$[\mathbf{b}(n)]_{i+1} = b_n(\lceil i/P \rceil, i \wr P)$. Notation $\lceil \cdot \rceil$ denotes upper integer part and $i \wr j$ is the remainder of dividing i into j. The above quantities can be decomposed as

$$a(i, p, j, q) = \sum_{l=0}^{L-1} \sum_{r=0}^{m-1} c_j(rL + l - q) s_j(n - r) w_n^*(i, l, p)$$

$$b_n(i, p) = \sum_{l=0}^{L-1} x(n, l) w_n^*(i, l, p) i,$$

$$j = 1, \ldots, N, \qquad p, q = 0, \ldots, P - 1.$$

Finally, the solution to (18) is

$$\mathrm{vec}(\mathbf{H}_o) = \left(\sum_{n=0}^{K-1} E_{\mathbf{s}(n)|\mathbf{x}(n); \mathbf{H}_i} \mathbf{A}(n) \right)^{-1} \cdot \left(\sum_{n=0}^{K-1} E_{\mathbf{s}(n)|\mathbf{x}(n); \mathbf{H}_i} \mathbf{b}(n) \right). \quad (19)$$

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Contention-TDMA Protocol: Performance Evaluation

Gianfranco Pierobon, A. Zanella, and A. Salloum

***Abstract*—In this correspondence, a hybrid access protocol known as contention time-division multiple access (C-TDMA) is presented and analyzed in a radio cellular multiuser system scenario. C-TDMA shows some features of contention-based (slotted-Aloha) and reservation-based [packet reservation multiple access (PRMA)] protocols. It has been recommended to be used in the uplink of future European multimedia distribution systems. A simple Markov model is proposed to describe the C-TDMA behavior. A complete statistical analysis of the model has been made in order to evaluate the performance of the protocol. However, due to the long computation time required by this method in the presence of a large number of users, a simpler approach known as equilibrium point analysis (EPA) is used. Moreover, on the basis of the EPA analysis and the C-TDMA design parameters, a fast algorithm has been developed to improve the achievable throughput of C-TDMA. Results in terms of throughput and delay under variable traffic conditions indicate that C-TDMA is able to grant optimum throughput/delay figures for typical multiuser systems. Moreover, for a digital speech scenario, a performance comparison with PRMA demonstrates that C-TDMA yields equivalent performance of PRMA in terms of number of users supported by the system with a limited packet dropping rate.**

***Index Terms*—Communication systems performance, equilibrium point analysis (EPA), protocols.**

I. INTRODUCTION

Currently, a great number of telecommunications actors are testing and evaluating the real market demand of interactive multimedia services for residential and business customers. Even if cable (coaxial and optical fiber) has demonstrated that it is able to satisfy the appetite for such services in most scenarios, there are particular areas where cellular radio systems offer a viable complementary solution by virtue of fast deployment, minimum infrastructure impact within cities, and cost effectiveness in rural or sparse populated areas. For these reasons, an European consortium called Cellular Radio Access Broadband Services (CRABS) has developed an ambitious project to provide digital interactive services via microwave cellular radio. As regards the access protocol for CRABS, the authors have proposed an efficient random-access and packet-switching technique [1]–[3], easily implementable with current cellular radio technologies, to handle the uplink of the multimedia distribution systems. It has been called contention time-division multiple access (C-TDMA).

In this correspondence, a complete statistical analysis is presented for the C-TDMA in a single-medium environment. The analysis is performed under the assumption of a Markovian model of the traffic offered to the system. However, typical values of the system parameters (number of users, number of channels, etc.), leading to a very large number of system states, cause serious difficulties for the performance evaluation by a detailed analysis. To overcome this drawback, an effective and simple mathematical method called equilibrium point analysis (EPA) [5], [6] is used to obtain very significant estimates of the C-TDMA performance.

This correspondence is organized as follows. In Section II, a general description of the C-TDMA protocol is given. Section III presents the proposed statistical Markov model of the C-TDMA traffic and develops the complete statistical analysis of the system. The EPA method

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is applied and discussed in Section IV, where particular attention is given to stability issues. Performance evaluation of C-TDMA in terms of throughput and delay is presented in Section V. Section VI introduces additional improvements of the C-TDMA in order to maximize its throughput. A performance comparison with the PRMA protocol [6] is made in Section VII. Section VIII outlines the conclusions.

II. The C-TDMA Protocol

A. System Structure

The environment for which the C-TDMA protocol has been developed is a cell in which a finite number, say, M, of fixed or slowly moving users try to access some services by sharing a common radio basestation. The uplink traffic generated by each user is supported by directional radio channels. The time is supposed to be divided into slots of duration T organized in consecutive frames with N slots per frame. Messages generated by the users are fragmented into packets. Each user is synchronized with the basestation in order to transmit its packets in such a way that they occupy exactly a time slot every frame.

During each frame, the basestation observes the incoming traffic in order to distinguish free and reserved slots. A slot is declared to be *free* by the basestation when either it is empty or a collision among packets occurred therein. On the contrary, if a successful transmission of a single packet occurred, the slot is declared *reserved*. At the end of the frame, the basestation broadcasts the list of the free slots to the users.

On the basis of the free slot list, the users that at the beginning of a frame have a new message to be transmitted try to occupy a free slot according to a contention policy; that will be discussed in the following. If the attempt is successful, say, at slot k of the frame, this is noted to the node by the absence of slot k in the free slot list at the beginning of the next frame. Then, the node may continue to transmit the packets of its message in slot k of the following frames. On the contrary, if the attempt fails for a collision, slot k appears to be free in the next list, so that the node becomes aware of the failure and tries again (possibly in a different slot) in the next frame.

The C-TDMA protocol differs from R-ALOHA [5] in that it does not use a broadcast uplink, so that informations about the state of the slots must be furnished by the basestation. Moreover, it differs from the PRMA protocol [6] in that the slot state is notified by the basestation only once per frame, with very little overhead.

B. Contention Policy

We assume as a very natural policy that the nodes apply a *permission of transmission and random choice* policy. Namely, the first packet of a message is allowed to be transmitted in the next frame with probability p and, only if permission is obtained, the node chooses at random the transmission slot. The *permission probability* p is a design parameter that should be optimized for best throughput and transmission delay.

III. The Mathematical Model

A. The Offered Traffic

We assume that each node alternates intervals in which it is transmitting a message and intervals in which it does not transmit and waits for a new message or contends for beginning a new transmission. The transmission intervals expressed in frames and, consequently, the message lengths expressed in packets, are assumed to be independent geometrical random variables with mean $1/\rho$. Similarly, the waiting times for new messages (expressed in frames) are considered as independent geometrical random variables with mean $1/\sigma$.

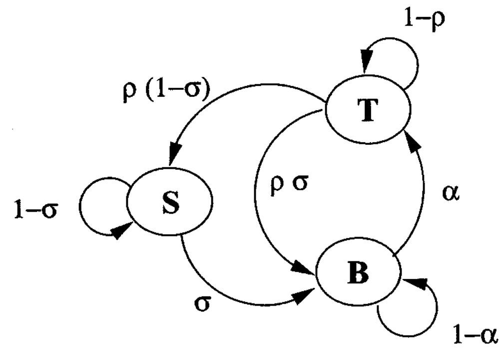

Fig. 1. State diagram of a single node.

This characterization of the traffic at a single node is assumed to be independent of both the past evolution of the network and the present situation of the other nodes.

We define the traffic offered by a node as the traffic that the node would transmit on a channel of its own, i.e.,

$$g = \frac{\frac{1}{\rho}}{\frac{1}{\rho} + \frac{1}{\sigma}} = \frac{\sigma}{\rho + \sigma} \quad \text{packets/frame.} \tag{1}$$

By assuming that the nodes are uniformly loaded, the global offered traffic is

$$G = \frac{M\sigma}{\rho + \sigma}. \tag{2}$$

B. Node States

The system behavior may be modeled in the following way. Each node can be represented as a three-state machine (Fig. 1) with a *silent* state (S), in which the node has no messages to be transmitted; a *talking* state (T), in which the node is transmitting its message; a *backlog* state (B), in which the node has a new message and tries to begin its transmission according to the policy described above. To simplify the analysis, we found it convenient to consider the frame in which the node generates a new message as belonging to the backlog phase. The state transitions are supposed to occur at the beginning of every frame, with the probabilities shown in Fig. 1. Note that as a consequence of the assumption about the backlog state, with σ the probability that a new message is immediately generated, the transition occurs directly to state B with probability $\rho\,\sigma$, while with probability $\rho(1-\sigma)$ the new state is S.

Two facts deserve to be noted. First, while the transitions from both T and S depend on the single node behavior, the contention phase is intimately related to the global behavior of the system and the probability α depends on the present state of all the nodes of the network. Second, it is assumed that a node cannot generate new messages until the transmission of the previous message is completed. Then, the amount of data generated is dependent on the channel condition. This traffic model is suitable to describe applications that are generally not too sensitive to delay or to variations in delay. In the following, we consider only this kind of applications, deferring to Section VII the analysis of some computer simulations results obtained in a digital speech scenario.

C. System Variables

We assume as state variables of the system b_n, t_n, and s_n, namely, the number of nodes in states B, T, and S, respectively, at the end of the nth frame. Of course, one of the three variables depends on the other two, because their sum must equate to the total number of nodes:

$b_n + t_n + s_n = M$. Note that the state variables t_n and b_n may assume the values $0, \ldots, N$ and $0, \ldots, M$, respectively, with the further constraint $t_n + b_n \leq M$. The time evolution of the state variables is governed by the following equations:

$$\begin{aligned} s_{n+1} &= s_n + x_n - w_n \\ b_{n+1} &= b_n + y_n + w_n - z_n \\ t_{n+1} &= t_n + z_n - x_n - y_n \end{aligned} \tag{3}$$

where

- x_n number of nodes passing from state T to state S in the nth frame;
- y_n number of nodes passing from state T to state B in the nth frame;
- w_n number of nodes passing from state S to state B in the nth frame;
- z_n number of nodes passing from state B to state T in the nth frame.

In the following, we show that, under the assumptions made, the vector process $\omega_n = (b_n, t_n)$ is a Markov chain. For this purpose, we study the statistics of the random variables x_n, y_n, w_n, z_n and prove that they depend only on the present values of b_n and t_n and are independent of their past evolution.

1) Statistics of x_n and y_n: The variables x_n and y_n statistically depend only on the number of the transmitting nodes t_n, through the memoryless mechanism of both transmission and silence duration. In particular, under the condition that $t_n = t$, y_n is a binomial random variable of index t and parameter $\rho\sigma$. Analogously, x_n is a binomial random variable of index t and parameter $\rho(1-\sigma)$. In particular, we get

$$\begin{aligned} &P[x_n = x, \, y_n = y | b_n = b, \, t_n = t] \\ &\quad = \binom{t}{x+y}\binom{x+y}{x}\rho^{x+y}(1-\rho)^{t-x-y}\sigma^y(1-\sigma)^x. \end{aligned} \tag{4}$$

The conditional average values of x_n and y_n are given by

$$E[y_n | b_n = b, \, t_n = t] = \rho\sigma t \tag{5}$$

$$E[x_n | b_n = b, \, t_n = t] = \rho(1-\sigma)t. \tag{6}$$

2) Statistics of w_n: The statistics of w_n depend only on the number of silent nodes $s_n = M - b_n - t_n$ and is independent of the past evolution of the network. Namely, provided that $b_n = b$ and $t_n = t$, w_n is a binomial variable with index $M - b - t$ and parameter σ so that

$$P[w_n = w | b_n = b, t_n = t] = \binom{M-b-t}{w}\sigma^w(1-\sigma)^{M-b-t-w}. \tag{7}$$

Moreover

$$E[w_n | b_n = b, \, t_n = t] = \sigma(M - b - t). \tag{8}$$

3) Statistics of z_n: The variable z_n depends on the number of backlogged nodes b_n, on the number of free slots in the list $N - t_n$, and on the contention policy. Preliminarily, we note that, provided that $b_n = b$, on the basis of the permission rule, the number of really contending nodes reduces to c_n, a binomial variable with index b, and parameter p, namely

$$P[c_n = c | b_n = b, \, t_n = t] = \binom{b}{c}p^c(1-p)^{b-c}. \tag{9}$$

The somewhat cumbersome computation of $P[z_n = z | b_n = b, \, t_n = t]$, based on combinatorial analysis [10], is here omitted for space limitation. We give the final expression only, remanding to [11] for the derivation details

$$\begin{aligned} &P[z_n = z | t_n = t, \, b_n = b] \\ &= \sum_{i=z}^{\min\{N-t,b\}} \binom{N-t}{i}\binom{i}{z}\binom{b}{i} i!(-1)^{i-z}\frac{(N-t-pi)^{b-i}}{(N-t)^b}p^i. \end{aligned} \tag{10}$$

As regards the conditional expectation, the number of nodes gaining the slot reservation is given by

$$z_n = \sum_{i=1}^{c_n} \chi_i \tag{11}$$

where χ_i is a {0, 1}-variable assuming value 1 if the ith contending node succeeds, i.e., if no other contending node transmits in the slot chosen by the ith node among the $N - t_n$ available slots. Then the success probability is given by

$$P[\chi_i = 1 | c_n = c, \, t_n = t] = \left(1 - \frac{1}{N-t}\right)^{c-1}. \tag{12}$$

Of course, the above probability vanishes if $t = N$ (no free slots) or if $c = 0$ (no contending nodes). Then, for $t < N$, we get

$$\begin{aligned} &E[z_n | b_n = b, \, t_n = t] \\ &\quad = \sum_{c=1}^{b} E\left[\sum_{i=1}^{c_n} \chi_i | c_n = c, \, b_n = b, \, t_n = t\right] \\ &\qquad \cdot P[c_n = c | b_n = b, \, t_n = t] \\ &\quad = \sum_{c=1}^{b} c\left(1 - \frac{1}{N-t}\right)^{c-1}\binom{b}{c}p^c(1-p)^{b-c} \\ &\quad = bp\left(1 - \frac{p}{N-t}\right)^{b-1} \end{aligned} \tag{13}$$

while $E[z_n | b_n = b, \, t_n = N] = 0$.

As a conclusion, the vector process $\omega_n = (b_n, t_n)$ is a Markov chain, whose transition probabilities

$$\begin{aligned} &P[\omega_{n+1} = (b', \, t') | \omega_n = (b, t)] \\ &= P[y_n + w_n - z_n = b' - b, z_n - x_n - y_n = t' - t | b_n = b, t_n = t] \end{aligned} \tag{14}$$

can be trivially computed by (4), (7), and (10), taking into account that the bivariate $(x_n, \, y_n)$ and the variables w_n and z_n are statistically independent under the condition $b_n = b, \, t_n = t$. For reasonable values of M and N, the number of states of the Markov chain (approximately NM) is too large to allow standard applications of the Markov analysis. Consequently, the performance of the protocol has been derived with a different approach. However, we have computed and used the transition probabilities in order to validate the results discussed in the following for relatively little values of these quantities.

IV. Equilibrium Point Analysis

The analysis of the performance of the C-TDMA protocol will be developed by using the EPA, which was introduced by [5] for the R-ALOHA protocol and subsequently used by [6] and [7] for the PRMA protocol. The same approach had been previously applied by [8] and by [9] in their pioneering analysis of the bistability of the ALOHA protocols.

The approach, particularized to the present case, is based on the following considerations. If the present state assumes an assigned value

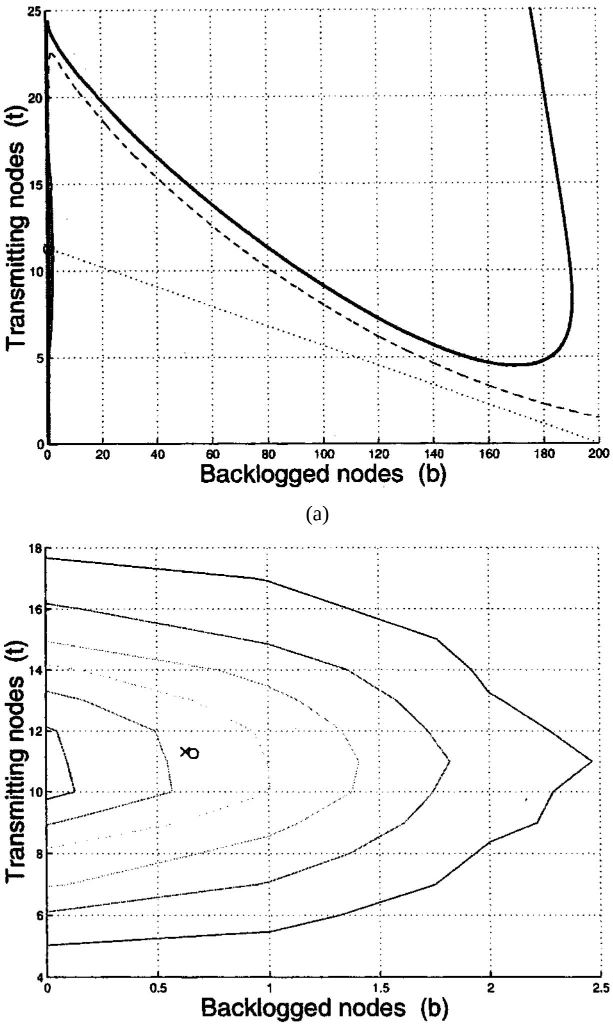

Fig. 2. (a) Equilibrium curves and (b) expansion of level curves of the stationary distribution ($\boldsymbol{M = 200, N = 25, \rho = 0.05, \sigma = 0.003,}$ and $\boldsymbol{p = 0.9}$).

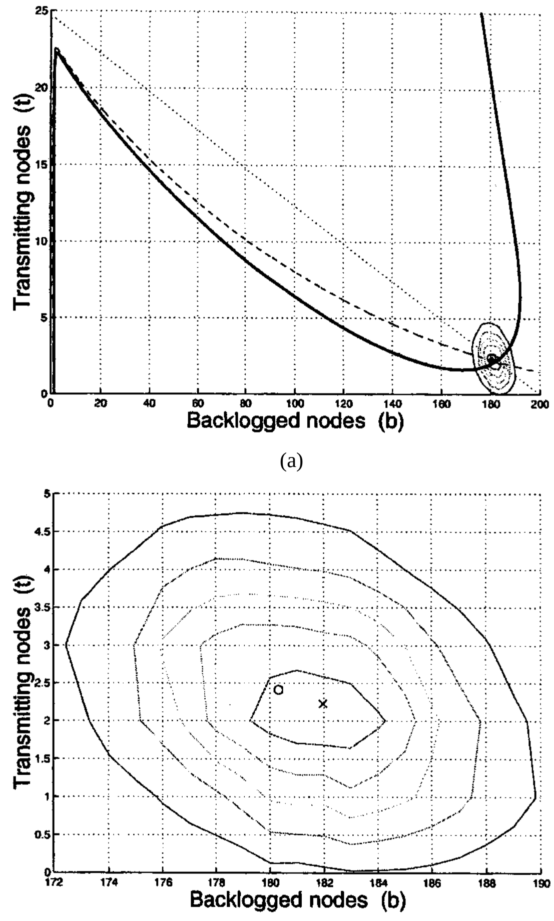

Fig. 3. (a) Equilibrium curves and (b) expansion of level curves of the stationary distribution ($\boldsymbol{M = 200, N = 25, \rho = 0.05, \sigma = 0.007,}$ and $\boldsymbol{p = 0.9}$).

$\omega_n = (b, t)$, the optimal mean square error estimation $\hat{\omega}_{n+1}$ of the next state is given by

$$\begin{aligned}\hat{b}_{n+1} &= E[b_{n+1}|b_n = b, t_n = t]\\ \hat{t}_{n+1} &= E[t_{n+1}|b_n = b, t_n = t].\end{aligned} \tag{15}$$

Now, we are induced to consider as *equilibrium points* of the system the states (b, t) such that $\hat{\omega}_{n+1} = \omega_n = (b, t)$, i.e., the solutions of

$$\begin{aligned}b &= E[b_{n+1}|b_n = b, t_n = t]\\ t &= E[t_{n+1}|b_n = b, t_n = t].\end{aligned} \tag{16}$$

Of course, such solutions are not integer, at least in general. However, (16) can be interpreted as *equilibrium curves* dividing the state space into regions where the differences $\hat{b}_{n+1} - b$, $\hat{t}_{n+1} - t$ have constant signs.

The derivation of (16) on the basis of the statistics of the previous section is straightforward. Indeed, by applying to (3) the conditioned averages found above, (16) becomes

$$bp\left(1 - \frac{p}{N-t}\right)^{b-1} = \sigma(M - b - t) + \rho\sigma t \tag{17}$$

$$bp\left(1 - \frac{p}{N-t}\right)^{b-1} = \rho t. \tag{18}$$

Analogously, the flow equilibrium equation of node S is

$$\rho(1-\sigma)t = \sigma(M - b - t) \tag{19}$$

linearly related to (17) and (18). Finally, because these equations are meaningless for $0 < b < 1$ and $N - p < t < N$, we have extended them to this region by linear interpolation.

Fig. 2(a) shows the three equilibrium curves for particular values of the system parameters. The dashed one is the flow equilibrium curve of node T [see (18)], while the solid curve is the equilibrium curve of node B [see (17)]. The dotted line is the equilibrium curve of node S. The curves exhibit a single common equilibrium point on the increasing side of the T equilibrium curve. Note that in this point, the number of transmitting nodes increases with the number of contending ones. The level curves around the equilibrium point, sketched with greater detail in Fig. 2(b), represent the stationary probability distribution of the state (b_n, t_n) computed by a simulation program. As the figure shows, the equilibrium point (denoted by the cross) is quite near to the probability distribution average of (b_n, t_n), denoted by the circle. The results show the substantial accuracy of the equilibrium point approach. Fig. 3 shows the equilibrium curves (with different values of the system parameters) with a single equilibrium point in the side of the T equilibrium curve where the transmitting nodes decrease when the contending nodes increase. Also in this case, the equilibrium point and the average state practically coincide.

Finally, we note that the solution of the equilibrium equations shows that the C-TDMA protocol is affected by the typical bistability phe-

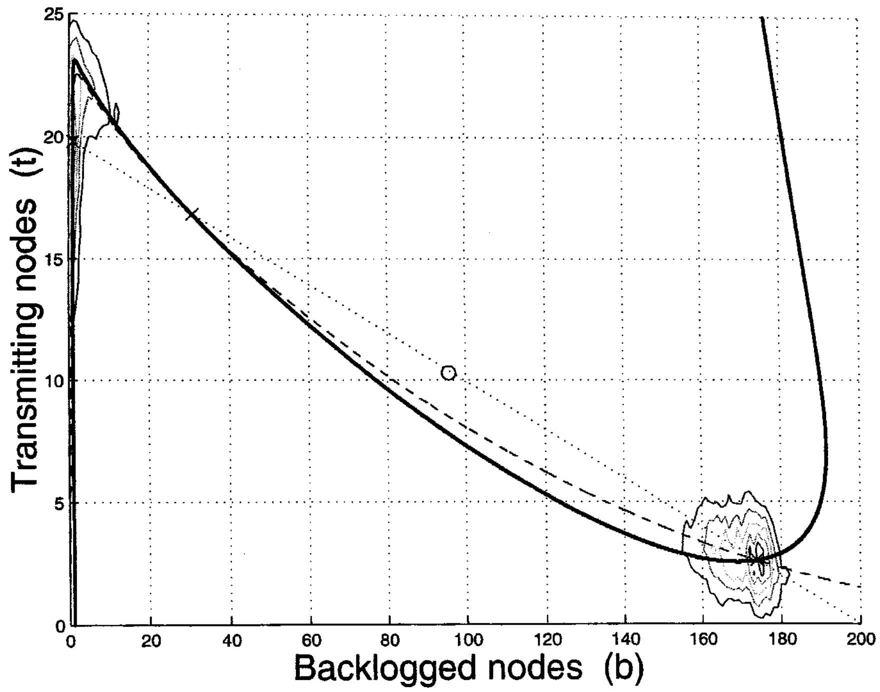

Fig. 4. Equilibrium curves and level curves of the stationary distribution in presence of bistability ($\boldsymbol{M = 200,\ N = 25,\ \rho = 0.05,\ \sigma = 0.0055,}$ and $\boldsymbol{p = 0.9}$).

nomena appearing in the ALOHA and ALOHA-derived protocols [5], [6], [8], [9]. Fig. 4 shows a case in which the equilibrium curves have three different common points. The simulated distribution probability is substantially bimodal, and two of the equilibrium points are centered into clusters of frequently visited states, whereas the intermediate equilibrium point belong to a rarely visited region. The simulation shows that the Markov chain tends to alternate periods of permanence in the two clusters and that the first exit time from one cluster is approximately proportional to the distance from the intermediate equilibrium point. Note that the average state is different from each of the equilibrium points, so that to consider the average state as a relevant index of the system behavior is completely misleading.

V. Throughput and Delay

The throughput and the delay can be obtained from the results of the EPA, provided that the computation approach gives a single equilibrium point. As regards the throughput, the number of packets transmitted during a frame coincides with the number of nodes in the transmission state T in the same frame. Then the equilibrium useful traffic expressed in packets per frame is given by

$$S = t. \tag{20}$$

Of course $S \le N$, and we can define the *channel utilization* as $\gamma = S/N = t/N$. Moreover, we define the *efficiency* of the protocol as

$$\eta = \frac{S}{G} = \frac{t(\rho + \sigma)}{M\sigma}. \tag{21}$$

As regards the *contention delay*, i.e., the number τ of frames that a node spends in waiting to reserve a slot, we make the following argumentation. For each node, the time can be subdivided into cycles formed by a silent period, with mean duration $1/\sigma$, followed by a (possibly missing) contention period with mean τ, followed in turn by a transmission period with mean $1/\rho$. Then the equilibrium traffic of the system is

$$S = M \frac{\frac{1}{\rho}}{\frac{1}{\sigma} + \tau + \frac{1}{\rho}}. \tag{22}$$

Equations (20) and (22) lead to the following expression of the contention delay (in frames):

$$\tau = \frac{\sigma M - (\rho + \sigma)t}{\sigma \rho t} = \frac{1}{\rho}\,\frac{G - S}{gS}. \tag{23}$$

Now, we discuss the results obtained in terms of different parameters as the single user offered traffic g, the number of users M, and the permission probability p. The number of slots in a frame is maintained at a fixed value $N = 25$. Fig. 5 shows the throughput and the delay as a function of the users number for $g = 0.4, p = 0.9$, and different values of the parameter ρ. For low values of ρ, i.e., for a high average length of the message, the throughput increases linearly with the number of users and reaches a maximum value quite near to the channel capacity, with approximately $M = N/g$. For a greater number of users, the throughput gradually decreases while the delay increases very rapidly. This can be explained by considering that in the saturated channel, a new message must wait for the end of a transmitted message: then, if the messages are long, also the waiting time is long. For high values of ρ, i.e., for short messages, the linear increase of the throughput is limited to a lower number of users, with reduced efficiency. This can be attributed to the fact that frequent attempts at transmission cause a growth of the collisions number. The above results have been confirmed by a large amount of computer simulations.

Similar results are obtained for different values of the single user offered traffic g. The above curves remain roughly equal: the main differences are given by the number M of users giving the maximum throughput. Only for very low values of g does the system show bistability phenomena. An example is shown in Fig. 6, where in an intermediate range of M the throughput exhibits two values corresponding to a

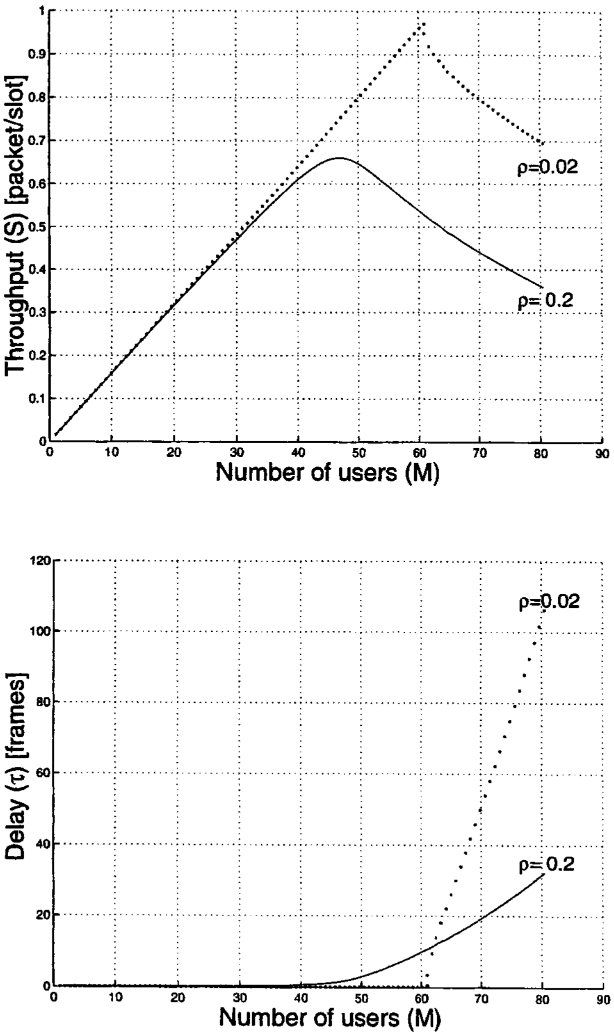

Fig. 5. C-TDMA performance with $g = 0.4$, $N = 25$, and permission probability $p = 0.9$.

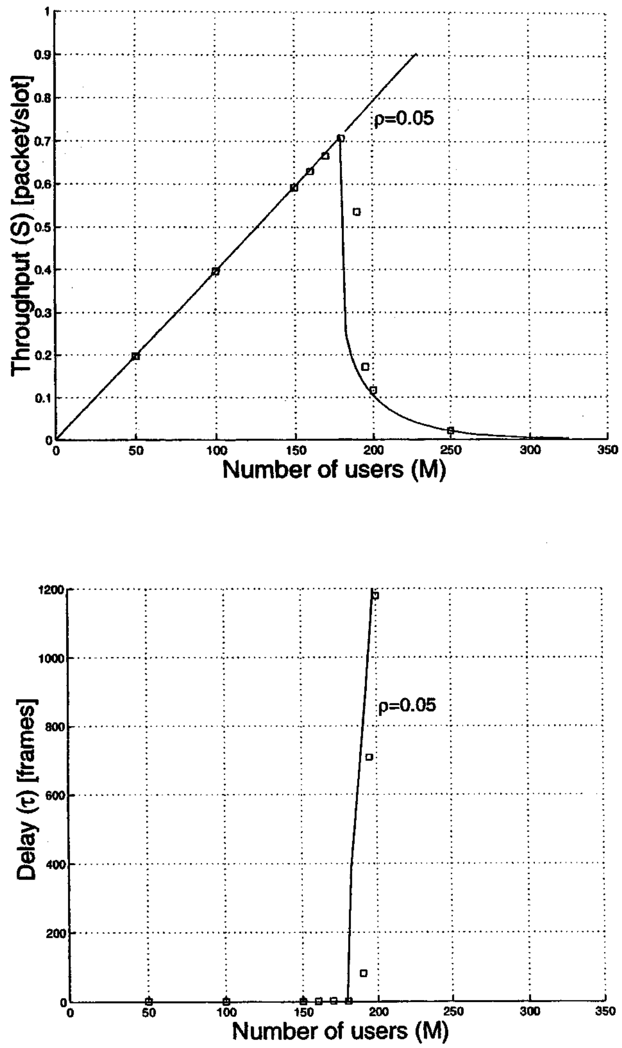

Fig. 6. C-TDMA performance with $g = 0.0991$, $N = 25$, and permission probability $p = 0.9$. Continuous line represents EPA results while square marks represent simulation results.

TABLE I
PARAMETER VALUES FOR DATA TRANSMISSION SCENARIO (INTERACTIVE VIDEO APPLICATION)

Parameter	Value
Mean talkspurt duration	1.00 s
Mean silence duration	1.35 s
Channel rate	720 kbit/s
Source rate	32 kbit/s
Frame duration	16 ms
Slots per frame	20
Slot duration	0.8 ms
Packet size	576 bits
Speech Delay Constraint (D_{max})	32 ms

bistability situation. In this case, the simulation agrees with the theory out of the bistability range, where on the contrary the simulated results assume intermediate values, corresponding to the fact that the system alternates periods of operation around the two stability points.

VI. OPTIMIZATION OF PERMISSION PROBABILITY

The permission probability p is a design parameter. In this section, we discuss its optimal choice in terms of the other system parameters, namely, the number M of users, the number N of slots per frame, and the traffic characteristics given by ρ and σ. Since p appears explicitly only into the output flow of the backlog state B [see (17)], we could proceed in the following recursive way. With an arbitrary value of p, we find the equilibrium pair $(b,\ t)$ of the backlogged and transmitting users; with these values, the output flow of B depends on p and has a maximum for $p' = (N - t)/b$. Provided that the new value p' is meaningful ($p \leq 1$), it is used as the permission probability and the new values of the equilibrium point are computed. The approach is iterated until convergence is reached.

VII. PERFORMANCE COMPARISON BETWEEN C-TDMA AND PRMA

To investigate potential advantages of C-TDMA with respect to other reservation-based protocols, a performance comparison has been made with PRMA [6].

In particular, we have compared the performance of the two protocols, by simulation, in a speech scenario. We have assumed the PRMA model considered by [6] with packet dropping after a maximum delay $D_{\max}$. The C-TDMA model has been adapted to speech transmission by considering a traffic model that describes speech statistics, independently of the channel conditions. Furthermore, the model includes the packet dropping mechanism to discard packets that wait for a time longer than $D_{\max}$. For both models, the parameters, summarized in

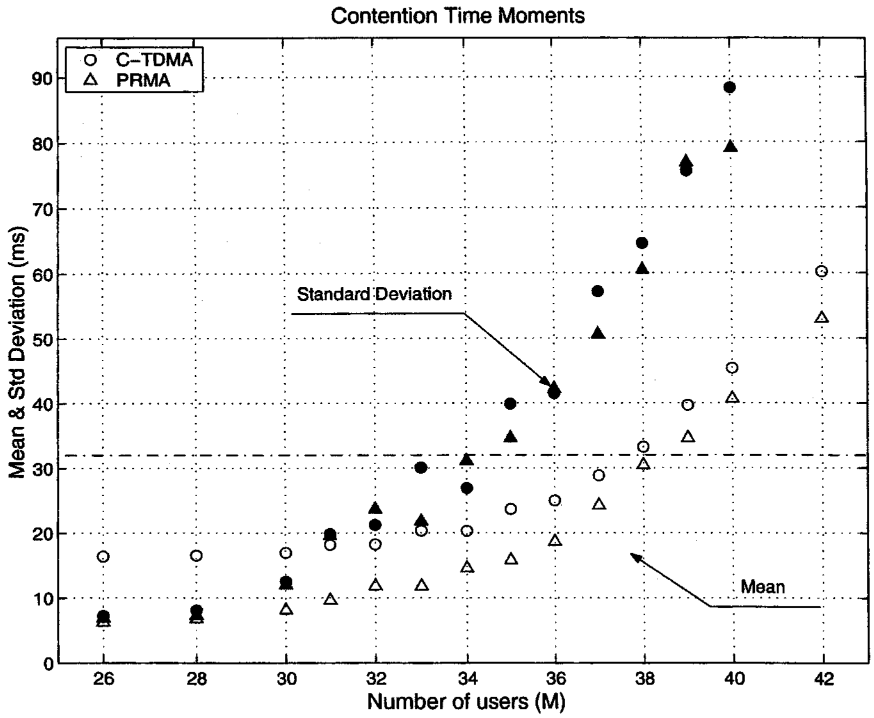

Fig. 7. Mean and standard deviation of the contention time for C-TDMA and PRMA versus the number of users M, estimated by computer simulation in a speech scenario (parameter values of Table II).

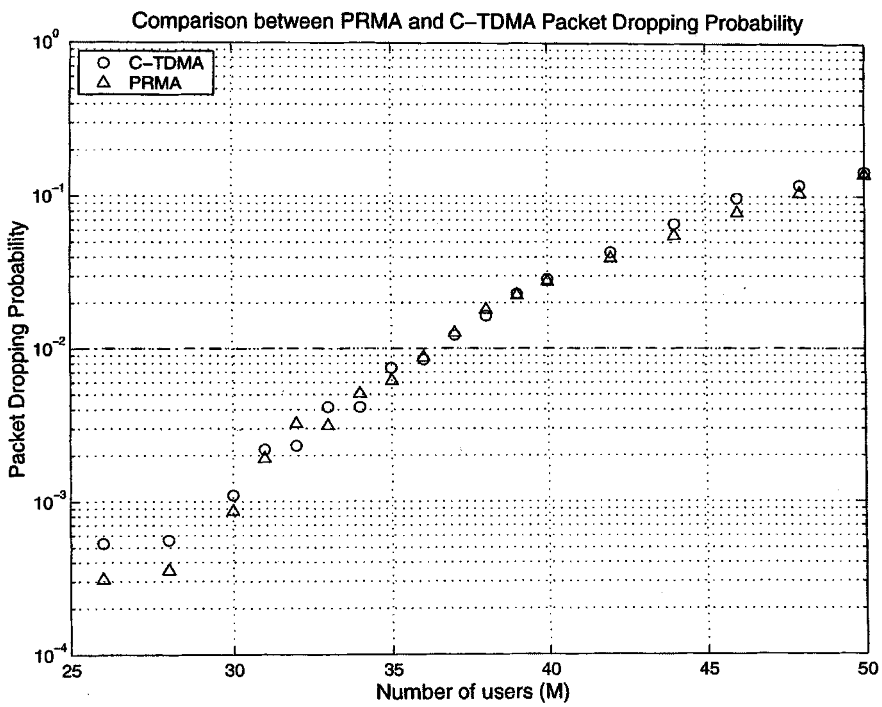

Fig. 8. Packet dropping probability for C-TDMA and PRMA versus the number of users M, estimated by computer simulation in a speech scenario (parameter values of Table II).

Table I, coincide with those considered in [6]. The permission probability is $p = 0.3$, as suggested in [6], for PRMA and $p = 1$ for C-TDMA.

Fig. 7 compares the mean and the standard deviation of the contention time versus the number of users M. Owing to the fact that C-TDMA operates on a frame by frame basis, its average contention time is higher than for PRMA, at least for low load, while for high load, the performances tend to be similar. Also comparable are the standard deviations, depicted in the same figure with filled markers. Fig. 8 shows the packet dropping probabilities, the major measure of the system efficiency versus the number of users. The simulation results show that the two models exhibit substantially equivalent performance.

In conclusion, the fact that in the C-TDMA the basestation send its information about the free slots only once per frame does not imply any significant penalty on the system performance.

VIII. Conclusion

An access protocol for the uplink channel of cellular multiuser systems has been described. The protocol, named C-TDMA, combines some properties of both the contention- and reservation-based protocols. C-TDMA has been studied by using both classical Markov analysis and equilibrium point analysis, which for practical conditions (large number of users and channels) is more convenient, due to its reduced computational cost.

Performance evaluation of C-TDMA has been made in terms of throughput and delay by using EPA and computer simulations. These results demonstrate the accuracy of the EPA method and indicate that C-TDMA yields high throughput values with a limited delay in typical cellular scenarios. A method of optimization of C-TDMA design also has been proposed to improve the maximum achievable throughput.

Finally, a simulation comparison with PRMA in a speech transmission scenario, with packet dropping, has shown that in this case, C-TDMA achieves substantially equivalent performance to PRMA.

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An Adaptive Asynchronous CDMA Multiuser Detector for Frequency-Selective Rayleigh Fading Channels

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***Abstract*—An adaptive asynchronous code-division multiple-access (CDMA) multiuser detector is proposed that uses a recently derived extended Kalman filter based algorithm [5] to perform joint data detection and parameter tracking in frequency-selective Rayleigh fading channels. A receiver structure based on this adaptive multiuser detector is presented and its performance in terms of parameter tracking and bit error rate (BER) is investigated. The receiver is a form of an adaptive RAKE that exploits multipaths to achieve performance gain.**

***Index Terms*—Bit error rate (BER), code-division multiple access (CDMA), extended Kalman filter (EKF), frequency-selective Rayleigh fading.**

I. Introduction

Spread-spectrum (SS) or code-division multiple-access (CDMA) systems have received growing attention as a promising way to efficiently use the RF spectrum especially in cellular mobile and indoor wireless communications. SS techniques offer desirable properties in antimultipath, anti-interception, higher capacity, and lower power consumption.

In asynchronous CDMA systems, the receiver performance in detecting the asynchronous symbols transmitted by different users largely depends on the accuracy in estimating and tracking the propagation delays. When the communications channel is frequency selective and slowly fading, the channel coefficients of the multipaths can be estimated and certain kinds of diversity combining methods can be used for efficient detection of the transmitted symbols. In the reverse link, since the base station has the knowledge of the pseudonoise (PN) codes of all the users, it can use a certain algorithm to jointly estimate the channel parameters and transmitted symbols for each user.

Among the various estimation methods, Kalman filtering [1], [2] is an optimum technique that can provide maximum *a posteriori* estimates for the channel coefficients. It is well known that a Kalman filter can give a much faster convergence than gradient-based algorithms such as the least mean square (LMS) algorithm. However, the major drawback of using a Kalman filter is its complexity. In fact, the extended Kalman filter (EKF) first proposed by Iltis *et al.* [3], [4] to jointly estimate the channel amplitude and delay, has a computational complexity that grows exponentially with the number of users. Thus, its implementation may become impractical.

Recently, Lim and Rasmussen [5] proposed an EKF multiuser detector that has a relatively lesser complexity of $O[K^2]$, where K is the number of users. In [5], only an additive white Gaussian noise (AWGN) channel is assumed. Subsequently, in [6], Lim *et al.* considered a standard Kalman filter detector in a frequency-selective and slow Rayleigh fading channel. However, in their detector, the path delays were not estimated but assumed perfectly known.

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