Goodput and Delay Analysis of a Data Link Layer Protocol envisioned for 3^{rd} Generation Cellular Systems

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***Abstract*— This work proposes a model to investigate the behavior of a third generation Radio Link Control (RLC) Protocol on the forward link of a Multi-carrier DS-CDMA architecture that employs Walsh and Quasi-Orthogonal channelization codes. Jointly modeling the features of the data link layer and of the underlying physical channels, we are able to identify the interaction between transmission design and the RLC protocol performance. The latter is assessed by analysis, determining the RLC protocol goodput and the average delivery time suffered by a data unit transferred over the radio channel, when two different coding approaches are adopted: namely, rate compatible punctured convolutional codes and code combining.**

***Index Terms*— Radio Link Control Protocol, Goodput and Delay, Performance Evaluation, Multicarrier DS-CDMA.**

I. Introduction

One of UMTS main objectives is to increasingly support multimedia data flows. Efficient packet access is therefore crucial and mandates for a thorough understanding of the performance that protocols in different layers of a communication architecture may achieve, provided a third generation radio bearer is considered. Examples of studies in this field are [1] through [7]. This work provides a contribution in the area of wireless protocol modeling and performance evaluation, as it focuses on a Radio Link Control (RLC) protocol specifically envisioned by 3GPP [8]: the goal is to assess its performance, in terms of goodput and mean delivery time of a Protocol Data Unit (PDU), and to identify the influence that a rather realistic description of the underlying physical layer has on these parameters. The most salient features of the RLC protocol under examination are captured by an analytical model, assuming each packet to be delivered to the mobile terminal is decomposed into a number of smaller PDUs, that can undergo more than one transmission before being correctly received. The procedure to handle retransmissions adheres to some of the specifications in [8], and mandates the usage of convolutional codes.

The protocol operating mode taken into consideration allows us to introduce an analysis based on the logical division of the time axis in statistically similar cycles, and to identify how alternative coding schemes and retransmission patterns influence the protocol behavior. The significant parameters we focus onto are: the RLC protocol goodput, defined as the ratio between the average transmission time of the PDUs that are *correctly* received in a cycle and the average cycle duration, and the average time needed to correctly deliver a network Protocol Unit, e.g., an IP datagram.

Regarding transmission design, the forward link of a multicarrier CDMA architecture, similar to the one foreseen by *cdma2000*, is examined. Three band-disjoint sub-channels affected by frequency selective Rayleigh fading and three RAKE correlation receivers are considered. To increase system capacity, quasi-orthogonal sequences are adopted as channelization codes [9] - [12], in addition to Walsh sequences. Among the transmission impairments, multipath dispersion, correlated interference between Walsh and QO sequences, and additive white Gaussian noise are accounted for. To increasingly protect the transmitted PDUs, two alternative coding schemes are confronted: the first uses Rate Compatible Punctured Convolutional (RCPC) codes and 2 puncturing matrices to obtain 2 codes, with rate $1/2$ and $1/3$, alternatively employed to retransmit multiple copies of the same PDU; the second scheme exploits the code combining technique, adopts the rate $1/2$ RCPC code as the base code, and combines each copy of a retransmitted PDU with the previously received versions, in order to obtain a more powerful code.

The effects on protocol performance of several transmission parameters are evidenced. Namely, it is demonstrated that with code combining it is possible to substantially increase the protocol goodput, to allow a relatively high number of simultaneous RLC connections to be active within the same cell and to transmit relatively long PDUs, still achieving average delivery times for the IP datagrams that are within a few hundreds of milliseconds.

The rest of the paper is organized as follows: Section II gives a description of the RLC protocol and puts forth the analytical model to evaluate its performance; Section III describes the transmitter and receiver characteristics, providing a bound to the PDU error probability. Section IV presents the numerical results and Section V concludes the paper.

II. RLC Protocol Model

This section analytically models the performance of an Automatic Repeat Request (ARQ) scheme capturing most of the characteristics of the RLC Protocol of 3GPP Release IV [8], when working in the *acknowledged* mode. The most significant protocol features are reported below:

1) two main operating procedures are envisioned: *stop-and-wait* working on blocks of PDUs or *selective repeat*;
2) acknowledgements are handled by a *delayed* ACK vector, called *status report*, a bit map indicating which PDUs in last block have been correctly received and which have been lost or corrupted;
3) an upper limit Λ_M is set to the maximum number of retransmissions of the same PDU;
4) a *polling* mechanism is additionally provided, that allows the transmitter to explicitely query the receiver about which PDUs have been correctly received; upon the reception of a *polling* request, the receiver is forced to reply with a *status report*.

We work under the assumptions that the transmitter always has some PDUs to send on the radio channel, that the protocol works as a *stop-and-wait* scheme sending blocks of PDUs and waiting for their cumulative ACK, and that the feedback channel is error-free. Namely, when an upper layer packet is received by the RLC protocol, we assume that

1) the packet is fragmented into N_0 PDUs of the same size, properly coded;
2) the transmitter sends this set of PDUs, and waits for the corresponding status report;
3) upon its reception, the PDUs erroneously received are protected by a more powerful code and retransmitted;
4) steps 2 and 3 are repeated, until either all PDUs of the original packet have been correctly received or the maximum number of retransmission attempts Λ_M has been reached.

The operating mode just described lends itself to a clean analytical model, based on the logical division of the time axis in *rounds*, during which transmission of PDUs with different characteristics occurs. Namely, round *zero* begins with the transmission of the original N_0 PDUs that constitute a packet and ends when the corresponding status report is notified to the transmitter. Round 1 then follows, in order to handle the retransmission of the N_1 PDUs that were unsuccessfully transmitted during the previous round; as before, the round ends when the status report is received by the sending end. Observe that PDUs transmitted in different rounds face different error probabilities, but PDUs belonging to the same round suffer the same error probability, as the coding employed is the same. Let Λ be the index denoting last executed round: rounds repeat until either all PDUs transmitted in last round, N_Λ, are correctly received, or the maximum number of retransmissions has been reached, i.e., $\Lambda = \Lambda_M$. When either circumstance occurs, the transmission cycle of the original packet ends and the cycle to deliver next packet begins. As cycles are statistically similar, we determine protocol throughput focusing on the average total length of the cycle. Fig. 1 depicts a typical transmitting sequence of the RLC protocol.

A. Round duration

Let $\mathcal{T}_\lambda$ be the duration of the generic λ-th round; from Fig. 1 we infer that

$$\mathcal{T}_\lambda = t_{pr} + N_\lambda t_{pdu} + t_{st}\,, \tag{1}$$

where t_{pr} is the propagation delay on the forward link, N_λ is the number of PDUs that are transmitted during the λ-th round, t_{pdu} is the PDU transmission time introduced by the physical layer, t_{st} is the time needed to deliver and process the *status report*. For short, define $t_{phy} = t_{pr} + t_{st}$. Observe that N_λ is a discrete random variable (r.v.), that takes on values $\{0, 1, \ldots, N_{\lambda-1}\}$, while N_0 is a deterministic quantity. Therefore the following inequalities

$$0 \le N_\Lambda \le \cdots \le N_\lambda \le N_{\lambda-1} \le \cdots \le N_0 \tag{2}$$

always hold. The actual N_λ value is defined at the end of the $(\lambda-1)$-th round, as it represents both the number of erroneous PDUs in round $(\lambda-1)$ and the number of PDUs that have to be transmitted during next round, the λ-th.

B. Conditional Density Function of the r.v.'s $\{N_\lambda\}$

As we assume that the probability of incorrectly receiving a PDU is constant and independent between PDUs, the number N_λ of erroneously received PDUs in the $(\lambda-1)$-th round is binomially distributed, once conditioned on the values $N_{\lambda-1}, \ldots, N_1$.

Therefore,having defined $\mathcal{P}_\lambda^{(e)}$ as the PDU error probability during the λ-th round and $\overset{a}{\underset{b}{\boldsymbol{\mathcal{B}}}}(c) \doteq \binom{a}{b} c^b (1-c)^{a-b}$, we write

$$\mathsf{p}_{N_1}(n_1) = \Pr[N_1 = n_1] = \overset{N_0}{\underset{n_1}{\boldsymbol{\mathcal{B}}}}\left(\mathcal{P}_0^{(e)}\right) \tag{3}$$

and similarly

$$\begin{aligned}\mathsf{p}_{N_\lambda}|_{N_{\lambda-1},\ldots,N_1}(n_\lambda) = \Pr[N_\lambda = n_\lambda | N_{\lambda-1}, \ldots, N_1] = \\ = \overset{N_{\lambda-1}}{\underset{n_\lambda}{\boldsymbol{\mathcal{B}}}}\left(\mathcal{P}_{\lambda-1}^{(e)}\right), \lambda \in \{2, \ldots, \Lambda_M\}\,.\end{aligned} \tag{4}$$

Note that the r.v. N_λ does not exist if $N_{\lambda-1} = 0$, as during the $(\lambda-1)$-th round all $N_{\lambda-1}$ PDUs have been correctly delivered.

C. Density Function of the r.v. Λ

The index of last round, Λ, is a discrete r.v. itself, that takes on values $\{0, 1, \ldots, \Lambda_M\}$. To derive its density function, remember that the Λ-th round is the last provided that $N_{\Lambda+1} = 0$. Recalling (3) and (4), its probability, p_Λ, is

$$\begin{aligned}\mathsf{p}_\Lambda = \sum_{n_1}^{N_0}\sum_{n_2}^{n_1}\cdots\sum_{n_\Lambda}^{n_{\Lambda-1}}\left(1-\mathcal{P}_\Lambda^{(e)})\right)^{n_\Lambda}\cdot \\ \cdot \mathsf{p}_{N_\Lambda}|_{N_{\Lambda-1},\ldots,N_1}\cdots\mathsf{p}_{N_2}|_{N_1}\mathsf{p}_{N_1}\,, \\ \Lambda = 0, 1, \ldots, \Lambda_M - 1\,,\end{aligned} \tag{5}$$

while from the unit constraint on the density function $\mathsf{p}_{\Lambda_M} = 1 - \sum_{\Lambda=0}^{\Lambda_M-1}\mathsf{p}_\Lambda$.

D. Mean Cycle Time $\mathbb{E}[\mathcal{T}]$

All previous density functions are necessary in order to determine $\mathbb{E}[\mathcal{T}]$, the average cycle duration, i.e., the mean time needed to correctly deliver the original N_0 PDUs,

$$\mathbb{E}[\mathcal{T}] = \mathbb{E}\left[\mathcal{T}_0 + \sum_{\lambda=1}^{\Lambda}\mathcal{T}_\lambda\right], \tag{6}$$

that is,

$$\mathbb{E}[\mathcal{T}] = \mathcal{T}_0 + \sum_{\Lambda=0}^{\Lambda_M}\mathsf{p}_\Lambda\left(\sum_{\lambda=1}^{\Lambda}\mathbb{E}[\mathcal{T}_\lambda]\right) \tag{7}$$

where p_Λ is given by (5) and $\mathbb{E}[\mathcal{T}_\lambda]$ can be computed recalling that the r.v.'s N_λ, $\lambda = 1, 2, \ldots, \Lambda$, are binomially distributed once conditioned to $N_{\lambda-1}, \ldots, N_1$, hence their expected value is

$$\mathbb{E}[N_\lambda]\big|_{N_{\lambda-1},\ldots,N_1} = N_{\lambda-1}\mathcal{P}_{\lambda-1}^{(e)}\,; \tag{8}$$

recursively applying this result,

$$\begin{aligned}\mathbb{E}[N_\lambda]\big|_{N_{\lambda-2},\ldots,N_1} = N_{\lambda-2}\mathcal{P}_{\lambda-2}^{(e)}\mathcal{P}_{\lambda-1}^{(e)} \\ \vdots \\ \mathbb{E}[N_\lambda] = N_0\prod_{\tau=0}^{\lambda-1}\mathcal{P}_\tau^{(e)}\,;\end{aligned} \tag{9}$$

it then follows that

$$\mathbb{E}[\mathcal{T}_\lambda] = t_{phy} + t_{pdu}N_0\prod_{\tau=0}^{\lambda-1}\mathcal{P}_\tau^{(e)}\,, \tag{10}$$

so that (7) finally becomes

$$\begin{aligned}\mathbb{E}[\mathcal{T}] = \\ = \sum_{\Lambda=0}^{\Lambda_M}\mathsf{p}_\Lambda\left((\Lambda+1)\,t_{phy} + t_{pdu}N_0\left(1 + \sum_{\lambda=1}^{\Lambda}\prod_{\tau=0}^{\lambda-1}\mathcal{P}_\tau^{(e)}\right)\right).\end{aligned} \tag{11}$$

From this result, it is quite clear that the mean delivery time is proportional to the block size, i.e., there is a linear dependence of $\mathbb{E}[\mathcal{T}]$ from the value N_0. To prove this statement, is will suffice to separate the summation in (11) into two distinct terms:

$$\begin{aligned}\mathbb{E}[\mathcal{T}] = t_{phy}\left[\sum_{\Lambda=0}^{\Lambda_M}\mathsf{p}_\Lambda(\Lambda+1)\right] + \\ + N_0 t_{pdu}\left[\sum_{\Lambda=0}^{\Lambda_M}\mathsf{p}_\Lambda\left(1 + \sum_{\lambda=1}^{\Lambda}\prod_{\tau=0}^{\lambda-1}\mathcal{P}_\tau^{(e)}\right)\right].\end{aligned} \tag{12}$$

The protocol throughput, $\mathcal{S}$, can now be determined as the ratio between the transmission time of the original N_0 PDUs and the average cycle time $\mathbb{E}[\mathcal{T}]$, needed to correctly deliver them (or, at least, to try Λ_M transmissions),

$$\begin{aligned}\mathcal{S} \doteq \frac{N_0 t_{pdu}}{\mathbb{E}[\mathcal{T}]} = \\ = \frac{1}{\sum_{\Lambda=0}^{\Lambda_M}\mathsf{p}_\Lambda\left((\Lambda+1)\frac{t_{phy}}{t_{pdu}N_0} + \left(1 + \sum_{\lambda=1}^{\Lambda}\prod_{\tau=0}^{\lambda-1}\mathcal{P}_\tau^{(e)}\right)\right)},\end{aligned} \tag{13}$$

where the PDU error probability in each round, $\mathcal{P}_\tau^{(e)}$, $\tau = 0, 1, \ldots, \Lambda_M$, is still needed. Its determination will be the subject of Section III.

E. Goodput

In order to accomplish a more complete insight into this protocol behavior, we now determine its *goodput*, $\mathcal{S}_{\mathcal{G}}$, defined as the ratio between the mean transmission time of the $N_{\mathcal{G}}$ *correctly* received PDUs at the end of a cycle and the average cycle time $\mathbb{E}[\mathcal{T}]$:

$$\mathcal{S}_{\mathcal{G}} \doteq \frac{\mathbb{E}[N_{\mathcal{G}}] \cdot t_{pdu}}{\mathbb{E}[\mathcal{T}]} . \tag{14}$$

Recalling the protocol description, this RLC scheme can indeed deliver some erroneous PDUs, as it allows up to Λ_M retransmission attempts, regardless of the original N_0 PDUs being correctly delivered or not. We further observe that, if the cycle stops at round $\Lambda = 0, 1, \ldots$ or $\Lambda_M - 1$, the protocol correctly delivers all the N_0 PDUs, whereas if the Λ_M-th cycle has been reached, it is quite likely that some PDUs will not be correctly received.

Hence, we can state that $N_{\mathcal{G}}$ is a discrete r.v. which takes on the values

$$N_{\mathcal{G}}(\Lambda) = \begin{cases} N_0, & \text{if } \Lambda = 0, 1, \ldots, \Lambda_M - 1 , \\ N_0 - N_e, & \text{if } \Lambda = \Lambda_M , \end{cases} \tag{15}$$

where N_e is the number of erroneous delivered PDUs at the end of the cycle. In turn, N_e is a r.v. too, and it exhibits the same binomial distribution of the r.v.'s $N_\Lambda, \Lambda = 1, 2, \ldots, \Lambda_M$, i.e.,

$$\Pr[N_e = n_e] = \underset{n_e}{\overset{N_{\Lambda_M}}{\boldsymbol{\mathcal{B}}}} \left(\mathcal{P}^{(e)}_{\Lambda_M}\right) . \tag{16}$$

Hence, taking the expectation of (15) with respect to N_e, still conditioned on Λ and N_Λ, leads to

$$\mathbb{E}[N_{\mathcal{G}}]\big|_{\Lambda, N_\Lambda} = \\ = \begin{cases} N_0, \text{ if } \Lambda = 0, 1, \ldots, \Lambda_M - 1 , \\ \\ \sum_{n_e=0}^{N_{\Lambda_M}} (N_0 - n_e) \underset{n_e}{\overset{N_{\Lambda_M}}{\boldsymbol{\mathcal{B}}}} \left(\mathcal{P}^{(e)}_{\Lambda_M}\right) = \\ = N_0 - N_{\Lambda_M}\mathcal{P}^{(e)}_{\Lambda_M}, \text{ if } \Lambda = \Lambda_M . \end{cases} \tag{17}$$

As $\mathbb{E}[N_{\mathcal{G}}]\big|_{\Lambda, N_\Lambda}$ is not a constant only when $\Lambda = \Lambda_M$, we now focus onto this latter case and observe that, if the Λ_M-th round has been reached,

$$N_0 \geq N_1 \geq \cdots \geq N_\Lambda \geq \cdots \geq N_{\Lambda_M} \geq 1 ; \tag{18}$$

so, if we now are willing to obtain an expression of $\mathbb{E}[N_{\mathcal{G}}(\Lambda_M)]$ unconditioned with respect to $N_1, N_2, \ldots, N_{\Lambda_M}$, we obtain

$$\mathbb{E}[N_{\mathcal{G}}(\Lambda = \Lambda_M)] = \\ = \sum_{n_1=1}^{N_0} \sum_{n_2=1}^{n_1} \cdots \sum_{n_{\Lambda_M}=1}^{n_{\Lambda_M - 1}} \left(N_0 - N_{\Lambda_M}\mathcal{P}^{(e)}_{\Lambda_M}\right) \cdot \\ \cdot \mathsf{p}_{N_\Lambda}\big|_{N_{\Lambda-1},\ldots,N_1} \cdots \mathsf{p}_{N_2}\big|_{N_1} \mathsf{p}_{N_1} , \tag{19}$$

which after some algebraic manipulations, turns into

$$\mathbb{E}[N_{\mathcal{G}}(\Lambda = \Lambda_M)] = N_0 \left(\mathsf{p}_{\Lambda_M} - \prod_{\Lambda=0}^{\Lambda_M} \mathcal{P}^{(e)}_{\Lambda}\right) . \tag{20}$$

This result, combined with (17), gives

$$\mathbb{E}[N_{\mathcal{G}}] = N_0 \left(\sum_{\Lambda=0}^{\Lambda_M - 1} \mathsf{p}_\Lambda + \mathsf{p}_{\Lambda_M}\left(\mathsf{p}_{\Lambda_M} - \prod_{\Lambda=0}^{\Lambda_M} \mathcal{P}^{(e)}_{\Lambda}\right)\right) . \tag{21}$$

Finally, replacing (21) and (11) in (14) we obtain the desired goodput expression

$$\mathcal{S}_{\mathcal{G}} = \\ = \frac{\left(\sum_{\Lambda=0}^{\Lambda_M - 1} \mathsf{p}_\Lambda + \mathsf{p}_{\Lambda_M}\left(\mathsf{p}_{\Lambda_M} - \prod_{\Lambda=0}^{\Lambda_M} \mathcal{P}^{(e)}_{\Lambda}\right)\right)}{\sum_{\Lambda=0}^{\Lambda_M} \mathsf{p}_\Lambda \left((\Lambda + 1)\frac{t_{phy}}{t_{pdu} N_0} + \left(1 + \sum_{\lambda=1}^{\Lambda} \prod_{\tau=0}^{\lambda-1} \mathcal{P}^{(e)}_{\tau}\right)\right)} . \tag{22}$$

It will be the subject of next section to evaluate proper bounds on $\mathcal{P}^{(e)}_{\lambda}$ depending on the adopted coding scheme.

III. Physical Layer Description

The performance of the RLC protocol modeled in last Section is assessed with reference to the *forward* link of a third generation cellular mobile radio system. The physical layer under investigation adopts an MC-CDMA (MultiCarrier Code Division Multiple Access) solution, analogous the one standardized for cdma2000. A single cell scenario is examined, with M band-disjoint sub-channels affected by frequency selective Rayleigh fading and M RAKE correlation receivers, one on each subcarrier. In order to increase system capacity, in accordance with [9] and [10], quasi-orthogonal sequences are adopted as channelization codes, in addition to Walsh code sequences. Let $\mathcal{W}_n = \{w_i | i = 1, 2, \ldots, N = 2^n\}$, n *even*, be the family of Walsh codes of length N and $\mathcal{Q}_n = \{q_i | i = 1, 2, \ldots, N = 2^n\}$ be *one* family of QO sequences, with N elements too. Order the whole set of sequences $\mathcal{W}_n \cup \mathcal{Q}_n = \{f_i | i = 1, 2, \ldots, 2N\}$ so that $f_i = w_i$, when $1 \leq i \leq N$, and $f_i = q_{i-N}$ when $N + 1 \leq i \leq 2N$, and introduce the corresponding cross-correlation matrix, $\mathfrak{C}_{2N} = \left[\mathcal{C}_{f_i f_j}\right]$ [13].

The RF signal carrying the PDU bits from the base to the reference user is

$$s(t) = \Re\left\{\sum_{m=1}^{M} S_m(t)\sqrt{2}\, e^{j(\omega_m t+\theta_m)}\right\}, \qquad (23)$$

where $S_m(t)$ is the baseband signal, having denoted by ω_m and θ_m the angular frequency and the phase of the m-th subcarrier. $S_m(t)$ is

$$S_m(t) = \\ = \sqrt{E_c}\sum_{k=1}^{K}\sum_{v=-\infty}^{+\infty} b_k(\lfloor \frac{v}{N}\rfloor)c_k(v)e^{j\psi_m^{(k)}}p(t-vT_c) \qquad (24)$$

where E_c is the common chip energy, K the number of active users within the cell, $N = 2^n$ the processing gain and $b_k(\lfloor v/N\rfloor)$ is the PDU data transmitted to k-th user, $b_k(v) \in \{\pm 1\}$; $c_k(v) = (-1)^{f_k(v)}$ represents the channelization code of the k-th user, $f_k \in \mathcal{W}_n \cup \mathcal{Q}_n$, and $c_k(v) \in \{\pm 1\}$. Finally, $\psi_m^{(k)}$ is the random phase assigned to the k-th user, uniformly distributed in $[0, 2\pi)$, and $p(t)$ is the chip pulse of duration T_c. The energy per data bit is $E_b = NME_c$.

The time invariant complex low-pass equivalent response of the m-th forward link transmission channel is $h_m(t) = \sum_{i=0}^{L-1}\alpha_{m,i}e^{j\beta_{m,i}}\delta(t-iT_c)$, where $\alpha_{m,i}$ are independent, Rayleigh distributed r.v.'s, and $\beta_{m,i}$ are independent, identically distributed, uniform r.v.'s over $[0, 2\pi)$. The received signal at the desired mobile unit is therefore

$$r(t) = \Re\left\{\sum_{m=1}^{M} S_m(t) * h_m(t)\sqrt{2}\, e^{j(\omega_m t+\theta_m)}\right\} + n(t) \qquad (25)$$

where $n(t)$ is additive white Gaussian noise (AWGN) with a two-sided power spectral density of $\eta_0/2$.

Indicate by $\gamma^{(\mathcal{U})}$ the signal-to-noise ratio (SNR) of the reference user $\mathcal{U}$, conditioned on the fading $\boldsymbol{\alpha} \doteq [\alpha_{m,l}]$: for short, $\mathcal{U} = \mathcal{W}$ denotes the first active Walsh user, $\mathcal{U} = \mathcal{Q}$ the QO one. Note that the way Walsh and QO code sequences are allocated within the cell might cause system subscribers to experience different values of $\gamma^{(\mathcal{U})}$, so that ultimately the PDU error probability they suffer is different.

Assuming that the phase of each carrier is perfectly recovered from the pilot signal detector, that there is perfect code and bit synchronization and that a maximal-ratio combiner is employed, it has been shown in [13] that $\gamma^{(\mathcal{U})}$ is

$$\gamma^{(\mathcal{U})} = \frac{|\mathbb{E}[Z^{(\mathcal{U})}|\boldsymbol{\alpha}]|^2}{Var\{Z^{(\mathcal{U})}|\boldsymbol{\alpha}\}} = \frac{|\sum_{m=1}^{M}\boldsymbol{\mu}_m^{(\mathcal{U})T}\boldsymbol{g}_m^{(\mathcal{U})}|^2}{\sum_{m=1}^{M}\boldsymbol{g}_m^{(\mathcal{U})T}\boldsymbol{B}_m^{(\mathcal{U})}\boldsymbol{g}_m^{(\mathcal{U})}} \qquad (26)$$

the matrices $\boldsymbol{\mu}_m^{(\mathcal{U})}$ and $\boldsymbol{B}_m^{(\mathcal{U})}$ being [13]

$$\mu_m^{(\mathcal{U})} = \alpha_{m,l}N\sqrt{E_c}b_{(\mathcal{U})}(0), \qquad (27)$$

and

$$B_{m,l,l'}^{(\mathcal{U})} = \\ = \frac{N}{2}\delta_{l,l'}\left(\eta_0 + E_c K\sum_{\substack{i=0\\ i\neq l}}^{L-1}\alpha_{m,i}^2\right) + \frac{E_c\alpha_{m,l}\alpha_{m,l'}}{2}\Omega_{K,N}^{(\mathcal{U})}, \qquad (28)$$

with

$$\Omega_{K,N}^{(\mathcal{U})} = \sum_{\substack{k=1\\ k\neq\mathcal{U}}}^{K}\left(\mathcal{C}_{f_{\mathcal{U}}f_k}\right)^2, \qquad (29)$$

and $\boldsymbol{g}_m^{(\mathcal{U})}$ the vector of the RAKE receiver tap gains in the m-th branch.

In order to numerically evaluate (29), the following code allocation policies are considered: **Policy 1** imposes that a Walsh code followed by a QO code is assigned within the reference cell, and this pattern is repeated until all $2N$ channelization codes are allocated. Hence, the law ruling the $\Omega_{K,N}^{(\mathcal{U})}$ growth as a function of K is

$$\Omega_{K,N}^{(\mathcal{Q})} \approx \Omega_{K,N}^{(\mathcal{W})} = N\left(K - \left\lfloor\frac{K}{2}\right\rfloor\right). \qquad (30)$$

Alternatively, **Policy 2** assigns all Walsh codes and only when their set is depleted, QO sequences are introduced in the system. The corresponding law is different for Walsh and QO users,

$$\Omega_{K,N}^{(\mathcal{W})} = \begin{cases} 0, & 1 \le K \le N, \\ N(K-N), & N < K \le 2N. \end{cases} \qquad (31)$$

$$\Omega_{K,N}^{(\mathcal{Q})} = \begin{cases} \nexists, & 1 \le K \le N, \\ N^2, & N+1 \le K \le 2N. \end{cases} \qquad (32)$$

Finally, we define the frame error probability $\mathcal{P}_\lambda^{(e)}\big|_{\boldsymbol{\alpha}}$ as the PDU error probability, *conditioned on the fading conditions* $\boldsymbol{\alpha}$, when a convolutional code with memory M_c is employed. Under the hypothesis of independent errors, $\mathcal{P}_\lambda^{(e)}\big|_{\boldsymbol{\alpha}}$ is upper bounded by [14],[16],[17]

$$\mathcal{P}_\lambda^{(e)}\big|_{\boldsymbol{\alpha}} \le 1 - \left(1 - \sum_{d=d_f^{(\lambda)}}^{\infty} a_d^{(\lambda)}P_d^{(\lambda)}\right)^{\mathcal{N}_b+M_c+n_c}, \qquad (33)$$

where $d_f^{(\lambda)}$ is the free distance of the selected RCPC code, $a_d^{(\lambda)}$ is its distance spectrum, $P_d^{(\lambda)}$ is the probability that a wrong path at distance d is selected,

d	λ even Rate $\frac{1}{2}$	λ odd Rate $\frac{1}{3}$
7	16	
8	24	
9	32	
10	80	
11	296	8
12	544	16
13	...	24
14		16
15		24
16		64
...		...

TABLE I
$a_d^{(\lambda)}$ AND $d_f^{(\lambda)}$ OF THE EMPLOYED RCPC CODES.

$\mathcal{N}_b$ is the number of PDU bits (header and data) and n_c the number of CRC bits.

We adopted two coding and retransmission schemes:

- the first uses the RCPC codes presented in [14] and executes puncturing with a period $P_c = 8$. It employs 2 puncturing matrices to obtain 2 codes, with rates $1/2$ and $1/3$. During the λ-th transmission round, if λ is even, we choose to transmit the bits of the uncoded PDU along with the parity bits of the rate $1/2$ code; if λ is odd, the uncoded bits are followed by the parity bits of the more powerful rate $1/3$ code.
  In this case, $P_d^{(\lambda)}$ is given by
  $$P_d^{(\lambda)} = \begin{cases} \dfrac{1}{P_c} Q\left(\dfrac{1}{2} d\, \gamma^{(u)}\right) & \lambda \text{ even}, \\ \dfrac{1}{P_c} Q\left(\dfrac{1}{3} d\, \gamma^{(u)}\right) & \lambda \text{ odd}, \end{cases} \tag{34}$$
  where P_c is the puncturing rate and $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-\frac{t^2}{2}} dt$. The free distances and distance spectra of the two RCPC codes are specified in Table I.
- The second scheme exploits the code combining technique, as proposed in [15]. The above mentioned rate $1/2$ RCPC code is employed as the base code. Each time a retransmitted PDU has been received, it is combined with the previously received copies, in order to obtain a more powerful code. Following [16], the probability of choosing a wrong path at distance d, in the λ-th round is
  $$P_d^{(\lambda)} = \frac{1}{P_c} Q\left(\frac{1}{2} d\, \lambda\, \gamma^{(u)}\right). \tag{35}$$

In our numerical evaluations we employ (33) to bound the PDU error probabilities and successively replace it in (11) and (22), pointing out an upper bound on $\mathbb{E}[\mathcal{T}]$ and a lower bound on the RLC protocol goodput conditioned to a specific fading condition. The averaging with respect to different propagation conditions is then numerically performed, by Monte-Carlo simulation, in order to derive both the mean delivery time and the goodput values presented in next section.

IV. Numerical Results

The results obtained for the RLC data link layer protocol modeled in Section II are reported next.

As described in Fig. 2, we first assume that one packet from the network layer is mapped into a set of N_0 RLC payload units (RLC-PU). An RLC-PU and its header form an RLC-PDU that is then passed to the MAC layer below, which concatenates the PDU, also known as MAC SDU, with the proper MAC header to create a MAC PDU. Each MAC PDU is then passed to the correct physical channel. Hereafter, we adopt an RLC header of $\mathcal{N}_{h-RLC} = 20$ bits, a MAC header size of $\mathcal{N}_{h-MAC} = 22$ bits, a CRC field of $n_c = 12$ bits, a round-trip delay $t_{phy} = 100$ ms [3]; the maximum number of allowed retransmission is fixed to $\Lambda_M = 3$. Unless otherwise stated, the MAC-PDU transmission time is $t_{pdu} = 80$ ms, corresponding to $\mathcal{N}_b = 3200$ bits, and each packet is fragmented into $N_0 = 12$ PDUs.

Regarding the physical layer architecture, the MC-DS-CDMA system under examination features $M = 3$ distinct subcarriers and a processing gain $N = 2^4 = 16$. An exponential PDP has been considered, assuming that on each subcarrier $L = 4$ paths are resolved by the RAKE receiver. We take $\mathbb{E}\left[\alpha_{m,i}^2\right] = \mathbb{E}\left[\alpha_{m,0}^2\right] e^{-ri}$, $r = 1$, and assume a unit energy constraint, i.e., $\sum_{i=0}^{L-1} \mathbb{E}\left[\alpha_{m,i}^2\right] = 1$. Throughout this section, whenever not explicitly remarked, we assume a signal-to-noise ratio $E_b/\eta_0 = 12$ dB and we employ **Policy 1** with one masking function when assigning the channelization codes.

In Fig. 3 the average delivery time $\mathbb{E}[\mathcal{T}]$ is shown for $K = 20$ active users, when the RLC-PDU size ranges from 7 to 397 bytes; equivalently, the PDU transmission time t_{pdu} ranges from about 2 ms to 80 ms. The solid line shows $\mathbb{E}[\mathcal{T}]$ when code combining is employed, whereas the dashed line refers to the RCPC code case. The code combining technique outperforms the RCPC codes in terms of mean delivery time of the original N_0 PDUs; its most significant drawback is however a greater request in storage capacity and the need of the more complex structure Viterbi decoder. It is worth noting that the mean delivery time $\mathbb{E}[\mathcal{T}]$ is almost linear in the RLC-PDU size, even if the proportionality coefficient does vary depending on the employed coding scheme.

Considering the RLC goodput $\mathcal{S}_{\mathcal{G}}$, Fig. 4 reports its behavior when the number of active users within the cell varies from $K = 2$ to $K = 32$, that is the maximum capacity of the cell if one masking function is employed. Observe that we can allow up to 20 subscribers within the cell and still obtain a value of 0.32 for the goodput of the RCPC code case. Once again, if the code combining technique is employed, it is possible to substantially increase the goodput, raising its value to $\mathcal{S}_{\mathcal{G}} = 0.57$ for $K = 20$. Note that in this circumstance, the adoption of **Policy 1** cannot duplicate cell capacity, but allows to introduce 4 more users, i.e., a 25% increase with respect to the case of Walsh subscribers only, without noticeably worsening the RLC protocol performance. We would like to point out that the goodput has been also evaluated numerically, exactly leading to the same results analytically obtained: as an example the lines with markers of Fig. 4 are the ones derived through the numerical approach

If we now fix the number of active subscribers to $K = 20$ and let the signal-to-noise ratio E_b/η_0 vary in the $[2, 20]$ dB range, Fig. 5 shows how the goodput benefits from a greater signal-to-noise ratio. From this figure it is possible to infer that for $E_b/\eta_0 \geq 20$ dB, the two coding schemes exhibit quite close a performance, as the two curves asymptotically converge. On the other hand, for values of $E_b/\eta_0 \leq 6$ dB, the code combining scheme outperforms the alternative strategy: as shown in eq. (35), this is justified by the linear dependence of its free distance from the index λ of the retransmission cycle.

The higher bit and PDU error probability of the RCPC scheme is evident in Fig. 6, that reports how the goodput reacts when the RLC-PDU size is varied from 7 bytes to 397; in this case again the number of active users is $K = 20$ and the signal-to-noise ratio $E_b/\eta_0 = 12$ dB. Also observe that the RLC-PDU size is lower than 100 bytes, its transmission time becomes much lower than the round trip time $t_{phy} = 100$ ms and this turns the protocol behavior into a *pure* stop-and-wait: indeed the time spent for the transmission of the original N_0 fragments and the following – if any – retransmissions is always much less than the round trip time, thus obtaining poor goodput values. Since code combining is more robust than the examined RCPC coding scheme, we also observe that the latter method cannot allow too long PDUs, as it does not guarantee the same performance of the code combining scheme. From Fig. 6 we infer that, for 20 active users, $E_b/\eta_0 = 12$ dB and $N_0 = 12$, the RLC-PDU size should be chosen in the $[100, 150]$ bytes range in order to maximize the RCPC scheme performance.

Fig. 7 depicts the flat behavior of the goodput as a function of N_0, the number of PDUs for each packet, when N_0 ranges from 2 to 30 and the RLC-PDU transmission time is fixed to $t_{pdu} = 80$ ms, i.e., its size is 397 bytes; once again, the number of active users is set to 20 and $E_b/\eta_0 = 12$ dB. The greater N_0, the higher the probability of one or more wrong PDUs within the original N_0 set, whereas the $\frac{t_{phy}}{N_0 t_{pdu}}$ ratio appearing in (11) (and (22)) diminishes with N_0: the compensation of these opposite trends leads to a moderate dependence of the goodput $\mathcal{S}_{\mathcal{G}}$ from N_0.

Finally, let us shift the attention towards the network protocol above RLC: with reference to the Internet Protocol, we now reasonably assume that a set of N_0 RLC-PDUs holds several IP datagram, namely, N_{IP}. Let $\mathcal{PU} = \mathcal{N}_b - \mathcal{N}_{h-MAC} - \mathcal{N}_{h-RLC}$ be the payload of an RLC-PDU and $\mathcal{DG}$ the mean IP datagram size, so that $N_{IP} = \left\lfloor \frac{N_0 \mathcal{PU}}{\mathcal{DG}} \right\rfloor$ and $\mathbb{E}[\mathcal{T}_{IP}] = \frac{\mathbb{E}[\mathcal{T}]}{N_{IP}}$. As [19] suggests the maximum transfer unit of the IP protocol over 2.5G/3G systems to be in the $[576, 1500]$ bytes range, we correspondingly obtain $N_{IP} = 8$ and $N_{IP} = 3$. These two values have been employed to obtain Figs. 8 and 9, that show the mean delivery time of an IP datagram varying the number of active users K and the signal-to-noise ratio E_b/η_0, respectively. In each figure, two distinct sets of curves are presented: the upper ones refer to a datagram size of 1500 bytes, whereas the lower ones to 576 bytes. When $\mathcal{DG} = 576$ bytes, $\mathbb{E}[\mathcal{T}_{IP}]$ exhibits a moderate dependence of K and E_b/η_0, with a reference value of a few hundreds of milliseconds; on the contrary, when $\mathcal{DG} = 1500$ bytes, $\mathbb{E}[\mathcal{T}_{IP}]$ shows an unbearable growth, especially for the RCPC coding scheme.

V. CONCLUSIONS

This study has proposed a novel approach to assess the performance of a 3^{rd} Generations Radio Link Control protocol on the synchronous downlink of a multicarrier DS-CDMA system, when Walsh and Quasi-Orthogonal channelization codes are employed in a frequency selective fading environment. An analytical evaluation of the protocol goodput and of the average delay suffered by data units transferred over the radio channel has been carried out. The influence on goodput and delay of different code allocation schemes and transmission qualities, as well as of several data-link layer parameters has been clearly highlighted.

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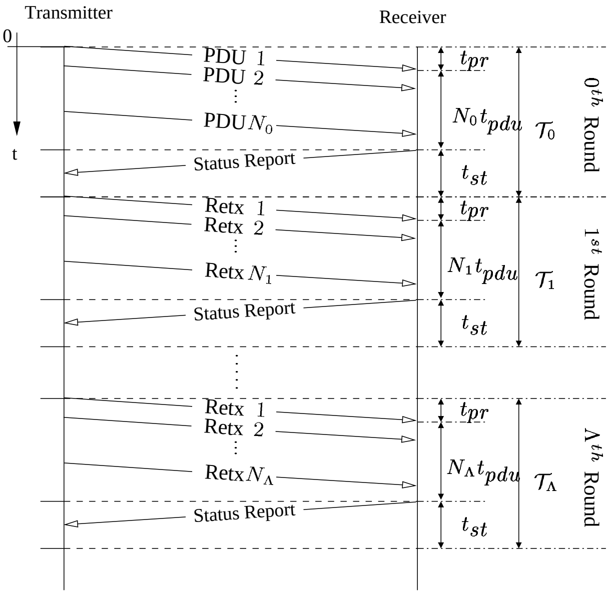

Fig. 1. Typical transmitting sequence of the ARQ protocol under investigation.

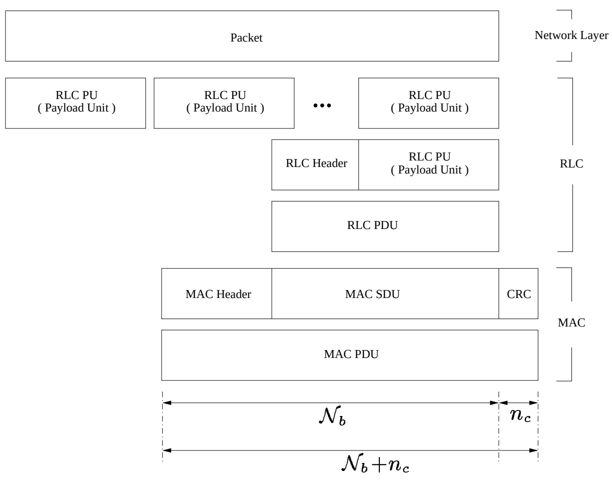

Fig. 2. Reference protocol stack model.

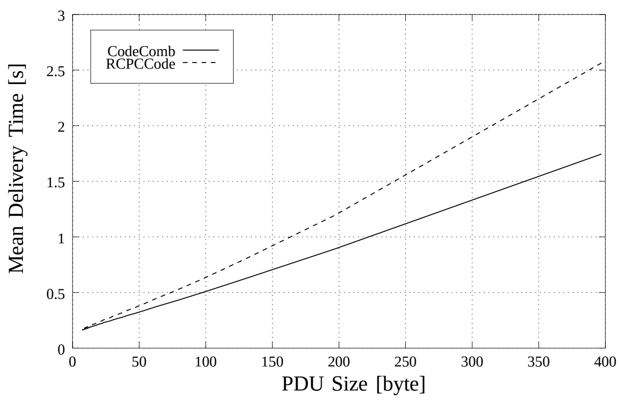

Fig. 3. Mean delivery time – Varying RLC-PDU size. Users=20, $E_b/\eta_0 = 12\,\text{dB}$, $N_0 = 12$.

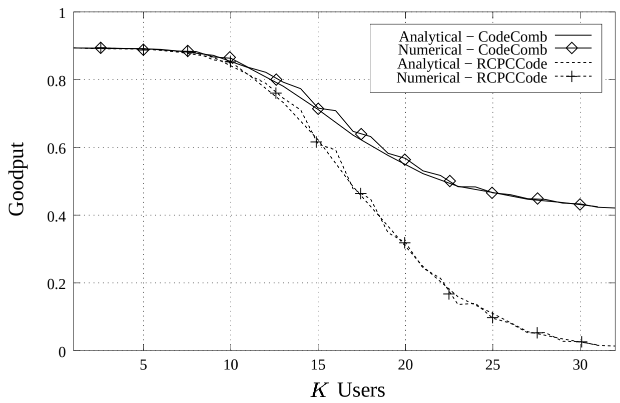

Fig. 4. Goodput – Varying No. of Users. $E_b/\eta_0 = 12\,\text{dB}$, $N_0 = 12$.

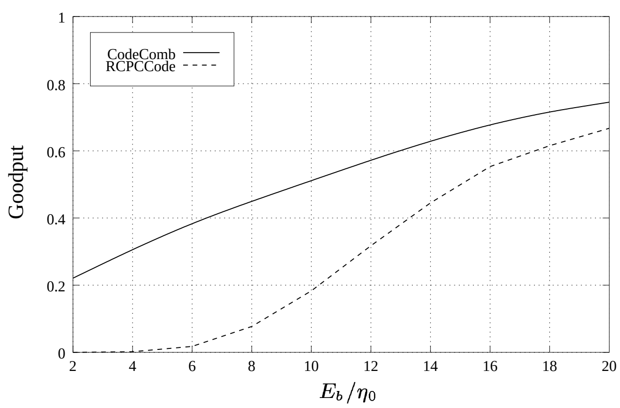

Fig. 5. Goodput – Varying $\frac{E_b}{\eta_0}$. $K = 20$ active users, $N_0 = 12$.

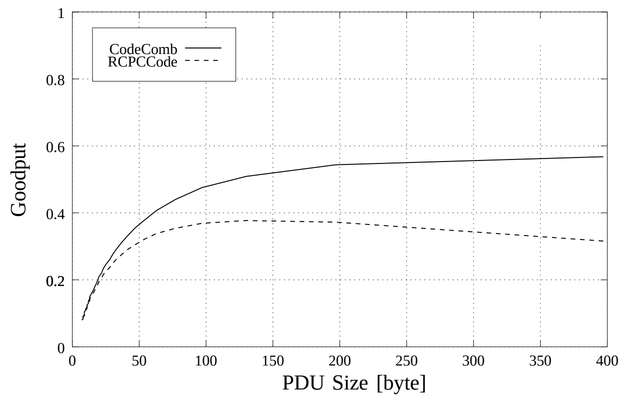

Fig. 6. Goodput – Varying PDU size. $K = 20$ active users, $E_b/\eta_0 = 12\,\text{dB}$, $N_0 = 12$.

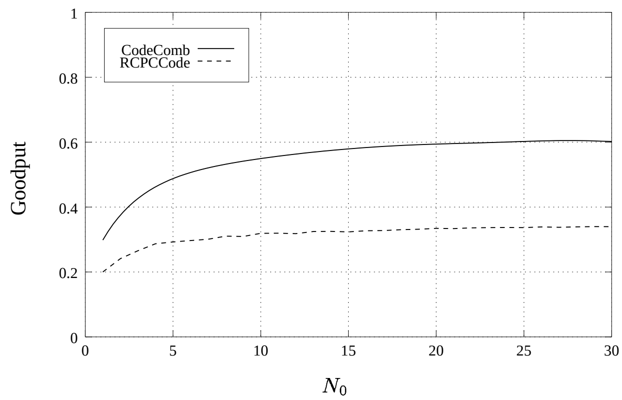

Fig. 7. Goodput – Varying N_0. $K = 20$ active users, $E_b/\eta_0 = 12\,\text{dB}$.

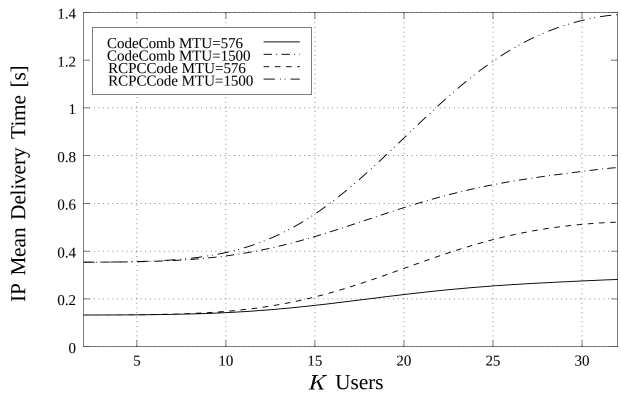

Fig. 8. Mean delivery time of an IP datagram – Varying No. of Users. $E_b/\eta_0 = 12\,\text{dB}$, $N_0 = 12$.

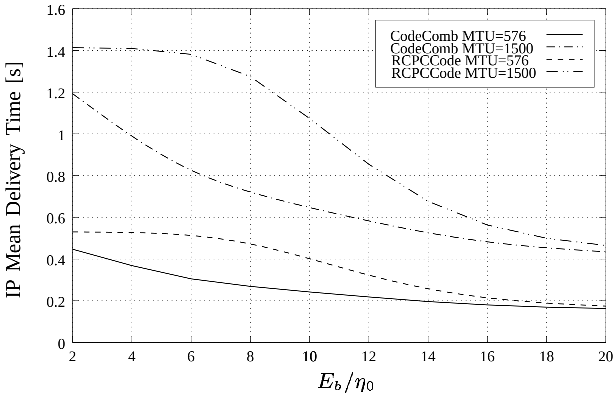

Fig. 9. Mean delivery time of an IP datagram – Varying $\frac{E_b}{\eta_0}$. $K = 20$ active users, $N_0 = 12$.