

QUEUEING ANALYSIS OF DCHF AND TOKEN-PASSING MAC  
PROTOCOLS WITH VARYING TURNAROUND TIME

BY

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"Queueing Analysis of DCHF and Token-Passing MAC Protocols with Varying Turnaround Time," a thesis prepared by Manikanden Balakrishnan in partial fulfillment of the requirements for the degree, Master of Science in Electrical Engineering, has been approved and accepted by the following:

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## DEDICATION

I dedicate this work to my beloved parents, as I find no better way to express my gratitude and appreciation for their undaunted support and encouragement to my education.

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## ABSTRACT

### QUEUEING ANALYSIS OF DCHF AND TOKEN-PASSING MAC PROTOCOLS WITH VARYING TURNAROUND TIME

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Wireless Networks are generally characterized by a broadcast medium shared among a group of users. This makes an appropriate Media Access Control (MAC) protocol essential for efficient channel utilization. Wireless MAC protocols show significant performance degradation in networks with long link-layer turnaround times and most of the recent research does not address this problem. This thesis develops a queueing model for a contention-based MAC protocol (DCHF) and a contention-free MAC protocol (Token-passing) and explores their statistical performance for varying link-layer turnaround times under varying Poisson loads.

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## 1.0 INTRODUCTION

Media Access Control (MAC) protocols perform the channel assignment function when the channel is shared among a group of nodes. The MAC mechanism arbitrates among the competing nodes in a network, and provides channel access to only one node at any instant. This channel access mechanism can either be centralized (a master node allocates the channel to other nodes in the network sequentially) or distributed (individual nodes cooperatively perform the MAC function). Further, the MAC protocols can be functionally categorized as contention-based protocols or contention-free protocols depending on the channel allocation method.

Contention-based MAC protocols require active nodes (nodes having traffic) to contend with each other for gaining channel access and the channel is assigned to the contention winner for data transmission time. Nodes that lose contention abide by the channel allocation process and defer their transmissions until the channel becomes free. Contention-free MAC protocols assign the channel to at most one node at any time for sending traffic and every node in the network gets its turn for accessing the channel. Collision free packet transmission is ensured as only one node gets to transmit in the channel at any instant and also the nodes have prior knowledge of when to access the channel. However contention-free schemes can incur considerable management overhead. Contention-based schemes do not introduce any management overhead, but multiple nodes transmitting at the same time is a possibility and so collision-free operation is not guaranteed. Contention-based protocols can perform better by employing carrier-sensing (monitoring the channel to know its state)

methods to reduce the probability of collisions.

Choice of a particular type of MAC protocol depends on the wireless network technology and workload. An inappropriate MAC protocol can degrade the network performance significantly [1]. One of the factors that influence the performance of a wireless MAC protocol is the link turnaround time, i.e., the time it takes for a node to acquire the channel and transmit a response upon reception of a packet. For some challenging channels like HF skywave, extensive physical layer processing may result in turnaround times on the order of seconds. A detailed explanation of link turnaround time is given in [1].

In this paper, queueing models for Distributed Coordination for HF radio (DCHF), a contention-based MAC protocol [1] and Token-Passing, a contention-free MAC protocol, are developed to measure the statistical performance of these protocols under varying turnaround times and arbitrary Poisson loads. Results of the analysis are then used to identify an appropriate MAC protocol for various network and traffic conditions. We begin with a review of the previous work and the protocols analyzed here.

## 1.1 Related Work

The impact of turnaround time on wireless MAC protocols has been discussed in detail by Johnson et al., [1]. The performances of DCHF and token-passing protocols were analysed for varying turnaround times, with a simple analytical model designed for saturated conditions. Bianchi [6] and Ergen [7] have thoroughly analysed the performances of IEEE 802.11 Distributed Coordination Function (DCF) and Wireless Token Ring Protocol (WTRP) respectively, but for saturated conditions and negligible link turnaround times. This thesis extends the research done by these researchers and provides a detailed study on the effects of link turnaround time on wireless MAC protocols with varying Poisson traffic in the network.

## 1.2 DCHF

The Distributed Coordination function for High Frequency (HF) radio (DCHF) protocol is based on the IEEE 802.11 DCF [2] with some features incorporated from MACAW [3]. Like MACAW, DCHF uses only "virtual carrier sensing," a collision avoidance scheme in which nodes reserve the channel by including reservation information in transmitted packets. Other nodes, on receiving this information, defer their transmissions until the reservation time period expires. This approach addresses the inability of physical carrier sensing to prevent collisions when hidden stations are present [4], as well as the challenges of reliably sensing carrier in some challenging channels (e.g., HF skywave).

Virtual carrier sensing is implemented in DCHF via the Request-To-Send (RTS)/Clear-To-Send (CTS) handshake mechanism, as in DCF. A Node having traffic to send will send a RTS control packet to the intended destination, if the channel is believed to be free. The destination responds with a CTS packet. If this two way handshake is successful the sender node has acquired the channel for data transmission. The RTS and CTS packets include the reservation information (duration of packet transmission), and other nodes hearing the RTS/CTS exchange defer their transmissions till the time reserved has elapsed. During the reservation period collision-free data transmission takes place with a MAC-layer acknowledgement sent for each received data packet. Data frames can be fragmented to smaller units if the traffic is huge. In this case, each fragment is acknowledged before the transmission of next data fragment.

In the RTS-CTS-Data-Ack transmission sequence each packet is separated by a Short Inter Frame Space (SIFS) and if the data is fragmented the Ack-DataFragment sequence is also separated by the same SIFS time. From [1] the length of SIFS is equivalent to a node's internal turnaround time.

$$\text{Internal Turnaround Time } (T_{IT}) = Y + d + g + h$$

where

$Y$  = Time taken for carrier detection

$d$  = Physical layer processing time for received packet

$g$  = MAC layer processing time

$h$  = Physical layer processing time for the response

A slotted contention window occurs whenever the channel becomes free, during which active nodes contend for channel access. The size of a slot is long enough to receive and process an RTS (or CTS) packet:

$$\text{Slot Time } (T_S) = T_t + b$$

where

$T_t$  = Link Turnaround time =  $T_{IT}$  + Channel Propagation time (  $t$  )

$b$  = Time taken to send an RTS (or CTS) packet

An active node randomly chooses any one of the contention slots to transmit its RTS packet, and it monitors the channel during the preceding slots. If no transmission is received during those preceding slots, the node transmits its RTS in the chosen slot and awaits a response. Other active nodes overhearing this RTS will

defer their transmissions to avoid interfering with the response from destination node. The destination responds with a CTS packet in the next slot and nodes overhearing this CTS go to defer (idle) state till the end of the data transmission and acknowledgement. This marks a successful channel acquisition that leads to collision-free data transmissions.

On the other hand, if the channel is acquired by some other node in the network during the backoff period, the contending node goes to defer state. Also if the RTS is not acknowledged with CTS, perhaps due to collisions, the node backs off and tries again later. The size of the contention window is doubled (up to a maximum value) if the channel acquisition is not successful, and is halved when it is successful (unlike DCF which simply resets the window size to minimum). As in MACAW, the window size of a node sending data is transmitted along with the data packet. This window size is then used by all the other nodes in the network for the next contention.

DCHF allows nodes with traffic to contend immediately for the channel; no synchronization among the nodes is needed. The protocol is self adjusting to nodes joining and leaving the network (no management overhead). Hidden station and partitioned network problems are addressed automatically by the protocol. The contention window size stays large when the network is congested and that reduces collisions in the contention slots. Also DCHF has the advantage over DCF of providing better fairness, as all nodes in the network have the same contention window size, which means equal opportunity to acquire the channel. However, the RTS/CTS control packets represent channel overhead, and channel capacity is lost

due to collisions (more when traffic is heavy). Nodes are not assured of channel access even if they have a lot of traffic to send, and the channel can be idle for many slots (all nodes backing off), even if all the nodes have packets queued up.

### 1.3 Token-Passing

Token-Passing is a contention-free MAC protocol in which a token (explicit permission to transmit) is passed among the nodes in the network to decide the sender at any instant. A node possessing the token has the right to transmit on the channel for a specified duration of time (token holding time) after which the token gets passed on to the next node [6, 7, 8]. If a node does not have any traffic to send, it must immediately pass the token to the next node instead of holding the token for the token holding time.

The nodes in the network that receive data packets queue their link-layer acknowledgements and send them upon getting the token. Token acknowledgements are implicit; in the sense when a node hears transmissions(s) from its successor node (to which the token is passed) it understands that the token has passed successfully, because nodes never transmit until they get the token.

A token-passing protocol ensures that each node in the network gets a portion of the channel time and the nodes ensure that they never hold the channel if there is no traffic to send. This is like a dynamic allocation of slots for the nodes having traffic to send in a self-synchronizing manner (no external timing or network synchronization protocol is needed). However the token is an overhead packet in the

network and passing the token between inactive nodes wastes some channel capacity.

Token-Passing suits network with heavy traffic in which most nodes usually have some traffic to send. A principal concern in token-passing networks is the need to recover from lost or multiple tokens and to manage the entry and departure of network member nodes (which represents management overhead).

## 2.0 STATISTICAL ANALYSIS

Two standard performance metrics are used to analyse and compare DCHF and Token-Passing MAC protocols:

- *Average Latency per Packet* is the total delay suffered by a packet from the time it arrives at a node until the time it gets transmitted on the channel. This metric identifies the responsiveness of the protocols for varying traffic conditions.
- *Channel Utilization* is the fraction of total time the channel is being utilized to transmit bits and is a measure of the efficiency of these protocols.

Queueing models for these MAC protocols were developed to estimate the stated metrics. The network consists of ' $N$ ' nodes with each node having a mean packet arrival rate of ' $\lambda$ ' packets per second. Packets arriving at a node are buffered in a FIFO queue and serviced one at a time. The packet interarrival times are exponential implying Poisson packet arrivals. The mean service rate of the channel is ' $\mu$ ' packets per second. The service time distribution is general; thus, DCHF and Token-Passing nodes are analysed as M/G/1 queueing centers. Once the channel is acquired, a node is allowed to transmit only one data packet after which it relinquishes the channel.

## 2.1 DCHF model

The DCHF model builds upon previous work in modeling the IEEE 802.11 DCF [2] and a simple model of DCHF that was limited to saturation conditions [1].

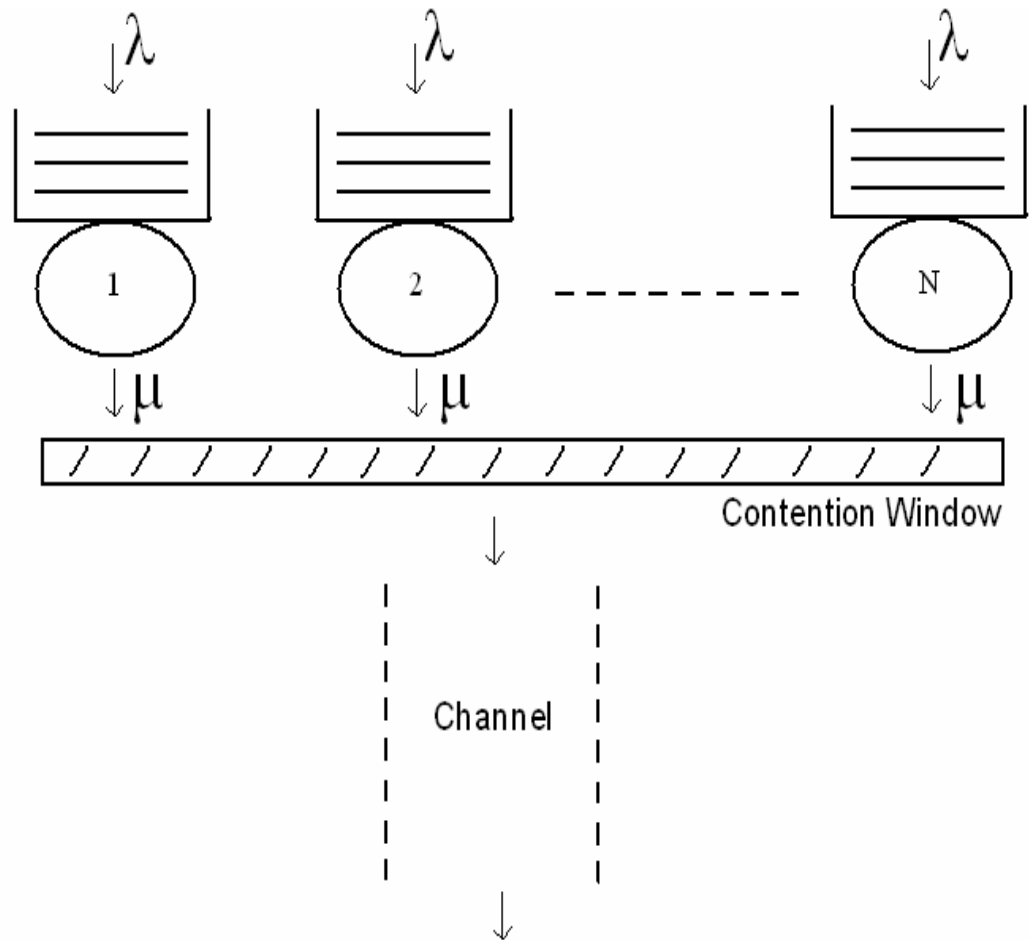
Key differences between DCF and DCHF are

1. DCHF excludes physical sensing of the channel and so the DCF Inter Frame Space (DIFS) time seen in DCF is omitted.
2. Also the contention window size is not reset to minimum in DCHF when there is a successful transmission in the channel (like DCF), but is halved.

Figure 2.1 shows the basic model of DCHF. Due to symmetry in the packet arrival and service processes, the statistics are the same for every node. Unlike the earlier analysis of DCHF in [1], the model presented here allows for unsaturated conditions with arbitrary levels of Poisson traffic in the network. Packets are serviced in FIFO order, and a node transmits only one packet when it acquires the channel after which the channel becomes free for servicing other nodes.

The node that relinquished the channel goes through the contention process again if it has more packets to send. With arrival rate of ' $\lambda$ ' packets per second and service rate of ' $\mu$ ' packets per second, the traffic intensity [5] in each node's queue is given by

$$\text{Node Queue Intensity } (\rho) = \frac{\lambda}{\mu}$$



$\lambda$  - Packet Arrival Rate (packets/s)  
 $\mu$  - Channel Service Rate (packets/s)

**Figure 2.1. DCHF model**

When a contention period begins, a node contends for the channel if it has non-empty queue. The probability of a node having at least one packet in its buffer is the probability that it contends:

$$\text{Probability of a node contending} = \frac{1}{m}$$

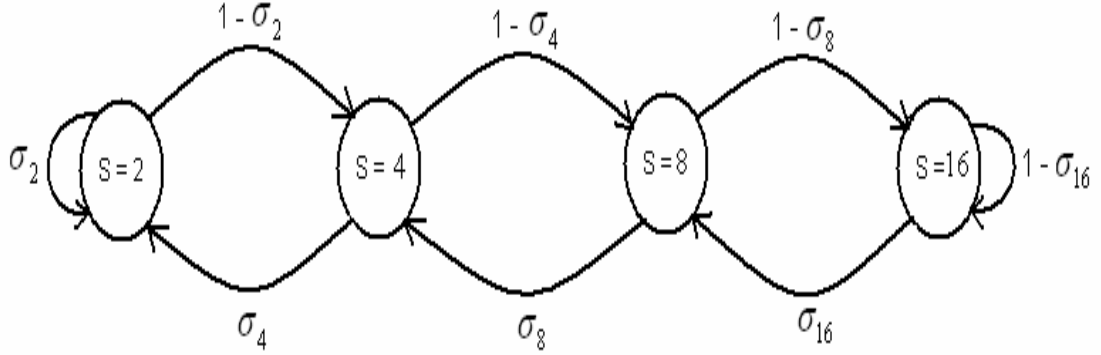
The average number of nodes contending for the channel in any contention window is

$$N_{contending} = N \left( \frac{1}{m} \right)$$

In this analysis, we use this mean value rather than weighting intermediate results using the actual probability distribution of  $N_{contending}$  (see Mean-Value Analysis in [5]). The nodes randomly choose a slot during the contention process and in DCHF all the nodes have the same contention window size ( $S$ ) at any instant. In this analysis we consider four possible values for  $S$ : 2, 4, 8 and 16 slots. A node's state is the size of its contention window at that instant. The window size starts from a minimum of 2 slots and increases to the next value of  $S$  when there is an unsuccessful acquisition attempt until the maximum value (16 slots) is reached; upon success the reverse process happens. The backoff algorithm can be analysed with a Markov model shown in Figure 2.2, where the probability of success in state  $S$  is denoted as ' $S_S$ '.

From [1], the probability that ' $i$ ' is the first occupied slot among  $S$  slots, when  $N_{contending}$  nodes are contending for the channel is,

$$A_{S, N_{contending}}(i) = \left[ \frac{S-i+1}{S} \right]^{N_{contending}} - \left[ \frac{S-i}{S} \right]^{N_{contending}}$$



**Figure 2.2. Backoff behavior of DCHF**

Appendix A presents the derivation of this probability. The expected value of first occupied slot in state S is,

$$A_{S, N_{contending}} = \sum_{i=1}^S i \left( \left[ \frac{S-i+1}{S} \right]^{N_{contending}} - \left[ \frac{S-i}{S} \right]^{N_{contending}} \right)$$

At any instant a node can be in any one of the four possible states and to estimate the state probabilities ( $P_S$ ), we have to calculate the probability of success in each state given that  $N_{contending}$  nodes are contending for the channel. The probability of success in slot ‘i’ is,

$$S_{S, N_{contending}}(i) = \frac{N_{contending}}{S} \left( \frac{S-i}{S} \right)^{N_{contending} - 1}$$

Appendix B shows the computation of this probability. The overall probability of success in state S is given by,

$$S_S = \sum_{i=1}^S S_{S, N_{contending}}(i)$$

With the Markov model in Figure 2.2 we have a set of simultaneous equations that can be solved to get the state probabilities ( $P_S$ ). The state probabilities computation is shown in Appendix C. The expected value of the first occupied slot in a contention process is,

$$A = \sum_S P_S A_{S,N_{contending}}$$

and the probability of successful acquisition of the channel is

$$P_{success} = \sum_S P_S S_S$$

When a node finds the channel unoccupied during its monitoring stage, it sends an RTS in the chosen slot. If it receives a CTS in the next slot, that marks a successful channel acquisition. Then the node sends a data packet and receives an acknowledgement. The time taken to send an RTS, CTS or acknowledgement equals the slot time ( $T_S$ ), so the total time taken in case of success is,

$$T_{success} = (A + 2)T_S + T_{pkt}$$

where,  $T_{pkt}$  is the mean time taken to transmit one packet in the channel.

If the RTS that is transmitted in slot A is lost or collides with another transmission in the channel, the acquisition fails. The sender does not get CTS in the next slot and it assumes there was a collision in the channel. Other nodes in the network also detect this collision and do not transmit. A new contention process, with an increased number of contention slots, begins after the CTS slot. The total time taken in case of failed channel acquisition is

$$T_{fail} = (A + 1)T_s$$

The Service time of a packet is the time taken for a single packet to be transmitted successfully in the channel after it reaches the head of its queue, and is given by

$$\text{Channel Service Time} = P_{success} T_{success} + P_{fail} T_{fail} \left( \frac{1}{P_{success}} - 1 \right)$$

where,  $P_{fail}$  is  $1 - P_{success}$ , and the term  $1/P_{success}$  denotes the average number of tries for a success.

A packet on arrival to a node is stored in the buffer before getting serviced.

*Queueing Delay* ( $T_q$ ) represents the time spent by a packet in node's buffer and for an M/G/1 model it is given by

$$T_q = \frac{1}{2} \frac{E(x^2)}{(1 - r)}$$

where

$E(x^2)$  is the expected second moment of the channel service time

$r$  is the traffic intensity in a node queue

Using these terms the average latency of a packet is calculated as

$$\text{Latency}_{average} = \text{Channel Service Time} + T_q$$

When all the nodes in the network have empty buffer, the channel is not used by any of the nodes in the network and that represents the fraction of time the channel is unutilized. Channel Utilization is computed as

$$\text{Channel Utilization} = 1 - (1 - r)^N$$

## 2.2 Token-Passing Model

Nodes in the network pass the token among themselves and the node possessing the token transmits on the channel. Figure 2.3 shows the basic model of token-passing protocol. The analysis is a generalization of [1] for arbitrary Poisson traffic in the network.

Each node upon receiving the token sends one data packet (if it has traffic to send), acknowledgements (if it has any) and then passes on the token to next node. Assuming symmetry in traffic destinations, each node will send, on average, as many acknowledgements as data packets. Hence the time delay per node is

$$T_{forward} = T_{token} + \frac{1}{m} (T_{pkt} + T_{ack}) + T_t$$

where

$T_{token}$  is the time for the token transit in the channel

$T_t$  is the link turnaround time

$T_{ack}$  is the time taken to send an acknowledgement

$\frac{1}{m}$  is the probability that a node has an acknowledgement or traffic to send

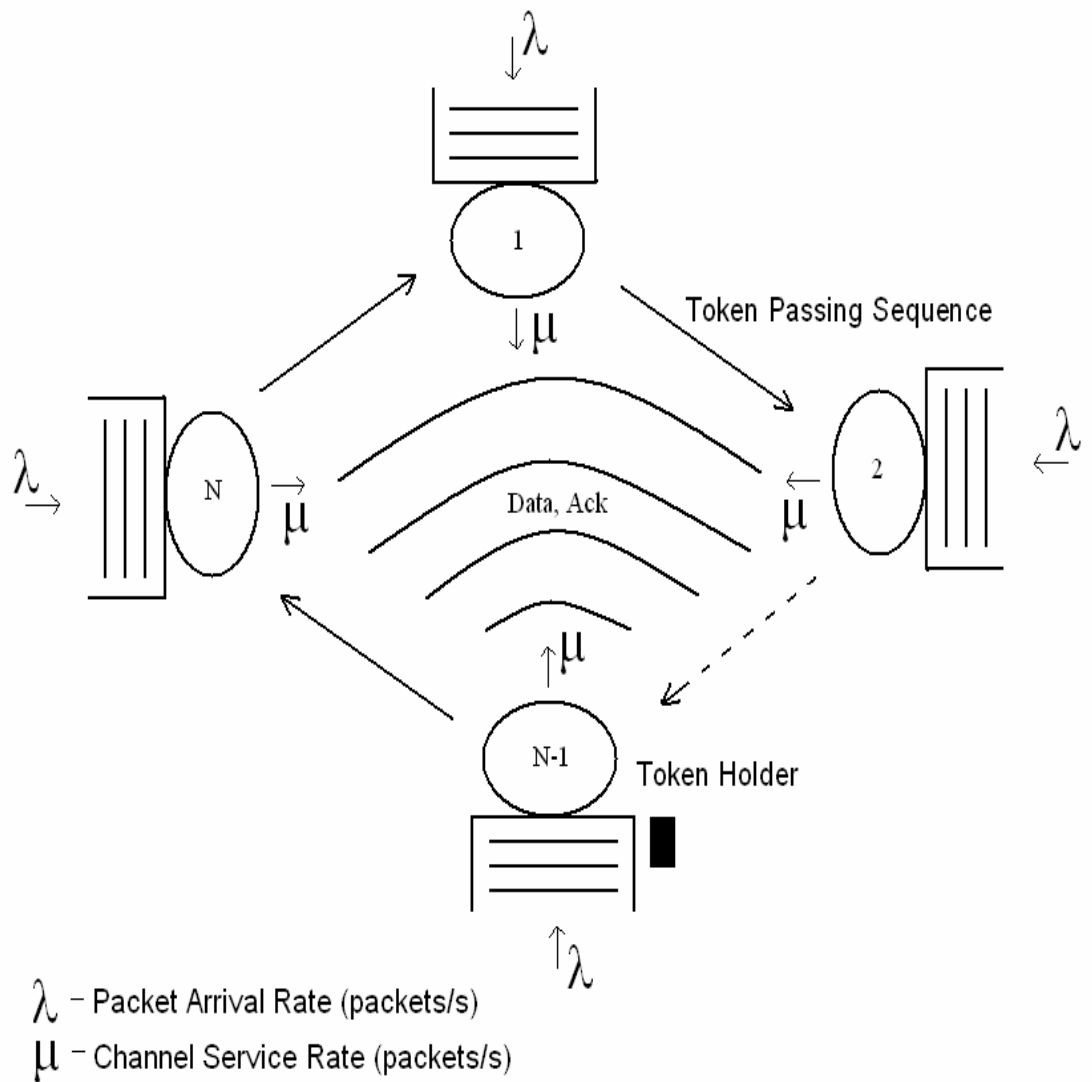
Other values are the same as specified in the previous section. Cycle Time is the average time taken for the token to complete one full rotation in the ring and is given by,

$$T_{cycle} = N T_{forward} + T_{mgmt}$$

where,  $T_{mgmt}$  represents the management overhead per cycle and is here approximated as in [1]

$$T_{mgmt} = \frac{\sqrt{N}}{10} T_s$$

Where,  $T_s$  is the slot time and the value is same as in DCHF.



**Figure 2.3. Token-Passing model**

Channel Service Time of a packet depends on whether the incoming packet encounters an empty buffer or not. If the buffer is empty the packet arrival at the head of the queue is not synchronized with the token rotation cycle; hence the time it has to wait to be serviced will be, on average, half the cycle time. If the buffer is non-empty, the packet waits to reach the head of the FIFO queue and then waits to get serviced. In this case, the delay to get back the token will be the time taken for the rest of  $N-1$  nodes to get served. The total latency suffered by a packet is the channel service time plus the queueing delay in the node's buffer.

$$Latency_{average} = \left(1 - \frac{1}{m}\right) \left[\frac{T_{cycle}}{2}\right] + \left(\frac{1}{m}\right) \left[\left(\frac{N-1}{N}\right) T_{cycle}\right] + T_q + T_{pkt}$$

where

$(1 - 1/m)$  is the probability that an arriving packet encounters an empty buffer. This is same as the steady state empty buffer probability, since it is an open system.

$T_q$  is the queueing delay and is same as in DCHF.

Channel Utilization can be computed in many ways. One way is finding the fraction of time the channel is unused. In token-passing, the nodes pass the token around even if they do not have traffic to send and so the turnaround times are the only time during which the channel is unutilized. Channel Utilization is given by,

$$ChannelUtilization = 1 - \frac{N T_t}{T_{cycle}}$$

### 2.3 Analytical Results

The results of the statistical analysis were obtained with the following parameter values (typical of an HF radio maritime wireless LAN):

Channel transmission rate: 6400 bits/second

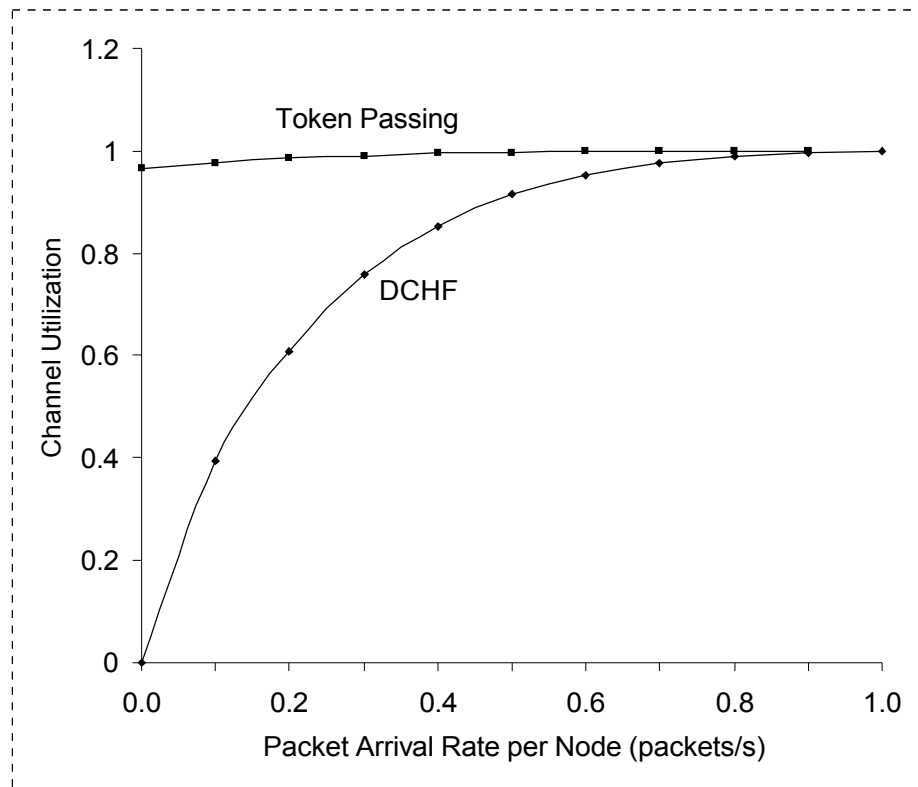
Number of nodes in the network ( $N$ ): 5 and 50

RTS/CTS/Acknowledgement packet size: 30 Bytes

Token size: 40 Bytes

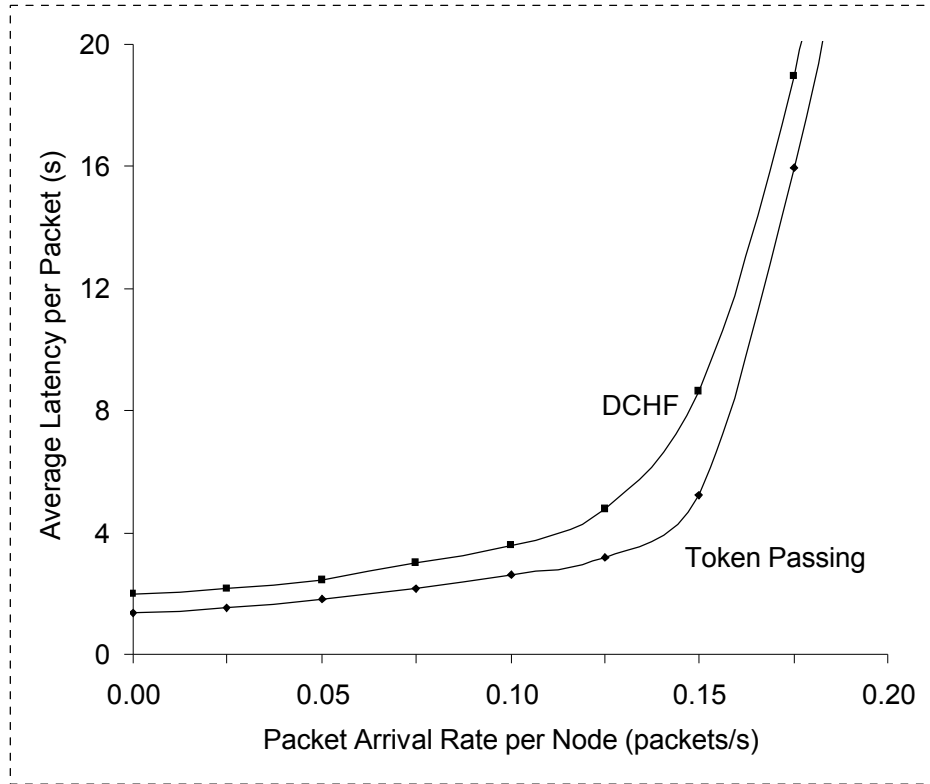
Data packet size: 1000 Bytes/packet (constant)

The channel utilization results for negligible link turnaround time (1ms) are shown in Figure 2.4.



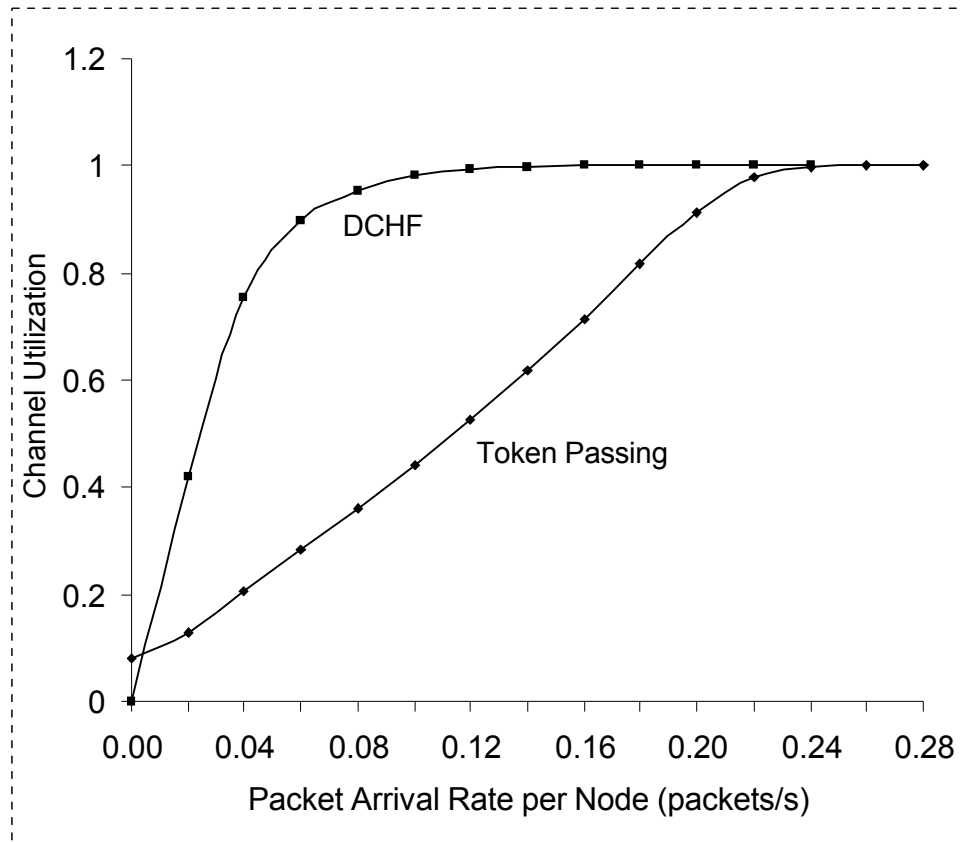
**Figure 2.4. Channel utilization results for  $T_t = 1\text{ms}$  and  $N = 5$**

In token passing even the inactive nodes are required to pass the token around and so the channel utilization is always high, given that the turnaround time is small. At light loads DCHF utilizes the channel more efficiently than token passing as the token overhead exceeds the amount of traffic in the network.



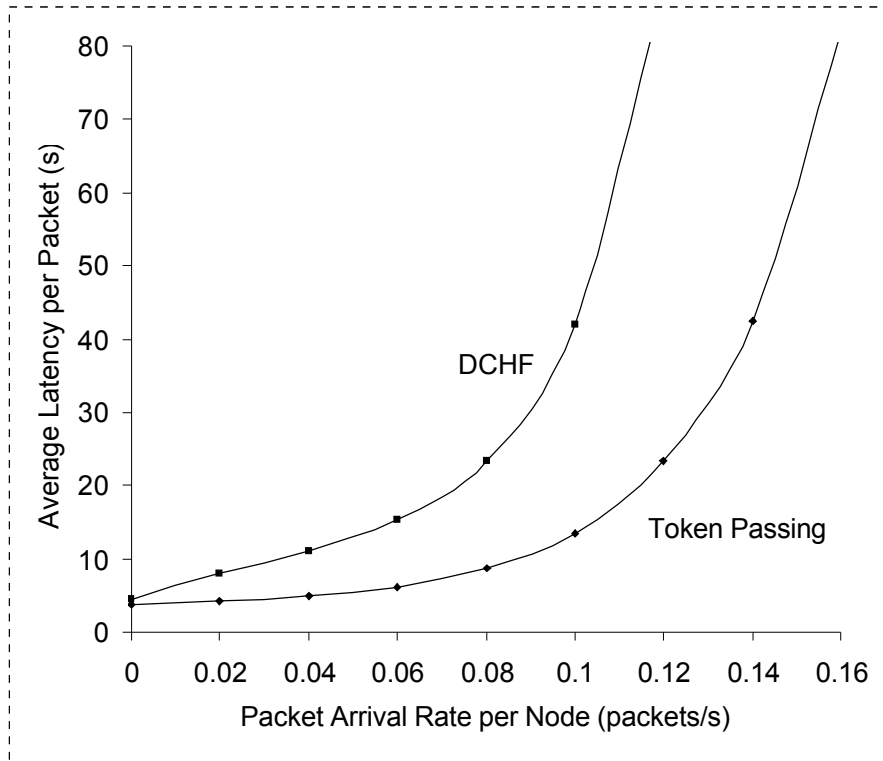
**Figure 2.5. Latency results for  $T_t = 1\text{ms}$  and  $N = 5$**

Figure 2.5 shows the latency characteristics of these protocols for small turnaround time. DCHF has marginally higher delay (per packet) than token passing, in spite of the token rotation. This is because the RTS/CTS hand shake in DCHF introduces two link turnarounds whereas token passing requires only one link turnaround per node.



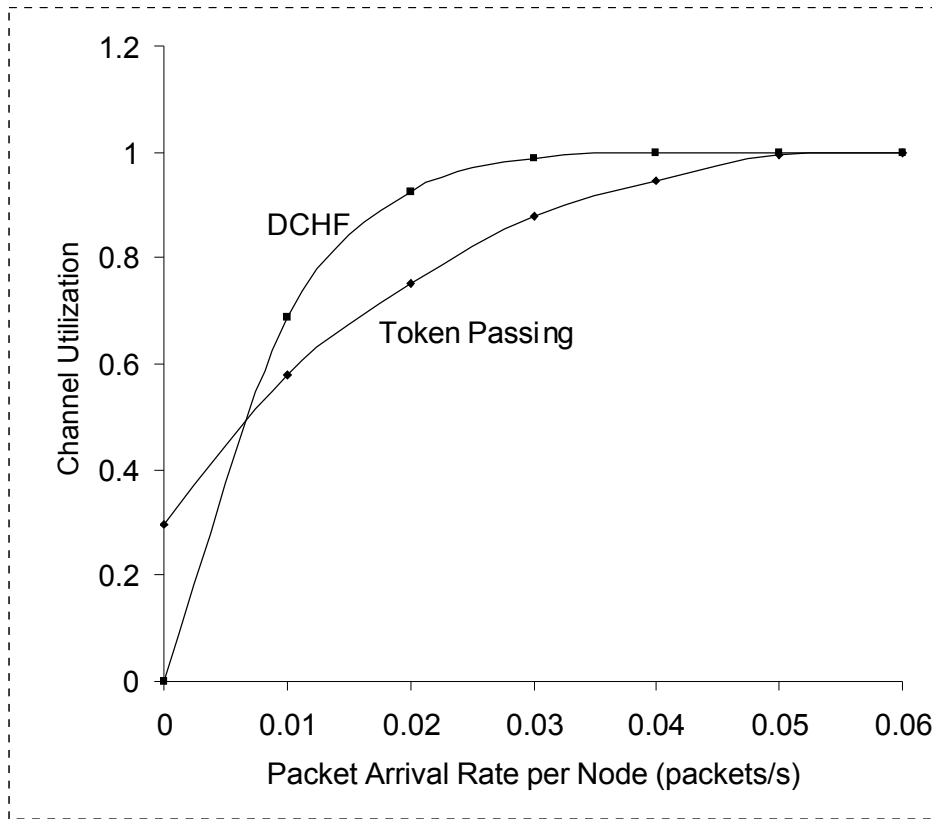
**Figure 2.6. Channel utilization results for  $T_t = 1s$  and  $N = 5$**

Figure 2.6 and 2.7 show the performance of DCHF and token passing for a long turnaround time (1s) in a small network. As might be expected, the network performance degrades considerably. The network saturates much more rapidly when compared to the performance with low turnaround time. These results clearly show that token passing has a superior performance than DCHF for networks having lengthy turnaround times.



**Figure 2.7. Latency results for  $T_t = 1s$  and  $N = 5$**

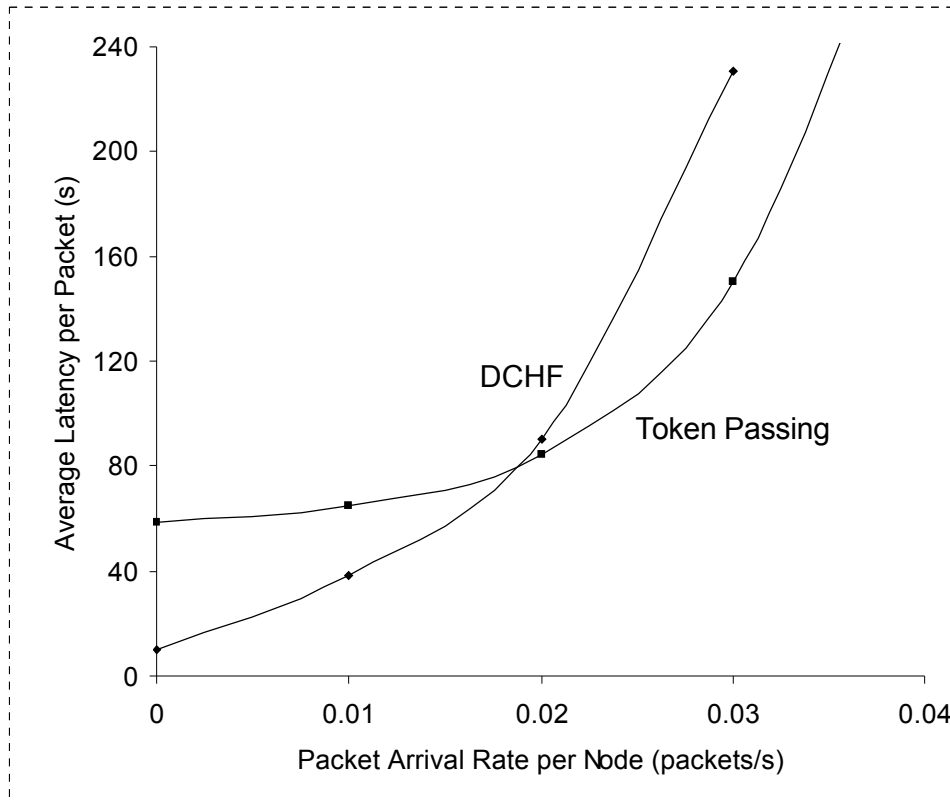
The reduced channel utilization for token passing when the traffic is light is due to longer idle periods while each node is in its turnaround time. As expected, DCHF performs poorly at heavy loads due to high packet collision probabilities. Also, token passing has smaller delay (per packet) than DCHF, since the huge turnaround time (experienced twice during the RTS/CTS in DCHF) outweighs the token rotation time.



**Figure 2.8. Channel utilization results for  $T_t = 1s$  and  $N = 50$**

Figures 2.8 and 2.9 show the performance of these protocols for large networks under long turnaround time (1s). At light loads, the performance of token passing is noticeably worse than DCHF because the token gets passed among a large number of nodes (even with no traffic) with a delay of one link turnaround time per node, resulting in a large token rotation time, and therefore a large average channel access time. DCHF performs better than token passing at low traffic in large networks, since inactive nodes do not congest the channel. However at heavy loads,

DCHF performance crashes because of packet collisions.



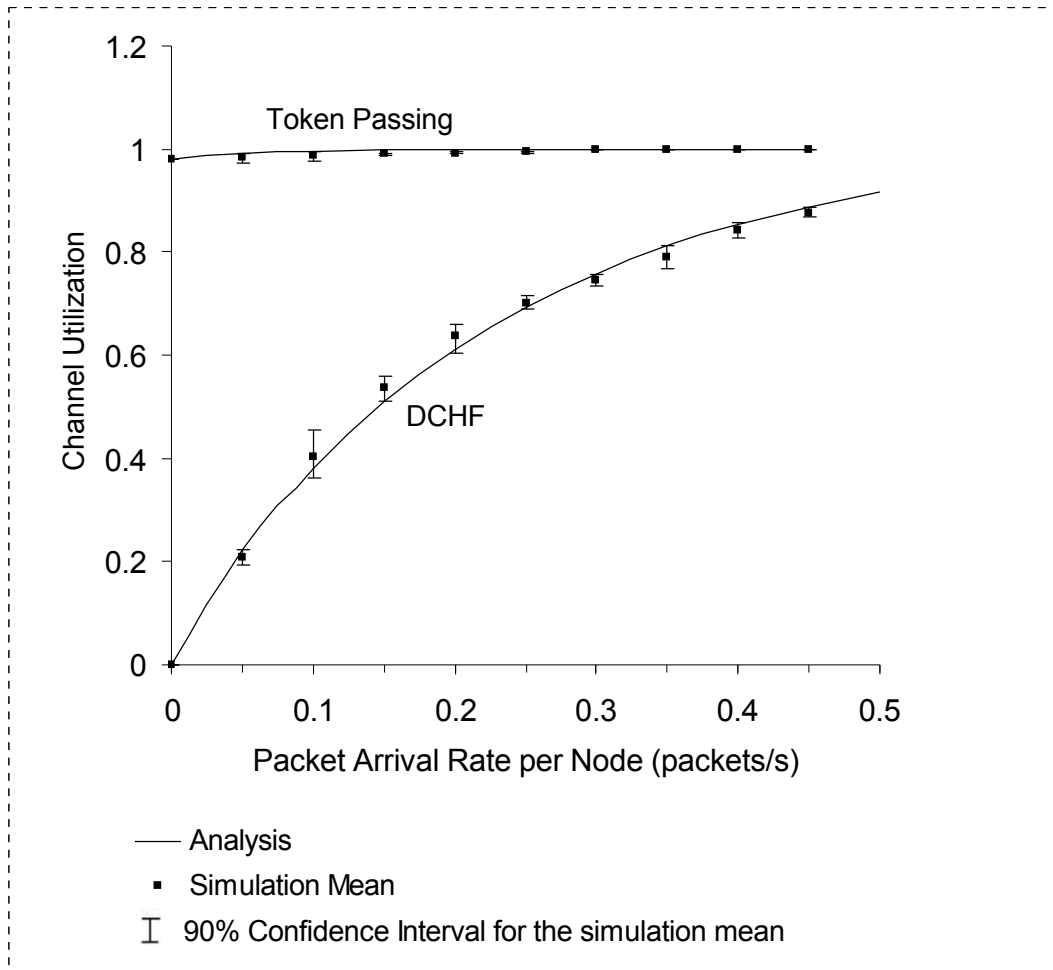
**Figure 2.9. Latency results for  $T_t = 1s$  and  $N = 50$**

The results show that contention free protocols perform better under heavy loads and high turnaround times because of their collision free operation. But in large networks with light traffic and long turnaround times, the contention based schemes perform better, since only active nodes transmit bits in the channel.

## 2.4 Verification Using Simulations

Simulation models of DCHF and token-passing protocols were developed using NetSim [9], a discrete event-driven network simulator, for verifying the analytical results. The Simulator (mainly the MAC module) was modified in accordance with the analytical model and the nodes communicate through a single lossless medium with a constant data rate of 6400 bits per second.

In token-passing, the analytical and simulation results were obtained with the size of acknowledgement packet same as that of the token packet (40 bytes). Also, the management overhead was not approximated as in statistical analysis, but was considered to be null, to provide more accurate comparison results. All the other parameter values, assumptions and MAC functionalities, in the simulation design concur with those in the statistical analysis. Figure 2.10 and Figure 2.11 show that the simulation results are in good agreement with the corresponding analytical results. Table 2.1 and 2.2 lists the comparison results.



**Figure 2.10. Simulation vs Analysis results for  $Tt = 1\text{ms}$  and  $N = 5$**

**Table 2.1. Simulation vs Analysis comparison table for  $Tt = 1\text{ms}$  and  $N = 5$**

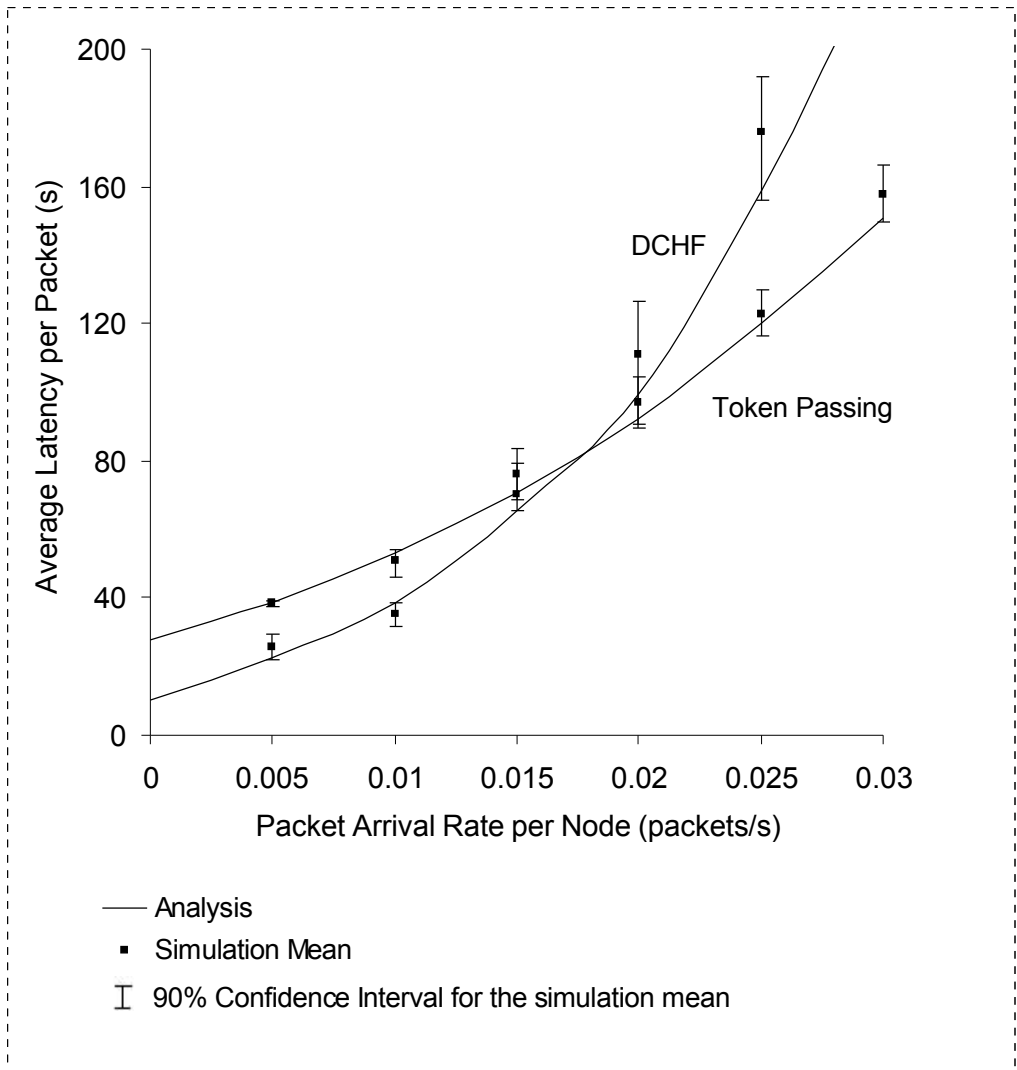
l	DCHF			Token-Passing		
	$X$	$\bar{X}$	90% CI	$X$	$\bar{X}$	90% CI
0	0	0	(0,0)	0.9804	0.9804	(0.9804,0.9804)
0.05	0.2238	0.2101	(0.1944,0.2258)	0.9929	0.9830	(0.9810,0.9931)
0.10	0.3811	0.4033	(0.3411,0.4171)	0.9962	0.9946	(0.9940,0.9967)
0.15	0.5094	0.5380	(0.5005,0.5455)	0.9977	0.9970	(0.9969,0.9980)
0.20	0.6108	0.6360	(0.6020,0.6600)	0.9986	0.9986	(0.9986,0.9986)
0.25	0.6925	0.7019	(0.6887,0.7151)	0.9992	0.9990	(0.9990,0.9992)
0.30	0.7583	0.7458	(0.7358,0.7558)	0.9996	0.9993	(0.9993,0.9997)
0.35	0.8115	0.7910	(0.7680,0.8140)	0.9998	0.9998	(0.9998,0.9998)
0.40	0.8542	0.8426	(0.8266,0.8586)	0.9999	0.9999	(0.9999,0.9999)

$l$  – Packet Arrival Rate per Node (packets/s)

$X$  – Channel Utilization from analysis

$\bar{X}$  – Mean Channel Utilization from simulation

CI– Confidence Interval for the simulation mean



**Figure 2.11. Simulation vs Analysis results for  $Tt = 1s$  and  $N = 50$**

**Table 2.2. Simulation vs Analysis comparison table for  $Tt = 1s$  and  $N = 50$**

l	DCHF			Token-Passing		
	$L$	$\bar{L}$	90% CI	$L$	$\bar{L}$	90% CI
0.005	22.49	25.876	(22.001,29.676)	38.675	38.595	(37.794,39.396)
0.01	38.657	35.65	(32.789,39.897)	52.976	50.673	(47.211,55.135)
0.015	65.678	70.177	(60.876,74.888)	70.789	76.3614	(68.884,83.839)
0.02	99.1645	110.78	(89.345,125.987)	92.002	96.8804	(89.319,104.441)
0.025	158.837	175.89	(155.987,190.997)	120.215	122.979	(116.31,129.642)

$l$  – Packet Arrival Rate per Node (packets/s)

$L$  – Average Latency per Packet from analysis

$\bar{L}$  – Average Latency per Packet from simulation

CI– Confidence Interval for the simulation mean

### 3.0 DISCUSSION

Contention based MAC protocols are less sensitive to network size when compared to the contention free schemes, allowing dynamic joining and leaving of nodes, with the least amount of management overhead. Contention based schemes are attractive for lightly loaded networks, as the inactive nodes do not consume any channel capacity (unlike in token-passing), offering superior latency characteristics. However, under heavy traffic, contention free schemes utilize the channel better as they dynamically pre-schedule the channel for data transmissions, allowing collision free operation.

Packet collisions are the main source of channel wastage in contention based protocols and they occur more often under heavy loading. The amount of channel capacity wasted due to collisions is severe when the link turnaround times are lengthy, since the RTS/CTS collisions may result in several unsuccessful hand shake attempts (with two turnaround times per hand shake) accounting to huge average channel access latency.

#### 3.1 Conclusion

In this paper, a statistical analysis of two functional categories of wireless MAC protocols was performed under varying link turnaround times. The performances were measured with varying Poisson loads. The analysis proves that link turnaround times influence the performance of MAC protocols significantly.

Contention free schemes are more suitable for small networks with long

turnaround times, under light or heavy loading, since the packet collisions and delay introduced by collision-avoidance schemes in contention based protocols make them ineffective. However for large networks with long turnaround times and light traffic, contention based schemes are appropriate, since the management overhead and synchronization schemes in contention-free protocols outweigh the channel time spent for transmitting data.

### 3.2 Future Work

Effects of packet losses (common in realistic channels) on the statistical performance of the wireless MAC protocols should be analysed and verified using simulations, modeled with a realistic lossy channel. Future work can also include an investigation of the overhead imposed on wireless MAC protocols due to high node mobility that leads to constant changes in network size and topology.

## APPENDICES

## APPENDIX A. DCHF-probability of first occupied slot

The probability of the first occupied slot among  $S$  slots when  $N_{contending}$  nodes are contending can be computed by deriving the probability of choosing a particular slot and then generalizing it for any slot. Probability that slot '1' is occupied equals the probability that any one of the contending nodes choose slot '1'. It is given by,

$$A_{S, N_{contending}}(1) = 1 - \left[ \frac{S-1}{S} \right]^{N_{contending}}$$

Probability that slot '2' is the first occupied slot equals the probability that any one of the contending nodes choose slot '1' or '2', minus the probability that slot '1' is occupied.

$$A_{S, N_{contending}}(2) = 1 - \left[ \frac{S-2}{S} \right]^{N_{contending}} - \left( 1 - \left[ \frac{S-1}{S} \right]^{N_{contending}} \right)$$

$$A_{S, N_{contending}}(2) = \left[ \frac{S-1}{S} \right]^{N_{contending}} - \left[ \frac{S-2}{S} \right]^{N_{contending}}$$

Probability that slot '3' is the first occupied slot can be calculated similarly, by just eliminating the probability of choosing slot '2' and rest of the slots other than

slot '3'. Eliminating slot '2' automatically eliminates the choice of slot '1' as per the above probability derivation.

$$A_{S, N_{contending}}(3) = \left[ \frac{S-2}{S} \right]^{N_{contending}} - \left[ \frac{S-3}{S} \right]^{N_{contending}}$$

These probabilities follow a similar pattern and in general, the probability that any slot 'i' is the first occupied slot is,

$$A_{S, N_{contending}}(i) = \left[ \frac{S-i+1}{S} \right]^{N_{contending}} - \left[ \frac{S-i}{S} \right]^{N_{contending}}$$

## APPENDIX B. DCHF-probability of success in a slot

Probability of success in a slot can be derived by calculating the probability of success in individual slots and then generalizing it to any slot. Probability of success in the first slot (with  $S$  slots and  $N_{contending}$  nodes competing in the network) is the probability that exactly one node chooses and transmits in slot ‘1’ and the rest of nodes does not choose slot ‘1’. It is given by,

$$S_{S, N_{contending}}(1) = \frac{N_{contending}}{S} \left( \frac{S-1}{S} \right)^{N_{contending} - 1}$$

The probability of success in slot ‘2’ is equal to the probability that nobody transmits in slot ‘1’ times the probability that exactly one node transmits in slot ‘2’, given that there was no transmission in slot ‘1’. This is necessary because, if there is a transmission in slot ‘1’, transmissions in slot ‘2’ will be deferred.

$$S_{S, N_{contending}}(2) = \frac{N_{contending}}{S-1} \left( \frac{S-2}{S-1} \right)^{N_{contending} - 1} * \left( \frac{S-1}{S} \right)^{N_{contending}}$$

$$S_{S, N_{contending}}(2) = \frac{N_{contending}}{S} \left( \frac{S-2}{S} \right)^{N_{contending} - 1}$$

Similarly the probability of success in any slot 'i' is,

$$S_{S, N_{contending}}(i) = \frac{N_{contending}}{S} \left( \frac{S-i}{S} \right)^{N_{contending} - 1}$$

## APPENDIX C. DCHF-state probabilities

The State Probabilities ( $P_S$ ) can be calculated from ' $\sigma_S$ ', the probability of success in state S. Figure 2 shows the Markov model of the DCHF backoff behavior and from that follows a sequence of simultaneous equations,

$$P_4 S_4 = P_2 (1 - S_2) \quad (1)$$

$$P_8 S_8 + P_2 (1 - S_2) = P_4 \quad (2)$$

$$P_{16} S_{16} + P_4 (1 - S_4) = P_8 \quad (3)$$

$$P_8 (1 - S_8) = P_{16} S_{16} \quad (4)$$

and also the sum of all probabilities is one.

$$P_2 + P_4 + P_8 + P_{16} = 1 \quad (5)$$

substituting  $P_{16} S_{16}$  from (4) in (3) we get,

$$P_4 (1 - S_4) = P_8 S_8$$

from (1) we get,

$$P_4 = \frac{P_2 (1 - S_2)}{S_4} \quad (6)$$

also,

$$P_8 = \frac{P_2 (1-s_2) (1-s_4)}{s_4 s_8} \quad (7)$$

$$P_{16} = \frac{P_2 (1-s_2) (1-s_4) (1-s_8)}{s_4 s_8 s_{16}} \quad (8)$$

Substituting (6), (7) and (8) in (5) we get,

$$P_2 = \frac{1}{W}$$

where,

$$W = 1 + \frac{(1-s_2)}{s_4} + \frac{(1-s_2)(1-s_4)}{s_4 s_8} + \frac{(1-s_2)(1-s_4)(1-s_8)}{s_4 s_8 s_{16}}$$

Finally  $P_2$  is substituted back in (6), (7) and (8) to obtain the other state probabilities in terms of the probability of success in a state.

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