Optimization of Hybrid Token-CDMA MAC System Using Cross-Layer Information

I-Sheng Liu, *Graduate Student Member, IEEE*, Fambirai Takawira, *Member, IEEE*, and Hong Jun Xu, *Member, IEEE*

Abstract—**This paper presents a joint medium access control and physical (MAC-PHY) layers solution for optimizing the system performance in the hybrid Token-CDMA MAC system. The proposed scheme is designed in order to provide continuous monitoring of the performance achieved by the users and adjusting transmission parameters using different spreading factors. Various performance metrics are used to demonstrate effectiveness of the cross-layer interaction for the hybrid Token-CDMA MAC protocol.**

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

I. INTRODUCTION

The past few years have seen tremendous interest in cooperative communications in the field of wireless communication research: the so-called cross-layer optimization [1]. Various possible cross-layer interactions can be considered when performing a cross-layer design within the OSI-layered model. To demonstrate, Fig. 1 displays the different control flows needed to provide a cross layer interaction between physical and upper layers of two remote nodes. When two nodes communicate, the receiving one measures the physical state, which is generally a vector of real values. An entity named Agent Manager estimates, measures and selects the appropriate values to be sent to the upper layers of the transmitting node. These layers will actuate accordingly to adapt to the actual channel conditions, performing the cross-layer interaction.

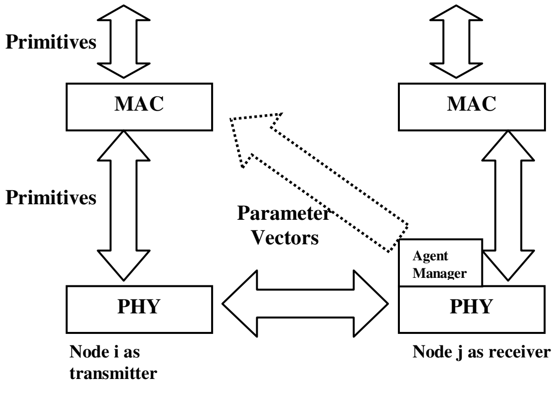

Fig. 1. Example of cross-layer interaction through an agent manager

The amount of literature on this issue is still relatively scarce and mostly at the physical layers [2], [3], [4], [5], [6], [7] and [8]. It has been shown in those literatures and references therein that from the perspective of the network, cross-layer design approach can benefit not only the nodes involved, but the whole network in many different aspects. Although originating from the physical layer cooperation, all the benefits can not be fully realized until proper mechanisms have been incorporated at higher protocol layers (e.g. MAC, network) and the necessary information is made available from the lower layers (e.g. PHY).

One of the most relevant areas in cross-layer optimisation is the interaction between physical (PHY) and medium access control (MAC) layers in wireless networks. This is due to the fact that the PHY layer is the most time variant entity in a wireless communications system and due to the proximity of the two layers in the OSI model stack and the inherent variability of the channel state. The MAC layer in wireless network is implemented to enable nodes to access the available channel(s) while attempting to enforce a fair and efficient usage of the channel(s). To accomplish this task, the MAC protocol makes use of input or feedback information that other layers of the protocol stack may forward to it directly or indirectly.

Typically, however, the MAC layer is mostly interested in the information it receives from the underlying physical (PHY) layer regarding the state(s) of the channel(s) and/or the occurrence of any events that are key to its operation (e.g., the successful transmission of a frame over the channel). Based on the feedback information, the MAC protocol dynamically adjusts its behavior in order to better allocate the channel(s) among competing nodes within the network.

The PHY layer, on the other hand, has the main job of receiving the bits of information from the MAC layer and, at the MAC's discretion, transmit the bits across the underlying communication channel(s) as fast and reliable as possible, according to appropriate (de)coding and (de)modulation schemes. The likelihood with which a transmission is successful will depend on how well the signaling used defends against channel impairments and interference from any source.

In wireless ad hoc networks, in particular, the signal transmissions from any node can potentially interfere with signal receptions at any other node in the network. Hence, the quality of a radio link depends on the transmission activity in the entire system. As a result, each node's transmission activity can affect the PHY-layer performance at every node in the network, which, in turn, can affect their MAC dynamics. Clearly, the dynamics of the MAC layer is tightly connected to the dynamics of the PHY layer, and the cross-layer interactions at each node will depend, fundamentally, on the activity of every node in the network.

With this idea in mind, this paper describes a jointly optimal design of the medium access and physical layer protocols for the hybrid Token-CDMA network. Using the cross-layer interaction, the PHY layer provides channel state information to be feed backed to MAC layer and based on the information, the MAC scheme accurately estimates the traffic loading condition and modifies the transmission rate by changing the spreading factor of each transmission. Therefore, the distributed rate adaptation [9], [10] through spreading factor selection uses both the traffic information provided by the MAC algorithm and the channel estimate from the PHY layer, which constitutes the cross-layer concept.

The novelty of this work lies in presenting a cross-layer interaction between PHY and MAC layers and conducting a performance analysis of the optimized hybrid token-CDMA MAC scheme. The remainder of this paper is organized as follows. Section II presents the comprehensive description of the hybrid Token-CDMA MAC scheme. Section III is devoted to the modeling of cross-layer framework between physical and MAC layers for the hybrid Token-CDMA scheme. Both the simulation model and results are presented in Section IV and conclusions are drawn in Section V.

II. 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 [11]. This section presents the structure, characteristics and properties of the new protocol.

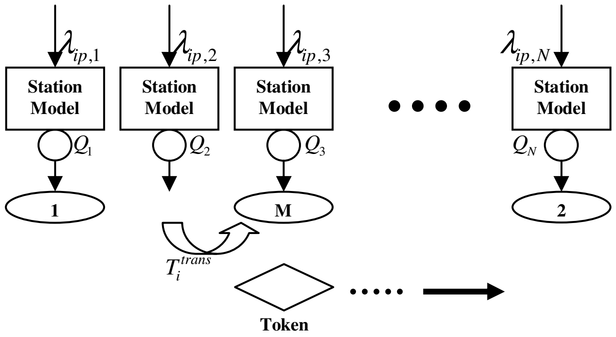

Fig. 2. Network model for hybrid Token-CDMA MAC protocol

A. Network Topology and Model

The hybrid MAC scheme is capable to implement in either ad hoc or wireless mesh networks (WMN). 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 ($M < N$). In Fig.2, Q_i denotes the queue model of station i and T_i^{trans} is the token transmission time between two stations and $\lambda_{ip,i}$ is the packet arrival rate for station i. 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 equipped with two transceivers; one if used for token transmission and the other is used for data transmission. 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. Channel Access Control

Once the token is generated in the network, it continuously circulates within the network, following a predetermined order. To monitor the usage of the CDMA codes, 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 without capturing it under two circumstances. 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 (TRT) is the time for the token to visit all the stations in the network ($TRT = \sum_{i=1}^{N} T_i^{trans}$), 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 [12] 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 modified leaky-bucket QoS guarantee [11], 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.

III. CROSS-LAYER MODELING FRAMEWORK FOR HYBRID TOKEN-CDMA MAC SYSTEM

It is discussed in section II that the network is capable of simultaneously processing a maximum number of *M* transmissions, i.e., the maximum number of active users supported by the network is *M*. Each active user's data is BPSK modulated and is transmitted to the receiver node asynchronously. Following the cross-layer philosophy, assume that the MAC protocol is aware of the channel state of the links between nodes. Among the functions of the MAC layer, the main objective of optimizing the packet delay is achieved where the MAC layer monitors the information forwarded from the PHY layer and its own layer and changes its transmission rate by selecting the appropriate spreading factors accordingly thereby reducing the mutual interference. Recent works in cross-layer design of PHY-MAC layers in CDMA networks demonstrated the possibility of designing more flexible collision recovery strategies [3] by employing signal processing methodologies to discriminate multiple colliding frames on the medium. The effect leads to reduction in collision intervals and number of retransmissions. In this paper, the concept is applied to the aim of enabling dynamic adaptation of the transmission parameters in order to improve data transmission performance.

A. Physical Layer properties

- CDMA System

It is assumed that BPSK modulation is used in the system and all nodes implement amplitude modulation (AM) that is independent of the bit rate. With the implementation of dynamic spreading factor adjustment, the current system can be denoted as a multi-rate CDMA system that supports *n* (*n=M*) different rates or subsystems. The transmitted signal of user number *k*, in subsystem *i*, is then of the form [13]

$$r_{ik}(t) = \sqrt{2P_i}\, a_{ik}(t)\, b_{ik}(t) \cos(\omega_c t + \phi_{ik}) \qquad (1)$$

where P_i is the power of each user in the subsystem and $a_{ik}(t)$ is a pulse amplitude modulation signal with a rectangular pulse shape of duration T_i. And $b_{ik}(t)$ is the spreading code waveform, consisting of N_i periodically repeated chips in a binary polar format with rectangular pulse shape of duration T_c (duration per chip) therefore $T_i = N_i T_c$. The modulator phase ϕ_{ik} are modelled as independent random variables, uniformly distributed over $[0, 2\pi)$.

- Channel Model

In mobile radio environments, the channel link performance is known to be dependent on the received desired signal strength in which it depends on the propagation loss and shadowing. The signal strength is normally limited by the co-channel interference (CCI) in the system. In this chapter, the shadowing effect (i.e. slow fading) is assumed to be a log-normal distributed random variable as it is characterized by [14]. And based on [15], the shadowing spatial correlation is assumed to be exponential decayed that is dependent on the distance between any two separate positions and the variation is modelled as a Gaussian-Markov stochastic process.

The channel interference is approximated as Gaussian, the derived equation for the performance on a single path given the amplitude from [13] is used and modified for a multi-rate BPSK system. The bit error rate performance of user *i* without antenna diversity is known to be

$$BER(\gamma_i) = Q\left(\sqrt{2\gamma_i}\right) \qquad (2)$$

where γ_i is the signal strength and it can be derived as

$$\gamma_i = \frac{1}{2} \cdot \frac{\chi_i^2}{\left[\dfrac{N_0}{E_b} + \dfrac{\left[\sum_{j \neq i}^{K} \dfrac{R_j}{R_i} \chi_j^2 \right]}{3N_i} \right]} \qquad (3)$$

where, E_b/N_0 represents the signal-to-noise ratio (SNR), *K* is the number of codes that are currently being used in the system and N_i is the spreading gain used by user *i* and R_i is the user *i*'s bit rate. χ_i is a log-normal random variable representing shadowing effect of user *i* and can be defined as

$$\chi_i = P_i \cdot 10^{\frac{\Omega_i(k)}{10}} \qquad (4)$$

where P_i is the instantaneous power of user *i* and $\Omega_i(k)$ is the received co-channel interference power at location *k*. With the spatial correlation property of shadowing effect modelled as a Gaussian-Markov process, if the spatial distance between *k* and *k+1* can be represented [15] as

$$\Omega_i[k] = \upsilon \cdot \Omega_i[k-1] + (1-\upsilon) \cdot V_i[k] \qquad (5)$$

where υ is the spatial correlation coefficient and the received co-channel interference power $\Omega_i(k)$ is a Gaussian random variable with mean assumed to be $\partial_i[k] = \partial_i$ and variance σ^2. $V_i[k]$ is a Gaussian random variable with mean ∂_i and variance

$$\sigma_V^2 = \frac{(1+\upsilon)\sigma^2}{(1-\upsilon)} \qquad (6)$$

Using the BCH error correcting code, the frame error rate can be derived as

$$FER^{i} = 1 - \left(1 - \sum_{j=4}^{31} \binom{31}{j} \left(BER(\gamma_i) \right)^{j} \left(1 - BER(\gamma_i) \right)^{31-j} \right)^{\varepsilon} \tag{7}$$

where ε is the length of the (31, 16) BCH blocks.

B. *MAC Layer Properties*

- Cross-Layer Interaction and Optimization

In the initialization stage, each node enters the network transmits data using a pre-defined set of transmission parameters that enables the highest bit-rate on the channel. In parallel, it listens to the token channel for token reception. For data transmission, it is assumed that a data packet is a frame. At MAC layer, it is assumed that there are n spreading factors having values expressed as $N_1 < N_2 < \cdots < N_n$.

For the transmission of the frame, the spreading factor is selected from the set $\{N_1, N_2, \cdots N_n\}$, based on the information forwarded from the PHY and MAC layer. The frame error rate is determined from the transmission and forwarded from the PHY layer to the MAC layer (cross-layer information). At the MAC layer, a rate-adaptation algorithm is implemented where it will choose the suitable spreading factor for the transmission of the next frame.

- Rate Adaptation Algorithm at MAC Layer

The algorithm is responsible for choosing the suitable spreading factor based on the information forwarded from the PHY and MAC layers itself. For each frame, the frame error rate of the frame is forwarded to the MAC layer from the PHY layer. If the BER is high, then the algorithm will choose a higher spreading factor to counter the interference. However, it is known that with the increase in spreading gain, the transmission time also increases which leads to increase in packet delay. Therefore in order to efficiently maintain a low BER and at the same time achieve low packet delay, the MAC layer, in this case, monitors the load condition (ρ) of the node.

$$\rho_{i,j} = \lambda_{i,tot} \cdot \mu_i = \left(\frac{\lambda_{i,in}}{1 - FER_{i,j}} \right) \cdot \alpha_{i,j} N_i T_c \tag{8}$$

where $\rho_{i,j}$ is the loading condition of the node *i* with packet *j*, $\lambda_{i,tot}$ is the total packet arrival rate including retransmission packets to node *i*, μ_i is the service time of packet j, $\lambda_{i,in}$ is the packet arrival rate to node *i* $FER_{i,j}$ is the approximated frame error rate of node *i*'s *j*th packet, $\alpha_{i,j}$ is the packet length of packet *j* and T_c is a chip duration.

In this case, both of the BER and spreading gain are taken into consideration when choosing the optimum gain setting. It is known that the packet delay is related to the loading condition, therefore if the low loading condition is achieved; the packet delay will also be minimized. Low loading condition is attained by choosing the optimum spreading factor. Before the packet is serviced, the channel loading condition is predicted from (8). Using the set of predefined spreading factors, each factor is implemented to predict the total packet arrival rate and its service time. Amongst all the values attained from the prediction, the node selects the spreading factor that achieves the lowest load condition and transmits the packet using that setting. This procedure is performed before every packet transmission in the system.

Using the algorithm, the nodes are provided with the optimization in terms of frame error rate and packet delay. In this way, if few nodes are active in the network, they can exploit the available resources by decreasing their spreading factors; while as the number of nodes or traffic intensity grows, those nodes which suffer most from interference can self-adjust to different transmission parameters in order to provide a higher level of robustness. The proposed rate adaptation scheme is aimed at providing continuous monitoring of the performance achieved by the users and selecting better transmission parameters to those who are suffering severe signal degradation due to interference.

IV. SIMULATION MODEL AND RESULTS

The proposed approach is validated through extensive simulations. This section presents the achieved results in terms of performance at the physical/MAC layers. The effectiveness of the cross-layer approach scheme and the original hybrid MAC scheme are compared for various performance metrics. The metrics used for the evaluation are throughput and queuing delay of the packets. A simulation model using C++ builder software package is built. The model is based on event driven packet level simulator for monitoring and recording results.

TABLE I
SYSTEM PARAMETERS

Symbol	Parameter
Number of nodes (*N*)	30
Number of codes (*M*)	15
$G_{spreading}$ set	8,16,32,64,128
Mean packet size ($\alpha_{i,j}$)	256 bits
Error correction scheme	BCH (16,31)
FEC correctable bits	3 bits
CDMA chipping rate ($1/T_c$)	3.84 Mcps
Modulation	BPSK
Fading channel	Log-normal
Token walk time (T_i^{trans})	100 us
Packet buffer capacity (Ω_i)	20000
Bad state duration ($\overset{-i}{\tau}_{bad}$)	3.2 ms
Bad state PEP_{bad}^{i}	1.0
Signal to Noise Rato (SNR)	5 dB
Spatial correlation coefficient (υ)	0.82
Variance of *Vi* r.v.(σ^2)	7.5dB

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) [16]. 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 λ_L^i is the mean arrival rate of the Poisson process in the Low load state and λ_H^i corresponds to bursts of high arrival load state for node i . The effective combined Poisson arrival rate for node *i* is then given by

$$\lambda_{ip,i} = \frac{\lambda_H^i \psi_L^i + \lambda_L^i \psi_H^i}{\psi_L^i + \psi_H^i} \qquad (9)$$

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. All parameters used in the simulation are summarized in Table I.

B. Performance Analysis

In Fig. 3, the code utilization graph comparing the performance of the cross-layer hybrid scheme with normal hybrid scheme is shown. This plot provides an indication of the optimum code usage in the network. The code utilization is plotted against the offered load, which is defined to be the traffic created for the entire network. In the figure, the cross-layer hybrid scheme's performance is compared with standard hybrid scheme that implemented fixed spreading factors (spreading factors of 16 and 64). When the traffic load increases in the network, it creates high packet error probability due to severe multiple access interference (MAI) as shown in Fig. 4. This effect is especially evident under heavy traffic load, and it is known that low spreading factor always generated high packet error rate, therefore it reaches maximum code utilization before the high spreading factor and cross-layer schemes due to high retransmission rate in which caused by high packet error rate. Using the rate adaptation algorithm and cross-layer dialogue, cross-layer hybrid scheme is able to maintain optimum code utilization under any load conditions.

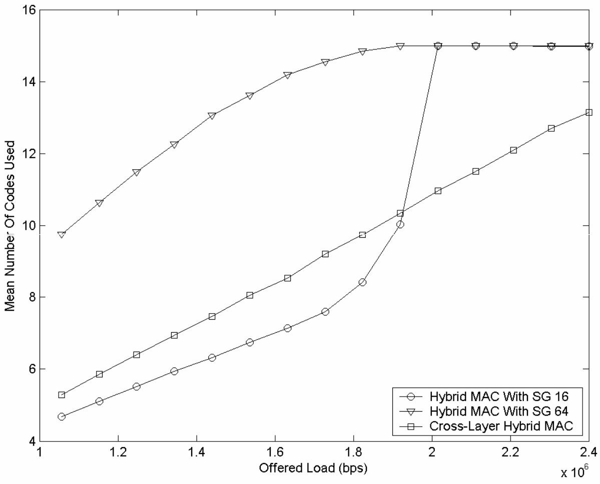

Fig. 3 Code utilization of standard hybrid protocol with different spreading gain settings and hybrid MAC protocol with cross-layer optimization with 15 CDMA codes assigned in the system under different load conditions

Fig. 4 displays the packet error probability for all schemes. This metric reflects the overall system performance of the schemes. It is clearly shown in the figures that the packet error probability increases with an increase in load and the low spreading factor scheme suffered the worst performance when load increases. The high spreading factor and cross-layer schemes exhibit relatively consistent error probability due to their high spreading gain and flexible gain settings. The algorithm finds the equilibrium between the packet error rate and spreading factor, it will choose lower spreading factor if it is needed to minimize delay performance, under the condition that packet error rate is still within tolerable range. This is illustrated in delay performance shown in Fig. 6.

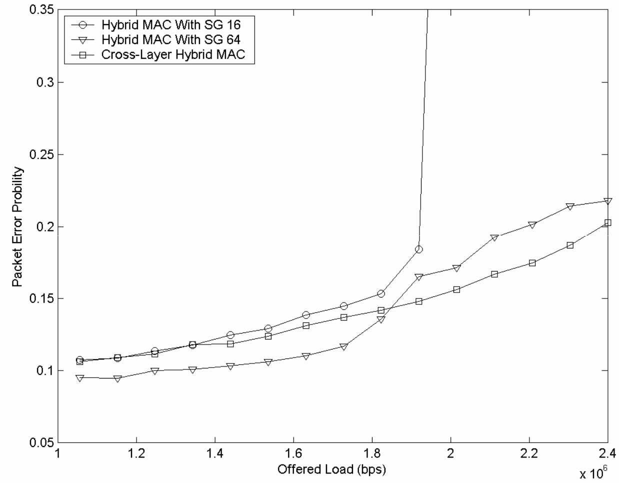

Fig. 4. Packet error probability of standard hybrid protocol with different spreading gain settings and hybrid MAC protocol with cross-layer optimization with 15 CDMA codes assigned in the system under different load conditions

Throughput performance of all the schemes is shown in Fig.5. It is clearly shown from the figures that the cross-layer scheme achieved better throughput performance than other two schemes. It is illustrated in the figure that as the load increases, the performance for low spreading factor hybrid scheme quickly deteriorates as its packet error probability increases drastically. The packets are therefore suffering from high retransmission rate, which consequently leads to a decrease in throughput as shown in Fig. 5.

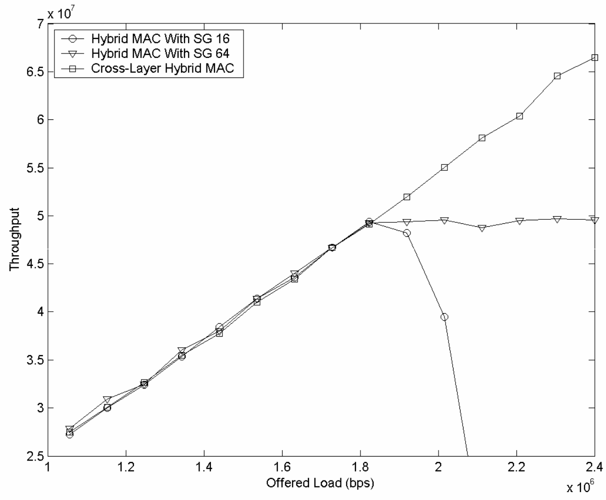

Fig. 5. Throughput of standard hybrid protocol with different spreading gain settings and hybrid MAC protocol with cross-layer optimization with 15 CDMA codes assigned in the system under different load conditions

The packet delay is defined as the time period from the time when a packet arrives at the packet buffer of a node to the time it is successfully transmitted to the intended receiving station. Fig. 6 displays the mean packet delay for all schemes. From the figure, it is clearly indicated that the cross-layer hybrid scheme outperformed the other two schemes under any load conditions. For the increase in load condition, low spreading factor scheme suffered the worst performance due to its high packet error rate as discussed previously.

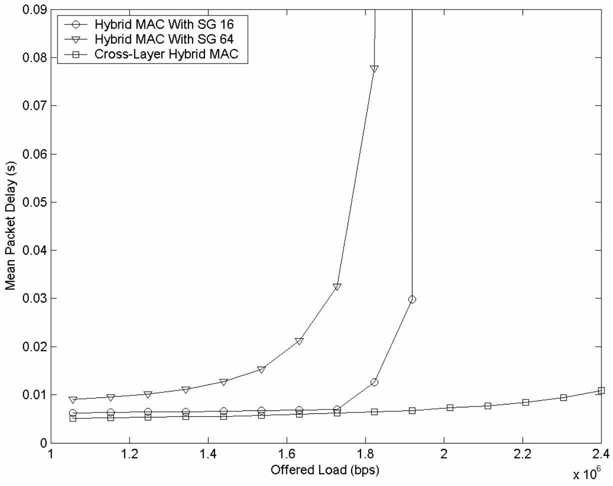

Fig. 6. Mean packet delay of standard hybrid protocol with different spreading gain settings and hybrid MAC protocol with cross-layer optimization with 15 CDMA codes assigned in the system under different load conditions

V. CONCLUSION

Cross-layer techniques in which different layers of wireless communication systems interchange control information in order to optimize the use of the scarce bandwidth are proven to be a relatively unexplored research area where tremendous potential benefits can be achieved. It is discussed in this paper that the interaction between PHY and MAC layers has been the first explored issue in this area. In this paper, a PHY-MAC cross-layer optimization for hybrid token-CDMA based wireless networks has been presented. To account for the effects of both cross-layer interactions and the interference among all nodes, a novel model was introduced with which topology and PHY/MAC-layer aspects are naturally incorporated into the nodes. The model is used to build a bridge between the physical and MAC layers and to balance the efficiency and fairness of resource allocation. In particular, the necessary and sufficient condition for finding an optimum system performance for the hybrid scheme is investigated when rate-adaptation algorithm is used. The cross-layer interaction proves to improve the spectrum efficiency, keeping the packet delay at the minimum possible value for different code and traffic load settings.

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Principal Author: Mr. Yi-Sheng Liu attained his BScEng degree in 2001 and MScEng degree with Cum Laude in 2003 at the School of Electrical, Electronic and Computer Engineering at the University of Natal, Howard College Campus, Durban. He is currently doing his doctoral degree, researching medium access control (MAC) protocols for wireless networks in the Radio Access Technology Research Centre at the University of KwaZulu-Natal, Howard College Campus.

Co-author: Professor Fambirai Takawira is the senior Professor in the faculty of Electronic Engineering, and head of the School of Electrical and Electronic Engineering at the University of KwaZulu-Natal. He is also the director of the Centre for Radio Access Technology (CRAT) at the same university. He holds a BScEng with first class honours in Electrical Engineering from Manchester University and a PhD degree from University of Cambridge, United Kingdom. His research interests are in the general areas of adaptive signal processing, digital and wireless communications and data networks.

Co-author: Professor Hong-Jun Xu is the associate Professor in the School of Electrical, Electronic and Computer Engineering at the University of KwaZulu-Natal, Howard College Campus. He received the BSc degree in 1984 from the University of Guilin Technology and the MSc degree from the Institute of Telecontrol and Telemeasure in Shi Jian Zhuang, 1989, and the PhD degree from the Beijing University of Aerinautics and Astronautics in Beijing, 1995. His research interests are in the area of digital and wireless communications and digital systems.