Approximate Discrete Time Analysis of the Hybrid Token-CDMA MAC System

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***Abstract*— In this paper we consider a hybrid Token-CDMA based medium access control (MAC) protocol. The novelty of this paper is that the proposed MAC scheme is analytically modeled as a multiserver multiqueue (MSMQ) system in the case of a gated service discipline. An approximated discrete time analysis for the queue inside the system where the analysis is concerned is presented with the general case in which the system accommodates several traffic classes. Each queue in the system is assumed to incorporate the input model, the vacation model and the buffer model. The packet arrival process is assumed to be Poisson, with the same rate for the queues in each traffic class, and data rate quality of service (QoS) is incorporated to regulate the input and to provide fairness guarantee. Packet service time is modeled with independent, identically distributed random variables with geometric distributions. We have taken various performance measures into considerations. In our analysis, moments of the queue length and the packet delay are derived using the probability generating function approach.**

***Index Terms*—Hybrid MAC design, MSMQ system, Quality of service, Discrete time analysis, Queue length, Packet delay.**

I. Introduction

TOKEN passing medium access control protocols for Ad -hoc networks are gaining popularity in recent years as they have the potential of achieving high channel utilization than CSMA type schemes [1] and are capable of including QoS guarantees [2]. There exist a plethora of papers that proposed MAC schemes using token mechanism for Ad-hoc networks [1], [2], [3], [4], [5], and [6].

Using a similar approach as [2] and [6], a new hybrid Token-CDMA MAC protocol that incorporated a quality of service guarantee (QoS) is proposed by [7], in which the token-based scheme implements code division multiple access (CDMA) techniques to resolve packet collisions and incorporates QoS mechanisms to the Ad Hoc networks.

In analytical terms, the proposed hybrid Token Multi-code CDMA MAC scheme can be considered as a system that consists of multiple queues which are serviced by multiple servers, where this configuration is commonly denoted as multiserver multiqueue (MSMQ) system. The novelty of the system is that a CDMA code is considered as a server in the analytical scenario. There exist three packet transmission schemes for MSMQ systems [12]. For the proposed system, the scheme is adopted where a queue may only poll a single server during packet transmission. All other servers in the network arriving at the queue during transmission must be passed onto the next queue in the network. The proposed MAC scheme has the identical system characteristics as the MSMQ system. In this case, the storage capacity at each queue is assumed to be infinite and the queuing discipline is FIFO at each queue. The service discipline is gated at all queues. The polling order is given by servers visiting queues in a fixed index order. The maximum number of servers that can simultaneously attend a queue is one.

With the compact notation introduced in [12] for MSMQ systems, the system studied in this case can be denoted as a G/M/G/∞/{1} queue model. There exists an abundance of literature on the MSMQ networks, however, majority of it implements the 1-limited service discipline [8], [9], and [10] as its analytical model or the queue may be attended by multiple servers. In [12] and [15], the analysis was extended by presenting an approximate analytical results for the average server cycle and vacation times, as well as approximated closed-form expressions for the average packet waiting time under 1-limited, gated and exhaustive service disciplines. There exist only a few papers that discuss the same packet transmission protocol for the gated type service discipline and vacation system. Based on [12], [16] presented an approximated analysis for the proposed gated multiple-vacation queue that supports multiple traffic classes. Using the approximated approach, the queue vacation time was derived.

As the Diffserv [18] is an emerging architecture for future IP-Networks, the proposed MAC scheme is designed to be adequately integrating multiple types of traffic, which is in term making provisions for future integrations. The analysis conducted has taken server vacation and QoS issues into considerations. The current contribution investigates the proposed gated MAC system in discrete time. The proposed multiple-vacation queuing model allows us to conduct the approximated discrete time analysis and derive the moments of queue length and packet delay using the probability generating function approach. The novelty of this work lies in viewing and modeling the proposed hybrid MAC scheme in discrete time and in terms of queuing system with server vacation. The model considered is the extension of the results from [16] both regarding packet arrival and vacation period.

The remainder of this paper is organized as follows. Section II describes the analytical model in detail. The approximated discrete time analysis for packet departure process is described in section III. Section IV presents the approximated discrete time analysis on moments of the queue length and packet delay. Numerical results for simulation and analysis are presented in section V and conclusion is drawn in section VI.

II. MODEL DESCRIPTION

In the proposed hybrid MAC scheme [7], a token is circulating in the system distributing CDMA codes to queues. To access the channel, the queue requires capturing the code. This model is similar to the multiple-server model, where the queues need to be polled by a server to be granted access to the channel. CDMA codes in this case are considered as servers. Using this approach, the proposed analytical model is built based on a multiple-server scheme.

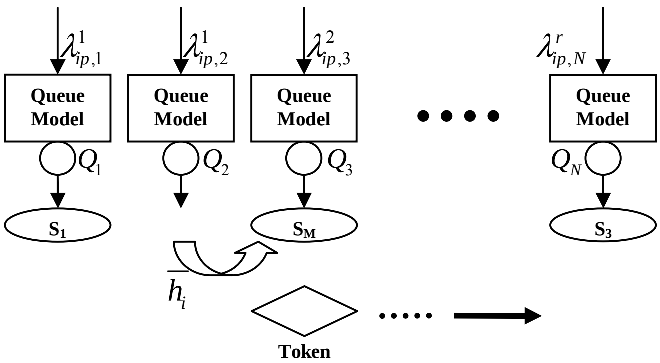

Fig. 1. System model

The system model consists of M codes/servers $S_1,\ldots, S_M$ and N queues $Q_1,\ldots,Q_N$, as shown in Fig. 1. The queue model in the system is displayed in Fig. 2. It is assumed that each server represents a code channel, each queue resembles a node and the system is operated in stable state. Each packet buffers in each queue, i, is assumed to have infinite capacity, into which packets arrive according to a Poisson process. The queues are categorized into r different classes where the number of queues in each class is denoted as q_1, q_2, $q_3\ldots$ q_r. Queues in each class have the identical mean data packet arrival rate with notation $\lambda_{ip,i}^{r}$.

To provide data rate QoS, a modified leaky-bucket input regulation system is implemented. Each queue has a permit pool for storing the generated permits. The permit generation rate $\left(T_p^i\right)^{-1}$ is proportional to the data rate $\rho_i \cdot \lambda_{ip,i}^{r};\ \rho_i \geq 1$. The packets that arrived to buffer Q_1 have to gain the permission through leaky-bucket policing mechanism, where it must obtain a permit from a permit pool. The permit pool has a maximum capacity of up to γ_i permits. If the generated permit finds that the pool is full, it is discarded. The packet length is assumed to be geometrically distributed with the mean of s bits/packet. Since the code channel rate is assumed to be constant in the analysis, the service time of a packet is then also geometrically distributed with a mean of μ^{-1} slots/packet.

As mentioned earlier, when the token visits a queue and there is a code available, the gated-service discipline is employed where the server will empty the packet buffer Q_3 as shown in Fig. 2, detailed description of the transferring of packets between queues is discussed in section IV. After servicing the packets, the queue returns the code to the token and enters the vacation period. The vacation ends when the token with codes visits the queue again. The approximated mean value analysis of the vacation period is presented in [16]. The analytical model is assumed to be symmetrical. In this case we assume that all servers are identical and carry the same load.

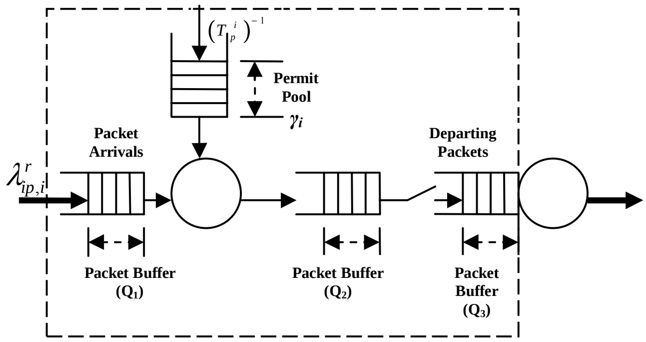

Fig. 2. Queue model

III. DISCRETE TIME ANALYSIS FOR PACKET DEPARTURE PROCESS

In this section we presented the discrete time analysis for the input model where we derived the probability generating function of the packet departing process from Q_1 to Q_2 where the packet passed through the modified leaky-bucket QoS scheme. The discrete time analysis method is used, in this case, time is slotted where the length of the each slot n is the permit generation slots with fixed slot length T_p^i and a new permit is generated at each slot boundary as depicted in Fig. 3. The length of the slot is proportional to the mean arrival rate where $T_p^i = \left(\rho_i \lambda_{ip,i}^{r}\right)^{-1}$. The queue model in the system consists of three queue buffers (Q_1, Q_2 and Q_3) as illustrated in Fig. 2.

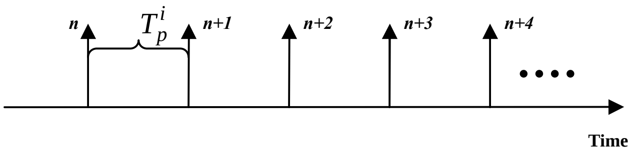

Fig. 3. State diagram of the discrete time system

For the analysis, we want to first derive the probability mass function (pmf) of the departing packets after the packet goes through the Leaky-Bucket (P_{B_n}) at the slotted time before we can derive the pgf for the process. It is known that the amounts of packets departing the leaky-bucket during the n_{th} slot are dependent on the queue length prior to permit generation instances [17]. For the steady-state joint probability distribution of the queue length Q_1 and the permit pool occupancy (P_{B_n}) at the slot boundary, its distribution function can be found at embedded permit generation point where the input queue can be modeled as a M/D/1 queue [13]. For the M/D/1 queue, its queue length distribution in steady state can be derived as,

$$P_{q_m}(a)=\Pr\{q_m=a\}=(1-\theta_i)\sum_{k=1}^{a}\left((-1)^{a-k}e^{k\theta_i}\left[\frac{(k\theta_i)^{a-k}}{(a-k)!}+\frac{(k\theta_i)^{a-k-1}}{(a-k-1)!}\right]\right) \quad (1)$$

where $\theta_i=\frac{\lambda_{ip,i}}{T_p^i}$ and with initial conditions,

$$P_{q_m}(0)=(1-\theta_i)$$
$$P_{q_m}(1)=(1-\theta_i)\left(e^{\theta_i}-1\right) \quad (2)$$

The number of packets that arrived to Q_2 in *nth* slot is dependent on the number of packets depart from Q_1 during the n_{th} slot. In the one packet departure case, in order to have one packet depart at the n_{th} slot, there must be at least one packet in the queue buffer Q_1 i.e. $\Pr(q_n\geq 1)$. Using the iterative process and with memoryless characteristic of the M/D/1 queue, the steady state probability distribution of the departing packet at slot boundary can be clearly derived as,

$$P_{B_n}(0)=\Pr(q_n=0)=(1-\theta_i)$$
$$P_{B_n}(1)=\Pr(q_n\geq 1)=\sum_{i=1}^{\infty}\Pr\{q_n=i\} \quad (3)$$

To summarize, we may now compute the distribution function for the departing packets,

$$\Pr\{B_n=j\}=\begin{cases}(1-\rho_i) & ,j=0\\ 1-\sum_{i=0}^{j}\Pr\{q_n=i\} & ,j=1\\ 0 & ,j>1\end{cases} \quad (4)$$

The probability generating function of the packet departing process $B(z)$ can now be derived using standard z-transform method,

$$B(z)=\sum_{j=0}^{\infty}\Pr\{B_n=j\}\cdot z^j=(1-\rho_i)+\left(1-\sum_{i=0}^{j}\Pr\{q_n=i\}\right)\cdot z \quad (5)$$

IV. Discrete Time Analysis for Moments of Queue Length and Packet Delay

A. Model Overview

In this section we incorporated the input model, queue model and the vacation model into the system model and performed an approximated discrete time analysis for the proposed MAC scheme. Various system performance measures are taken into consideration such as the queue length and the packet delay at the primary (Q_3) and secondary queue buffers (Q_2).

For discrete time analysis, the time is divided into fixed length intervals (slots). It is discussed in section III that the number of packets arriving in the consecutive slots and the service time (in slots) of these packets are a series of independent identically distributed random variables with Poisson and geometric probability mass function P_{A_n} and P_{S_n} respectively and with corresponding probability generating function $A(z)$ and $S(z)$ respectively. It is known from Fig 2 that the modified leaky bucket is implemented to enforce data rate QoS, and it is derived in section III that the number of packets depart for Q_2 in the consecutive slots is assumed to be a random variable with probability mass function P_{B_n} and with corresponding probability generating function $B(z)$.

For transferring of packets between queue buffers, packets that depart Q_1 arrive at Q_2 and wait in the queue buffer before the gate and move in batch to the queue buffer Q_3 only when the gate opens. The gate is only opened at the end of the last slot of the vacation period. Once the gate is opened the packets in Q_2 is then move to Q_3 and are then served according to first-in-first-out (FIFO) principle before departing the system. A vacation starts when Q_3 empties and the gate opens at the end of each vacation. However, if the server finds Q_3 empty upon returning from vacation, it will immediately start another vacation until Q_3 has packets when the server returns from the vacation (multiple vacation policy). The mean value of the vacation length is derived from [16] and it is modeled as a Pólya distributed random variable with probability mass function P_{V_n} and corresponding probability generating function $V(z)$.

B. Queue Length at Q_2 and Q_3

For the queue model under consideration, a queue cycle is defined to consist of a busy period that follows with a vacation period. When the busy period starts, the buffer content in Q_3 is emptied by serving all the packets , all the packets that arrived during the busy period is stored in Q_2 since the gate is closed in busy period. Once the server has served the last packet in the Q_3, it moves to the next queue in the system. In this case we considered that the server takes on the vacation after it finished serving the packets in Q_3. At the end of the vacation period, the gate is opened and all the packets that stored in Q_2 are now conveyed to Q_3 in the FIFO order.

We now defined c_{l+1} as the slot following the l_{th} cycle and let X_i as the number of packets in the Q_3 at the beginning of the slot *i*. [14] indicated that the number of packets in the Q_3 at c_{l+1} can then be defined as,

$$X_{c_{l+1}} = \sum_{i=1}^{X_{c_l}} \sum_{j=1}^{g_i} B_i^j + W_{l+1} \tag{6}$$

where g_i is defined as the service time of the packet *i* during the l_{th} cycle, B_i^j is defined as the number of departures from Q_1 to Q_2 during the *jth* service slot of the packet and W_{l+1} is defined as the number of departures from Q_1 to Q_2 during the vacation period in the $l+1_{th}$ cycle. We defined $X_{c_l}(z)$ as the probability generating function of the number of packets in the queue at the end of the l_{th} cycle. With some derivations, its pgf can be shown as,

$$X_{c_{l+1}}(z) = X_{c_l}\left(S\left(B(z)\right)\right)\cdot \overline{W_0}(z) + X_{c_l}\left(S(b_0)\right)\cdot\left(W_0(z) - \overline{W_0}(z)\right) \tag{7}$$

where $W_0(z)$ is defined as the probability generating function of the number of departures from Q_1 to Q_2 during the vacation period of a random cycle under the condition that there exists no packets in Q_2 at the end of the slot preceding the vacation period. $\overline{W_0}(z)$ is defined as the probability generating function of the number of departures from Q_1 to Q_2 during the vacation period of a random cycle under the condition that there is minimum one packet in Q_2 at the end of the slot preceding the vacation period. It can be easily derived that $\overline{W_0}(z) = V\left(B(z)\right)$ since under the condition that if there are at least one packets in Q_2 before the vacation starts, the server will then only take one vacation. However, the server will take multiple vacations until there exist a packet in the Q_2 when it comes back from the vacation. Modifying the analysis from [14] and by conditioning on the number of necessary vacations,

$$W_0(z) = \frac{V\left(B(z)\right) - V(b_0)}{1 - V(b_0)} \tag{8}$$

To find the probability generating function of the queue length at the end of the cycle, we first defined $X_c(z) = \lim_{l\to\infty} X_{c_l}(z)$ as its pgf for the queue length at the end of the cycle in equilibrium. It is proven from [11] that this condition is valid under the assumption where,

$$\delta_i = S_i^{'}(1) B_i^{'}(1) < 1 \tag{9}$$

where δ_i is the load of the queue model *i* and from the equilibrium assumption, (21) can now be derived as,

$$X_c(z) = X_c\left(S\left(B(z)\right)\right)\cdot \overline{W_0}(z) + J\cdot\left(W_0(z) - \overline{W_0}(z)\right) \tag{10}$$

where $J = X_c\left(S(b_0)\right)$ is the probability that the Q_2 is empty before the start of the vacation period. It is now clearly shown that various moments of $X_c(z)$ can be derived using implicit determination and that the value of *J* can be determined numerically using recursive technique. In our case, we first consider the series $z_i = S\left(B(z_{i-1})\right)$, $z_0 = 0$, $i > 0$. Under the condition that $\delta_i < 1$, it can be determined that the series converges to one. Now, let $q_{i+1} = J / X_c(z_i)$, with the substitution of $z = z_i$ in (10), then

$$q_{i+1} = \frac{\overline{W_0}(z_i)\, q_i}{1 + \left(\overline{W_0}(z_i) - W_0(z_i)\right) q_i} \tag{11}$$

The value of *J* can then be determined recursively by starting from $q_1 = 1$ and $J = \lim_{i\to\infty} q_i$. Once the queue length at the end of the cycle can be found, the joint probability generating function of the buffer length at other epochs in Q_2 and Q_3 can now be derived.

For the buffer length at the end of packet service, we defined $X_d(z_1, z_2)$ as the joint probability generating function of the queue length at the Q_3 and Q_2 at the start of the slot right after a service of a packet from Q_3, its pgf can then be derived as,

$$X_d(z_1, z_2) = \frac{S\left(B(z_2)\right)}{X_c^{'}(1)} \cdot \frac{\left[X_c\left(S\left(B(z_2)\right)\right) - X_c(z_1)\right]}{\left[S\left(B(z_2)\right) - z_1\right]} \tag{12}$$

Where $X_{d,1}$ and $X_{d,2}$ are defined as the queue length in the Q_3 and Q_2 at a random service epoch respectively and X_c is previously defined as the total buffer length in Q_3 and Q_2 at the end of the random cycle.

C. *Packet Delay at Q_2 and Q_3*

In the discrete time analysis, the packet delay is denoted as the number of slots between the end of the slot the tagged packet arrives in at Q_1 and the end of the slot where that tagged packet leaves Q_3. The service time of the packet is taken into consideration in determining the delay from Q_3 as the packet only departs from the queue once it is being served. For the modified leaky-bucket QoS scheme, the exact delay expression for packets in Q_1 has been derived by [13] therefore we will concentrate on the delay expressions on Q_2 and Q_3. The number of packets that depart from Q_2 in a slot are grouped to form a "batch customer" which forms a system with Bernoulli "batch-customer" arrivals. The probability generating function for the departures $B^*(z)$ and their service times $S^*(z)$ are given by,

$$B^*(z) = b_0 + (1 - b_0)z,$$
$$S^*(z) = \frac{B\left(S(z)\right) - b_0}{1 - b_0}, \tag{13}$$

Let $X_d^*(z_1, z_2)$ denote the probability generating function of the Q_3 and Q_2 queue length at departure epochs for this system. By considering a random batch packet and let $D^*(z_1, z_2)$ denote the joint probability generating function of its delay in Q_3 and Q_2 buffers. For the batch-packets that arrive during its delay in the Q_2 are moved to Q_3 along with the tagged batch-packet. And for all the batch-packets that arrive during its departure in the Q_3 are present in the Q_2 at its departure. It is then shown by [14] that the probability generating functions of batch-packet delay and queue contents at batch-packet departure epochs can be easily related as,

$$D^*\left(B^*\left(z_2\right),B^*\left(z_1\right)\right)=X_d^*\left(z_1,z_2\right) \tag{14}$$

To relate the delay of the packet to the delay of its batch, the delay in the Q_2 of a packet equals the delay of its batch as they enter and leave Q_2 at the same time slot. The waiting time of a packet is denoted as the number of slots between the end of its arrival slot and the beginning of the slot where this packet starts its service. Therefore the waiting time in Q_3 of a packet is then the sum of the waiting time of its batch, with combination of the service times of all packets that arrived during the same slot prior to the tagged packet. Based on [14] and with modifications to our model, the packet delay in the Q_2 and Q_3 can be derived as,

$$D\left(z_1,z_2\right)=\frac{S\left(z_1\right)\left[B\left(S\left(z_1\right)\right)-1\right]}{B'(1)\left[S\left(z_1\right)-1\right]}\cdot\frac{X_d^*\left(\frac{z_2-b_0}{1-b_0},\frac{z_1-b_0}{1-b_0}\right)}{S^*\left(z_1\right)} \tag{15}$$

Where b_0 is $P_{B_n}(0)$. Various moments of the packet delay for both Q_2 and Q_3 queue buffers can now be derived using derivatives techniques for (15).

V. Numerical Results for Mean Packet Delay at Q_2 and Q_3 Queue Buffers

To derive the first moment expression for the gated multiple vacation queue model, we start with the probability generating functions for the departures into Q_2, $B(z)$ has been derived from (5), and since the service times of the consecutive customers are a series of geometrically distributed random variables, its probability generating function $S(z)$ is,

$$S(z)=\frac{z}{\mu^{-1}+\left(1-\mu^{-1}\right)z} \tag{16}$$

where μ^{-1} denotes the mean service time of a packet. For the vacation time, it is assumed from previous section to be a Pólya distributed random variable with probability generating function $V(z)$,

$$V(z)=\left(\frac{p_{nb}}{1-\left(1-p_{nb}\right)z}\right)^k \tag{17}$$

where $p_{nb}=k\left(\overline{V_i}+k\right)^{-1}$ and the constant k can be approximated from [12] to be $M+1/M-1$.

For the numerical examples, we present results from the simulation and analysis to demonstrate the effects of the traffic loading conditions, on the performance of the queue contents and the packet delay at both packet buffer Q_2 and Q_3 of difference class queues. The simulation program is written in C++ Builder programming package and the analysis is computed using Matlab software language. Simulation and analysis are conducted using the parameters shown in Table I.

TABLE I
System Parameters

Symbol	Parameter
Number of nodes (*N*)	9
Number of codes (*M*)	6
Number of classes (*r*)	3
Nodes in each class (q_i)	3
Traffic load for class 1 (λ_i^1)	$\lambda_i^1=1.5\lambda_i^2$
Traffic load for class 3 (λ_i^3)	$\lambda_i^3=2\lambda_i^2$
QoS parameter (ρ_i)	1.2
Mean service time (μ^{-1})	1.25 sub-slot/packet
Mean Token walk time ($\overline{h_i}$)	0.01 sub-slot
Permit pool capacity (γ_i)	20

Both the simulation and analysis results of the mean packet delay in queue buffer Q_2 for different traffic class queues are shown in Fig. 4. It displays that class 3 queue buffer has the highest delay amongst all the class queue buffers and class 2 buffer has the lowest delay. This is expected as for the system under consideration, class 3 queue has the highest data rate therefore more packets are stored in the queue comparing to other classes subsequently leads to the increase in packet delay. It is interesting to note that the system under consideration remains stable during the light to medium, even under heavy traffic state. We also observe that in this range the system performance is very sensitive to the changes in the loading condition as illustrated in Fig. 4 and 5. Fig. 4 also shows that the analysis result of the delay for all classes under mid to heavy system load conditions compare favorable to simulation results.

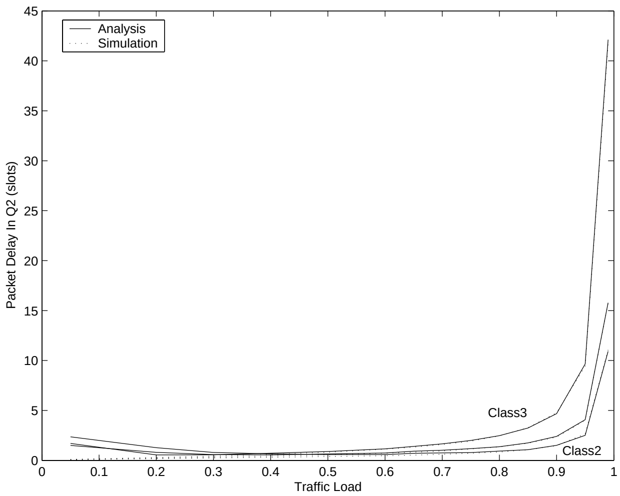

Fig. 4. Mean packet delay for the packet stored in Q_2 for different traffic classes in the network under different load conditions

For the mean packet delay in queue buffer Q_3 of different class queues, the simulation and analysis results for various system load conditions are displayed in Fig. 5. Clearly, when the system is under a light traffic condition, the probability that a packet arrives during the cycle is low, therefore leads to low packet delay for all classes. For different traffic classes, it is observed that the lightest traffic class 2 and heaviest traffic class 3 have the highest and lowest packet delay respectively. This is as predicted, since the class 3 queue buffer generates more packets than class 2 buffer.

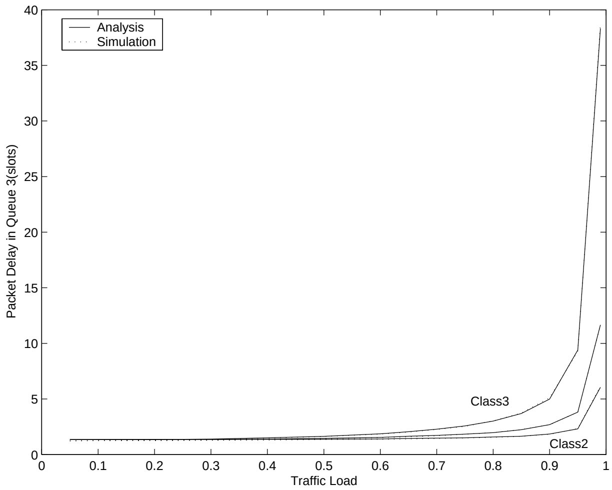

Fig. 5. Mean packet delay for the packet stored in Q_3 for different traffic classes in the network under different load conditions

VI. CONCLUSION

The paper presented the analytical model of the hybrid Token-CDMA MAC scheme with gated service discipline and data rate QoS. Approximated discrete time analysis was also conducted for the packet departure and for the moments of packet delay at various queue buffers. Some numerical examples for the proposed analysis are presented, and it was illustrated that the analytic results compare favorably to simulation results.

REFERENCES

[1] M. Ergen, D. Lee, R. Sengupta, and P. Varaiya, "Wireless Token Ring Protocol-Performance Comparison With IEEE 802.11," *in IEEE 8th International Symposium on Computers and Communication (ISCC) 2003*, pp. 710–715, 2003.

[2] L. Donatiello and M. Furini, "Ad Hoc Networks: A Protocol for Supporting QoS Applications," *in IEEE International Sympusium on Parallel and Distributed Processing 2003*, pp. 219–226, IEEE, April 2003.

[3] R. L. Davies, R. M. Watson, A. Munro, and M. H. Barton, "Ad-Hoc Wireless Networking: Contention Free Multiple Access Using Token Passing," *in IEEE 45th Vehicular Technology Conference (VTC) 1995*, vol. 1, pp. 361–365, IEEE, July 1995.

[4] S. Taheri and A. Scaglione, "Token Enabled Multiple Access (TEMA) for Packet Transmission in High Bit Rate Wireless Local Area Networks," *in IEEE International Conference on Communcations (ICC) 2002*, vol. 3, (New York City), pp. 1913–1917, IEEE, May 2002.

[5] M. Takahashi, Y. Komoriya, I. Sasase, and T. Arita, "A Medium Access Control Protocol with Token Passing and Retransmission by the Hub Station in the Asynchronous Transfer Mode of Wireless 1394," *in IEEE Global Telecommunications Conference (GLOBECOM) 2001*, vol. 6, pp. 3728–3732, November 2001.

[6] M. Ergen, D. Lee and P. Varaiya, "WTRP-Wireless Token Ring Protocol", accepted for publication in *IEEE Transaction on Vehicular Technology* (November 2004 Issue).

[7] Y.S. Liu, and F. Takawira, "Token Based Medium Access Control in Wireless Networks," *in Proc. Southern African Telecommunication Networks and Applications Conference (SATNAC)*, pp 277-282, September, 2001.

[8] VC. Hamacher, and EA. Kamal, "Approximate analysis of non-exhaustive multiserver polling systems with applications to LAN," *Computer Networks and ISDN Systems*, vol 17, 1989, pp 15-27.

[9] EA Kamal, "The multi-token ring network protocol," *Computer Networks and ISDN Systems*, vol 26, 1994, pp.1477-1494.

[10] J. Cai, A. Fumagalli, and I. Chlamtac, "The multitoken interarrival time (MITT) access protocol for supporting variable size packets over WDM ring network," *IEEE Journal on selected areas in communications*, vol.18, no.10, pp.2094-2104, Oct, 2000.

[11] S. Sumita, "Performance Analysis of Interprocessor Communications in an Electronic Switching System with Distributed Control," *Performance Evaluation*, vol.9, pp.83-91, 1989.

[12] A. Marsan, L. F. de. Moraes, S. Donatelli and F. Neri, "Cycles and waiting times in symmetric exhaustive and gated multiserver multiqueue systems*", IEEE Infocom'92*, vol. 3, pp.2315-2324, 1992.

[13] M. Sidi, W.Z. Liu, I. Cidon, and I. Gopal, "Congestion Control Through Input Rate Regulation," *IEEE Transactions on Communications*, vol.41, no.3, pp.471-477, March, 1993.

[14] D. Fiems, J. Walraevens and H. Bruneel, "The Discrete-Time gated vacation queue revisited", *International Journal of Electronics and Communications*, vol. 58, no. 2, pp.136-141, 2004.

[15] CH. Chen, and L. N. Bhuyan, "Design and analysis of multiple token ring networks," *IEEE/ACM SIGCOMM 88'*, vol.19, no.4, pp. 170-181, Nov. 1988

[16] Y. Liu, H. Xu, and F. Takawira., "Approximate Analysis of Queue Vacation Time in Gated Multiserver Multiqueue System," *in IEEE International Conference on Communication (IEEE ICT 2005)*, accepted for publication, May, 2005.

[17] N. Gautam, "Buffered and Unbuffered Leaky Bucket Policing: Guaranteeing QoS, Design and Admission Control," *Telecommunication Systems*, vol. 21, pp. 35-63, 2002.

[18] K. Nichols, V. Jacobson, and L. Zhang, "A Two-Bit Differentiated Services Architecture for the Internet," *Tech. Rep. (IETF RFC:2638)*, Internet Engineering Task Force (I.E.T.F.), July 1999

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