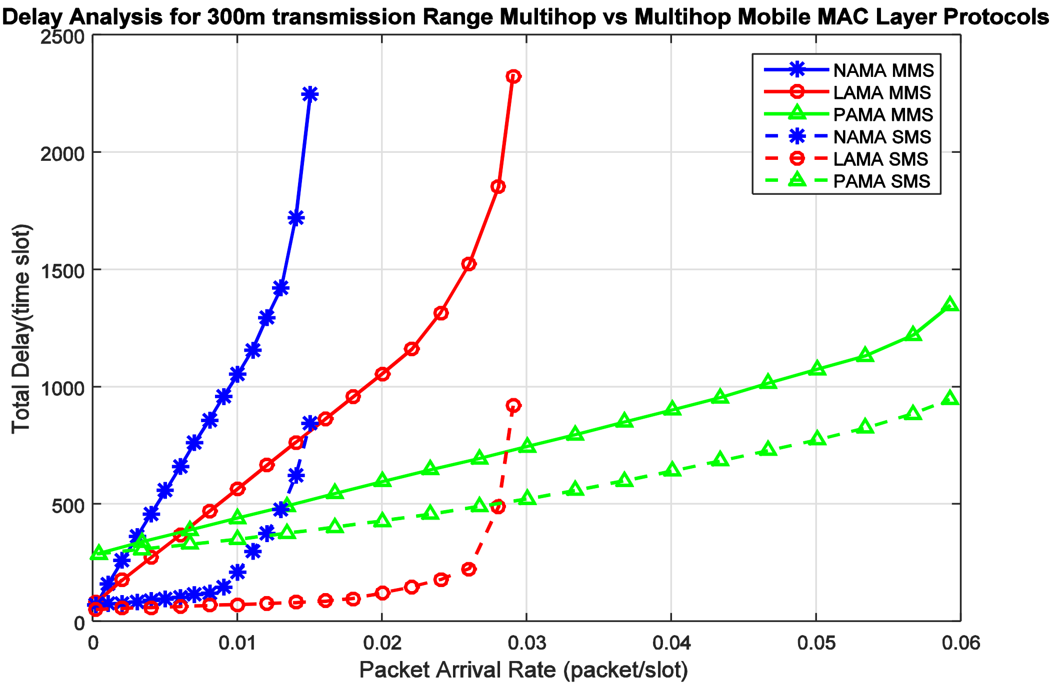

Figure 5.19: Delay comparison of SMS vs MMS for 300m transmission range

In Figure 5.20 and 5.21 throughput levels of MAC layer protocols under two different mobility levels are given. For both levels, nodes have pseudo random movements from their original locations. This random movement satisfies different acceleration and velocity to each node at each time slot. Random movement occurs in two dimensions. For MMS Level 1, nodes may change their location in both directions of [±5m] while for MMS Level 2 they have [±10m] location change in both directions. Throughput of MMS Level 1 reaches steady state earlier than MMS Level 2 since nodes may stacked into smaller region for a longer time in MMS Level 1 with respect to MMS Level 2. This causes higher throughput in MMS Level 2.

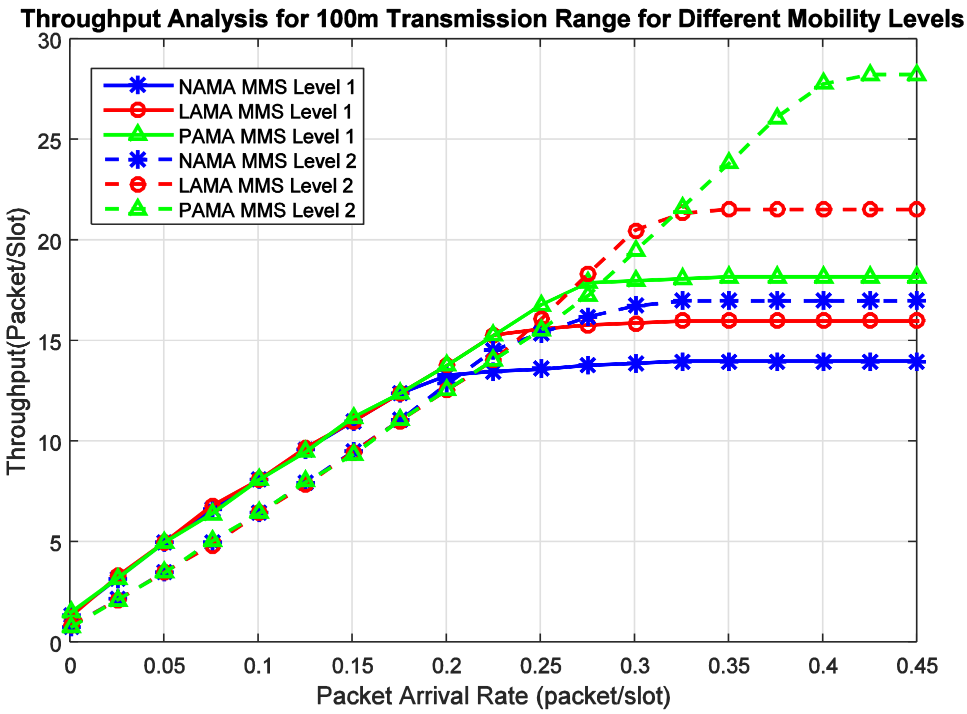

Figure 5.20: Throughput comparison of MMS for different mobility levels of nodes with 100m transmission range

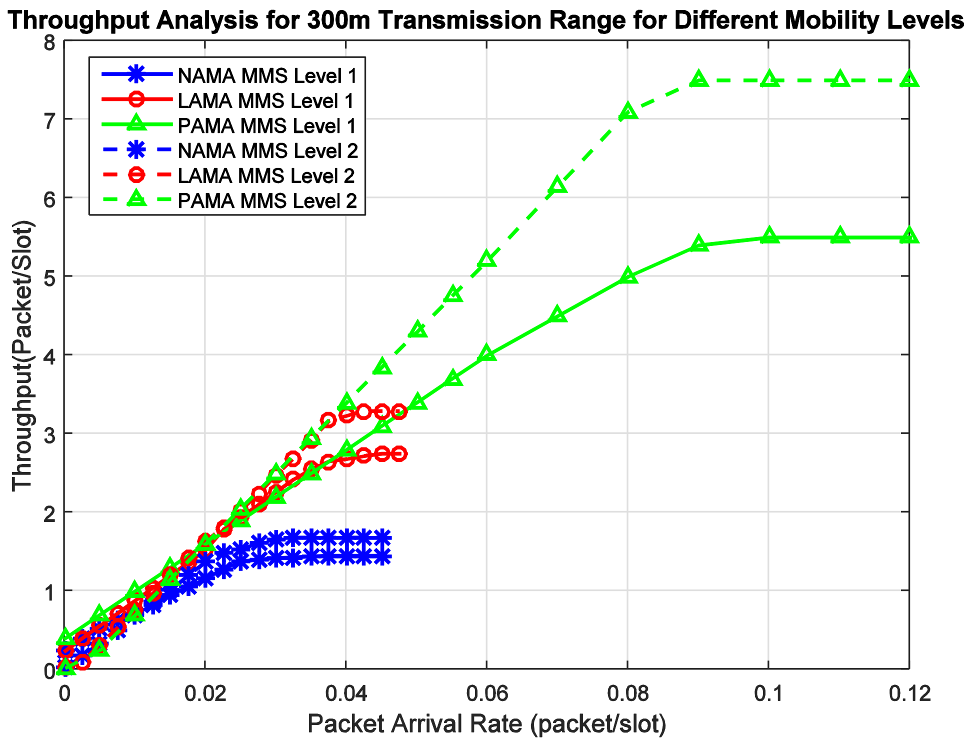

Figure 5.21: Throughput comparison of MMS for different mobility levels of nodes with 300m transmission range

Delay characteristics of three MAC layer protocols under two different mobility levels are exhibited in Figure 5.22 and Figure 5.23. Mobility of nodes in MMS Level 2 is higher than the other scenario which concluded with worse delay performance. Increase in delay is an expected result; since, setting up a neighborhood relation for an organized network becomes harder and time to send packets increases as the topology gets more mobile.

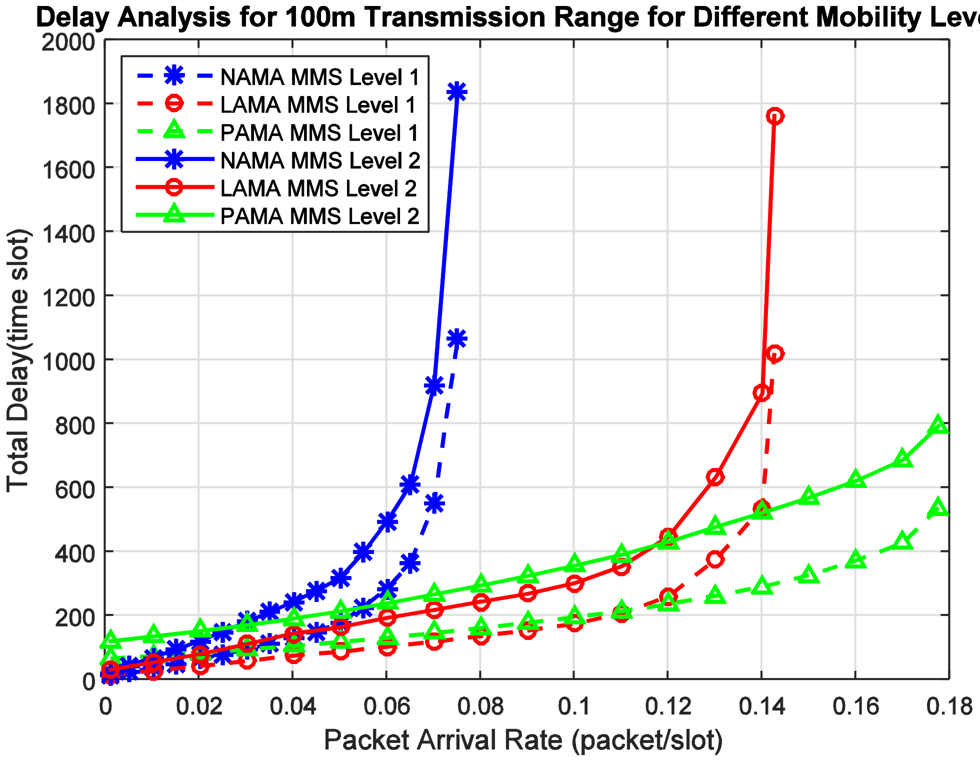

Figure 5.22: Delay comparison of MMS for different mobility levels of nodes with 100m transmission range

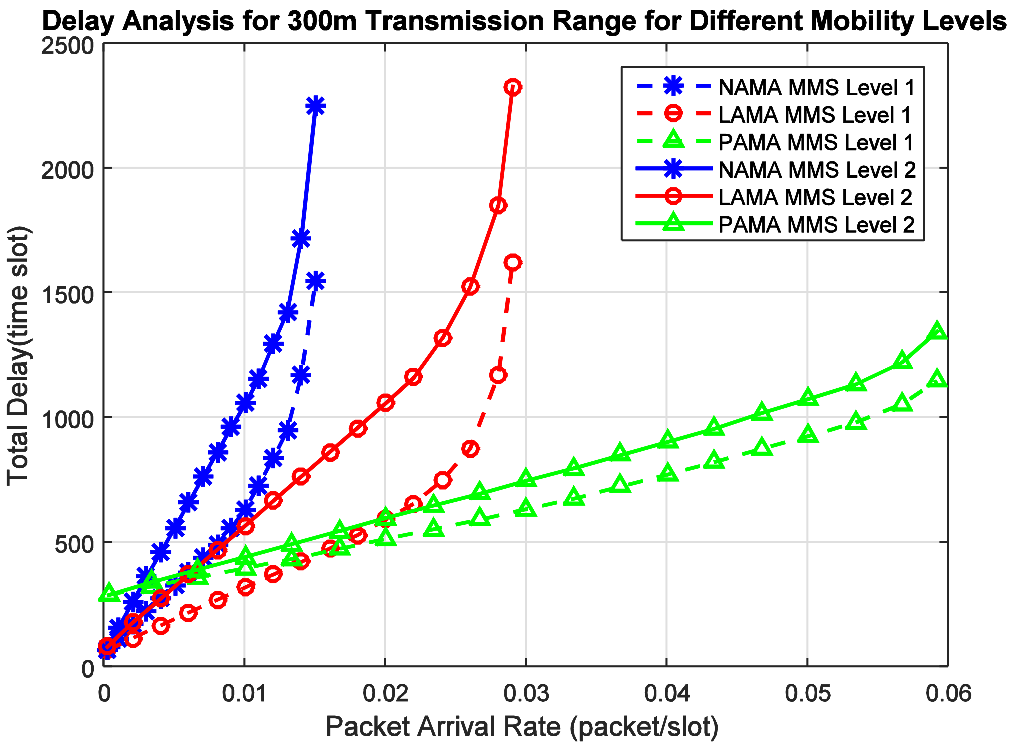

Figure 5.23: Delay comparison of MMS for different mobility levels of nodes with 300m transmission range

Each result shown above are handled by running the simulation software 10 times to reduce the impact of randomness. But, since each simulation runs for 50000/100000 (FCS/ MMS and SMS) time slots, there is a very small difference among each simulation result in range [%±5 difference].

5.5 COMPARISON WITH EXISTING RESULTS

In this part of study, a comparison between simulation results and theoretical results [7] is demonstrated.

In Figure 5.24, the top two graphics are theoretical results of throughput and delay of FCS for 5 nodes. When packet arrival rate 0.2 packet/slot and further, throughput approaches 1. This means at each time slot, a packet (0.2 packet per slot x 5 nodes = 1 packet/slot) exists to be transmitted. In the delay graphic, as arrival packet rate approaches 0.2 packet/slot, delay of the system increases significantly. Since each time slot becomes fully loaded with transmission packets, there is no free slot to be filled for the new packets.

The remaining two graphs are acquired from our simulation results which seem consistent with the theoretical results. When packet arrival rate is 0.2 packet/slot, throughput value begins to approach 1. If we compare with the theoretical results, simulation result approaches to 1 a little later but smoother. It is considered to result from the simulation environment and not fully ensure the environment conditions. Comparison of delay performances of them matches well.

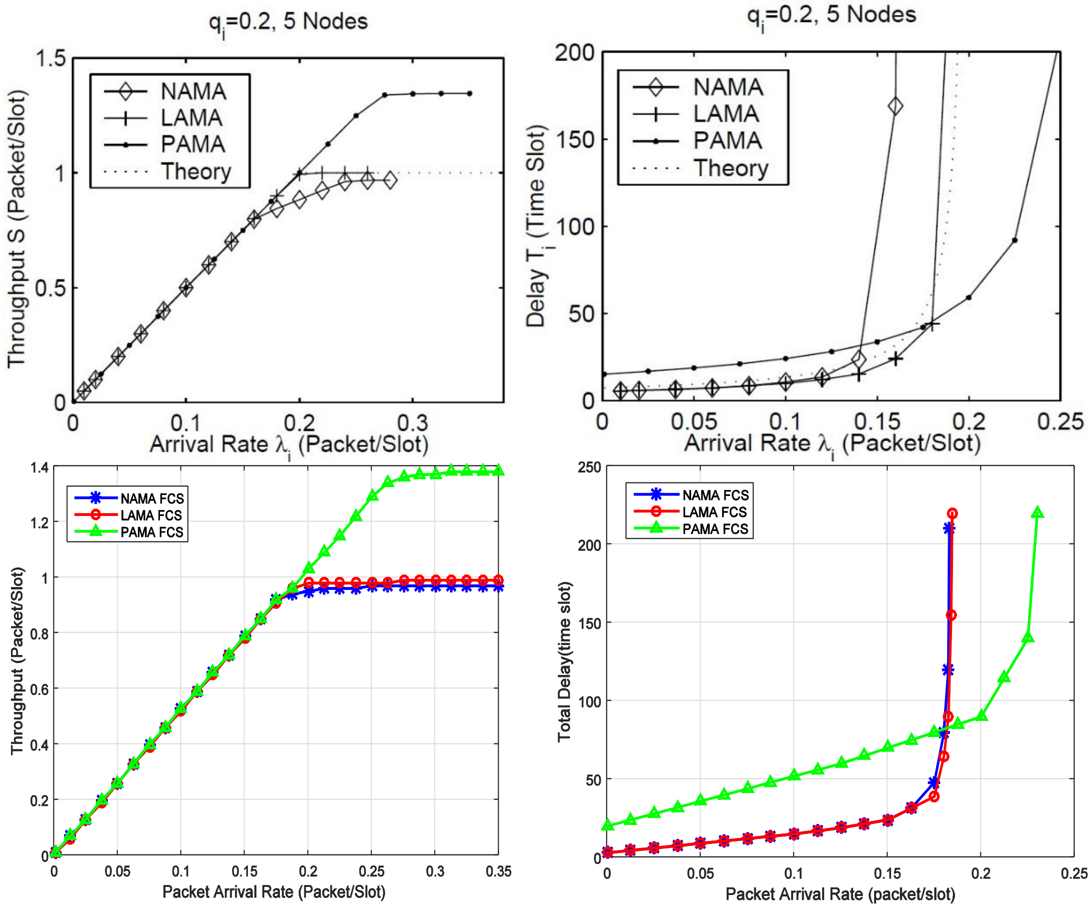

Figure 5.24: Throughput and Delay comparison of FCS for 5 nodes

Besides Figure 5.25 give comparison results of throughput and delay performances of FCS with 10 nodes. In a similar manner, delay and throughput characteristics of simulations are consistent with theoretical results. Main difference from 5 node comparison is that throughput and delay reach steady state at 0.1 packet/slot instead of 0.2 packet/slot since a time slot is shared between 10 nodes instead of 5 nodes.

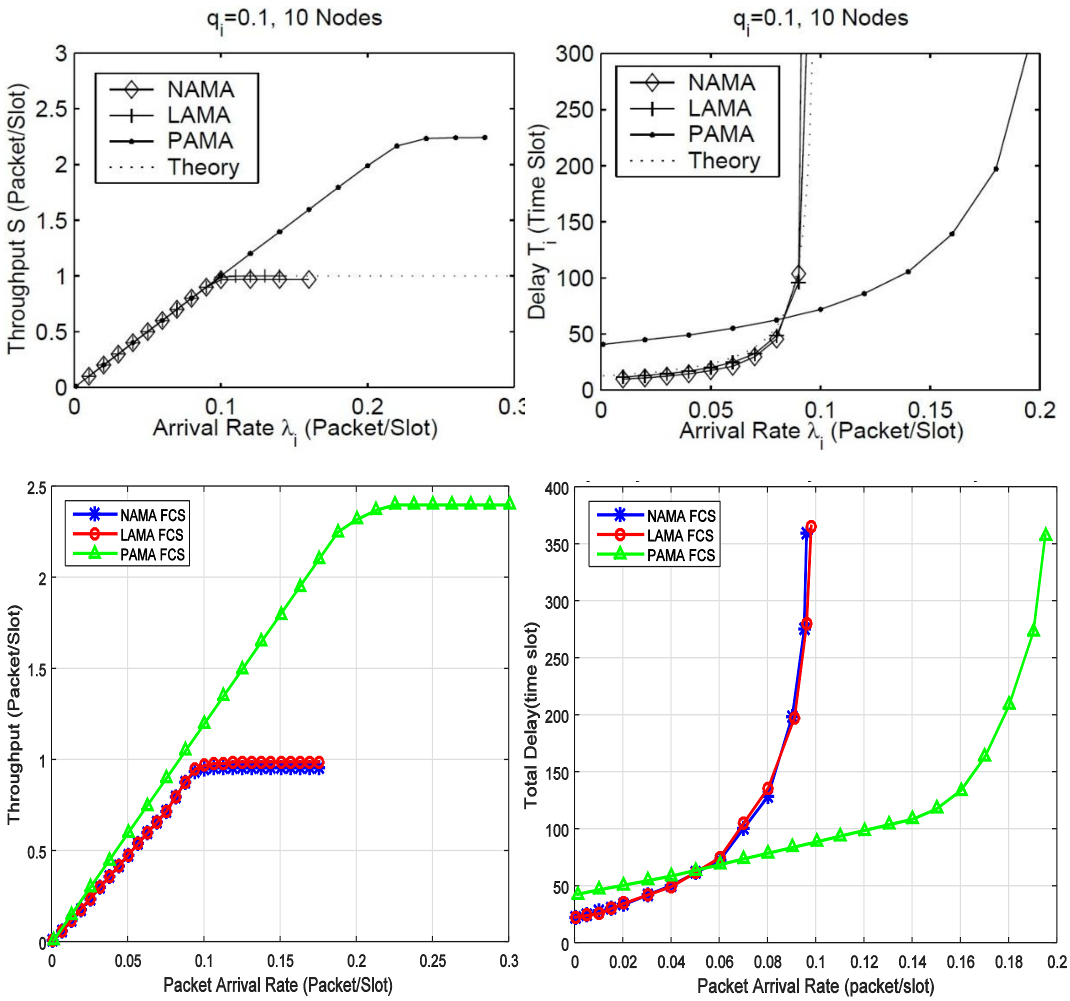

Figure 5.25: Throughput and Delay comparison of FCS for 5 nodes

The comparison of simulation results with theoretical results for SMS are listed in the figure below. Throughput value in the simulation reached steady state earlier than theoretical values. This can be explained by differences in the simulation environment. According to the figure, it can be concluded that, under the same assumptions, simulation results are analogous with theoretical ones.

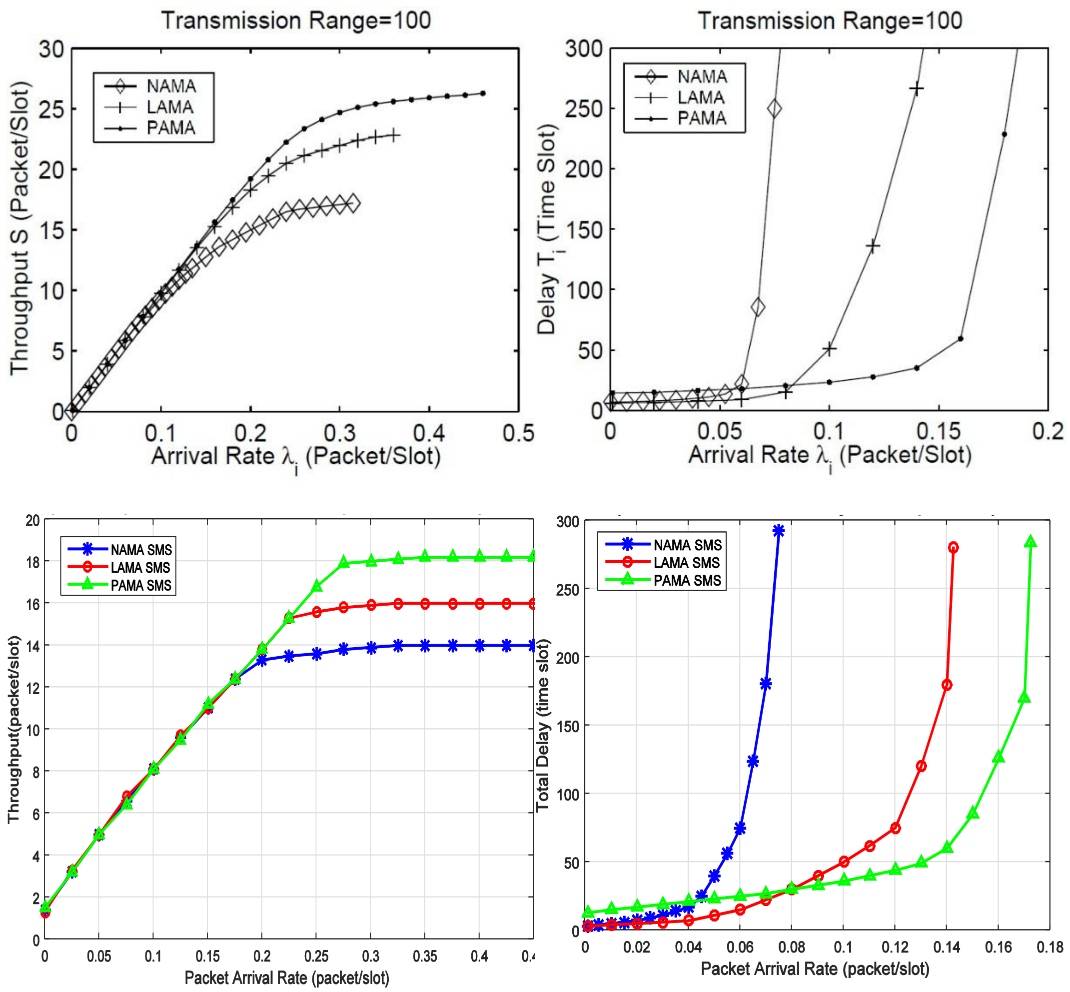

Figure 5.26: Throughput and delay comparison of SMS for 100m transmission range

When Figure 5.27 is examined, similar conclusions can be made as Figure 5.26. As expected, throughput value decreases as compared to SMS for100m transmission range. Delay performance become worse when transmission range of nodes increase which results more competitors for the shared resource.

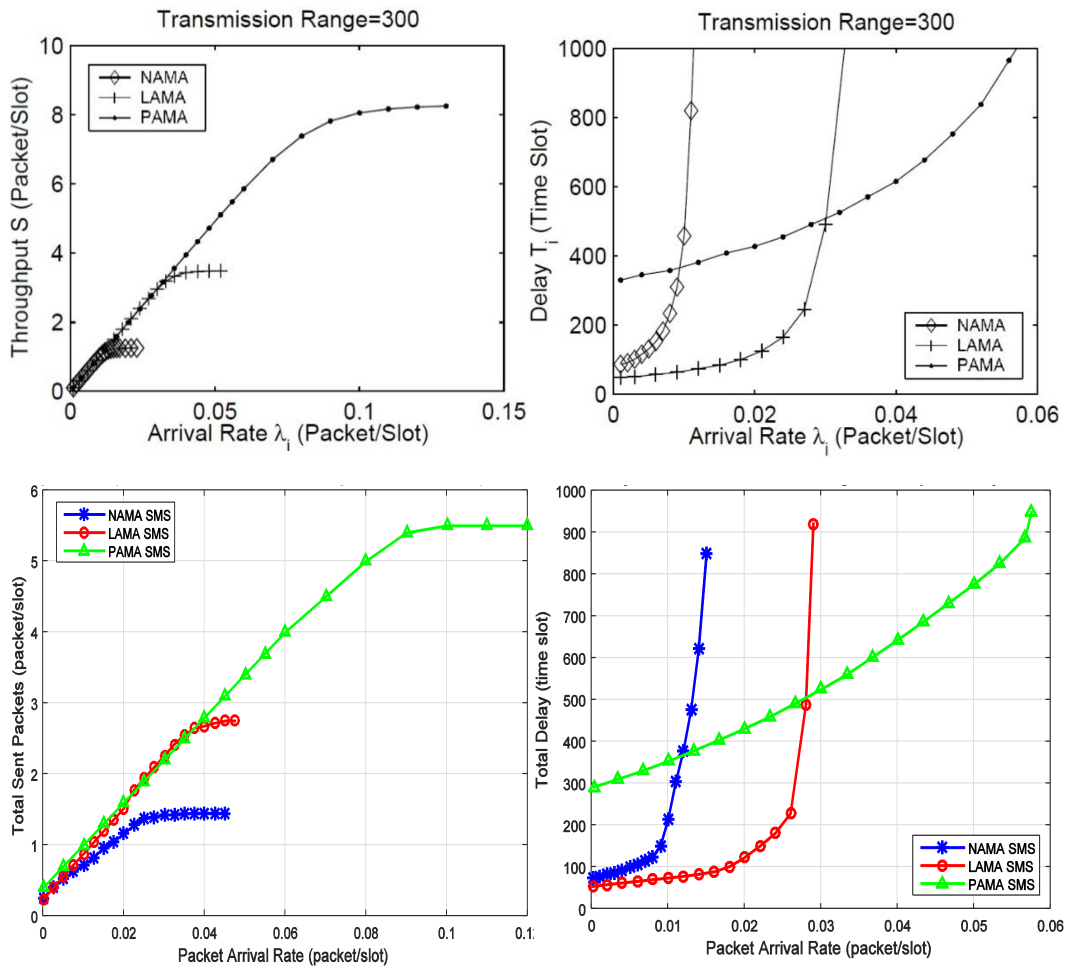

Figure 5.27: Throughput and delay comparison of SMS for 300m transmission range

In the table below, quantification of differences between existing results and simulation results exist. In the measurements, steady state values of both results are referenced for quantification.

Table 5.2: Quantification results

Scenario	Throughput			Delay		
	NAMA	**LAMA**	**PAMA**	**NAMA**	**LAMA**	**PAMA**

FCS 5 nodes	±[%0.5]	±[%0.5]	±[%1.5]	±[%15]	±[%15]	±[%17]
FCS 10 nodes	±[%0.5]	±[%0.5]	±[%10]	±[%4]	±[%4]	±[%10]
SMS 100m	±[%18]	±[%25]	±[%28]	±[%7]	±[%7]	±[%9]
SMS 300m	±[%18]	±[%19]	±[%30]	±[%18]	±[%9]	±[%10]

Detailed results are not available for mobile scenarios in the literature. Hence, a fair comparison with the results obtained in this thesis cannot be made.

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

Contention resolution is a challenging problem in ad-hoc networks. This thesis evaluates three MAC layer protocols to overcome the difficulties of quality of service (collision free communication), hidden terminal and exposed terminal problems for ad-hoc networks. With two hop neighborhood information in MAC layer protocols NAMA, LAMA and PAMA; the common resource can be allocated to one or more selected nodes/links at each contention context namely at each time slot. Using these protocols, channel access is assigned to nodes in case of schedule-based scheme. Therefore, troubles of contention-based medium access protocols could be avoided.

NAMA, LAMA and PAMA protocols are applied to different scenarios: FCS, SMS and MMS.

For FCS, effects of node number on throughput and delay characteristics are observed. When node number increases, throughput and delay reach their steady state values earlier, due collective resource sharing. Another observation is that, PAMA exhibits different characteristics than NAMA and LAMA, since link activation method (priorities are assigned to links) used in PAMA allows multiple links to be activated at the same time which causes greater channel capacity.

Analyzing SMS gives results about effect of transmission range of nodes, channel reuse on throughput and delay performances. When channel reuse increases (highest in PAMA) under high packet arrival rate, throughput performance get better and delay decreases. Increase in transmission range results higher delay and lower throughput values. MMS gives similar results for same variables.

Also SMS and MMS scenarios are compared in terms of their throughputs and delay performances. The throughput comparison analysis shows that, they have almost same throughput result but delay performance of SMS protocol is much better than MMS. In general NAMA and LAMA protocols have better performance under sparse loads while PAMA protocol has a better performance under heavy loads.

Another comparison is made between existing results and simulation results. Quantification is made between these results and they seemed consistent.

These MAC layer protocols using NCR have many advantages over other channel access scheduling algorithms for ad-hoc networks. They need only two-hop neighborhood information and this information is gathered from the broadcasted messages to one-hop neighbors while some other algorithms need whole topology information. The common resource is shared fairly between the contender nodes and this avoids resource starvation for the nodes. Also these protocols do not need any contention stage i.e. they do not waste time in contention stage.

As future works, we expect to improve this research in the following areas: the effects of dynamically allocating the shared resource. Using dynamic allocation, priority of a node with higher message arrival rate starts to increase. Chance to win a contention and the probability to use the common channel increases due to dynamic allocation.

Comparing these algorithms with other channel access schemes is planned, and some different scenarios may be generated to simulate these algorithms.

The effects of directional antennas in place of omni-directional ones can be studied as well. Transmission ranges and directivities of nodes would change and this could be more realistic situation since using identical antennas is almost impossible.

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