THE IMPACT OF MAC SERVICE-TIME AND ROUTE DISCOVERY TIME ON PACKET QUEUING DELAY IN SATURATED AD HOC NETWORKS

A Thesis by

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The following faculty members have examined the final copy of this thesis for form and content, and recommends that it be accepted in partial fulfillment of the requirement for the degree of Master of Science with a major in Computer Networking.

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DEDICATION

To my parents and late sister

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ABSTRACT

This thesis presents a quantitative analysis of packet queuing delays in saturated DCF networks. It presents the relationship between medium access control (MAC) delays, routing delays, and the packet queuing delays, in terms of MAC service-time and route discovery time. The effects of network size and data transmission rates on the queuing delays were also analyzed. The simulations reveal that the MAC service-time affects the packet queuing delay in stationary networks; whereas the route discovery time along with the MAC service-time affects the queuing delays in mobile networks. Also, the average queuing delay increased with an increase in the network sizes and data transmission rates, especially for network sizes of 20 and more.

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LIST OF ABBREVIATIONS

AODV	Ad hoc On Demand Distance Vector
CA	Collision Avoidance
CBR	Constant Bit Rate
CSMA	Channel Sense Multiple Access
CTS	Collision To Send
CW	Contention Window
DCF	Distributed Coordination Function
DIFS	Distributed Inter-Frame Space
DSSS	Direct Sequence Spread Spectrum
EIFS	Extended Inter-Frame Space
MAC	Medium Access Control
MANET	Mobile Ad hoc Network
PIFS	Point Coordination Inter-Frame Space
QoS	Quality Of Service
RERR	Route Error
RREP	Route Reply
RREQ	Route Request
RTS	Request To Send
SIFS	Short Inter-Frame Space
TCL	Tool Command Language

CHAPTER 1

INTRODUCTION

Wireless Local Area Networks (WLANs) are the wireless equivalent of local area networks. With the emergence of real-time applications such as VoIP, interactive multimedia, and video streaming in mobile ad hoc networks (MANETs), the delay guarantees increasing demand. In order to optimize the delays associated with packet transmission processes at various layers of TCP/IP, it is necessary to model them and perform a thorough analysis of their dependencies in the network. Packet queuing delay is one of the important delay components in computer networks that must be studied for effective implementation of real-time services like VoIP and video streaming in wireless ad hoc networks. The importance of such studies increases in saturated ad hoc networks that contain the network nodes which always have a packet readily available to transmit at any point in time. These delays primarily depend on the medium access control (MAC) and network layer delays. Hence, it is important to study the effect of MAC delays and routing delays on the packet queuing delays.

This thesis presents a quantitative analysis of the impact of MAC and routing delays on the queuing delays in single hop saturated ad hoc networks. The effect of MAC frame service-time and the route discovery process on packet queuing delay is analyzed for varying network sizes and data rates. The simulations required for supporting this analysis was conducted on the network simulator-2 (ns-2) for both stationary and mobile networks. The simulation results reveal that an increase in the MAC contention (network size) has a dominating effect on stationary networks, whereas mobility has a dominating effect on mobile networks. The increase in network size and data rates further increased the queuing delays.

The remainder of this thesis is organized as follows. Chapter 2 presents a literature survey for this research. Chapter 3 presents the analytical model for packet queuing delays in saturated ad hoc networks. Chapter 4 presents the simulations, their results and their analysis. Chapter 5 concludes this thesis.

CHAPTER 2

LITERATURE SURVEY

This chapter presents the literature survey on MAC and routing protocols for wireless ad hoc networks in the following three sections.

2.1 MAC Protocols

The MAC layer basic services include asynchronous data services and optional real time services. These services can be offered by the help of different types of inter-frame spacing (IFS). IFS refers to the time interval between the transmissions of two successive frames by any node. There are four types of IFS: SIFS, PIFS, DIFS and EIFS. SIFS is the shortest and EIFS is the longest. The priority is high to low when we move from SIFS to EIFS. SIFS (Short IFS) is used for the acknowledgement of data frames and polling responses. PIFS (PCF IFS) is the waiting time between SIFS and DIFS. It is normally used for real time services. DIFS (DCF IFS) is used under the DCF mode to transmit data. This is normally used for asynchronous data transfer in the contention based network. EIFS (Extended IFS) is used for resynchronization when the physical layer detects incorrect MAC frame reception. The commonly used access method in IEEE 802.11 is Distributed Coordination Function (DCF).

CSMA/CA and CSMA/CA with RTS/CTS are two access protocols in IEEE 802.11. In CSMA/CA, each node senses the medium before initiating the transmission to see if any other node is transmitting. If the medium is idle for a time period that exceeds DFIS, the node proceed with transmission. If the medium is busy, then the node postpones its transmission until the completion of the current transmission. The Node will initiate a backoff interval before starting the transmission again. The Backoff timer will start by selecting the backoff interval. This interval is chosen randomly from [0, CW]. CW stands for contention window. When the medium is idle, the value of the backoff timer starts to decrease, but if the medium is busy, then the backoff timer freezes. If the medium remains idle longer than DIFS after a busy time, then the backoff time resumes, and this is the only condition when the backoff time resumes. When the backoff timer approaches zero, a node starts transmission. The Receiver will send a reply back to the sender in the form of an acknowledgement (ACK) after an SIFS if it received the frame successfully. Figure 1 shows this mechanism.

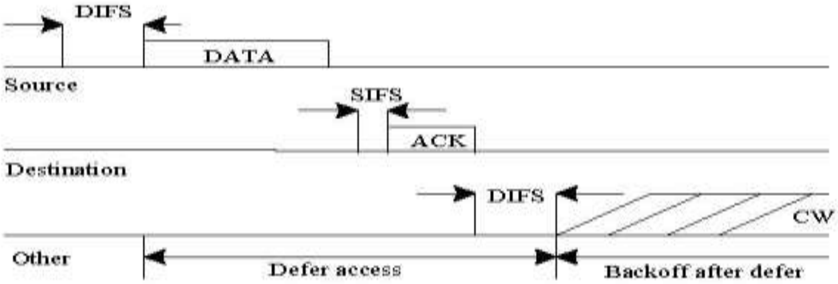

Figure 1. Basic Access Protocol CSAM/CA.

Before starting to send the data, a node will generate the broadcast of RTS in CSMA/CA with RTS/CTS protocol. This RTS frame represents how long the data frame will be in the coming transmission. When the destination receives RTS, it replies by broadcast of CTS, which also contains the length of data frames. Any node in the vicinity of source and destination hears RTS/CTS, and it stops their transmission long enough for the data frame to be transmitted. After successful RTS/CTS, the node starts transmission of data. Figure 2 depicts this mechanism.

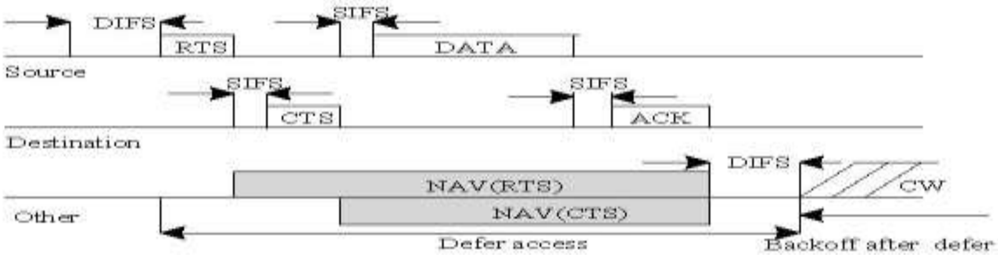

Figure 2. CSMA/CA with RTS/CTS protocol.

2.2 Routing Protocols

Ad hoc wireless network routing protocols can be classified into three major categories:

- Proactive or Table Driven: In these protocol types, every node maintains the network topology information in form of routing tables by exchanging routing information on a periodic basis.
- Reactive or on-demand: These types of protocol do not maintain the network topology information. They obtain the necessary path when required but do not exchange routing information on a periodic basis.
- Hybrid: These protocols combine the features of the above two.

One of most commonly used reactive protocols is Ad Hoc On-Demand Distance Vector (AODV). AODV is based on the Bellman-Ford algorithm. In AODV, the source node initiates a route discovery process if it does not have the route to a destination. The source node sends a broadcast called Route Request (RREQ) to its neighbors to find the route to the destination. Neighbors forward this broadcast to their neighbors until this broadcast reaches the destination or an intermediate node which has the route to the destination. Figure 3 shows this broadcast process.

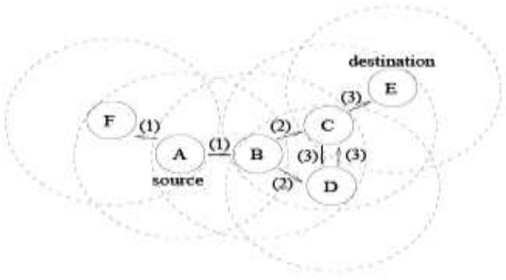

Figure 3 Flooding RREQs

In order to avoid loops in the routes and provide route freshness, AODV uses destination sequence numbers. Each node maintains its own sequence number and a broadcast ID. This broadcast ID is incremented each time a source node initiates the discovery process. The broadcast packet of RREQ is uniquely identified by the broadcast ID and the address of the source node. The RREQ also contains the latest sequence number that the source node has for the destination. In this way, intermediate nodes reply to RREQ only if they have the corresponding sequence number of the destination greater than or equal to what they get in RREQ. This leads to freshness of the route. The intermediate nodes save the address of neighbors from which they received the first copy of RREQ packet before forwarding the RREQ. They record the address of neighbors in their route tables. This helps them in establishing the reverse path. Intermediate nodes could receive a similar RREQ later because of flooding, but all would be discarded. Once the RREQ reaches the destination or an intermediate node that has the fresh route to the destination, the intermediate node or destination sends back the Route Reply (RREP) packet to the neighbor from which it first received the RREQ. RREP is unicast. All the nodes along the reverse path that RREP takes install forward route entries in their route tables. In this way, it helps avoid loops in routing. Figure 4 represents this process.

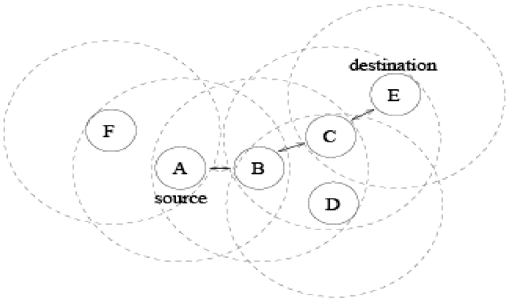

Figure 4. Establishment of route.

A timer is used to flush the unused routes in the routing table. If a node changes its location within a route, then its upstream neighbor notices this movement and generates a Route Error (RERR) message for each of its active upstream neighbors to inform them about this change. Each node that receives this RERR packet propagates it to their active upstream neighbors until the source node is notified. After that, the source node initiates the route discovery process again to find the route to the destination. Hello messages are also transmitted on a periodic basis to find link failures.

2.3 Analytical Studies on IEEE 802.11 DCF Protocol

An analytical model is presented by Tickoo and Sikdar [1] for characteristics of delay and queue length in IEEE 802.11 networks while considering random arrival patterns with nodes in arbitrary numbers. Their analysis provided a probability-generating function for delay and queue length that can be used for some real time applications like call admission control in a voice network. Their model can also be used to evaluate the number of connections which can be supported for a given delay. They extended their model for IEEE 802.11e, which is the QoS support to WLAN, and derived an expression of delay for such networks as well. They verified the results of their model through extensive simulations. They extended their model for finite load in [2].

Bianchi [3] proposed a model to compute throughput performance of the IEEE 802.11 DCF network. They presented the model for both schemes of DCF, i.e. basic CSMA/CA based access and CSMA/CA with RTS/CTS. They make an assumption of constant and independent collision probability of a packet transmitted by each node in the network irrespective of the number of retransmissions already suffered. They proved the accuracy of the assumption with the help of simulation.

Bisnic and Abouzeid [5] investigated how end-to-end delay and throughput in a random access based MAC multi-hop wireless network having stationary nodes depend on the number of nodes, the transmission range and the traffic pattern. A closed form expression to calculate average end to end delay and maximum achievable throughput is obtained by the help of a proposed queuing network model. They calculated queuing delays at source and intermediate nodes while assuming fixed size packets with a random arrival process. The simulations and numerical computations verified the analytical results.

Maode et al. [6] employ a Markov Chain model to analyze the probability of transmission at each node in an arbitrary slot and derive the wireless channel access delay. Wth the help of the proposed model, they evaluated the end-to-end average packet delay in the IEEE 802.11 unsaturated DCF network. They used the model to evaluate the delay in wireless ad hoc networks for both single hop and multi-hop scenarios.

The access delay is the time interval between the instant when the packet reaches the head of the transmission queue and begins contending for the channel, and the time when the packet is successfully received at the destination, according to Vu and Sakurai [8]. They feel that delay-sensitive applications like VoIP will also be running on WLAN in the near future so there should be some performance model available that could evaluate delay characteristics. They obtained an expression by making a stochastic model of DCF for access delay. They derived explicit formulae for the mean, the standard deviation and the generating function. It is possible to obtain all moments of access delay by using this generating function.

The service time distribution for IEEE 802.11 DCF with a RTS/CTS access method is studied by Abdrabou and Zhuang [4]. They have shown that the distribution of the number of packets successfully transmitted over a time interval from any of the active nodes in a saturated ad hoc network follows a general distribution which is closed to Poisson distribution. They illustrated that service time distribution, with its near memory-less behavior and discrete nature, can be approximated by geometric distribution. The queuing model based on the discrete time queuing system (M/Geo/1) is proposed by them for the IEEE 802.11 saturated single hop ad hoc networks. They argued this because the probability distribution of the number of packets in the queuing system for the real situation is closely related to M/Geo/1 queuing system.

Kadiyala et al. [16] analyzed the impact of variations in MAC delays on packet service time in saturated ad hoc networks and also derived the lower and upper bounds of packet service time in these networks. They observed the increase in collisions and cross transmissions by increasing the number of contending nodes in the network. Due to these reasons, the average number of transmissions for successful delivery of packets is increased, which in turn, increased the packet service time. According to their simulation results, retransmissions and cross transmissions are high in the case of saturated networks.

In a mobile environment, the changing of the queue is different from those in static conditions, according to Ping and Peiyan [9]. They listed a mathematical model based on M/M/1 queuing and Poisson distribution to calculate the queuing delay in MANET.

The average service time and jitter of a packet observed in the saturated ad hoc network of IEEE 802.11 is computed by Carvlaho and Garcia [7] with the help of an analytical model. Their model is for single hop ad hoc networks under ideal channel conditions with a RTS/CTS based DCF scheme. Their model is unique as compared to others because they do not assume fitted distribution but use the bottom-up approach and build the first two moments of the node’s service time based on the IEEE 802.11 binary exponential backoff algorithm. They conducted a performance evaluation of average service time and jitter for a node for the Direct Sequence Spread Spectrum (DSSS) and the Frequency Hopping Spread Spectrum (FHSS) physical layer specifications. They verified their model through extensive simulations.

Blocking of transmission due to finite buffering capacity is an important field of study. According to Zeng and Chlmatac [10], increasing the capacity of the queue to get rid of blocking is not an acceptable feature, because it will create additional queue delay. In this way, it will seriously impact the multimedia applications that have strict time constraints. They established a finite queuing model for MAC protocol in IEEE 802.11 WLANs and evaluated its performance in terms of blocking probability and mean delay.

Wang et al. [11] have shown the relationship between node transmission probability to delay performance. They determine the probability mass function of the delay between any two consecutive successful transmissions. They show how nodes can minimize the delay by carefully choosing the packet transmission probability. They presented numerical results that demonstrate the existence of an optimal transmission probability that each node chooses in order to maximize the probability for achieving a target delay. Such an optimal transmission probability approach can be further extended to control the end-to-end delay in an IEEE 802.11 ad hoc network.

In order to provide estimation for throughput and end-to-end packet delay in single hop and multihop IEEE 802.11 networks under all loading conditions, Khalaf and Rubin [12] provided a simple analytical model. Their model used a regenerative approach based on CSMA approximation to calculate throughput. For the calculation of end-to-end delay, they used both the regenerative approach to calculate the packet service time and an M/G/1 approximation to calculate the packet waiting time in the queue.

Xie et al. [13] obtained closed form expressions for packet delay, the delay jitter and packet loss probability of IEEE 802.11 DCF in multihop ad hoc networks by proposing an analytical model. According to their analytical results, the increase in the maximum retransmission number of one node decreases its packet loss probability but has little influence on its delay and delay jitter and on the performance of other nodes. They found that an increase in the minimum contention window of tagged node increases their packet loss probability with a decrease in packet loss probability of other nodes, but it has little impact on the delay and the delay jitter of other nodes. They validated the analytical results by simulations.

Li et al. [15] provided a model to evaluate throughput, delay and fairness in IEEE 802.11 wireless networks. Their model is unique in comparison with previous models as it obtains these three metrics all together. They considered the fact that the packet may be dropped after a finite number of retrials, but previous models assumed infinite retrials for a given packet and thus led to overestimation of throughput and packet delay.

An analytical model to calculate the average number of collisions and the average packet delay in IEEE 802.11 wireless ad hoc networks under VoIP traffic is presented by Barcelo et al. [14]. Their model can be used to predict the impact of different configuration parameters (codec, packetization interval, and data rate) in the delay. Their simulation results show not only the configuration parameters, but also the distribution of the nodes' VoIP packet generation times in a packetization interval that modify the packet delay.

The impact of the route discovery process on the end-to-end delay that a packet is faced in IEEE 802.11 DCF network is studied by Kadiyala and Pendse [17]. They observed that MAC layer affects the route discovery process which then affects the end-to-end packet delay.

From the three sections above it is clear that the prior research on queuing delays primarily focused on a specific layer of TCP/IP stack. The impact of medium access delays on the queuing delays at the routing layers, and the overall queuing delays at an ad hoc node were not previously analyzed. It is very important to study the dependencies of the queuing delays in ad hoc networks to minimize the queuing delays and to develop new algorithms for faster and more effective communication in the network. In this thesis, the overall queuing delays are modeled in terms of MAC and routing delays. The dependency of the queuing delay on the MAC delays is thoroughly analyzed.

CHAPTER 3

ANALYTICAL MODEL FOR QUEUING DELAYS

This chapter analyzes the packet queuing delays in stationary and mobile ad hoc networks. The frame service-time at MAC layer, route delays, and queuing delays at network and MAC layer together constitute the packet service-time at an ad hoc node as discussed in the following subsections. Furthermore, the lower and upper bounds of queuing delays in ad hoc networks are analyzed.

3.1 For Stationary and Mobile Ad Hoc Networks

In a stationary network, the routing delays are negligible compared to the MAC delays, once a route between source and destination nodes is established. The MAC delay depends on the average number of transmissions n_{tr} required for the successful delivery of the frame. Let T_{uRTS} and T_{sRTS} be the time spent in unsuccessful and successful frame transmissions, respectively. $E[BO_j]$ represents the expected value of the backoff-interval for j^{th} transmission, and $E[CT_j]$ represents the expected value of time spent in cross-transmissions. Then, the expected value of backoff intervals are given by [16]

$$E[BO_j] = 2^i CW_{min}/2, 0 \leq j \leq m \qquad (1)$$

where m is the highest backoff stage for the frame transmission.

$$T_{uRTS} = DIFS + RTS + \mu + E[BO_j] + E[CT_j] \qquad (2)$$

$$T_{sRTS} = DIFS + RTS + CTS + DATA + ACK + 4\mu + 3SIFS + E[BO_j] + E[CT_j] \qquad (3)$$

Therefore, the average MAC delay d_M is given by [16]

$$d_M = [(n_{tr} - 1) \text{ x } T_{uRTS}] + T_{sRTS} \qquad (4)$$

$$d_M = (n_{tr} - 1)\,(DIFS + RTS + \mu) + [DIFS + RTS + CTS + DATA + ACK + 4\mu$$

$$+ 3SIFS] + \sum_{j=0}^{(n_{tr}-1)} (E[BO_j] + E[CT_j]) \qquad (5)$$

Suppose that there are *i* packets in a queue. Then, the average queuing delay $d^s_{Q(i)}$ in stationary ad hoc networks is given by [16]

$$d^s_{Q(i)} = (i - 1) \text{ x } d_M \qquad (6)$$

Therefore, the frame service-time $d^s_{ST(i)}$ at an ad hoc node is [16]

$$d^s_{ST(i)} = i * d_M \qquad (7)$$

In mobile networks, the nodes discover a new path to the destination after the route failures, and then initiate data transmission. The time spent in successful route discovery is known as route discovery time. If d_{rq} is the time spent in a successful delivery of the route request (RREQ) packet and $d_{rrepTout}$ is the timeout period for the route reply (RREP) packet, then the route discovery time d_{RD} is given by [16]

$$d_{RD} = (d_{rq} + d_{rrepTout}) \text{ x } n_{RD} \qquad (8)$$

where n_{RD} is the average number of route discoveries required to be initiated for successful discovery of a path to the destination.

Because the other routing delays in mobile ad hoc networks are negligible compared to route discovery time, the routing delay essentially comprises of route discovery time. Suppose that there are *i* packets in the queue, and *x* packets required route discovery process to be initiated. Then, the queuing delay for i_{th} packet is given by [16]

$$d^m_{Q(i)} = x\,\{d_{RD} + d_M\} + (i - x - 1)\,d_M \qquad (9)$$

The packet service-time at the ad hoc node is given by [16]

$$d^m_{st(i)} = x\,\{d_{RD} + d_M\} + (i - x)\,d_M$$

Hence, the queuing delays of the i^{th} packet in the queue depends on the routing delays and MAC transmission delays of (i -1) packets in saturated ad hoc networks.

3.2 Lower Bound of Queuing Delay

In contention-less saturated networks with n_{tr} equal to one, the queuing delay for the first packet in the queue is equal to zero.

3.3 Upper Bound of Queuing Delay

When n_{tr} reaches the threshold $(m + 1)$ and $E[CT_j]$ is equal to infinity, the maximum bound of queuing delay for last packet in the queue becomes infinity. However, the minimum value for this upper bound can be derived by assuming $E[CT_j]$ to be zero. Therefore,

$$d_M = \text{m}\ (DIFS + RTS + \mu) + [DIFS + RTS + CTS + DATA + ACK + 4\mu$$

$$+ 3SIFS] + \sum_{j=0}^{m} (E[BO_j] \qquad (10)$$

For DSSS physical layer specification, maximum backoff stage (m) is equal to 5. By substituting this value of m in (10), we obtain the average MAC delay

$$d_M = [\ 5 * (DIFS + RTS + \mu)\ ] + (DIFS + RTS + CTS + 3SIFS + 4\mu$$

$$+ DATA + ACK) + [\ CW_{min}/2 + CW_{min} + 2CW_{min} + 4CW_{min}$$

$$+ \ldots\ldots\ldots\ ] \qquad (11)$$

The sum of expected values of various backoff intervals for different backoff stages in (11) is given by the sum of geometric series of $(m + 1)$ terms as shown below.

$$\Sigma\, E[BO] = CW_{min}/2 \ + \ \sum_{i=1}^{5} 2^{i-1} CW_{\min}$$

$$\Sigma\, E[BO] \ = CW_{min}/2 + CW_{min}\ [1\text{-}2^5 / 1\ \text{-}2]$$

$$= CW_{min}/2 + 31CW_{min} \qquad (12)$$

From (11) and (12), we have

$$d_M = [6 * (DIFS + RTS)] + 3SIFS + 9\mu + (CTS + DATA + ACK) + (CW_{min}/2 + 31CW_{min}) \qquad (13)$$

For instance, if $Min(d_{Q(max)})$ represents the lowest limit of upper bound, $d_{Q(max)}$ then by substituting value of d_M obtained from (13) in (9), we have,

$$Min(d_{Q(max)}) = (x * d_{RD}) + (l - 1) * [6 * (DIFS + RTS) + 3SIFS + 9\mu + (CTS + DATA + ACK) + (CW_{min}/2 + 31CW_{min})] \qquad (14)$$

where l represents last packet in the queue.

Hence,

$$0 \leq d_Q < d_{Q(max)}$$

CHAPTER 4

SIMULATIONS AND RESULTS

This section presents simulations and their results. The simulations were carried out on a network simulator-2 (ns-2) to analyze the variations of the packet queuing delay for variations in network size and mobility. The MAC and routing protocols used in the simulations were the IEEE 802.11 DCF protocol and AODV, respectively. The queuing delays were analyzed for both stationary and mobile nodes. TCL script files were used to simulate a single hop saturated DCF network and to input various values to ns-2. The simulation results were obtained as trace files which were analyzed to observe the output patterns and to draw conclusions. Shell scripts were used for analysis and computational purposes. Simulations ran for 100 sec. The default simulation parameters and their values are presented in Table 1.

TABLE 1

DEFAULT VALUES USED FOR SIMULATIONS

PARAMETER	**VALUE**
Physical Layer Standard	DSSS
CWmin	32
CWmax	1024
RTS	44bytes
CTS	38bytes
DATA	500bytes
ACK	38bytes
Slot-time	20μs
DIFS	50μs
SIFS	10μs
Routing Protocol	AODV
Node Transmission Range	250 mts
Channel Capacity	2 Mbps
Application Traffic Generator	CBR

4.1 Network Topologies

This section presents the stationary and mobile nodes network topologies that are created for simulations.

4.1.1 Stationary Nodes Network Topology

The network was set up in such a way that several nodes transmit Constant Bit Rate (CBR) traffic to a specific destination node; whereas this destination node acts as a source node and transmits a different flow of packets to another destination node. The network nodes are stationary.

In scenario one, the network consists of 10 network nodes out of which nodes 0 through 7 transmit CBR traffic to node 8, while node 8 transmits another CBR stream to node 9. Similarly, four more scenarios were simulated as described below. Scenario two consists of 20 nodes in which nodes 0 to 17 transmit CBR traffic to node 18, and node 18 transmits a different stream of CBR traffic to node 19. Scenarios three and four consist of 30 nodes and 40 nodes, respectively. The data transmission rates of 30k, 40k, 50k and 60k were used for all the four scenarios explained previously. Simulations were run with the DATA packet size of 500 bytes within the terrain area of 200 * 200 m^2. Further simulations were performed with the DATA packet size of 300 bytes within the terrain area of 500 * 500 m^2. Tables 2 through 5 represents the average values of queuing delays obtained from the above mentioned scenarios with the variations in DATA packet size and terrain area. These tables show the variations in queuing delay (in seconds) for different network sizes of 10, 20, 30 and, 40 nodes and for data transmission rates of 30, 40, 50, and 60 Kbps.

TABLE 2

THE QUEUING DELAYS FOR ALL FOUR SCENARIOS FOR A DATA RATE OF 30KBPS

NODES	AVERAGE DELAY(sec)	MIN DELAY(sec)	MAX DELAY(sec)
10	0.016502382	0	0.226007691
20	0.709289419	0	8.02081026
30	3.451560459	0	21.08768561
40	6.459625607	0	28.9732755

TABLE 3

THE QUEUING DELAYS FOR ALL FOUR SCENARIOS FOR A DATA RATE OF 40KBPS

NODES	AVERAGE DELAY(sec)	MIN DELAY(sec)	MAX DELAY(sec)
10	0.016629701	0	0.254516
20	2.300759761	0	14.351858
30	4.770919352	0	23.693757
40	5.622769661	0	24.55688341

TABLE 4

THE QUEUING DELAYS FOR ALL FOUR SCENARIOS FOR A DATA RATE OF 50KBPS

NODES	AVERAGE DELAY(sec)	MIN DELAY(sec)	MAX DELAY(sec)
10	0.0191795	0	0.362045
20	3.6340811	0	13.429939
30	4.8970236	0	18.748631
40	5.796631	0	23.903634

TABLE 5

THE QUEUING DELAYS FOR ALL FOUR SCENARIOS FOR A DATA RATE OF 60KBPS

NODES	AVERAGE DELAY(sec)	MIN DELAY(sec)	MAX DELAY(sec)
10	0.019093145	0	0.410828853
20	4.014608862	0	13.81383215
30	5.033810264	0	20.96556847
40	6.092384744	0	26.92134428

4.1.2 Mobile Nodes Network Topology

The topology of the network in mobile scenarios is similar to that in stationary scenarios discussed previously. The network nodes are mobile.

The source nodes are divided into two groups with the same number of nodes based on their location with respect to the destination node. The mobility for these nodes is enabled in such a way that any specific group can access the destination node only 50% of their operational time. For instance, scenario one consists of 10 nodes in the network such that nodes 0 through 7 transmit CBR traffic to node 8 while node 8 transmits CBR traffic to node 9. The source nodes 0 to 3 belong to one group while nodes 4 to 7 belong to another. When the simulation begins, node 8 is accessible by all the nodes. Later, destination node 8 moves to a location closer to the group one, and group two cannot access node 8. Later, node 8 moves to its original position where all the nodes can now access the destination. After some time, node 8 moves closer to group two and remains there for a period of time. The group one nodes cannot communicate with the node 8 during this period. The node 8 moves to its original position after this period where both the groups can access the destination. All source nodes from node 0 to 7 along with node 9 were enabled to move with lower speeds, whereas node 8 was enabled with higher speed in order to provide multiple oscillations (in the movement). The pattern of node movement is the same throughout the network. The other four scenarios were similarly simulated. Scenario two consisted of 20 nodes in which nodes 0 to 17 transmit CBR traffic to node 18, and node 18 transmits different CBR stream to node 19. Nodes 0 to 8 are put in group one, and nodes 9 to 17 are put in group two along with node 19. Node 18 oscillates in two different positions such that one position is close to group one and other is close to group two. Scenarios three and four consist of 30 nodes and 40 nodes, respectively. The data transmission rates of 30k, 40k, 50k and 60k were used for all the four scenarios explained previously. Simulations were run with DATA packet size of 500 bytes and further with 300 bytes. Tables 6 through 9 represents average values of queuing delays obtained with variations in DATA packet size as mentioned above. These tables show the variation in queuing delay (in seconds) for network sizes of 10, 20, 30 and, 40 nodes and for data transmission rates of 30, 40, 50, and 60 Kbps.

TABLE 6

THE QUEUING DELAYS FOR ALL FOUR SCENARIOS FOR A DATA RATE OF 30KBPS

NODES	AVERAGE DELAY(sec)	MIN DELAY(sec)	MAX DELAY(sec)
10	0.858776198	0	8.511532288
20	0.786381583	0	9.379931045
30	2.022480183	0	16.43276542
40	4.828318489	0	23.26317319

TABLE 7

THE QUEUING DELAYS FOR ALL FOUR SCENARIOS FOR A DATA RATE OF 40KBPS

NODES	AVERAGE DELAY(sec)	MIN DELAY(sec)	MAX DELAY(sec)
10	0.55613991	0	6.409223101
20	0.917151291	0	9.852183391
30	3.061282789	0	26.21924714
40	5.038955707	0	22.83476884

TABLE 8

THE QUEUING DELAYS FOR ALL FOUR SCENARIOS FOR A DATA RATE OF 50KBPS

NODES	AVERAGE DELAY(sec)	MIN DELAY(sec)	MAX DELAY(sec)
10	0.415939784	0	5.536085622
20	0.960877484	0	13.45001655
30	3.947360522	0	28.75392542
40	5.666023518	0	25.15564328

TABLE 9

THE QUEUING DELAYS FOR ALL FOUR SCENARIOS FOR A DATA RATE OF 60KBPS

NODES	AVERAGE DELAY(sec)	MIN DELAY(sec)	MAX DELAY(sec)
10	0.354658877	0	5.237031957
20	1.683121947	0	11.26707565
30	4.106727573	0	18.46051096
40	5.580387816	0	22.69295066

Figure 5 shows the average queuing delay against the number of nodes in the stationary network. It can be observed that an increase in the number of nodes increased the average queuing delay for a particular data rate. The value of average delay in all data rates is almost the same for a network size of 10. This is because of less MAC contention leading to a few collisions, backoffs, and cross-transmissions. For other network sizes, the average queuing delay increased with respect to data rates.

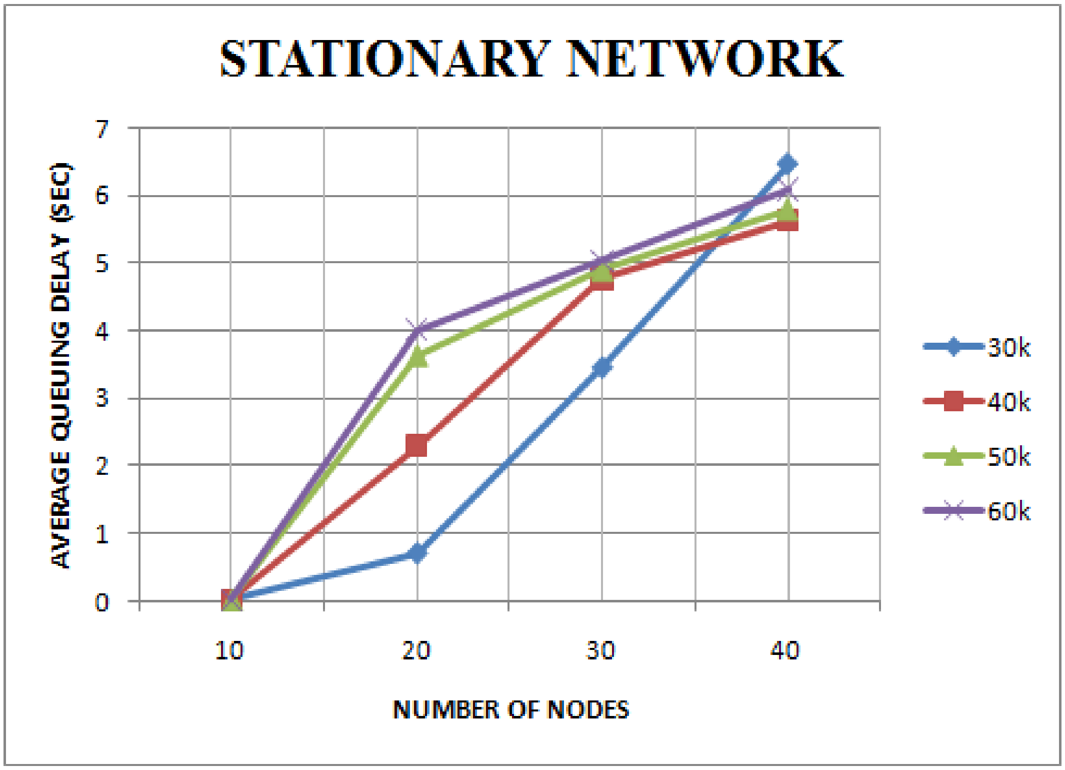

Figure 5. Average Queuing Delay with Variation in Number of Nodes and Data Rates.

Figure 6 shows average queuing delay against the number of nodes in a mobile network. An increase in network size and data rate increased the average queuing delay. While the network size of 10 had observed less increase in queuing delays, the network size of 20 or more increased the queuing delays significantly.

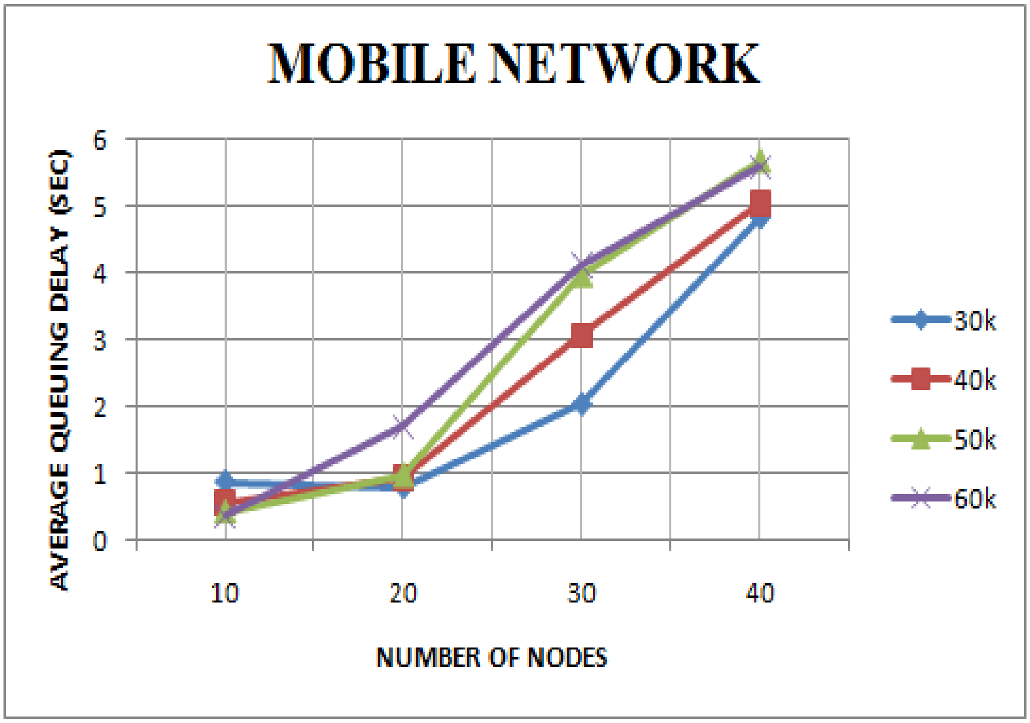

Figure 6. Average Queuing Delay with Variation in Number of Nodes and Data Rates.

4.2 Analysis

This section presents the analysis based on observations during simulations.

4.2.1 Stationary Networks

The average queuing delay increased with an increase in the frame transmission rates from 30 Kbps to 60 Kbps. For specific data transmission rates, an increase in the network size increases the average queuing delay. The effect of the increase in the transmission rate was less for a network size of 10 nodes. A network size of 20 produced a significant increase in the average queuing delay. A similar pattern was observed for network sizes of 30 and 40.

The average queuing delay increases with increase of data transmission rate. This consistent behavior continues up to 30 nodes. When network density reaches 40 nodes, there is a disruption in the pattern of average queuing delay. There are three reasons for this pattern of average queuing delay as listed below.

1. Huge burst losses caused because of high contention in the network with an increase in the network size. With 40 nodes in the network, the contention increases to such an extent that the burst losses repeatedly occurred causing inconsistency in the packet queuing delay.
2. Contention in the network also disrupts the patterns of collisions which seem to be similar to the deviations in the patterns of queuing delays.
3. In addition to burst losses and collisions, the patterns of Cross-Transmissions were responsible for the deviations in the pattern of queuing delays. The Cross-Transmissions are increased with an increase in the network size. However, in a highly populated network with 40 nodes, the variations in data transmission rates did not show a clear delay patterns.

It was observed that average queuing delays in stationary networks are primarily affected by the medium access control (MAC) delays. With an increase in the number of retransmissions for the current packet, the waiting time for the queued packets also increased, which finally resulted in a higher packet service time for the subsequent packets. The MAC delay parameters such as collisions, back-off intervals, and cross-transmissions directly affected the packet queuing delays of the subsequent packets in the queue.

4.2.2 Mobile Nodes

The average queuing delay increased with the increase in data transmission rates and network sizes, as seen in stationary networks. However, the effect of mobility on queuing delay is dominant compared to MAC contention. With increase in the network size from 20 to 40 nodes, the average queuing delay also increases consistently. This pattern was not clear for networks of smaller sizes such as those with 10 nodes in which an unsettled pattern was visible. This was caused because of lower number of successful packet transmissions in the networks. The motion of nodes caused dropping of several packets because of unreachability between source and destination node. In simple terms, this behavior can be attributed to the network topology and mobility in the network which reduced the actual network size to half as compare to stationary networks.

As the nodes are mobile and only 50% of network nodes can communicate with the destination, the impact of MAC contention on queuing delays is less than that in the stationary networks. As the nodes are mobile, the number of transmission attempts required to successfully deliver the packet also increases similarly to that of MAC contention. As the network size increases, there are more mobile nodes which increase the transmission attempts for successful delivery of packets. When the node loses the connectivity with the destination, it initiates a route discovery process and then transmits the data packet, thereby increasing the overall packet service time. This results in an increase in the waiting time for the already queued packets.

The MAC service-time increases the queuing delays in stationary networks, whereas route discovery time along with the MAC service-time affects the queuing delays in mobile networks.

CHAPTER 5

CONCLUSIONS

This thesis presents a quantitative analysis of packet queuing delay in saturated ad hoc networks. The medium access control (MAC) collisions, back-off interval, and cross-transmissions affect the packet queuing delays in stationary networks; whereas the route discoveries, along with the above mentioned MAC parameters, affect the queuing delays in mobile networks. Inconsistency in queuing delay is observed beyond 30 nodes in the stationary network. To better analyze the queuing delay in the network scenarios, the network size must be restricted to less than 40 nodes. The consistent behavior of queuing delays is observed with 20 or more nodes in the mobile network. The queuing delays in mobile network can be better analyzed with the network size of 10 nodes that is if there are atleast 10 nodes in the transmission range of each other as seen in 20 nodes scenario presented in the simulation. The MAC service-time affects the queuing delay in stationary networks, whereas the MAC service-time along with route discovery time affects the queuing delays in mobile networks. Also, the average queuing delay increased with an increase in the network sizes and data transmission rates, especially for network sizes of 20 and more.

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