THE QUANTITATIVE ANALYSIS OF MEDIUM ACCESS DELAYS IN SATURATED AD HOC NETWORKS AND THEIR IMPACT ON THE PACKET SERVICE-TIME

A Thesis by

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

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DEDICATION

To my Parents, brothers and my dear friends

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I would like to thank my Parents for their values, without which I would not have reached this stage of life. I would like to thank my adviser, Dr Ravi Pendse for his constant encouragement, support and suggestions throughout my stint at Wichita State University. Next, I would like to thank all the faculty members who have directly or indirectly helped me at Wichita State University. I would also like to thank Murali Krishna Kadiyala for his guidance, encouragement and for the thoughtful discussions we had, without which I would not have produced quality work. Last but not least, I would like to thank my friends at Wichita, who have made this place home away from home, for their unconditional love and support.

ABSTRACT

This thesis presents a quantitative analysis of medium access control (MAC) delays in saturated ad hoc networks and their impact on node packet service-time. First, the medium access delay at an ad hoc node was modeled in terms of the time spent in collisions and successful transmission. Secondly, the variations in route discovery time with respect to the variations in medium access delays were analyzed. Finally, the overall effect of MAC delay on node packet service time was discussed. In stationary networks, the routing delays are negligible after the initial route discoveries; hence MAC delays determine the packet service-time. In mobile networks, the upper layer delays associated with node transmission such as route discovery time together with MAC delay effect the node packet service-time. The simulations were carried out for stationary network scenarios, and the results support the presented model.

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LIST OF ABBREVATIONS

MAC	Medium Access Control
RTS	Request To Send
CTS	Clear To Send
DCF	Distributed Coordination Function
DSR	Dynamic Source Routing
AODV	Ad hoc On Demand Distance Vector
MANET	Mobile Ad Hoc Network
QoS	Quality of Service
RREQ	Route Request
RREP	Route Reply
DIFS	Distributes Inter-Frame Space
SIFS	Short Inter-Frame Space
DSSS	Direct Sequence Spread Spectrum
TCL	Tool Command Language
CBR	Constant Bit Rate
PTA	Packet Transmission Attempts

LIST OF ABBREVATIONS (CONT.)

BS	Backoff Stage
CT	Cross Transmission
BI	Backoff Interval
RET	Retransmission Attempts
NC	Node Count
ATA	Average Transmission Attempts
ACT	Average Cross Transmissions
AC	Average Collisions
ATST	Average Time Spent in Successful Transmission

CHAPTER 1

INTRODUCTION

The medium access control (MAC) delays represent the severity of MAC contention in the network. As the number of transmitting nodes in the vicinity increases, the time taken by an ad hoc node for channel access and packet transmissions also increases, thereby increasing the queuing delay of the subsequent packets along with the routing delay. The waiting time spent by the packet in the node's queue is known as queuing delay. The route lookup time and route discovery time constitute the routing delay. If a route to destination already exists in the routing table, the source node does not have to discover a new route. However if the route does not exist, the source node initiates a route discovery process. The time taken to successfully discover at least one route to the destination is known as the route discovery time. The MAC delay, queuing delay and routing delay together influence the packet service-time. A comprehensive analysis of medium access delays in association with packet transmission process in ad hoc networks helps in identifying the parameters affecting the upper layer delays and packet service-time.

This thesis models the MAC delay and its impact on node packet service-time. The collisions and cross-transmissions in the network increase with an increase in the number of nodes. As a result, the minimum number of transmissions required for successful delivery of a packet increases. Hence the queuing delay of the subsequent packets also increases. Further the MAC delays influence the upper layer delays such as route discovery time, and finally affect the packet service-time. While MAC delay determines the packet service time in stationary ad hoc networks, the MAC and routing delays together affect the packet service-time in mobile networks. The thesis also presents upper and lower bounds for packet service-time in ad hoc networks.

The Remainder of this thesis is organized as follows. Chapter two discusses the related work. Chapter three presents the model for MAC delays and packet service-time. Chapter four discusses simulation and results. Chapter five concludes this thesis.

CHAPTER 2

RELATED WORK

Bianchi [1] discussed two packet transmission mechanisms for 802.11 DCF networks, basic access and request-to-send/clear-to-send (RTS/CTS) in IEEE 802.11 DCF. He proposed a two-dimensional Markov chain to compute the DCF throughput, assuming finite number of terminals and ideal channel conditions. The model assumes that the collision probability of a transmitted packet is constant and independent regardless of the number of retransmissions suffered.

Tickoo and Sikdar [2] developed an analytical model for the delay and queue length characteristics in IEEE 802.11 networks considering the random arrival patterns, packet size distributions and number of nodes. Their model had closed form expressions for medium access delay and queue length. Based on the proposed model the authors devised and evaluated the methods to improve support for delay sensitive (real time) traffic. They also analyzed the effectiveness 802.11e which was designed for wireless lans. They validated the proposed model using the simulations in ns-2 for variations in network sizes and network load. They extended this work for finite loads [3] and characterizing the packet inter-arrival time distribution [4].

Sitharaman [5] proposed that the packet service-time at MAC queues follow a simple exponential pattern when hidden node scenarios are considered. The author used Chen-Stein Poisson method to develop a distribution in which several neighborhood backoff processes are superposed that takes an exponential form of service time intervals at every MAC queue. He proved that under saturated network conditions the network exhibits Poisson Service distribution.

The author also showed that the distribution of inter-arrival times at the next-hop nodes take an exponential pattern.

Abdrabou and Zhuang [6] showed that the packet transmissions in ad hoc network follow a pattern close to Poisson distribution. Further, they showed that the service-time distribution exhibits geometrical distribution. Finally they propose the usage of discrete-time queuing system (M/Geo/1) as a queuing model for the previously mentioned networks.

Kadiyala and Pendse [7] analyzed the impact of route discovery process on the packet end to end delay in IEEE 802.11 DCF networks. They also highlighted the role of MAC layer in the route discovery process and its effect on packet end to end delay.

Vu and Sakurai [8] derived a generating function for access delay in IEEE 802.11 DCF protocol. Their research showed the dependence of node’s backoff period on cross-transmissions. They showed that delay distribution can be obtained by numerically inverting the generating function.

Hou et al. [9] developed a model for analyzing the transient behavior of mobile ad hoc networks. They designed the model using a mix of discrete event simulations and numerical method based queuing analysis. They discussed the behavior of Dynamic Source Routing (DSR) protocol for the path failures (because of node movement) by emphasizing on the buffer overflows due to irregular packet arrival pattern. Further, they proposed a response mechanism for the routing protocol for failure in routes to improve the network performance.

Shi et al. [10] analyzed the problem of real time traffic support in multi-hop IEEE 802.11 mobile ad hoc networks (MANETs) . They proposed techniques to calculate quality of service (QoS) metrics like bandwidth, delay and packet loss. They concluded that the real time traffic is supported in MANETs only for a light load and it is not possible to support voice applications under heavy load conditions as delay and packet loss increase due to hidden node problems.

CHAPTER 3

ANALYTICAL MODEL

The primary components of packet service-time in wireless ad hoc networks are routing delay, queuing delay and MAC layer delays. In static ad hoc networks, routing delay is negligible after the initial route discoveries. Therefore, the average packet service-time (t_{PS}) is given by

$$t_{PS} = t_Q + t_M \tag{1}$$

where t_Q and t_M are average queuing delay and average MAC layer delay

The queuing delay for the ith packet $t_{Q(i)}$ in the MAC layer is given by [7]

$$t_{Q(i)} = (i - 1) * t_M \tag{2}$$

Therefore, the average packet service-time for i^{th} packet in the queue ($t_{PS(i)}$) is given by

$$t_{PS(i)} = i * t_M \tag{3}$$

In mobile networks, the link failures occur frequently. If a node does not have a route to the destination, it initiates route discovery process to reach the destination. The time spent in a route discovery process is ($t_{RREQ} + t_{RPTout}$), where $t_{RREQ}$is the time spent for RREQ transmission and t_{RPTout} is the RREP timeout period. If the average number of route discoveries required to be initiated to obtain a route is n_{RDPs}, then the total time spent in route discovery process t_{RDPs} is given by [7]

$$t_{RDPs} = (t_{RREQ} + t_{RPTout}) * n_{RDPs} \tag{4}$$

The average packet service-time (t_{PS}) is, therefore, given by

$$t_{PS(i)} = (i * t_M) + t_{RDPs} \tag{5}$$

The average time required for a successful RTS transmission T_{sRTS} is given by [7]

$$T_{sRTS} = DIFS + BO_i + CR + RTS + CTS + DATA + ACK + 4\mu + 3SIFS \quad (6)$$

where $DIFS$ is the distributed inter-frame space, BO_i is the average backoff period for the i^{th} backoff stage, CR is the average time spent in cross-transmissions, $DATA$ is the time required for data transmission, $SIFS$ is the short inter-frame space, and μ is the propagation delay.

The average time spent in an unsuccessful RTS transmission T_{uRTS} can be represented as [7]

$$T_{uRTS} = DIFS + BO_j + CR + RTS + \mu + SIFS \quad (7)$$

Here, BO_j is the average backoff period for the j^{th} backoff stage.

If n_{Tr} is the average number of transmission attempts required for successfully transmitting a packet, then the average MAC delay is given by [7]

$$\begin{aligned} t_M &= [(n_{Tr} - 1) * T_{uRTS}] + T_{sRTS} && (8) \\ &= (n_{Tr} - 1)\,[DIFS + RTS + \mu + SIFS] \\ &\quad + DIFS + RTS + CTS + DATA + ACK + 4\mu + 3SIFS \\ &\quad + \textstyle\sum_{j=0}^{n_{Tr}-1}(E[BO_j] + E[CR_j]) && (9) \end{aligned}$$

Where $E[BO_j]$ is the average backoff period for the j^{th} backoff stages of the packet transmission, and $E[CR_j]$ is the average cross transmission period for the j^{th} backoff stages. When the number of nodes in the network increases, the average time spent in backoff and cross-transmissions also increases.

From equation (3) and equation (5), the upper and lower bounds of $t_{PS(i)}$ can be written as

$$t_{PS(i)} >= (i * t_M) \quad (10)$$

$$t_{PS(i)} <= (i * t_M) + t_{RPTout} \tag{11}$$

Therefore, the lower and upper bounds of the first packet in a node's queue are t_M and $(t_M + t_{RDPs})$, repectively.

In static ad hoc networks,

$$t_{PS(1)} \approx t_M \tag{12}$$

Furthermore, considering the two scenarios, ideal and worst case scenarios we can derive scalar values for packet service-time for static ad hoc networks.

CHAPTER 4

SIMULATIONS AND RESULTS

The simulations required for the analysis of packet service-time in ad hoc networks was carried out in network simulator version 2.34. The variation in the node's packet service-time was analyzed by varying the number of nodes in ad hoc network. The variation in MAC parameters such as number of collisions and number of cross transmissions were also studied and, the impact of these parameters on node's packet service-time was analyzed. The default values for some of the parameters used in the simulations have been tabulated in Table 1.

TABLE 1

DEFAULT VALUES USED FOR SIMULATIONS

PARAMETER	**VALUE**
Physical Layer Standard	DSSS
CW_{min}	32
CW_{max}	1024
RTS	44 bytes
CTS	38 bytes
DATA	500 bytes
ACK	38 bytes
Slot-time	20 µs
DIFS	50µs
SIFS	10µs
Data Rate	100 kbps
Routing Protocol	AODV
Node Transmission Range	250 mts
Terrain area	200mts x 200 mts
Simulation time	90s

The network size in the simulations was varied in the steps of 10, starting from 10 nodes to 50 nodes in the topology. Nodes were configured to be operated in IEEE 802.11 DCF network. Every scenario had a tcl script file with required configuration for the parameters. Results were obtained in the form of trace files, these trace files were used to study the parameters of interest like average number of collisions, average number of cross transmissions, etc.

A set of source nodes transmit Constant Bit Rate (CBR) traffic to a particular destination. Parallely, the destination node acts as a source node for another flow destined to another node (which is not already a source). In the 10 node scenario, nodes 1 through node 8 transmit CBR traffic to node 9, and node 9 transmits its own data to node 10. Similarly, in scenario 2 node 1 through node 18 transmit packets to node 19, and node 19 would be transmits its packets to node 20.The same pattern is followed for remaining scenarios also. Table 2 represents the number of nodes in each of scenario, considered for simulations.

TABLE 2

NUMBER OF NODES INVOLVED IN DIFFERENT SCENARIOS

Scenario Identifier	Number of Nodes in the Network
Scenario 1	10
Scenario 2	20
Scenario 3	30
Scenario 4	40
Scenario 5	50

For each scenario five out of numerous available data is presented in this chapter. The results for 10 node scenario are tabulated as shown in Table 2. First column represents the sample number. Second column displays total number of packet transmission attempts (PTA) i.e. the number of times a particular node has attempted before finally succeeding a data packet. The Third column shows the backoff stages (BS) associated with the packet transmissions. The fourth column represents the number of cross transmissions (CT) in each backoff stage. The fifth column shows the total time spent in each backoff stage (TTBS) .

TABLE 3

MAC TRANSMISSION STATISTICS FOR NETWORK SCENARIO 1

#	**PTA**	**BS**	**CT**	**TTBS (ms)**
1	2	0	1	6.346
		1	0	6.500
2	1	0	1	11.608
3	1	0	5	29.326
4	2	0	13	69.876
		1	8	47.054
5	2	0	15	77.288
		1	20	120.920

Results for 20 node scenario have been tabulated in Table 3.As the number of nodes in the transmission range increases, probability of collisions also increases, due to sharing of common medium for communications. Due to increase in collisions, nodes have to back off more than previous scenarios, because of this there would be increase in cross transmissions.

TABLE 4

MAC TRANSMISSION STATISTICS FOR NETWORK SCENARIO 2

#	**PTA**	**BS**	**CT**	**TTBS (ms)**
1	3	0	2	7.132
		1	4	20.666
		2	17	99.410
2	1	0	2	12.374
3	2	0	2	12.010
		1	12	15.288
4	2	0	9	42.434
		1	8	81.932
5	3	0	5	29.122
		1	11	59.012
		2	29	148.946

For 30 node scenario, node 1 to node 28 transmitted CBR traffic to node 29 and node 29 transmitted its own data to node 30, simultaneously. Here node 29, would receive the data from 28 nodes and also would be sending its own data to node 30. Results for this scenario are as shown in table 4.

TABLE 5

MAC TRANSMISSION STATISTICS FOR NETWORK SCENARIO 3

#	**PTA**	**BS**	**CT**	**TTBS (ms)**
1	4	0	1	1.228
		1	26	125.252
		2	57	262.500
		3	99	464.648
2	4	0	8	46.274
		1	26	130.270
		2	7	36.348
		3	11	59.548
3	3	0	16	28.462
		1	16	73.340
		2	6	36.424
4	4	0	1	6.126
		1	17	78.834
		2	19	84.772
		3	117	562.434
5	4	0	11	53.450
		1	7	36.216
		2	36	182.560
		3	58	304.694

In 40 node scenario, node 1 to node 38 transmitted CBR traffic to node 39, and node 39 transmits it CBR traffic to node 40 simultaneously. Results for this scenario are as shown in table 5. In this scenario, there were several instances where a node was not able to get a chance to transmit data, after trying to send out data for seven times, eventually it would drop all the further packets. These scenarios were seen with RETs code in the trace files.

TABLE 6

MAC TRANSMISSION STATISTICS FOR NETWORK SCENARIO 4

#	**PTA**	**BS**	**CT**	**TTBS (ms)**
1	6	0	5	7.722
		1	31	59.594
		2	99	200.106
		3	150	344.982
		4	53	125.156
		5	354	762.692
2	4	0	19	43.382
		1	3	8.682
		2	15	45.380
		3	10	37.870
3	3	0	1	1.380
		1	16	27.340
		2	21	84.516
4	5	0	1	1.252
		1	14	36.994
		2	25	73.266
		3	120	371.618
		4	205	543.936
5	4	0	10	28.738
		1	21	35.870
		2	39	91.084
		3	23	60.474

In scenario 5, node 1 to node 48 transmitted CBR traffic to node 49, and node 49 transmitted its own CBR traffic to node 50. With the increase in the number of nodes, it was evident from the trace files that number of collisions and no of cross transmissions also increased dramatically. Number of RET occurrences reached peak.

TABLE 7

MAC TRANSMISSION STATISTICS FOR NETWORK SCENARIO 5

#	**PTA**	**BS**	**CT**	**TTBS (ms)**
1	7	0	1	1.724
		1	13	37.894
		2	12	25.784
		3	101	354.198
		4	222	927.126
		5	582	1967.032
		6	73	740.376
2	4	0	14	51.880
		1	4	18.724
		2	78	291.928
		3	297	1241.816
3	3	0	11	49.454
		1	13	50.740
		2	10	40.544
4	7	0	10	42.768
		1	13	55.486
		2	16	67.580
		3	70	282.486
		4	160	658.250

TABLE 7 (CONT)

		5	210	848.032
		6	450	1958.374
5	4	0	5	19.126
		1	6	10.500
		2	31	123.932

Table 8 presents the comprehensive information of all the scenarios from node 10 to node 50. The First column NC indicates the node count, ATA represents Average Transmission Attempts, ACT is the average cross transmissions, AC is average collisions and finally, ATST is Average time spent by a node for successfully transmitting the packet.

TABLE 8

CUMULATIVE STATISTICS FOR ALL THE FIVE SCENARIOS

NC	**ATA**	**ACT**	**AC**	**ATST (ms)**
10	2.22	15.55	1.22	85.877
20	2.33	34.11	1.33	144.682
23	3.60	74.6	2.60	573.0
28	4.30	160.5	3.30	668.3
30	4.55	167.33	3.55	935.744
40	4.77	372.44	3.77	919.602
50	5.11	426.333	4.11	1956.434

From the above table, we can observe that as the number of nodes increases, chances of transmitting the packet in first attempt decreases, i.e. it makes more attempts and finally succeeds.

4.1 Analysis

This section presents the observations from the simulation results.

(a) Theoretical Observations

This subsection highlights the general observations from the tables 3 through 8.

1. Increase in the number of nodes increases the network contention.
2. The medium access delay of a packet influences the queuing delay of the subsequent packets in the queue.
3. Medium access delays increase the upper layer latencies such as route discovery time.
4. Lower and upper bounds for the average MAC delay can be derived from the analytical model discussed in chapter 3.

(b) Key Points from Simulations

1. Maximum number of transmission attempts increased from 1 to 7 as we proceeded from scenario 1 through scenario 5.
2. However, another essential point to be observed is the pattern of minimum number of transmission attempts, while the pattern may closely follow that of maximum number of transmission attempts; the value remains same for scenario 1 and 2 indicating that some of the nodes could transmit the packets in a single attempt.
3.

(c) Lower and Upper Bounds

For DSSS physical layer modulation technique [1], CWmax= 1024 and CWmin=32, where CWmax is maximum contention window size and CWmin is minimum contention window size. These two parameters are related as shown in the below equation

$$CW_{max} = 2^m \text{ x } CW_{min} \tag{13}$$

For i^{th} backoff stage, equation (13) can be written as

$$CW_i = 2^i \text{ x } CW_{min} \tag{14}$$

(a) Lower Bound

In a network without collisions and cross transmissions (where number of transmitting nodes are relatively very less)

Here the node is able to send the packet in its very first attempt, therefore there will not be any back off attempted by the node.

So, i = 0, $n_{Tr} = 1$. Thus,

$$\begin{aligned} t_M &= T_{sRTS} \\ &= DIFS + RTS + CTS + DATA + ACK + 4\mu + \\ &\quad 3SIFS + E\,[BO_0] \end{aligned} \tag{15}$$

In general, sum of total time spent in i backoff stages is given by

$$E[BO_j] = 2^j \, CW_{min}/2 \tag{16}$$

So,

$$E\,[BO_0] = CW_{min}/2 \tag{17}$$

Substituting in equation (15) will yield,

$$t_M = DIFS + RTS + CTS + DATA + ACK + 4\mu + 3SIFS + CW_{min}/2 \tag{18}$$

(b) Upper Bound

When the transmitting node makes maximum attempts to transmit a packet

i=m = 5, $n_{Tr} = 6$. Therefore,

$$t_M = [\,5 * TuRTS\,] + TsRTS$$

$$= DIFS + 6RTS + CTS + DATA + ACK + 9\mu + 8SIFS + \sum_{j=0}^{5} E[BO_j] + \sum_{j=0}^{5} E[CR_j] \tag{19}$$

From equation (16)

$$\sum_{j=0}^{5} E[BO_j] = 31CW_{min} \tag{20}$$

Hence, equation (19) becomes

$$t_M = 6DIFS + 6RTS + CTS + DATA + ACK$$

$$+9\mu + 8SIFS + 31CW_{min} + \sum_{j=0}^{5} E[CR_j] \tag{21}$$

The time spent in cross-transmissions ($E\left[CR_j\right]$) is analyzed through simulations.

4.2 Plots

The results obtained in the simulations are plotted in figures 1, 2 and 3. Figure 1 shows the variation in average number of transmission attempts for variation in number of network nodes. Figure 2 shows the variation in average number of cross-transmissions for variation in number of network nodes. Similarly, figure 3 shows the variation in node's average packet service for variations in number of network nodes.

(a) Average Number of Transmission Attempts :

From figure 1 we can observe that, as the number of nodes increases, the average number of transmission attempts also increases. This variation is due to increase in the number of collisions and backoff intervals due to the collisions. One of the key observations is that the average number of transmission attempts for successful delivery of packet rapidly increases after the node count in the network crosses 20. In scenario 4 and scenario 5, nodes reached the maximum retransmission attempts (RETs) and nodes which could not transmit packets successfully and reached maximum retransmission attempts aborted further transmissions.

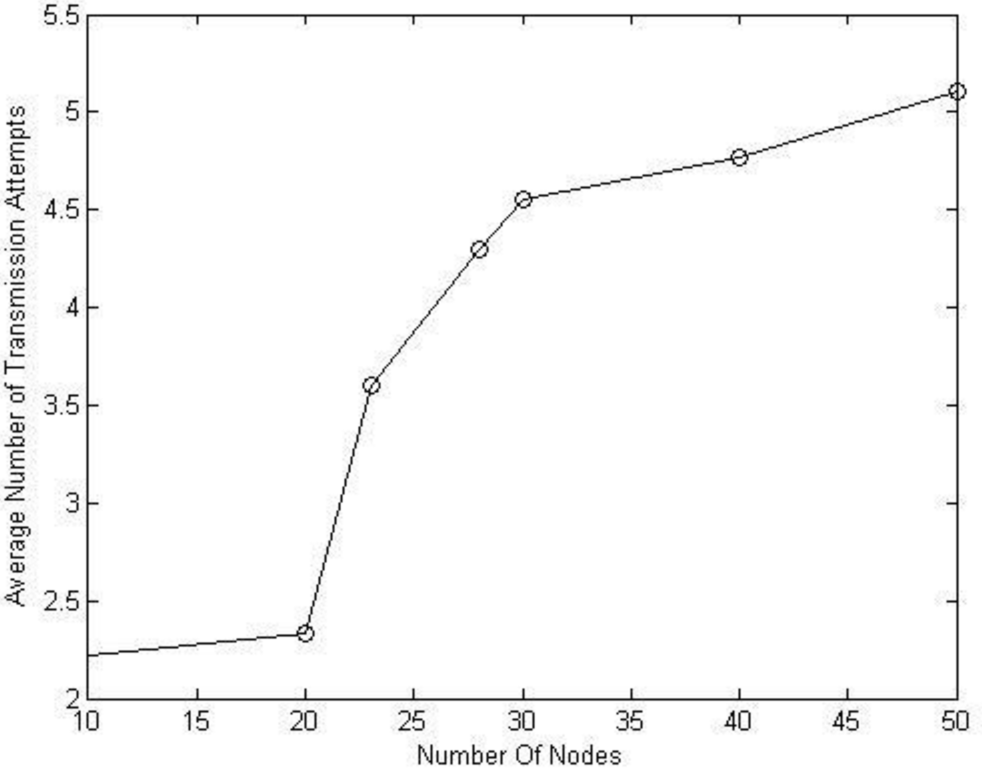

Figure 1. Variation of average transmission attempts required for node to successfully transmit packet with the variation in number of nodes in network

(b) Average Number of Cross-Transmissions

From figure 2 it can be observed that, with an increase in the network nodes, the cross-transmissions also increase. However, after crossing a node count of 20 this increase was more rapid than before. So, we did simulations for few intermediate values between 20 and 30, we simulated network for 23 nodes and 28 nodes and we observed the results to follow the pattern.

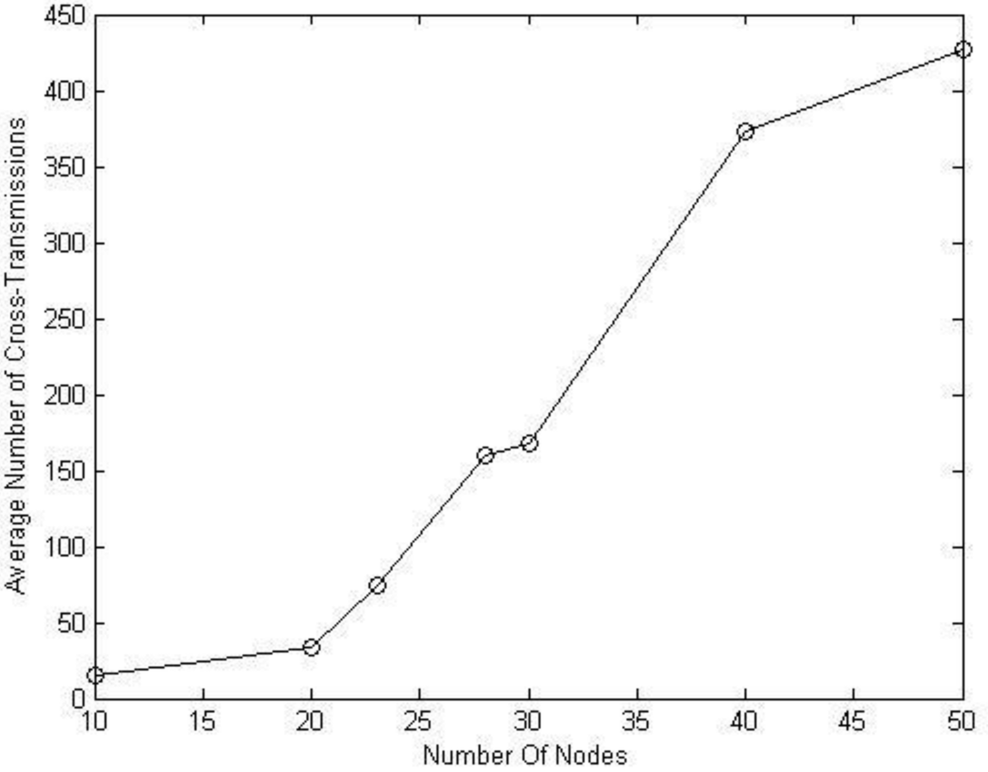

Figure 2. Variations in average cross-transmissions with variations in number of nodes in the network

(c) Average Packet Service-Time

From figure 3 it can be observed that with the increase in number of nodes, the average packet service-time also increases. However after crossing the node count of 20, the average packet service-time increases sharply. This pattern is similar to figures 1 and 2 for average transmission attempts and average cross-transmissions. This pattern is due to the combination of transmission rate and number of neighboring nodes in the vicinity.

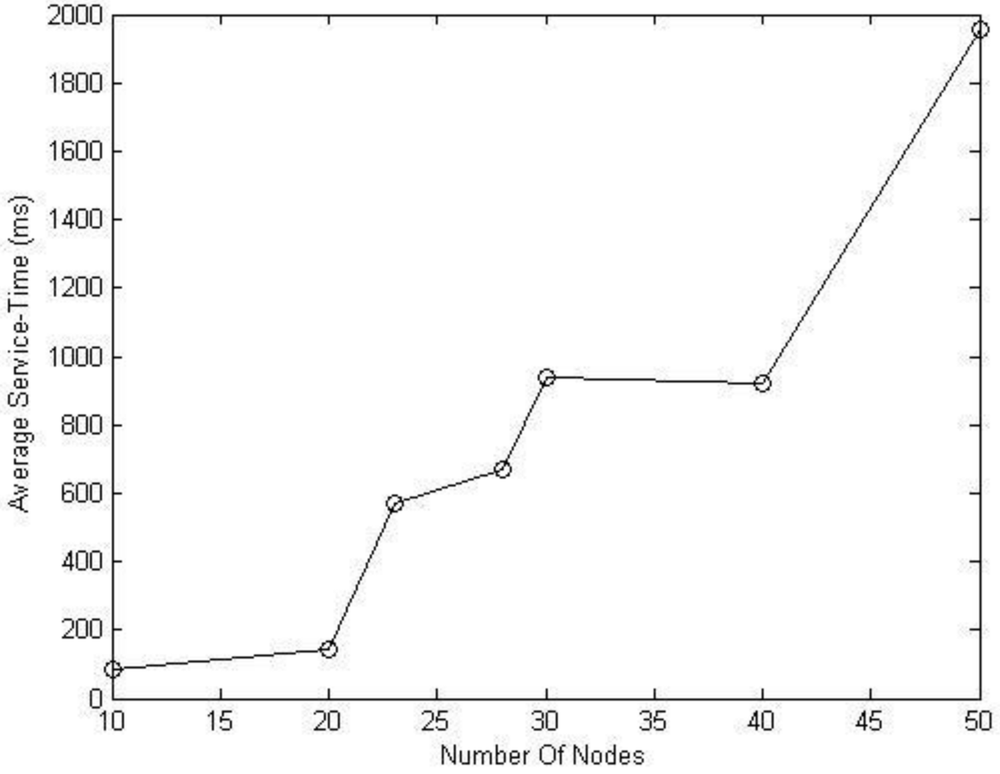

Figure 3. Variation of packet service-time because of variations in number of nodes in network

CHAPTER 5

CONCLUSION

This thesis models the MAC delay in saturated ad hoc networks and its impact on node packet service-time. The collisions and cross-transmissions in the network increase with an increase in the number of nodes. As a result, the minimum number of transmissions required for successful delivery of a packet increases. Hence the queuing delay of the subsequent packets also increases. Further the MAC delays influence the upper layer delays such as route discovery time, and finally affect the packet service-time. While MAC delay determines the packet service time in stationary ad hoc networks, the MAC and routing delays together affect the packet service-time in mobile networks. The thesis also presents upper and lower bounds for packet service-time in ad hoc networks.

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