Performance of Hybrid ARQ for NDMA Access Schemes with Uniform Average Power Control

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***Abstract*—Traditionally, a packet with errors, either due to channel noise or collisions, is discarded and needs to be retransmitted, leading to performance losses. Network Diversity Multiple Access (NDMA) handles collisions by combining a multipacket detection scheme with time diversity. In NDMA, the Base Station (BS) forces mobile terminals (MTs) to transmit P copies of each packet when P MTs collide. Diversity combining is limited to P copies of the packets, not allowing it to adapt to severe errors due to channel noise. This paper considers a multipacket detection scheme recently proposed, which reduces the Packet Error Rate (PER) when more than P packet copies are available.**

In this paper, a Hybrid-ARQ NDMA (H-NDMA) access mechanism is proposed. The access mechanism forces MTs with reception errors during a collision resolution epoch to transmit more than P times. Analytical models for Poisson traffic are proposed for the throughput and delay. The proposed system's performance is evaluated for a Single-Carrier with Frequency Domain Equalization (SC-FDE) scheme, and compared to classical NDMA. H-NDMA parameter configuration is defined in terms of Quality of Service (QoS) requirements. [1] [2]

***Index Terms*—Multipacket Detection; Network Diversity Multiple Access (NDMA); Hybrid-ARQ; Analytical Performance.**

I. INTRODUCTION

When different users simultaneously access a given channel in a wireless system a collision occurs. The conventional approach to cope with collisions is to discard all packets involved in the collision and to retransmit them. Multipacket detection mechanisms use the signals associated to multiple collisions to separate the involved packets. In [1] a multipacket detection technique was proposed where the Medium Access Control (MAC) protocol, Network Diversity Multiple Access (NDMA), forces all users involved in a collision of P packets to retransmit their packets $P-1$ times. This technique [1] is only suitable for flat-fading channels. Due to the linear nature of the receivers in [1], the residual interference levels can be high and/or can have significant noise. In [2] a frequency-domain multipacket detection scheme was proposed, which allows an efficient packet separation in the presence of successive collisions. This receiver is suitable for severely time dispersive channels and does not require uncorrelated channels for different retransmissions. However, it fails to address low Signal to Noise Ratio (SNR) scenarios, where packet separation may not be possible due to noise interference.

A discarded packet with errors has important information, since it could be used to improve the detection performance of subsequent retransmissions [3]. Hybrid-ARQ (H-ARQ) techniques are an efficient way to cope with high noise levels [3]–[5]. For classical diversity-combining systems (e.g. [3]), the individual symbols from all packet copies are combined to create a single packet with more reliable constituent symbols. H-ARQ with scheduled access supports higher throughput than NDMA, although with a higher packet delay [6]. Caire and Tuninetti [7] studied the performance of H-ARQ with random access for the Gaussian collision channel, and concluded that the more packets are combined the better.

NDMA relies on time diversity to resolve collisions or errors. Successive Interference Cancellation Tree Algorithm (SICTA) [8], for instance, uses time diversity to resolve collisions based on a Successive Interference Cancellation (SIC) approach combined with a Tree Algorithm. There are, however, extensions to NDMA using Code Division Multiple Access (CDMA) [9].

In [10] an improved multipacket detection scheme that applies diversity-combining was proposed. For a collision of P packets, it may use the data of more than P retransmissions to decode the packets, handling lost packets due to errors or collisions. However, additional retransmissions are only useful for the packets that were unsuccessfully received after the initial $P-1$ retransmissions, for a collision of P packets.

This paper proposes H-ARQ NDMA, a new MAC protocol that extends NDMA by incorporating an H-ARQ technique. A suitable analytical model is presented for the system's behaviour with unsaturated load. From the model, it is possible to calculate the throughput and packet delay for Poisson sources; the model's design shows how it can meet specific performance requirements. The system overview, including our multi-packet detection technique and the MAC protocol are presented in section II. The system's performance is analyzed in section III. A set of performance results is presented in section IV and Section V presents the conclusions.

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II. SYSTEM CHARACTERIZATION

This paper considers a structured wireless system where a set of Mobile Terminals (MTs) send data to a Base Station (BS). The MTs' uplink employs a Single Carrier with Frequency-Domain Equalization (SC-FDE) scheme. MTs are low resource battery operated devices whereas the BS is a high resource device that executes a multi-packet detection algorithm with H-ARQ error control in real-time. The MTs have a full-duplex radio and send data frames using the time slots defined by the BS (for the sake of simplicity, it is assumed that the packets associated to each user have the same duration). The BS controls the maximum number of MTs, J, using a given channel. The BS detects collisions and uses a broadcast downlink channel to signal them, requesting the MTs involved to resend their packets. It is assumed that perfect channel estimation and synchronization between local oscillators exist. It is also assumed that each data frame on each slot arrives simultaneously, and perfect power control and time advance mechanisms exist to compensate different propagation times and attenuations.

A. Medium Access Control Protocol

H-ARQ NDMA is a slotted random access protocol with gated access. The uplink slots are organized as a sequence of epochs. The BS broadcasts a synchronization signal, SYNC, through the downlink channel to mark the beginning of each epoch, allowing any MT with data packets to transmit at the next slot, otherwise MTs wait until the next epoch.

A BS is capable of discerning all colliding data packets, DATA, up to J users. During each epoch, up to P MTs transmit data, where $1 \leq P \leq J$. During the first slot of an epoch, the BS detects collisions and uses a broadcast downlink channel to signal a collision, requesting all the MTs involved to resend their data packets. When $P > 1$ MTs are involved in the collision, the BS asks for $P - 1$ retransmissions. After this initial set of P slots, the BS acknowledges the reception of the data packets, and it may request up to R additional retransmissions, intended for the packets that were unsuccessfully received. The BS signals an acknowledgement, ACK, through the downlink channel before each additional retransmission, defining which MTs should retransmit at the next slot. The epoch ends when all data packets are correctly received or after $P + R$ retransmission slots for a collision of P users. The BS also uses the SYNC to acknowledge the reception of the data packets successfully received during the previous epoch.

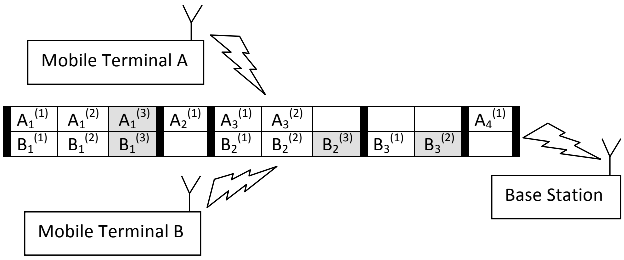

Figure 1. H-ARQ Multipacket Reception scheme.

Figure 1 illustrates the H-ARQ NDMA slotted access scheme, where up to $J = 2$ MTs contend the uplink channel by transmitting data once they receive a SYNC block from the BS; the SYNC is represented by the dark bars. The additional data packets retransmitted after the first P copies, due to reception errors, are represented by light grey blocks. The figure shows a sequence of five epochs, where H-ARQ was used in epochs one, three and four. It shows that H-ARQ NDMA behaves like a standard diversity combining H-ARQ scheme [5] when a single MT transmits during an epoch.

III. PERFORMANCE ANALYTICAL MODEL

The remaining section studies how the throughput and delay of a generic H-ARQ NDMA system are influenced by the PER (Packet Error Rate). The following modelling conditions were adopted:

a) Finite Population: A finite number of J independent MTs are transmitting packets of length equal to one time unit (slot) to a BS. MTs can store an infinite number of packets.
b) Immediate feedback: By the end of each slot the MTs are informed of the feedback immediately and errorlessly, as in [1] and [8]. It is also assumed that the number of colliding MTs is precisely determined by the BS.
c) Poisson arrivals: The buffer of each MT receives packets that are generated according to a Poisson source, with a λ generating rate.

Due to the nature of a full-duplex system communication, no spacing is used between each slot during the detection phase. For the sake of simplicity, the duration of the ACK and the SYNC on the downlink communication is not considered in the analysis.

A. Epoch Analysis.

The MT behaviour can be approximately modelled by a sequence of *epochs*. An epoch is defined as an empty slot or a set of slots where MTs send the same packet due to a BS request. When P users contend the first slot of an epoch, the BS forces the MTs to transmit P copies of the packets - guaranteeing that P copies of the packets exist and are decoded using the multipacket detection scheme in [10]. Then, following an H-ARQ approach, the BS requests additional packet transmissions for the unsuccessfully received packets. In this section, l is numbered from 0 up to R, and denotes the number of additional retransmission slots involved in the H-ARQ interference cancellation scheme.

The system's state during an epoch can be defined by the last slot where each MT transmits, after the initial set of P transmission slots. In an H-ARQ retransmission slot l, the last retransmission of MT p is ϕ_p^l, where $\phi_p^l \leq l$. A MT p that transmits only during the initial P slots of the epoch (i.e. with zero H-ARQ retransmission slots) has

$\phi_p^l = 0$, for all l H-ARQ retransmission slots. A MT p that retransmits up to the kth H-ARQ retransmission slot has $\phi_p^l = l$ for $l \leq k$ and has $\phi_p^l = k$ for $l > k$. The set of ϕ_p^l for all P MTs is denoted by Φ^l, $\Phi^l = \{\phi_p^l, p = 0, \ldots, P\}$, defines the epoch state. The packet error rate of MT p at the lth H-ARQ retransmission slot is denoted by $PER_p\left(\Phi^l\right)$. For an uncoded system with independent and isolated errors, the PER for a fixed packet size of M bits is

$$PER_p\left(\Phi^l\right) \simeq 1 - \left(1 - BER_p\left(\Phi^l\right)\right)^M . \qquad (1)$$

The $BER_p\left(\Phi^l\right)$ is calculated using (3) from [10], which depends upon H_k, a $(P+l) \times P$ matrix with the channel response. This matrix has zero coefficients for idle transmission slots, i.e. when MTs do not retransmit additional copies. Due to the Hybrid ARQ approach followed, the PER depends on all the transmissions that occurred during the epoch. Therefore, Φ^l includes the information about all previous packet transmissions (including Φ^{l-1}), where ϕ_p^l has $l+1$ possible values (from 0 to l).

Assuming that at retransmission slot l, the MT p's last transmission occurs for retransmission slot j, then the conditional probability that the MT p's last transmission at retransmission slot $l+1$ occurs for slot k is

$$\begin{aligned} &Pr\{\phi_p^{l+1} = k|\Phi^l \text{ with } \phi_p^l = j\} \\ &\quad = \begin{cases} PER_p\left(\Phi^l\right) & k = l+1 \ \wedge \ j = l \\ \left(1 - PER_p\left(\Phi^l\right)\right) & k = j = l \\ 1 & k = j < l \\ 0 & k > j > l \end{cases} , \end{aligned} \qquad (2)$$

where $Pr\{\phi_p^0 = 1\} = 1$ (i.e. MTs always transmit at the first P slots). A MT transmits on slot $l+1$ when the reception after retransmission l fails, or stops transmitting after a successful reception. The last two conditions define coherence rules. Assuming that the MTs' reception errors are independent, the following conditional probability follows

$$\begin{aligned} &Pr\{\Phi^{l+1} = \mathbf{K}|\Phi^l = \mathbf{J}\} \\ &\quad = \prod_{p=1}^{P} Pr\{\phi_p^{l+1} = \mathbf{K}_p|\Phi^l \text{ with } \phi_p^l = \mathbf{J}_p\}, \end{aligned} \qquad (3)$$

where $\mathbf{K}$ and $\mathbf{J}$ denote integer vectors with P positions. The probability that MT p's last transmission occurred at slot k, for l retransmission slots, is given by

$$\begin{aligned} &Pr\{\phi_p^l = k\}\left(\Phi^l\right) \\ &\quad = \begin{cases} \prod_{u=0}^{l-1} PER_p\left(\Phi^u\right) & k = l \\ \left(1 - PER_p\left(\Phi^k\right)\right)\prod_{u=0}^{k-1} PER_p\left(\Phi^u\right) & k < l \end{cases} . \end{aligned} \qquad (4)$$

The equation above can be calculated applying a Bayesian approach for all Φ^l possible values within the state space, which might result in a huge state space exploration for the generic case of multiple reception powers, with P^R states. However, for the scenario considered in this paper, with perfect average power control that leads to an uniform average signal to noise ratio for all MTs, the space state dimension can be reduced. It is irrelevant which MTs stopped transmitting; it is of interest to know the number of MTs whose packets were successfully received and altogether stopped transmitting. The compressed system state can be represented by the number of MTs that stopped transmitting at retransmission slot $k = 0, ..., l$ after l retransmission slots, denoted by ψ_k^l. The array of all ψ_k^l is $\Psi^l = \{\psi_k^l, k = 0...l\}$, where

$$\sum_{k=0}^{l} \psi_k^l = P , \qquad (5)$$

i.e. the total number of MTs is equal to P. The state space of Ψ^l is a $l+1$-dimension Pascal's simplex, with a finite number of values for $K \in \Omega_P^l$ that satisfy the equation above.

Each compressed state $\psi_0^l = K_0, ..., \psi_l^l = K_l$ groups $P!/(K_0!...K_l!)$ states with K_0 MTs stopping packet transmission after the initial P slots, K_1 MTs stopping packet transmission after the first retransmission ($l = 1$), and so on until K_l MTs stopping transmission at the last possible retransmission slot $0 \leq l \leq R$. In order to obtain the epochs state, all possible retransmission slots must be taken into consideration. Therefore, each epoch state probability, $Pr\{\Psi^R = K\} = Pr\{\psi_0^R = K_0, ..., \psi_R^R = K_R\}$ can be easily obtained applying (2), (3), (4) to all $\Psi^R = K \in \Omega_P^R$, obtained by full state exploration. The epoch duration is defined by the last retransmission slot of an epoch where any MT transmits, denoted by $dur\left(\Psi^R = K\right)$,

$$dur\left(\Psi^R = K\right) = \max\{k, \forall l > k, K_l = 0\}. \qquad (6)$$

Therefore, the nth order moment of the epoch expected duration, $dur\left(\Omega_P^R\right)$, can be obtained using the Bayes' theorem,

$$\begin{aligned} &E\left[dur\left(\Omega_P^R\right)^n\right] = \\ &\quad \sum_{K \in \Omega_P^R} Pr\{\Psi^R = K\} \frac{P!}{\prod_{i=0}^{R} K_i!} dur\left(\Psi^R\right)^n , \end{aligned} \qquad (7)$$

where the expected duration is simply $E\left[dur\left(\Omega_P^R\right)\right] = E\left[dur\left(\Omega_P^R\right)^1\right]$. A packet is not correctly received if it is transmitted on all epoch slots, and its reception fails after the last slot. Consequently, the expected number of packets received with errors during an epoch is

$$E\left[err\left(\Psi^R = K\right)\right] = K_R PER_{p_R}\left(\Phi^R\right) , \qquad (8)$$

where Φ^R is one of the states with $\Psi^R = K$, and p_R is the index of any MT that transmits during the last slot of the epoch, when possible (otherwise, $E\left[err\left(\Psi^R = K\right)\right]$ is zero); K_R denotes the number of MTs that transmit in the Rth retransmission slot. Assuming that MTs fail independently, the packet error probability for an epoch

Ω_P^R is given by

$$p_{err}\left(\Omega_P^R\right) = \sum_{K\in\Omega_P^R} Pr\{\Psi^R = K\}\frac{P!}{\prod_{i=0}^{R} K_i!}E\left[err\left(\Psi^R = K\right)\right]. \tag{9}$$

B. Queue Analysis.

Dinis *et al* [2] proposed a model for the NDMA system, which can be adapted for the H-ARQ NDMA system presented in this paper. The MT behavior can be approximately modeled by a sequence of *relevant epochs*, in which packets belonging to the MT are sent, and *irrelevant epochs*, in which no packets from the MT are sent. The model focus its attention to the number of packets in the buffer at the beginning of each epoch, denoted by q_m, where the subscript m denotes the epoch. The sequence $q_m, q_{m+1}, q_{m+2}, \dots$ constitutes an embeded Markov Chain. Paper [2] proposes a solution for $P_e = lim_{m\to\infty} Pr\left\{q_m = 0\right\}$, the probability of a MT's buffer being empty at the beginning of an epoch. It shows that P_e is a solution in the interval $[0,1]$ for

$$1 - P_{err} - G'\left(1\right) - P_e\left(1 + F'(1) - P_{err} - G'(1)\right) = 0\ , \tag{10}$$

where P_{err} denotes the average packet error probability, given by

$$P_{err} = \sum_{k=0}^{J-1} bi(J-1, k, 1-P_e)p_{err}\left(\Omega_{k+1}^R\right)\ , \tag{11}$$

and $F'(1)$ and $G'(1)$ denote the first moment of the steady state generating functions for the relevant and the irrelevant epochs respectively for $z = 1$. Function $bi(J,k,p) = C_k^J p^k (1-p)^{J-k}$ denotes the binomial distribution. The analysis proposed in [2] remains valid for H-ARQ NDMA, except for the $F'(1)$ and $G'(1)$ which are now equal to

$$G'(1) = \lambda \sum_{k=0}^{J-1} bi\left(J-1, k, 1-P_e\right)E\left[dur\left(\Omega_{k+1}^R\right)\right], \tag{12}$$

and

$$F'(1) = \lambda P_e^{J-1} + \lambda \sum_{k=1}^{J-1} bi\left(J-1, k, 1-P_e\right)E\left[dur\left(\Omega_k^R\right)\right]. \tag{13}$$

C. Throughput Analysis

The throughput can be calculated using (14)

$$S = \frac{\displaystyle\sum_{k=1}^{J} bi(J,k,1-P_e)\sum_{j=1}^{k} jbi(k,j,1-p_{err}\left(\Omega_k^R\right))}{\displaystyle P_e^J + \sum_{k=1}^{J} bi(J,k,1-P_e)E\left[dur\left(\Omega_k^R\right)\right]}. \tag{14}$$

D. Delay Analysis.

Delay analysis may consider the duration of an irrelevant epoch, denoted by h_{ir}, where the MT does not transmit, plus the duration of one or more relevant epochs, denoted by h_r, until the packet is correctly received. From the property of M/G/1 queue with vacation [11], the average system delay for a data packet can be expressed as

$$D = \overline{h_r} + \frac{\lambda\overline{h_r^2}}{2(1-\lambda\overline{h_r})} + \frac{\overline{h_{ir}^2}}{2\overline{h_{ir}}}, \tag{15}$$

where $\overline{h_r}$, $\overline{h_r^2}$, $\overline{h_{ir}}$ and $\overline{h_{ir}^2}$ are the first and second moments of the relevant and irrelevant epoch respectively. For the moments of the irrelevant epoch, we get $\overline{h_{ir}} = F'(1)/\lambda$ and $\overline{h_{ir}^2}$ is

$$\overline{h_{ir}^2} = P_e^{J-1} + \sum_{k=1}^{J-1} bi\left(J-1, k, 1-P_e\right)E\left[dur\left(\Omega_k^R\right)^2\right] \tag{16}$$

A relevant epoch may last more than one epoch, due to errors. Assuming that the sender keeps transmitting a packet until being correctly received, the relevant epoch's moments are

$$\overline{h_r} = \frac{G'(1)}{\lambda\left(1 + P_{err}\right)} \tag{17}$$

and

$$\overline{h_r^2} = \frac{\left(1+P_{err}\right)}{\left(1-P_{err}\right)^2}\sum_{k=0}^{J-1} bi\left(J-1, k, 1-P_e\right)E\left[dur\left(\Omega_{k+1}^R\right)^2\right]. \tag{18}$$

IV. PERFORMANCE ANALYSIS

In this section, the system performance is analysed, considering the PER, throughput and delay. An uniform system is analysed, composed by Poisson sources. A severely time dispersive channel was considered, with multipath propagation and uncorrelated Rayleigh fading for each path and user. MTs transmit uncoded data blocks of $N = 256$ QPSK data symbols for a transmission time of $4\mu s$. The PER was computed using the model presented in [10]. The results were validated through simulations.

Figures 2 and 3 reproduce the PER results from [10] for $P = 1$ MT and $P = 4$ MTs respectively, comparing different Ψ^R values for $R = 4$. They show that the error rate is a monotonically decreasing function of parameters R and the bit energy to noise ratio E_b/N_0. The PER is reduced when more MTs are involved in the collision and when more packets are combined. H-NDMA with four additional retransmissions ($\Psi^R = [00004]$) has a gain of 12 dB compared to the classical NDMA ($\Psi^R = [40000]$) considering a PER=10^{-2}. It is also clear that for the same number of additional retransmissions, H-NDMA ($\Psi^R = [40000]$) slightly outperforms H-ARQ ($\Psi^R = [00001]$), although three additional transmissions are made for $P = 4$ MTs. Figure 4 depicts the PER results for $P = 4$ MTs and $R = 4$ slots, where three MTs transmit during the four initial slots of an epoch and only

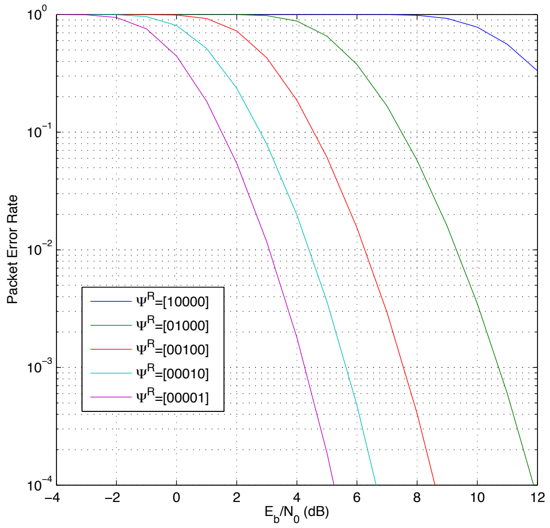

Figure 2. PER for $J = 1$ MT comparing different Ψ^R values.

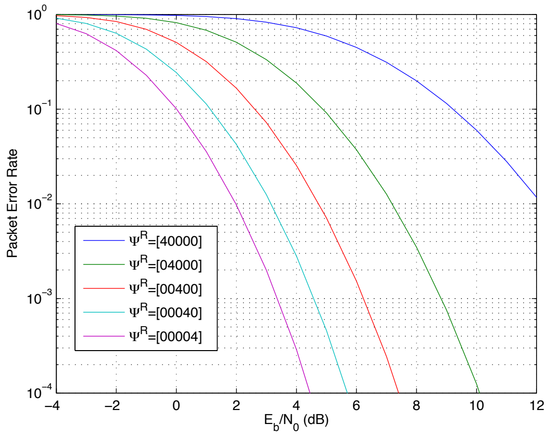

Figure 3. PER for $J = 4$ MTs comparing different Ψ^R values with equal number of retransmissions.

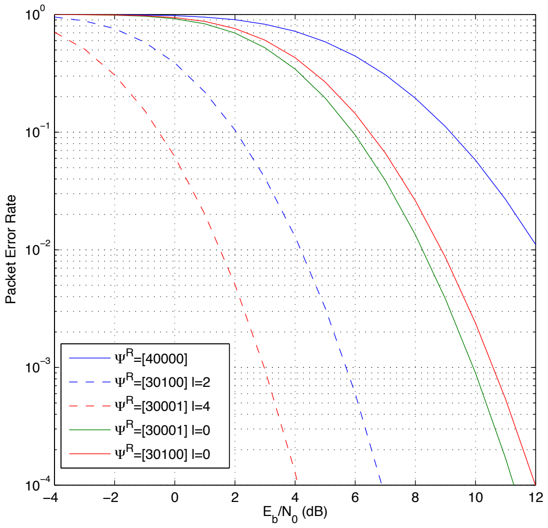

Figure 4. PER for $J = 4$ MTs comparing different Ψ^R values with different number of retransmissions.

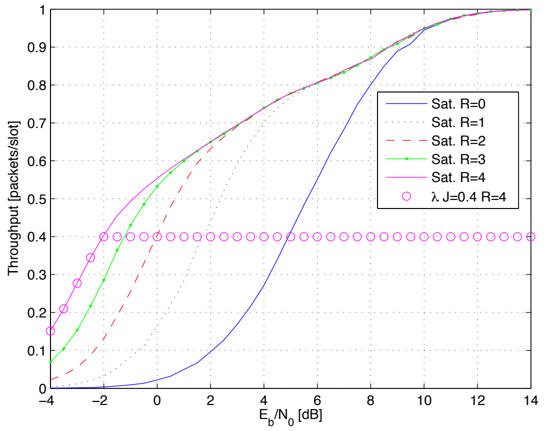

Figure 5. Throughput for $J = 4$ MTs comparing saturation with different R values and non-saturation scenario.

one MT transmits additional packet copies. Observing the PER for the MTs that transmit only four times, the figure shows that the PER still decreases when other MTs transmit on additional slots. The PER for $\Psi^R = [30001]$ with $l = 0$ has a gain of 4 dB when compared to $\Psi^R = [40000]$ for $PER = 10^{-2}$, due to the additional retransmissions of the fourth MT. The fourth MT that transmits more times its packet has a PER almost as equal as if all MTs transmit the same number of times (e.g. the MT for $l = 4$ with $\Psi^R = [30001]$ has a PER similar to $\Psi^R = [00004]$). It is possible to conclude that the multipacket receiver proposed in [10] is fitted for an H-ARQ system.

To understand the maximum achievable throughput with this system, a saturated network was considered, where MTs always have a packet to transmit (i.e. $P_e = 0$). Figure 5 shows the saturation throughput with $J = 4$ MTs for different R values, where $R = 0$ corresponds to the classical NDMA system. It shows a throughput network capacity increment for higher R values when $E_b/N_0 < 10$dB, where the incremental step becomes smaller when R becomes bigger. The throughput S for $\lambda J = 0.4$ packets/slot is also represented, showing that S is equal to 0.4, except when this load is below the saturation throughput. Figure 6 depicts the level curves for the saturation throughput for $J = 4$ MTs and for different R values. In order to support a given network utilization of λJ, the values for E_b/N_0 and R must be at the right of the curve represented in the picture corresponding to λJ. Otherwise, the load will not be supported. Figure 7 depicts the average packet delay using (15), for $J = 4$ MTs and $\lambda J = 0.4$ packets/slot. It shows that H-NDMA improves the delay for $E_b/N_0 < 12$dB, increasing significantly the E_b/N_0 range with a total network utilization of 40%. For $R = 4$ it is possible to have an average delay below 20 slots for $E_b/N_0 = 0$dB. Delay is not influenced by R for $E_b/N_0 > 12$dB.

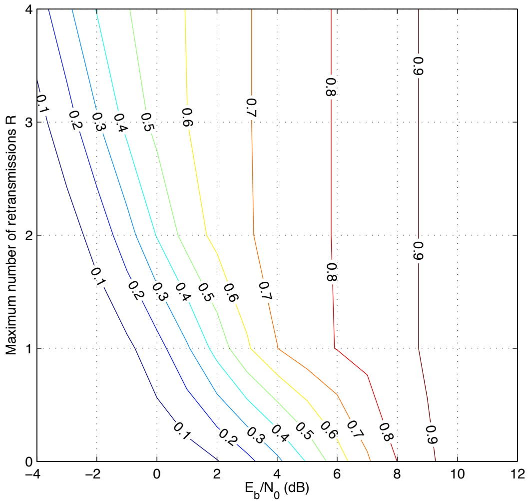

Figure 6. Level curves for the saturation throughput for $J = 4$ MTs and different R values.

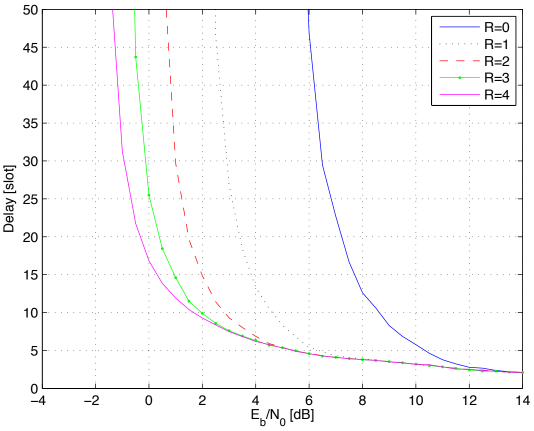

Figure 7. Delay for J=4 MTs and $\lambda J = 0.4$ packets/slot comparing saturation with different R values and non-saturation scenario.

Figure 8 shows how the delay depends on the network utilization (λJ) with $J = 4$ MTs, for $E_b/N_0 = 0$dB and $E_b/N_0 = 4$dB. In terms of delay, it shows that the minimum R value strongly depends on the E_b/N_0 at the reception. For $E_b/N_0 = 4$dB, $R = 3$ and $R = 4$ produce the same packet delay (and the same network capacity), but with $E_b/N_0 = 0$dB, the delay is smaller for $R = 4$ slots.

The set of results presented so far show that performance always improves for higher R values, extrapolating the conclusions of [7] for the H-NDMA case. However, the implementation complexity of the proposed H-ARQ NDMA receiver also increases for higher R values. Therefore, the optimal R value in physical prototypes will be bounded by the available processing capacity for a given number of MTs. The following set of experiments assume that this limit is $R = 4$.

Figure 9 presents the network throughput level curves in function of the network utilization (λJ) and E_b/N_0, showing that E_b/N_0 is the most important parameter for the network configuration. For each network utilization load, there is a minimum E_b/N_0 level, for which the system saturates. The average energy per bit is measured at the receiver (the BS), which can use it to estimate the communication path loss to all the MTs, so that MTs can regulate their transmission power. This figure defines the minimum E_b/N_0 that can be set for a given load. In some practical situations it is also required to satisfy a maximum delay. Figure 10 represents the average packet delay in function of the network utilization (λJ) and E_b/N_0, showing that as long as E_b/N_0 is 2dB above the saturation limit identified above, the delay is below 100 slots. Therefore, a delay requirement can be translated into a shift of the E_b/N_0, for a network load below 0.9 packets/slot.

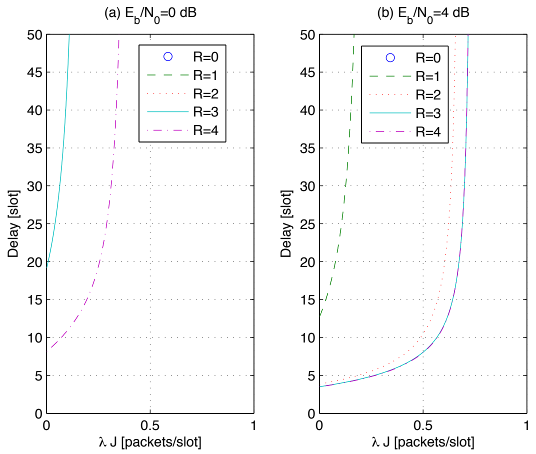

Figure 8. Delay for $J = 4$ and different λJ with (a) $E_b/N_0 = 0$ dB and (b) $E_b/N_0 = 4$ dB.

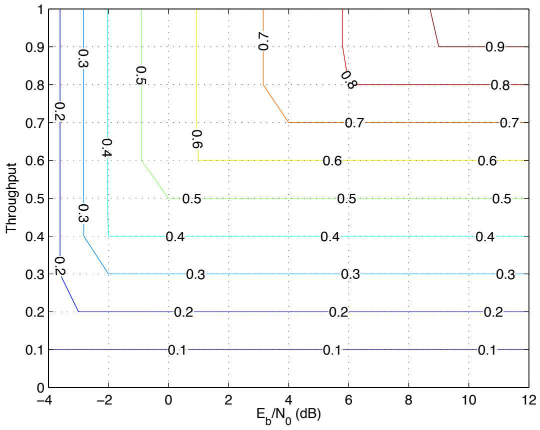

Figure 9. Throughput level curves for $J = 4$ MTs and different λJ.

The proposed system is scalable, since it improves its performance when the number of MTs, J, increases. Figure 11 illustrates the saturation throughput with $R = 4$ slots for three values of E_b/N_0, 0dB, 4dB and 8dB. Figure 12 represents the level curves of the saturation

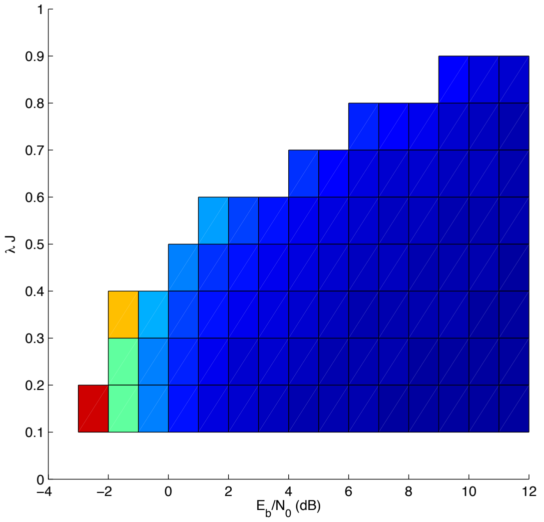

Figure 10. Delay for $J = 4$ and different λJ and E_b/N_0.

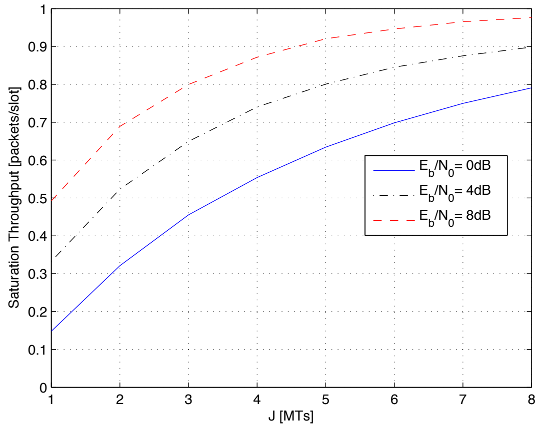

Figure 11. Scalability of saturated throughput over J for R=4 MTs comparing different E_b/N_0 values.

throughput with E_b/N_0 and J. The figures show that the network capacity increases when J increases, in result of diluting the packet retransmission overhead over a larger number of MTs. This result is particularly relevant since it shows that the H-NDMA system's performance is improved when more MTs transmit during a slot. The case when $J = 1$ MT corresponds to a diversity combining classical H-ARQ system ([3], [5]), where a single MT transmits in each slot. Therefore, it is shown that H-NDMA also improves the network capacity when compared to a classical diversity combining H-ARQ. As expected, lower E_b/N_0 values reduce the average throughput network capacity.

Figures 13 and 14 depict the packet delay for $R = 4$ and λJ=0.4 packets/slot, showing that the delay decreases when J increases for the same network utilization (a total throughput of 40%), almost stabilizing on a delay dependent of the E_b/N_0 value. This result confirms the system scalability with the number of MTs. However, the implementation complexity of the proposed H-ARQ NDMA receiver also increases with the maximum number of MTs it can discern, alongside with additional R transmissions. Therefore, the optimal values for the maximum J and R in physical prototypes will be bounded, once again, by the available processing capacity. Their values should be the maximum values permitted by the available technology.

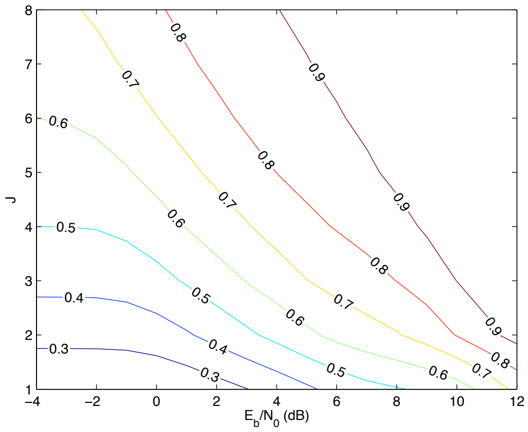

Figure 12. Level curves for saturated throughput over J and E_b/N_0 for R=4 slots.

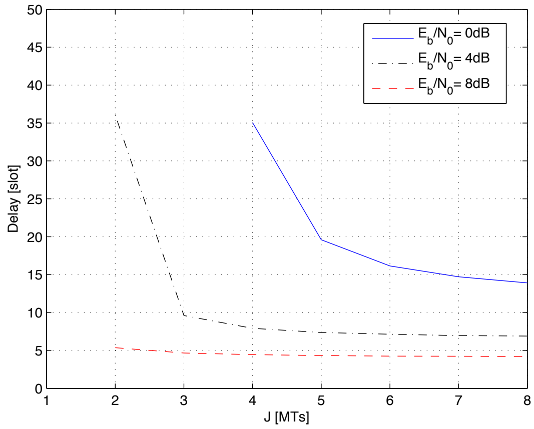

Figure 13. Delay for R=4 slots and $\lambda J = 0.4$ comparing different E_b/N_0 values.

V. CONCLUSION

A new H-ARQ NDMA protocol was described, named H-NDMA. It was designed to improve the network capacity for a hybrid detection scheme with multipacket detection and packet combining, following a cross-layered approach. An analytical model was presented for the network throughput and packet delay. H-NDMA performance was evaluated for a low complexity SC-FDE receiver [10]; it was shown that H-NDMA improves the network capacity and reduces the packet delay when compared to a basic NDMA MAC protocol, but also when compared to a classical Hybrid-ARQ protocol. It was also

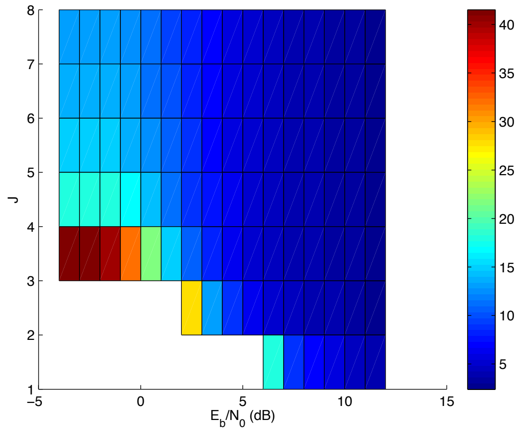

Figure 14. Delay for R=4 slots and $\lambda J = 0.4$ comparing different E_b/N_0 values.

shown that H-NDMA is scalable with the number of MTs and that the performance is improved when more MTs transmit during an epoch. Therefore, H-NDMA is a good option for future very-high data rate cellular networks. Using the analytical model proposed in this paper, it is possible to optimize the system performance, calculating the minimal bit energy to noise ratio that satisfies the delay and load requirements for a given application.

The present work considered perfect average power control, however, the H-ARQ NDMA receiver considered in [10] can also be used with non-uniform bit energy to noise ratio values, which introduce new requirements into the MAC protocol design.

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REFERENCES

[1] M. Tsatsanis, R. Zhang and S. Banerjee, “Network Assisted Diversity for Random Access Wireless Systems”, *IEEE Trans. on Signal Processing*, Vol. 48, pp. 702–711, Mar. 2000.

[2] R. Dinis, P. Montezuma, L. Bernardo, R. Oliveira, M. Pereira and P. Pinto, "Frequency-domain multipacket detection: a high throughput technique for SC-FDE systems," IEEE Transactions on Wireless Communications, vol. 8, Jul. 2009, pp. 3798-3807.

[3] P. Sindhu, "Retransmission error control with memory," IEEE Trans. Commun., vol. 25, pp. 473-479, May 1977.

[4] A. Gusmão, R. Dinis and N. Esteves, "Adaptive HARQ Schemes Using Punctured RR Codes for ATM-compatible Broadband Wireless Communications", *IEEEVTC'99(Fall)*, Amsterdam, Netherlands, Sep. 1999.

[5] D.J. Costello, J. Hagenauer, H. Imai and S.B. Wicker, "Applications of error-control coding", IEEE Transactions on Information Theory, vol. 44, 1998, pp. 2531-2560.

[6] M. Pereira, L. Bernardo, R. Dinis, R. Oliveira and P. Pinto, "Performance comparison of diversity combining ARQ error control schemes with multi-packet detection schemes," IEEE ICCCN 2010, Zurich, Switzerland, Aug. 2010.

[7] G. Caire and D. Tuninetti, "The Throughput of Hybrid-ARQ Protocols for the Gaussian Collision Channel," *IEEE Transactions on Information Theory*, vol. 47, pp. 1971-1988, Jul. 2001.

[8] Y. Yu and G. Giannakis, “SICTA: A 0.693 Contention Tree Algorithm Using Successive Interference Cancellation”, *IEEE INFOCOM'05*, Miami, USA, Mar. 2005.

[9] R. Samano-Robles, M. Ghogho and D. C. McLernon. "Quality of Service in Wireless Network Diversity Multiple Access Protocols Based on a Virtual Time-Slot Allocation," ICC 2007.

[10] F. Ganhão, L. Bernardo, R. Dinis, P. Carvalho, R. Oliveira, and P. Pinto, "Analytical Performance Evaluation of SC-FDE Modulations with Packet Combining and Multipacket Detection Schemes," *IEEE VTC'11 (Spring)*, Budapest, Hungary, May 2011.

[11] D. Bertsekas and R. Gallager, *Data Networks*, 2nd ed., Prentice-Hall, 1992.

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