Performance Analysis for a QoS-Aware Hybrid Token-CDMA MAC Protocol

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Abstract—**This paper presents the performance analysis of a hybrid Token-CDMA MAC protocol. The protocol is based on a token passing scheme with the incorporation of code division multiple access (CDMA). The protocol provides both QoS guarantee and high network resource utilization. The performance of the MAC scheme is analyzed by event-driven simulations. Markov-modulated Poisson process (MMPP) is modeled for the traffic input sources and the issue on the channel link error caused by the wireless link has been taken into consideration by implementing multi-layered Gilbert-Elliot model which takes into account the number of interfering codes for simulating bit errors on a wireless link. Various performance metrics are used to demonstrate effectiveness of the hybrid protocol.**

Index Terms—**CDMA, Gilbert-Elliot model, Medium Access Control (MAC), Quality of Service (QoS), token passing.**

I. INTRODUCTION

Ad hoc and wireless mesh networks (WMNs) [1] are commonly known to implement IEEE 802.11 related schemes as their medium access control (MAC) protocols. It is known from [2,3] that with the 802.11 based scheme; the performance is degraded by the fairness problems, backoff inefficiencies, and unavoidable high collision rate problems under a highly loaded situation.

It is well known from [4,6] that token-passing MAC schemes outperform CSMA schemes and they are proved to be the most reliable MAC schemes in the industry [5]. Therefore, token passing medium access control protocols for ad hoc networks have gained popularity in recent years as researches are extending the concept of token passing scheme to wireless settings since they have the potential of achieving higher channel utilization than CSMA type schemes [4].

From the currently proposed token protocols, [6,7,8] presented a wireless token ring network that only accommodates one traffic type and the network is underutilized since no spatial-reuse is implemented. In [9], a scheme that supports multiple transmissions at the same time has been proposed. However, the scheme is designed solely for low mobility nodes in small confined space (static environment). The most significant drawback of these MAC schemes is that they do not discuss wireless aspect of ad hoc networks since most wireless channel errors are omitted or discarded at the link layer.

It is commonly known that a wireless link transmission is much more error prone than the cable-based links and link layer retransmission triggered by corrupted data decreases the bandwidth efficiency which results in inferior performance at the upper layers of the OSI model. Several physical considerations are deemed to cause errors in wireless links: multipath fading, path loss, adjacent channel interference, man-made interference, dynamic topology, station mobility, partial connectivity and channel noise [10]. The issue of wireless channel interference on the wireless token passing MAC protocols is discussed by [11] and the paper discovered that token passing MAC is vulnerable to channel errors where the system stability is severely hindered by the loss of a token and thereby affecting the utilization of the network bandwidth.

In this paper, a hybrid token-CDMA multiple access control scheme is presented. It is designed to handle heterogeneous classes of traffic in all traffic load types. The novelty of the proposed MAC scheme is that it combines the advantages of guarantee-access characteristic of the token passing mechanisms and the supportability of multiple packet transmissions within the network with the incorporation of QoS guarantee for different classes of traffic. With its unique characteristic, the hybrid protocol is able to support ad hoc network or WMNs structures.

The intriguing part of the proposed scheme is that the issue of scarce bandwidth has been addressed where the token is used as the CDMA channel distributor and the channels are shared amongst the nodes in the network. By integrating the CDMA mechanism into the MAC scheme, the CDMA codes are now effectively distributed amongst the nodes using the token. It is known that for current CDMA system, every user is equipped with a specific code so the maximum number of users that may join in a network is dependent on the number of codes. With the newly proposed MAC, the CDMA codes can be dynamically assigned to the nodes.

Extensive performance measures of the proposed MAC scheme are evaluated in a wireless environment using simulation. A key part of the simulation is the channel link error models, and in reality, wireless channel errors are usually bursty and dependent in occurrences, rather than uniformly and independently distributed. To capture such behavior in the wireless channel, a multi-layered two-state Markov Chain model, commonly known as the Gilbert-Elliot model [12], [13] is used in modeling the channel link error.

The novelty of this work lies in conducting a performance analysis of the hybrid token-CDMA MAC scheme with data rate

QoS guarantee and with consideration of wireless channel interference. The remainder of this paper is organized as follows. Section II describes the proposed MAC protocol in detail. The finite state machine of the proposed MAC scheme is described in Section III. Both the simulation model and results are presented in Section IV and conclusions are drawn in Section V.

I. HYBRID TOKEN-CDMA MAC SCHEME DESCRIPTION

In this section, a comprehensive description of the hybrid MAC protocol is discussed. Detailed discussion on how the proposed MAC scheme deals with issues on token protection, node join and lost, network initialization and provision for multiple rings is presented in [14]. This section presents the structure, characteristics and properties of the new protocol.

A. Network Topology and Model

The hybrid MAC scheme is capable to implement in either ad hoc or WMN networks. For WMN configuration, stations are served as access networks utilizing non-mobile relaying nodes to provide wireless backbone services for nomadic users to access the wired Internet. In this paper, it is assumed that the network is a distributed, de-centralized ad hoc wireless network that consists of N stations with incorporation of M CDMA codes ($M < N$) and with r traffic classes. Each station is assigned to a specific traffic class as illustrated in Fig. 1. In this figure Q_i denotes the queue model of station i (as illustrated in Fig. 2) and T_i^{trans} is the token transmission time between two stations and $\lambda_{ip,i}^r$ is the packet arrival rate for station i of class r. Each station is assumed to have the ability to communicate with its adjacent stations over a single-hop. The token implemented in the hybrid token-CDMA scheme is used to distribute M CDMA codes in the network. Each station is provided with a common code channel that is used specifically for token transmissions. Each station is also assumed to be equipped with a MUD (multiple user detection) capabilities, in order to be able to receive multiple transmissions simultaneously.

B. Station and Token Structure and Properties

The station is assumed to equip with two transceivers in which one is used for token transmission and other is used for data transmission. The stations maintain an updated STATION_LIST of their immediate neighbors in order to send the token to its successor. Several timers are equipped in each station for implementing various functions of the MAC scheme. A token is created during the initialization phase of each network. For the CDMA code allocation mechanism, unlike [15] which uses a distributed algorithm to assign code to each node, the hybrid MAC scheme uses a token to utilize the code capacity. It is assumed that each station in the network has the pre-defined knowledge of all the M CDMA code words used for the network.

The structure of the token consists of the ring-leader address, source address, destination address, number of codes available (*NOC*), and other network parameters as shown in Table I. The capacity of the address field of the station is kept to reasonable size of 6 bits, this is sufficiently enough as it can fit to maximum of 2^6 stations in a single network. Detailed description of the token properties can be found in [14].

Table I: Token structure

P M	Hop Leader ID	Source ID	Destination ID	NOC	S-List	C-List	D B	EOT

C. Quality of Service Guarantee

Quality of service (QoS) guarantees can generally be defined as a mechanism for networks to satisfy the varied quality and grade of service required by an application, while at the same time maximizing bandwidth utilization. In a wireless communication system, there are numerous methods to formulate the QoS objectives quantitatively. Amongst all of the papers that proposed a token based scheme for Ad Hoc networks, a majority of papers proposed to provide the QoS by means of timing guarantee. In the hybrid MAC protocol, based on leaky-bucket traffic policing mechanism, a data rate QoS guarantee is enforced to support real time multimedia applications.
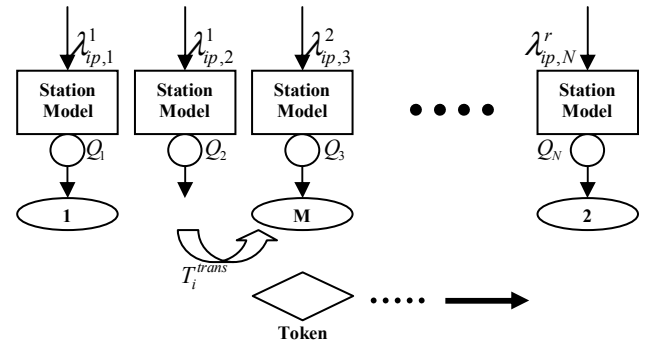

Fig. 1. Network model for hybrid Token-CDMA MAC protocol

Fig. 2 shows the station model used when incorporating data rate QoS. In order to provide this service, a permit generation system is implemented. The queue inside the station is equipped with a permit buffer for storing the generated permits. The permit generation rate (α_p^i) is proportional to the designated data rate ($\lambda_{g,i}^r$),

$$\alpha_p^i = \rho_i \cdot \lambda_{g,i}^r; \ \rho_i \geq 1 \qquad (1)$$

The subscript i of $\lambda_{g,i}^r$ denotes the queue number (station number) and ρ_i is the proportional constant which is the same for all the stations in a traffic class. The main purpose of the QoS parameter is to provide fairness in the network by ensuring that all stations receive sufficient access to the network. This fairness mechanism is achieved by constraining the station-transmit capacity, limiting the maximum number of packets that can be transmitted by varying the QoS parameter. If a token has been captured by station i, then the packet buffer is emptied such that the number of packets removed is equal to the number of permits in the permit buffer (the scheme is gated).

D. Channel Access Control

Once the token is generated in the network, it continuously circulates within the network, following a predetermined order.

The token uses the parameter NOC ($0 \le NOC \le M$) to control the amount of traffic flow in the network. If the station has data packets that it wishes to transmit, it has to wait for the arrival of the token. When a station is visited by a token, it forwards the token to the successor station (the next available address in the STATION_LIST) without capturing it under two circumstances.
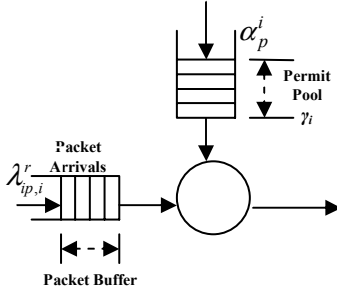

Fig. 2. Station model with data rate QoS guarantee

In the first scenario, the station forwards the token if the station itself is still busy transmitting data packets from previous token cycle. A token cycle (T_c) is the time for the token to visit all the stations in the network ($T_c = \sum_{i=1}^{N} T_i^{trans}$), T_i^{trans} is the time for a token to travel from station i to its successor station $i+1$. In the second scenario, the station forwards the token if it has finished transmitting data packets and also occupies a code channel. In the latter scenario, the station has to release the code back to the token irrespective of whether or not it has packets that it wishes to transmit. This is the global fairness algorithm [16] employed to ensure that all the stations have the same opportunity to access the network. The algorithm is implemented to avoid the station from constantly withholding the code for its own transmission, thereby disrupting the fairness of the network. Once the code is released, the token increments its NOC value by one. If the station is neither transmitting nor has a code channel when the token arrives, it may capture the token if the QoS requirement is met. If the station fails to satisfy QoS guarantee, it will then be obliged to forward the token to its successor station according to the pre-defined order.

If the token has been successfully captured, the permission for transmission is now acknowledged, the station decrements the NOC value by one, indicating that it has occupied a code channel. Using that specified code channel, the network allows the station in the ring to send its packets. The gated service discipline has been applied to awaiting packets in the queue buffers and packets are then served according to first-in-first-out (FIFO) principle.

The station forwards the token to its successor in the pre-defined order before it begins with its data transmission. This assumption permits the token to be relayed to next station before the actual data transmission starts. The policy of not withholding token while transmitting data packets has the advantage of decreasing the overhead of the token rotation time and consequently leads to improve network bandwidth utilization. To transmit data packets, the sender station first looks up the code assignment table to search for the available code of its intended receiver station. The code assignment table is read from the token's Channel-List (C-List) when it has visited the station. C-List displays the available code channels for each station. For the transmission and reception of data packets, the sender station inserts the destination station's address into the data packet before transmission. The data packets are then sent using the received code. The receiving station, with its MUD ability, constantly monitors its code channels to detect any incoming data traffic destined for it.

E. CDMA Code Allocation

It is known from section II that during the initialization stage or before joining the network, each station is equipped with the knowledge of all the M CDMA code words used for the network. And with the property of MUD, the station is assumed to be able to receive M transmissions simultaneously. However, when there are multiple channels available for data transmission, there exists the possibility that multiple stations use the identical CDMA code to send data packets that are destined for the same receiving station. This effect creates packet collisions and consequently leads to the destruction of the packets. In the hybrid MAC scheme, packet collision avoidance (PCA) algorithm is implemented to avoid packet collisions on the receiver station's code channels. The station uses the C-List in the token (as shown in Table 1), to initiate the *PCA* algorithm. The C-List shown in Fig. 3 is structured to depict the status of the code channels that are being used in the receiving station. Once the token has visited the station and the QoS guarantee has been satisfied, the station then looks up the C-List in the token to observe whether the intended receiver station has the available code channel to receive data transmissions.

If there is a code channel available, the sender station changes the status of the bit to 1 and uses that code channel to transmit data packets. Once the transmission from the sender is completed, the receiver will change the status bit back to 0 when the token visits it. Using this method, packet collisions can be avoided since each station can only transmit data if there is an appropriate code available in the C-List. If all the codes are in use, the sender will have to wait for other stations to finish their transmissions before it may start sending its packets.
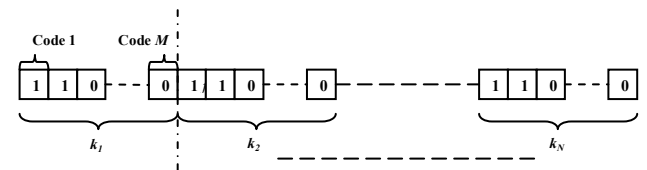

Fig. 3. Channel-List structure

II. FINITE STATE MACHINE

The finite state machine (FSM) for the hybrid MAC scheme is presented in Fig. 4. Detailed description of the transition conditions can be found at [14]. The states for the finite machine are: IS (Initialization State), JS (Join State), SS (Sense State), TS (Token transmit State), PS (Packet transmit State) and LS (Lost State). The issue of mobility within the network has been addressed as the proposed MAC scheme is operated in

the dynamic mobile wireless environments, therefore the topology of the constructed network is frequently changing. As the topology deforms, the stations may be lose or join the network due to its mobility.

FSM has incorporated both states of JS and LS to handle the process of joining and leaving the network. Sense State (SS) is for detecting the token transmission, where in this case, the station checks the token code channel for reception. Once the token is captured and QoS is satisfied then the station sends the token to its successor station by going to the token transmit state (TS) before start servicing the packets (PS). The start of the protocol is created by the initialization state (IS).
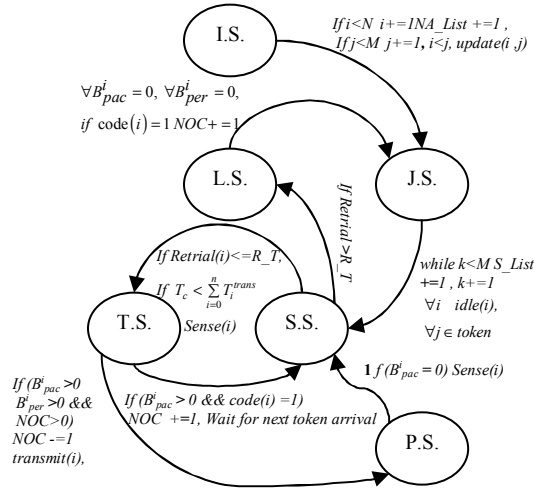

Fig. 4. Finite state machine of the hybrid Token-CDMA MAC scheme

III. SIMULATION MODEL AND RESULTS

In this section, the simulation model and results for the hybrid MAC protocol through the simulation studies are presented. A simulation model using C++ builder software package is custom built. The model is based on event driven packet level simulator for monitoring and recording results. The built model consists of the link layer, and the token-CDMA MAC protocol at the MAC layer. It is assumed that all the transceivers equipped in the stations can perform proper hearback. It is also assumed that all the properties of the timers are incorporated in the stations and all the delay properties (e.g token forward, transmission times) are also considered within the simulation model. The reader should refer to [14] for a deeper comprehension of the simulation model for hybrid MAC scheme.

A. Traffic model

For the hybrid MAC scheme, it is assumed that the arrival traffic process is typically described by an Markov-modulated Poisson processes (MMPP) [17]. Four parameters are used to represent the 2-state MMPP source of each traffic class. ψ_H^i (ψ_L^i) is defined as the mean transition rate out of the Low load (High load) state, and $\lambda_{r,L}^i$ is the mean arrival rate of the Poisson process in the Low load state and $\lambda_{r,H}^i$ corresponds to bursts of

high arrival load state for node i of traffic class r. The effective combined Poisson arrival rate for node i is then given by

$$\lambda_{ip,i}^r = \frac{\lambda_{r,H}^i \psi_L^i + \lambda_{r,L}^i \psi_H^i}{\psi_L^i + \psi_H^i} \qquad (2)$$

For the simulation, it is assumed that traffic arrives as packets of varying lengths to different class nodes and the packet length is geometrically distributed with mean packet length of ξ_r^i bits.

B. Wireless link error model

In order to model wireless characteristics of the CDMA channel within the network, multi-layered Gilbert-Elliot channel error model [12], [13] is implemented into the simulation. This two-state model has been found to be a useful and accurate model for link-layer (packet level) analysis [18]. The wireless link (code channel) is modelled as an independent Markov Chain where in the good state, packet transmissions are received with a high probability of success. However, some of the packets may still fail to be transmitted with a probability that depends on the interference level.

The bad state of the Markov Chain corresponds to a deep fade (or shadowing) in which all packet transmissions are unsuccessful. Using the similar approach as proposed by [19], the number of available code channels M, together with token channel ($M+1$ CDMA code channels) is modeled in the network as $M+1$ independent Markov Chains in our simulation. The issue on dependencies between the links when modeling the link errors in the good state is also addressed in the following section.

The packet-lost probability in the bad state for a wireless link is set to one. That is if link i is in the bad state, all packets sent by code channel i are dropped on the wireless link with probability one. For the packet-lost probability in the good state, it is assumed that it is a function of the interference level. In our case, the interference level is dependent on the total number of codes used in the network with inclusion of additive white Gaussian noise (AWGN). The widely used Holtzman approximation [20] is then used to calculate the bit-error rate (BER). Based on the BER, and with incorporation of a error correction scheme which implemented *(31, 16)* BCH code, the packet-lost probability for the good state can be calculated. Equations and detailed discussion of packet-lost probability are presented in [14]. All parameters used in the simulation are summarized in Table II.

C. Performance Analysis

In this section, the performance of the hybrid MAC scheme is evaluated. Various performance metrics are used to compare the effectiveness of the Hybrid CDMA-Token, WTRP and CDMA type protocol. For the BER of the WTRP, with the inclusion of AWGN, its BER can be derived as $BER(j) = Q\left(\sqrt{2SNR}\right)$.

For performance comparisons, the same parameters are used for simulations. Three traffic classes are established for each MAC scheme in which each class's traffic load is correlated to other classes (as shown in table II). Comparisons of the operation of the Hybrid and other MAC schemes are shown in

Figs. 5, 6 and 7. These figures displayed performance metric comparisons of the two schemes under the condition that the QoS parameter $\lambda_{g,i}^r$ is assigned to a fixed value that is independent of $\lambda_{ip,i}^r$ and it can accommodate the maximum normalized load capacity of 0.8.

Fig. 5 and 6 display the packet error probability and throughput for all MAC schemes. These two metrics reflect the overall system performance of each traffic class in the three MAC schemes. It is clearly shown from Fig. 5 that the packet error probability increases with an increase in load for both hybrid and CDMA MAC schemes. WTRP exhibits relatively consistent error probability due to its single channel configuration. It is also shown that the packet error probability for CDMA scheme achieves the worst performance due to severe interference.
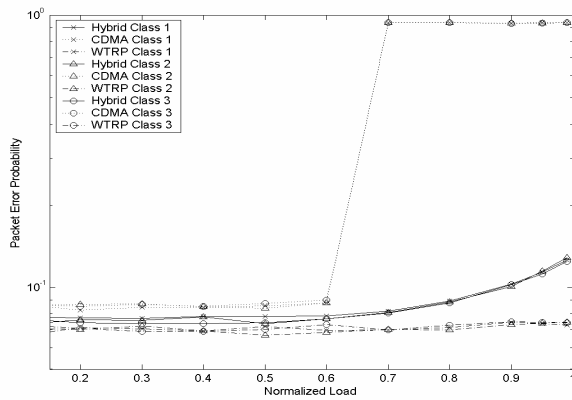

Fig. 5 Packet error probability of all MAC schemes under the condition that link is in good state with probability 0.9 and with fixed QoS parameters that accommodate the maximum normalized load of 0.8

Based on the same token-access control mechanism, the hybrid and WTRP schemes achieve an identical throughput as displayed in Fig. 6. However, CDMA scheme suffers rapid deterioration in throughput starting from medium loading condition due to its high packet error probability. The impact of different load conditions on the packet delay of all three MAC algorithms is also analyzed. The packet delay is defined as the time period from the time when a packet arrives at the front of buffer of a station to the time it is successfully transmitted to the intended receiving station. The packet transmission time is not included, i.e., the packet delay is the time delay determined by the efficiency of each MAC algorithm.

Fig. 7 and 8 show the mean packet delay for all MAC algorithms respectively. From the figures, it is clearly indicated that the hybrid algorithm outperformed other two schemes for all traffic class nodes. As the packets are lost due to interference, the retransmission of packets leads to longer buffer length which consequently increased the queuing delay. It is observed that CDMA scheme suffered the worst delay performance. This corresponds to the discussion earlier and also the WTRP system experiences longer packet delay than the hybrid scheme. This is predicted as for most of the token-based protocols with single transmission medium available, long access delay is unavoidable in order to have guaranteed access. For the hybrid scheme, with its capability of dynamic channel allocation, the token can adjust itself to fit any asymmetric traffic loading condition to achieve low access delay.
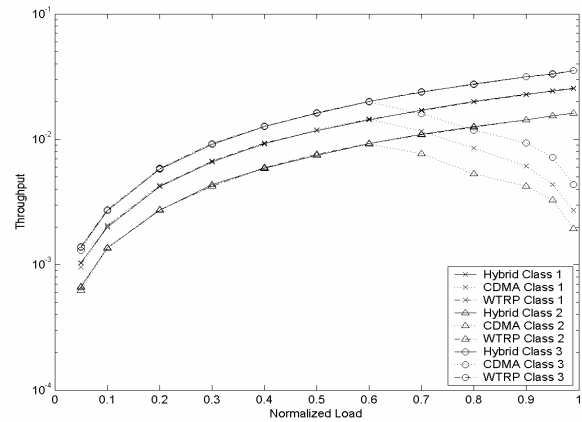

Fig.6. Throughput of all MAC schemes under the condition that link is in good state with probability 0.9 and with fixed QoS parameters that accommodate the maximum normalized load of 0.8
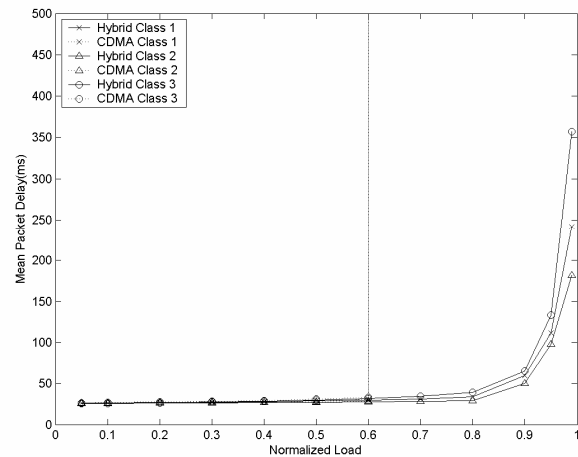

Fig. 7. Mean packet delay of hybrid and CDMA MAC schemes under the condition that link is in good state with probability 0.9 and with fixed QoS parameters that accommodate the maximum normalized load of 0.8
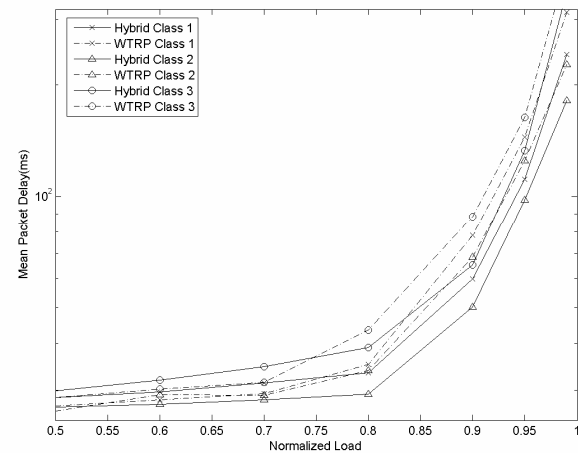

Fig. 8. Mean packet delay of hybrid and WTRP MAC schemes under the condition that link is in good state with probability 0.9 and with fixed QoS parameters that accommodate the maximum normalized load of 0.8

IV. CONCLUSION

In this paper, the description on the hybrid Token-CDMA MAC scheme is presented. Important features of our approach are that it exploits the availability of multiple transmissions, and also takes the error-prone wireless channel conditions into consideration. Various performance measures of the hybrid MAC scheme are compared with the single-token WTRP MAC protocol and standard CDMA scheme under the same simulation conditions. Simulation results demonstrate that the hybrid scheme outperforms both schemes in system performance. Our scheme can easily be implemented in a distributed fashion and, based on its token-based design, it can effortlessly incorporate other QoS guarantees to provide better support of heterogeneous services in both mobile ad hoc and traditional wireless networks.

TABLE II
SYSTEM PARAMETERS

Symbol	Parameter
Number of nodes (N)	30
Number of codes (M)	18
Number of classes (r)	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)	1.10
$G_{spreading}$	32
PHY header size	128 bits
Mean packet size (ξ_r^i)	796 bits
Mean Token size	321 bits
Mean frame size	1023 bits
FEC correctable bits	3 bits
CDMA channel bit rate	1.28 Mbps
Modulation	BPSK
Permit pool capacity (γ_i)	20
Packet buffer capacity (Ω_i)	20000
Bad state duration ($\overline{\tau}_{bad}^i$)	3.2 ms
Bad state PEP_{bad}^i	1.0
Good state PEP_{good}^i	Holtzman's approximation
WTRP Channel bit rate	1.28 Mbps
Signal to Noise Rato (SNR)	8 dB

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