A Cross-Layer MAC/PHY Framework for PER Guarantee in Multiuser Detection Based Ad Hoc Networks

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***Abstract*—In this paper, we propose a cross-layer MAC/PHY (Medium Access Control Layer/Physical layer) framework to increase the throughput respecting a target packet error rate (PER) required by the nodes. High capacity CDMA ad hoc network with full multiuser detection (MUD) MAC layer is considered. The fundamental scenario studied is made of a terminal or radio which detects several neighbors' signals by the means of a multi-user detector. At the receiver's level, adaptive filter, rate adaptation scheme, and multi-rate transmitter are integrated in a predictive framework that connects MAC and physical layer mechanisms. Then the performances are evaluated by simulation where PER guarantee transmissions are compared to simple existing systems. The results show the performance gain of the PER guarantee transmissions.**

Index Terms--- *Cross-layer, Adaptive physical layer, prediction, multi-user detection, MAC layer, scheduling*

I. INTRODUCTION

Recently, multiuser detection concept has been used to design MAC protocol which allows for detecting one principal user and several neighbor signals to cancel them as interferers[1]. Then full MUD protocol has been designed. They decode several users' packets simultaneously in the neighborhood [2-3]. In the literature two medium access views exist in the design of multiuser detection based MAC protocols. The first is materialized by the random access [4], where the users contend for the channels to send packets, and the receivers detects them asynchronously. The second view is materialized by scheduled access protocol [5] which schedules the users in to transmit or detection, and works synchronously. This kind of protocol was not much investigated until the three last years, because of its signaling mechanism complexity and the cost of the implementation of the multiuser detector. Today, the systems are more powerful due to the software define radio concept. Military domain ad hoc networks are also equipped with powerful processors and a lot of memory, so the mentioned barriers can be overcome. This makes MUD based protocol implementable. Our interest is to develop the cross-layer aspect of the MUD protocol; the cross-layer methodology is described in [5] and consist of a synergy between different layers in the OSI architecture to improve the network performance.

The main contributions of this work is the flexibly we have provided in the quality of service (QoS). This makes available a wide range of packet error rates and data rates; the second contribution is a more efficient interface MAC/Physical layer than the classical interface. A framework has been designed, to achieve this goal. Data packets are sent according to some channel thresholds. A good packet error rate is ensured by the multi-user detection (MUD) of the received signals. The interactions between the physical channel predictor and a scheduling algorithm, guarantee the target PER, required by the different nodes in connection with the receiver. We investigated a large range of PER guaranteed constraints is investigated for the different nodes in a context of mobile in motion experiencing flat fading.

The paper is organized as follows. In Section 2 we present the structure of the MUD based protocol, the inter-layer structure and the physical layer background. The framework under consideration is described in Section 3. In Section 4 the scheduling algorithms simulated and the performance metrics are detailed. The results of the simulation are analyzed in Section 5.

II. DESCRPTION OF THE MAC, PHYSICAL AND CROSS-LAYER STRUCTURE

A. *Description of MAC Layer*

The network under consideration supports two types of channels that are separated by the transmissions codes: a common channel for the exchange of the connectivity information and several dedicated channels at MAC layer for the scheduling and the data transmission. The users send their control packets using a common code and their data packets with dedicated codes. The different radios work synchronously. Synchronization is out of the focus of this paper. However it is an important issue for ad hoc network, treated in the references [6-8]. Time axis is divided into super-frames as depicted in Figure 1. Each super frame is split into one connectivity frame and ten data frames. In the connectivity frame, the nodes entering in the network exchange some information with the neighbouring nodes and each execute an algorithm to select a dedicated available code in their data base of codes and the receivers update the receiving codes if new neighbours appeared or if certain nodes disconnect [5].The next ten data frames are scheduled for the node's data transmission. In detail, a data frame is composed of a scheduling slot and a data transmission slot as shown in Figure 1. The scheduling slot is subdivided into three sub-slots. In the first sub-slot, a primary algorithm named ''*initial scheduling algorithm*'' set the status of the current node as a data transmitting or data receiving. The second sub-slot's goal is to modify the network configuration. It gives the opportunity to the isolated nodes that are not in the data transmitting or data receiving mode, to establish their connection. In the last sub-slot, all the transmitters confirm their connections and negotiate the quality of service (QoS) of their links [5].

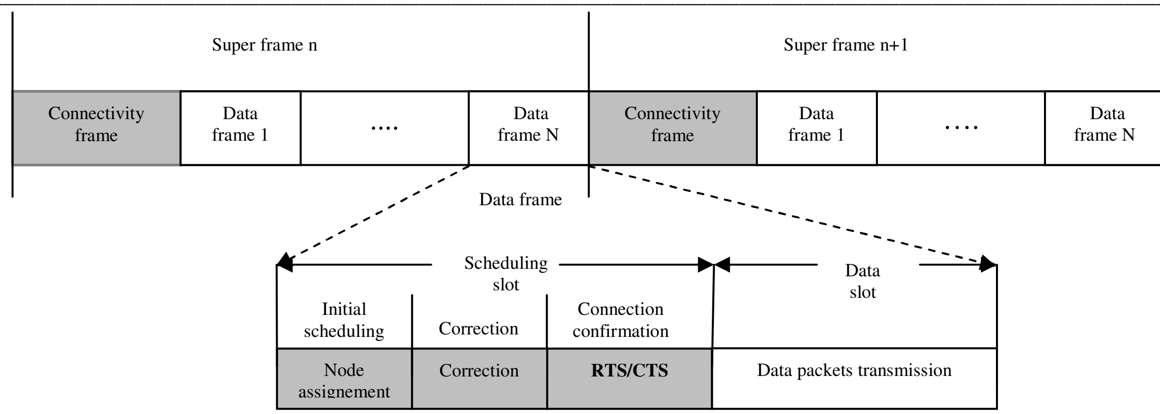

Figure 1 The time division structure

B. Description of the Proposed Cross-layer Mechanism

The scheme and mechanism developed are executed following the configuration of the scheduling defined above. We focus on the part of the data frame, from the beginning of the connection confirmation sub-slot, to the end of the data transmission sub-slot where the network snapshot consists of a set of receivers connected to the neighboring transmitters. So the basic topology of neighborhoods is resumed to a central node connected to several transmitting nodes. In order to support the QoS negotiation, some modifications in the MUD based MAC protocol need to be introduced. This has been done following to the cross-layer design methodology [9]. The QoS in our study is essentially the packet error rate (PER) and the data rate. In order to allow the receiver to admit the requested connections, it must know of these metrics. When the transmitting node sends the request-to-send (RTS), the receiver predicts the PER and the data rate of the different connections. Then, it confirms the links established by broadcasting a clear-to-send (CTS) packet, the resulting PERs and data rates of the different links. The handshaking mechanism to support the QoS described is illustrated in Figure 2.

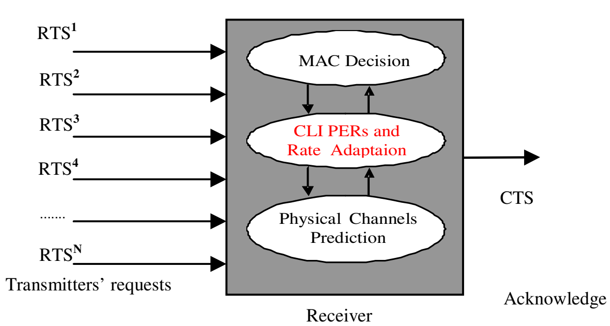

Figure 2 The handshaking mechanism for QoS

In addition to the above modifications, the structure of the RTS packet was modified to add three fields which carry the required PER, the data rate, and pilot bits to enable for the prediction of these two metrics, respectively. Its can be transport the transmitters' QoS requests to the receiver's MAC layer. The CTS packet was also modified to include a series of fields, to transport the acknowledgement/non-acknowledgment (ACK/NACK) of the receiver's. Figure 3a and Figure 3b illustrate the modified RTS and CTS control packets, respectively.

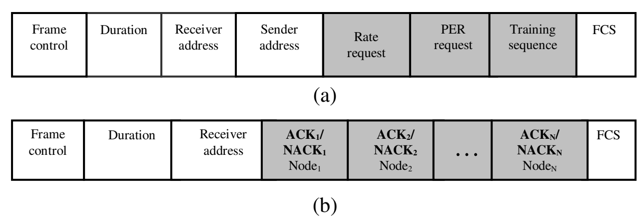

Figure 3 a) RTS control packet b) CTS control packet

The QoS negotiation could be performed according to several policies. The first is the strict and static QoS allocation. This consists, for each receiver, to strictly provide the demand of each user. If a user's transmission can not meet the exact QoS it is rejected. The second policy is the dynamic or iterative negotiation. It consists to iteratively admit the users: firstly are admitted the users that meet the QoS, secondly are provided, after a negotiation between the receiver and the transmitters, the available QoS to the users which can relax their QoS condition; thirdly are rejected the users that required the strict QoS and cannot meet it.

C. MMSE Multiuser Detection and Rate Adaptive based Physical Layer

- MMSE MUD Background

The most investigated MUD in CDMA are linear multi-user receivers [10-14]: the decorrelating receiver, the minimum mean square (MMSE) detectors, and the linear successive interference cancellation (SIC). The best in term of packet error rate is the MMSE receiver, as it maximizes the signal-to-noise and interference ratio (SINR) [10]. This receiver has a significant cost of processing, but is suitable in high capacity radios. The model of the MMSE equivalent filters implemented in the radios to detect packets [14]. It depends on the signature sequence adopted in the slot and can be written by:

$$c_k(t) = \sum_{j=1}^{K} \left(\boldsymbol{M}_{jk}^{-1} \right) s_j(t) \qquad (2.1)$$

where **M** is defined by $\boldsymbol{M} = \left(\boldsymbol{R} + \sigma^2 \left(\boldsymbol{A}^T \boldsymbol{A} \right)^{-1} \right)$, and $\boldsymbol{M}_{jk}^{-1}$ is the element of the inverse of the matrix **M**, on the line j and the column k. $\boldsymbol{A}=diag\{A_1,A_2,\ldots,A_K\}$is the vector of the different transmitters signal amplitude, **R** is the correlation matrix of their codes, σ^2 is the power of the background noise. $s_k(t)$ defines the signature waveform with unit energy.

- Multi-processing gain transmission

A multi-rate technique consists to send data packets at different data rates. Several multi-rate schemes exist; they are analyzed in [15-16]. We consider multi-processing gain as it is easy to implement [15]. So data packets are sent at different bit rates by varying the spreading factor and the parameters of transmitters are T_c, the chip interval, $G_i=w/R_i$, $G_1,G_2,\ldots,G_n$ the series of spreading factor that correspond to the series of the transmission data rates offered $R_1,R_2,\ldots,R_n$, where w is the signal bandwidth. The series of the signal powers to achieve the data rates is represented by $P_1,P_2,\ldots,P_n$. The data rates are equal to $R_1 = 1/T_1 > R_2 = 1/T_2, \ldots, > R_n = 1/T_n$ and generally, for practical raisons are chosen as multiple of the lowest rate R_n.

III. THE FRAMEWORK

A. *Framework Description*

The framework as depicted in Figure 4 includes four main modules: The *observation/estimation module* extracts the training bits demodulated from the transceiver to estimate the channel fading gain, $h_e(t)$, the *Prediction module* forecasts the users channels based on the estimated gain, $h_e(t)$, for the next data slot, the *QoS module* uses the predicted parameters to calculate the different links rate and PER.

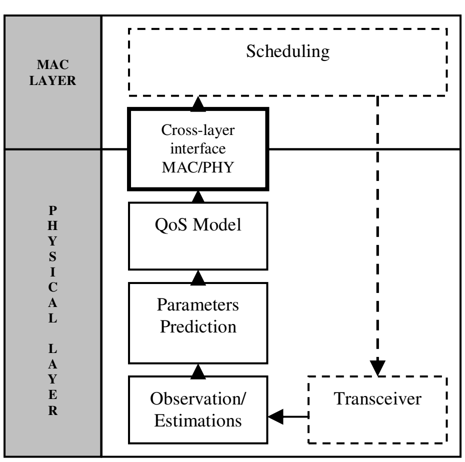

Figure 4 The cross-layer framework

Finally, the *Cross-layer interface (CLI)* transports the required links' rates and PERs from the PHY to MAC layer in addition to ensuring procedures of the communication between the two layers. The PHY layer executes a synchronization operation to get the training sequence field in the RTS packets received. Then it extracts the training bits with the fading for the estimation. Later, the QoS module calculates the PER. Finally, the CLI excludes the training sequence, inserts the link rate and the calculated PER to be used by the MAC layer.

B. *Parameters Observation and Estimation*

As mentioned above, the training or pilot bits included in the RTS packet are used to estimate the channel gain. The different user's observation samples are acquired after synchronization, from the output of the receiver. If $y_k(i)$ is the sample taken from the output of the matched filter of user k at the i-th bit instant, a simple estimation of the channel gain $he_k(i)$ can be calculated as follows [17]:

$$he_k(i) \approx \frac{y_k(i)}{d_k(i)\sqrt{P_{tx}}}, \quad k = 1,\ldots,K \qquad (3.1)$$

where P_{tx} is the power level at which the control packets are sent and $d_k(i) \in \{\pm 1 \pm j\}$ represents the bits of the training sequence.

C. *Parameters Prediction*

For each user, the knowledge of the N_{Pilot} bits of the RTS packet gives a block of N_{Pilot} estimated samples which are buffered at the output of the estimator to feed the input of the predictor. This involves a bank of K predictors for K users. Linear prediction [12] is preferred over the heavy computation methods presented in [18-19] to reduce the complexity. The channel gain process is calculated by the mean of auto-regressive (AR) model. The computation consists to determinate the coefficients a_l, where $l=0,1,2,\ldots,L-1$ of the finite impulse response (FIR) filters, that minimizes the mean square error (MSE) between the estimated and the predicted samples. L is the prediction order of the filter. The channel gain $hp_k(i)$ at the bit index i is then computed using the L past samples so the filter coefficients as follows:

$$hp_k(i) = \boldsymbol{a}_k(i) \cdot \boldsymbol{he}_k(i) = \sum_{l=0}^{L-1} a_l^k(i).he_k(i-l), \; k=1,\ldots,K \qquad (3.2)$$

where $\overline{he}_k(i) = [he_k(i), he_k(i-1), \ldots, he_k(i-L+1)]^T$ is the vector of L past samples of the user k. The vector $\overline{a}_k(i) = [a_0^k(i), a_1^k(i), \ldots, a_{L-1}^k(i)]^T$ represents the filter coefficients. The coefficients $\overline{a}_k(i)$ that minimizes the MSE are derived by the orthogonality principle [20]. In order to minimize the impact of the processing time on the network delay, we choose to update the FIR filter coefficients adaptively by the least mean square (LMS) algorithm.

$$\boldsymbol{a}_k(i) = a_k(i-1) + \mu_k . e_k^*(i-1)\boldsymbol{he}_k(i-1) \quad k = 1,\ldots,K \qquad (3.3)$$

Where $e_k^*(i)$ is the adaptation error in the training phase:

$$e_k^*(i) = hp_k^*(i) - he_k^*(i)\ ,\ k = 1,...,K\ . \qquad (3.4)$$

In the tracking phase:

$$\tilde{e}_k^*(i) = hp_k^*(i) - \tilde{h}e_k^*(i)\ ,\ k = 1,...,K \qquad (3.5)$$

Where $\tilde{h}e_k(i)$ is the interpolation of the gain at the *i-th* bit defined by, $\tilde{h}e_k(i) = hp_k(i-1)$, $k = 1,...,K$.

In slots of milliseconds, several fading may appear so taking the average of the predicted samples along the entire slot involves a loss of information. For this purpose, we average the channel on several windows of length N_w samples in the slot for the rate adaptation as:

$$h_k^{(n)} = \frac{1}{N_w} \sum_{i=n.N_w}^{(n+1).N_w} hp_k(i), \quad i = 1, 2.N_w, ..., n.N_w \qquad (3.6)$$

Where $h_k^{(n)}$ is the channel gain of the user *k* at the adaptation step *n*, N_w is the size of the windows and $hp_k(i)$ is the predicted channel sample.

D. QoS Management

The channels prediction provides the gains which are mapped on the corresponding codes in the multi-processing gain transmissions. This module subdivides the interval of the channel gain variations into several sub-intervals limited by the thresholds $ch=[ch_1,ch_2,...,ch_L]^T$ where $ch_1<ch_2<....<ch_L$. The code c_j(t) is used if the predicted gain falls between the thresholds of index *j* and *j+1*, $ch_j<h<ch_{j+1}$, $j=1...L-1$.We determinate the thresholds $ch_1,ch_2,...,ch_L$ under a condition that the multi-processing gain transmitter work at the optimum point [15] i.e. at a constant signal-to-noise ratio (SNR) for all the transmitters.

$$\frac{2A_1^2 ch_1}{R_1 N_0} = \frac{2A_2^2 ch_2}{R_2 N_0} = ... = \frac{2A_n^2 ch_n}{R_n N_0} = SNR_t \qquad (3.7)$$

Where *i* is the index of the selected rates. A_i is the signal amplitude and ch_i the thresholds over which the transmitter sends the packets at the rate R_i, finally,

$$ch_i = \frac{SNR_t.R_i}{2A_i^2}, \quad i=1,..., n \qquad (3.8)$$

Practically the transmission SNR_t is known, the fixed transmission power $2A_i^2$ is chosen according to the transmitter amplifier capacity; the transmission rates could be calculated using the code G_i and the transmission bandwidth such that $R_i = W / G_i$. Thus we can easily compute the threshold ch_i .

E. Cross Layer Interface

This section describes the set of the procedures, executed by the central receiver in connection with the surrounding neighbors. It executes the following tasks, in the receiving mode :

Procedure 1: Listen to the entire neighborhood;

Procedure 2: analyze the received RTS packets' headers to find the destination addresses;

Procedure 3: extract the QoS requests of the transmitters that desire to establish connections;

Procedure 4: estimate and predict the channel gain;

Procedure 5: select the corresponding rate and calculate the PER for the next data slot;

Procedure 6: Replaces the training bits in the RTS by the selected rate and the calculated PERs value for MAC layer.

Procedure 7: According to the selected rate, the predicted PER, the allowable delay, and the packets' priorities, the MAC layer will schedule the optimal configuration of transmitters.

When it confirms the connections, it sends the CTS packet to confirm the connections. The CTS packet has the structure presented in Figure 3b.

IV. SCHEDULING ALGORITHMS AND PERFORMANCE METRICS

A. Scheduling

Two scheduling algorithms are proposed for the study of the framework. They are respectively named, the ''clairvoyant channel aware scheduler'' and the ''blind scheduler''[21]. The ''clairvoyant scheduler'' utilizes the channel prediction to calculate the future PER. If the calculated PER involve a number of error correctable by the Forward Error Correction (FEC) algorithm, the node sends the packet, else it waits for the next slot. In our case, we add another constraint on this decision criterion. *That is if the calculated PER is inferior to the PER required by the transmitter*, as mentioned in section 2.2. The second algorithm or the blind scheduler does not use the channel prediction to send the packets. The packets are sent independently of the channel state. This algorithm is used for the comparison with the clairvoyant scheduler.

B. Performance metrics

In the following we present the metrics utilized to evaluate performances. The probability of bit error on one phase in QPSK modulation, for Rayleigh fading channel is given by [22-23]:

$$P_{e,k}^{I/Q} \approx \frac{1}{2}.\left(1 - \sqrt{\frac{\overline{\gamma}_k^{MMSE}}{1+\overline{\gamma}_k^{MMSE}}}\right) \qquad (4.1)$$

where $\overline{\gamma}_k^{MMSE}$ the SINR.

The SINR defined in the reference [24] according multi-rate transmissions:

$$\overline{\gamma}_k^{MMSE} \approx s_k^* \left(\frac{\boldsymbol{R_{rates}}}{R_k^2} \boldsymbol{ss}^* + \frac{\sigma^2}{A_k^2} \boldsymbol{I} \right) s_k \qquad (4.2)$$

where R_k is the rates of the user k , $\boldsymbol{R_{rates}}$ is the vector of the user rates, s_k is the signature of the user *k*, **s** is the vector of the signatures of the users in connexion.

The probability of error is thus given by [22-23]:

$$P_{b,k} = \frac{1-(1-P_{e,k}^{I/Q})(1-P_{e,k}^{I/Q})}{2} \qquad (4.3)$$

The Packets error rate is calculated using the following expression:

$$PER_k = 1-(1-P_{b,k})^{N_b} \qquad (4.4)$$

The packets loss rate of the user k is resumed to :

$$Loss_k = Npackets_k \times \sum_{i=1}^{N_G}\left(\sum_{l=1}^{Npackets_k} PER_l^i\right) \qquad (4.5)$$

where PER_l^i is the PER of the *l-th* packet when the user transmits with the code G_i. N_G is the number of the total class of codes. $Npackets_k$ is the total number of data packets transmitted.

The ratio of received packets, relative to the total packet sent, by the users in connexion is:

$$(\%)PDR = \frac{\sum_{k=1}^{N_{users}}\left(Npackets_k - Loss_k\right)}{Npackets_k}.100 \qquad (4.6)$$

where N_{user} is the number of users.

The goodput is the average successful received data rate, without the packet overhead, and without the retransmission, given by:

$$Goodput = \frac{\sum_{k=1}^{N_{users}}\left(Npackets_k - Loss_k\right)}{t} \qquad (4.7)$$

where t is the total duration of transmissions.

V. SIMULATIONS RESULTS

Monte Carlo simulations are performed to evaluate the performance of the system. We suppose a perfect power control that compensates the shadowing and the path loss effect on the signal. Only flat Rayleigh is consider and modeled here by Jake's simulator [18-19].The scenario studied is a central receiving node, connected with 15 surrounding user in motion, at 10m/s. More intensive study will be performed in others works to study the increase of the number of users and the impact of the mobility on the system. The simulation parameters are presented table 1. The results have been averaged for the packet delivery ratio (PDR), and the goodput aggregated, on transmission of 160 ms duration, data frames of 8 ms.

Table 1Simulation parameters

Bandwidth	2MHz
Transmitter SNR	20 dB
Series of spreading gains	[512 256 128 64 32 4]
Series of the bit rate	[0.016 0.03 0.06 .12 0.25 0.5 1] Mbits/s
Length of the data slot	8ms
Pilot bits	20 bits
CTS packet length	264 bits
CRC	32 bits
Channel sampling frequency	10^6 Hz
The rate adaptation step	0.2 ms
Carrier frequency	2.4 GHz
Jake simulator parameters	8 sinusoids
The LMS filter coefficients	40 taps

A. *Multi-rate vs single rate*

In Figure 5 we compare the goodput of the rate adaptation to performance of the existing single-rate for target PER_0 varying from 10^{-5} to 10^{-1}. The goodput of the schemes is better than the one of the single-rate case. For more stringent target PERs, it is more reduced but stays over the single-rate case. Figure 6 compares the PDR of the rate adaptation against the relative PDR of the single-rate case. The relative PDR is the number of packets received in single rate over the number of packets transmitted in rate adaptation. The PDR of the rate adaptation case is lower compared to this of the single-rate case. The performances of is around 52.5% for the different target PER_0 and 46%, for our scheme and single rate respectively. The rate adaptation achieves good performance in QoS guarantee.

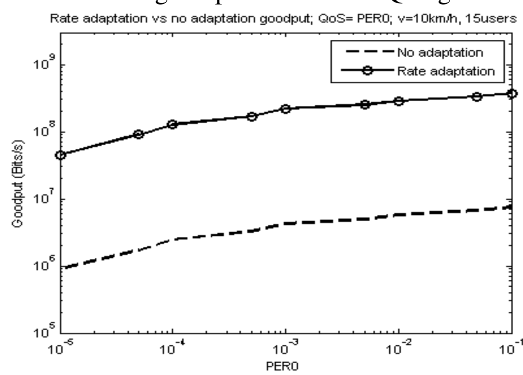

Figure 5 Goodput comparison of multi-rate rate vs single-rate in clairvoyant transmissions

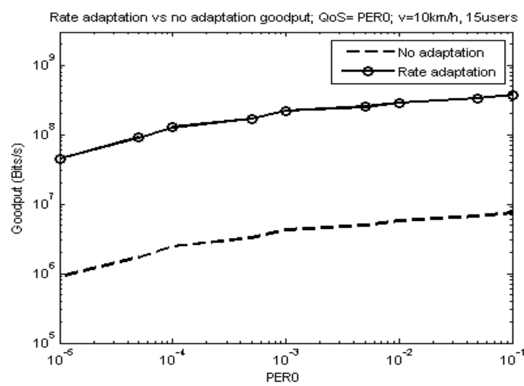

Figure 6 Packet delivery ratio comparison of multi-rate vs single-rate in clairvoyant transmissions

B. *Comparison of the clairvoyant and blind scheduler*

Figure 7 and Figure 8 compare the rate adaptation with QoS guarantees to the existing case, without QoS guarantee. In term of goodput, the result is better for QoS guarantees. Figure 9 shows the PDR for the rate adaptation with QoS guarantee compared to the case without QoS. The goodput is high but the PDR of the two cases stays around 50%. This is due to the nature of the multiuser detector used that ensures low bit error performance for the two cases. Without QoS guarantee, packets are transmitted during a long time but with very low performance compared to the QoS guarantee case that gives high quality transmission in short time.

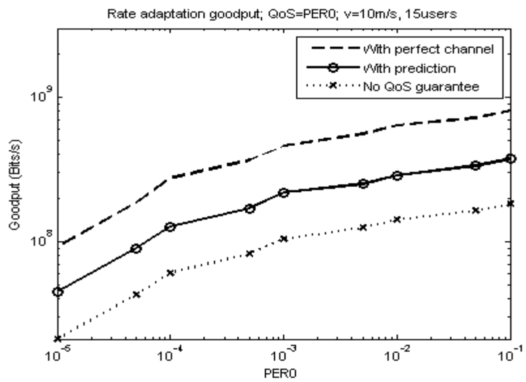

Figure 7 Goodput comparison in multi-rate transmissions

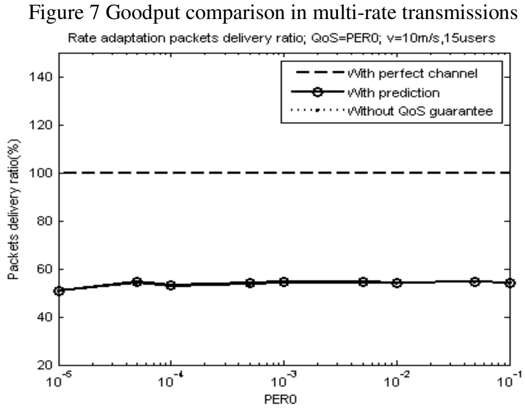

Figure 8 Packet delivery ratio comparison in multi-rate

VI. CONCLUSION

In conclusion, we developed a framework to improve the efficiency of the MUD based MAC protocol following cross-layer methodology. The radios choose an appropriate data rate to each station according to some calculated threshold. The particularity of this work relies on analyzing the performance of the protocol for a QoS guarantee PER_0 going form 10^{-5} to10^{-1}. We compared the QoS guarantee in the rate adaptation to the case where there is no adaptation, and show that the goodput increase is 50 times. Comparing the rate adaptation with QoS guarantee to the simple rate adaptation without any quality of service required, the goodput increase is 2 times. Our multiuser detection based framework, in addition to offering a wide range of transmission, allows for high quality data transmissions. However we notice a general PDR of the order of 50%, due the degradation introduced into the signal by Rayleigh fading. More complex receiver structure with diversity techniques can be used to improve the reception. Also at MAC layer, more complex QoS scheduling scheme can be studied. These topics constitute our future research.

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