A p-persistent CSMA protocol suitable for packetized mobile radio-telephone cellular networks with capture and a number of mobile terminals transmitting to a common receiver is considered. In a micro-cellular environment, messages from different transmitting terminals will suffer different attenuations (path loss and fading phenomena), yielding different levels of energy at the receiver. Thus, one out of 'i' attempting transmission packets will be successfully transmitted with some capture probability f. Assuming that the receiver is within the range and in line-of-sight of all the mobile users in the cell, the capture probabilities can be determined by means of simulation, and a new probabilistic Markov model for the above network is introduced and analysed using the slot property of the channel. Under moderate packet length size the results obtained in respect of the throughput-delay performance and stability under heavy traffic conditions are promising compared with those of the corresponding conventional p-persistent CSMA schemes.

Keywords: Markov chain analysis, packetized mobile network, capture, CSMA protocol, simulation, performance analysis
It is assumed that the base station is within the range and line-of-sight of all the mobile users in the cell. All the mobile users are aware of the status of the base station (busy or idle) in each time slot through a separate, and independent, secondary channel, and behave accordingly. Thus, if a collision with no successful transmission occurs, the channel is seen to be free immediately, and all the ready mobile users will compete again in the following time slot. Alternatively, if a collision results in a successful transmission, the transmission period of \( \theta \) time slots starts, during which time no attempts are made by the mobiles.

Any ready mobile receives the information about the status of the channel through the secondary channel in each time slot and proceeds as follows. If the status is idle the contention period starts, during which all the ready mobiles attempt to transmit their packets with probability \( \delta \). Alternatively, if the status is busy, this is due to a successful transmission and all the ready mobiles postpone their attempts up to the time slot at which the transmission is finished.

Note that in the last time slot of the transmission period the base station changes its status from busy to idle, and informs all the ready mobiles, through the secondary channel, accordingly. Thus, attempts with probability \( \delta \) by the ready mobiles will be allowed from the next time slot, when the transmission is due to finish and the contention period begins. Inevitably, during this period collisions with no successful transmission will occur, but due to the different levels of energy between the attempting transmission packets at the base station, one of the colliding packets will be successfully transmitted in some time slot. This event terminates the contention period and the transmission period will start in this time instant.

**MODEL ANALYSIS**

In Figure 1 the operation of the system is presented. The slotted time axis is divided into cycles, each one of which consists of three periods: the idle, the contention and the transmission periods. We proceed by giving the exact definitions.

A cycle is defined as the elapsed time (in slots) between the time instants in which two consecutive successfully transmitted packets and their transmission. The idle period of a cycle is defined as the time interval (in slots) between the time instant when the successfully transmitted packet of the previous cycle ends its transmission leaving behind no ready users, and the time instant when one or more new packets arrive. If, by the end of the transmission period of the previous cycle, one or more ready users are left behind, the idle period is zero and the system immediately enters into the contention period.

Depending on whether the idle period of a cycle is zero or not, there are two cases in which the contention period can be defined. Thus, if the idle period is zero, the contention period is defined as the time interval (in slots) between the time instant when the successfully transmitted packet of the previous cycle ends its transmission leaving behind one or more ready users (beginning of a new cycle), and the time instant when the first collision with a successful transmission occurs. Alternatively, if the idle period is not zero, the contention period is defined as the time interval (in slots) between the time instant when the idle period ends leaving behind one or more ready users, and the time instant when the first collision with a successful transmission occurs. The contention period is zero if a collision with a successful transmission occurs at the first time instant. Finally, the transmission period of a cycle immediately follows the contention period and has fixed duration of \( \theta \) slots.

It is now evident that the state of the system can be described through the number of ready users left behind by the end point of each cycle. To derive the transition matrix of the system one has to find out the number of ready users left behind by the end point of each period and subsequently in each time slot. Then the transition 

![Figure 1. Channel operation. \( \ast (\ast) \): collision with no (a) successful transmission occurred; \(-\): no attempt is allowed by any mobile user](image-url)
matrix will be calculated as a product of single slot transition matrices. In the following the transition matrices of each period are derived.

Transition matrix of the cycle's idle period

Let us assume that the idle period of a cycle has \( k \) single slots duration. In each one of the first \( k - 1 \) slots no packet arrival occurs, and therefore the total number of ready users in the system remains at zero. In the last time slot some fresh packet arrivals occur, and therefore this number changes to some non-zero value. Let \( H_- = (h_{ij}) \) be the one step transition matrix describing the state of the system in each one of the first \( k - 1 \) single slots, and \( H_+ = (h_{ij}) \) be the one step transition matrix for the last single slot of the idle period. Then:

\[
- h_{ij} = \begin{cases} 
    b(N,0,\sigma) & \text{if } i = j = 0 \\
    0 & \text{otherwise}
  \end{cases}
\]

\[
+ h_{ij} = \begin{cases} 
    b(N,j,\sigma) & \text{if } i = 0 ; j = 1,2, \ldots, N \\
    1 & \text{if } i = j ; j = 1,2, \ldots, N \\
    0 & \text{otherwise}
  \end{cases}
\]

All the Eigenvalues of the Matrix \( H_- \) are absolutely less than one, and therefore the series \( \sum_{k=0}^{\infty} H_-^k \) converges. Using the single slot property of the channel the transition matrix \( H = (h_{ij}) \) of the idle cycle period is given by:

\[
H = \sum_{k=1}^{\infty} H_-^{k-1} H_+ = (I - H_-)^{-1} H_+ \quad \text{with elements}
\]

\[
h_{ij} = \begin{cases} 
    b(N,j,\sigma) / \{1 - b(N,0,\sigma)\} & \text{if } i = 0 ; j = 1,2, \ldots, N \\
    1 & \text{if } i = j ; j = 1,2, \ldots, N \\
    0 & \text{otherwise}
  \end{cases}
\]

Note that \( H1 = 1 \) with 1 be a \((N+1) \times 1\) dimensions column vector of ones. All the involved matrices \( H, H_-, H_+ \) and \( I \) are of \((N+1) \times (N+1)\) dimensions.

Transition matrix of the cycle's contention period

In a similar manner, let the contention period of a cycle have \( m \) single slots duration. Attempts are allowed in each one of the \( m \) time slots with probability \( \delta \) by any ready user. In the first \( m - 1 \) time slot all the attempts result in a collision with no successful transmission, while in the last time slot a collision with a successful transmission occurs. Let \( R_- = (r_{ij}) \) be the one step transition matrix describing the state of the system in each one of the first \( m - 1 \) single slots, and \( R_+ = (r_{ij}) \) be the one step transition matrix for the last single slot of the contention period, respectively. Then:

\[
r_{ij} = \begin{cases} 
    b(N-j,\sigma) / \{1 - b(N,0,\sigma)\} & \text{if } i = 0 ; j = 1,2, \ldots, N \\
    1 & \text{if } i = j ; j = 1,2, \ldots, N \\
    0 & \text{otherwise}
  \end{cases}
\]

and:

\[
r_{ij} = \begin{cases} 
    b(N-j,\sigma) \{1 - (\delta a)\} & \text{if } i = 1,2, \ldots, N \\
    1 & \text{if } i = j \text{ and } j = 1,2, \ldots, N \\
    0 & \text{otherwise}
  \end{cases}
\]

Alternatively, in case \( \delta \neq 1 \) (\( \delta \)-persistent CSMA protocol), let \( V \) be the number of attempts made by the ready users in a time slot. Then:

\[
r_{ij} = \begin{cases} 
    b(N-j,\sigma) \sum_{v=0}^{\infty} b(v,v,\delta) \{1 - v\} & \text{if } i = 1,2, \ldots, N \\
    1 & \text{if } i = j \text{ and } j = 1,2, \ldots, N \\
    0 & \text{otherwise}
  \end{cases}
\]

Note that in both cases, the event of ending the contention period with \( N \) ready users left behind and having a collision with a successful transmission is impossible. Again, all the Eigenvalues of the matrix \( R_- \) are absolutely less than one, and thus the series \( \sum_{m=0}^{\infty} R_-^m \) converges. Using the single slot property of the channel the transition matrix of the contention period of a cycle \( R = (r_{ij}) \) is calculated as follows:

\[
R = \sum_{m=0}^{\infty} R_-^{m-1} R_+ = (I - R_-)^{-1} R_+ \quad \text{with } R1 = 1
\]

All the involved matrices \( R_- \), \( R_+ \) and \( R \) are of \((N+1) \times (N+1)\) dimensions. Generally, the matrix \( R \) cannot be calculated explicitly.

Transition matrix of the cycle's transmission period

The transmission period of a cycle always has a fixed duration of \( \theta \) time slots. During this period new arrivals from free users may occur, but attempts are not allowed. Let \( X_- = (x_{ij}) \) be the one step transition matrix for each of the first \( \theta - 1 \) single slots and \( X_+ = (x_{ij}) \) be the one step transition matrix for the last single slot of the transmission period, respectively. Then:

\[
x_{ij} = \begin{cases} 
    b(N-i,\sigma) & \text{if } i = j = 0 \\
    b(N-i,i+1,\sigma) & \text{if } i = j \text{ and } j = 1,2, \ldots, N \\
    0 & \text{otherwise}
  \end{cases}
\]

and:

\[
x_{ij} = \begin{cases} 
    b(N-i,\sigma) \{1 - (\delta a)\} & \text{if } i = 1,2, \ldots, N \\
    1 & \text{if } i = j \text{ and } j = 1,2, \ldots, N \\
    0 & \text{otherwise}
  \end{cases}
\]

Note that in the last time slot of the transmission period an additional arrival, coming from the transmitting user, may or may not occur. Therefore, the number of ready users may or may not decrease by one.
Since the transmission period of a cycle is fixed, the transition matrix $X = (x_{ij})$ is calculated as $X = X^d - 1 X^1$.

**System transition matrix**

The chain defined between the consecutive end cycle points is Markovian. The system transition probability matrix $P = (p_{ij})$ is calculated as a product of several single slot transition matrices:

$$P = HRX = (I - H_\alpha)^{-1} H_\alpha (I - R_\alpha)^{-1} R_\alpha X^d - 1 X_1.$$ 

Therefore, the steady state distribution vector $\pi = (\pi_0, \pi_1, \ldots, \pi_N)$ can be obtained by solving the linear system $\{ \pi = \pi P \text{ with } \sum_{i=0}^{N} \pi_i = 1 \}$.

**Capture probabilities**

There are several methods to calculate the capture probabilities $f_i; i = 0, 1, 2, \ldots, N$. The most efficient method requires explicit knowledge of the area covered by the radio-telephone network. Using topographical databases it is possible to create maps showing the mean levels of energy, produced at the base station (receiver) by a mobile user transmitting from different regions of the covered area. Information from statistical surveys is also used to estimate the effect of the different attenuation such as path loss and shadow or Rayleigh fading. The above information is combined with the relative number of mobile users expected in the respective regions to give the probability distribution $f(x) = P[E < x]$, where $E$ is a random variable showing the level of power caused by a mobile.

Namislo indicates that even in the most simple cases it is extremely difficult to calculate the exact values of the capture probabilities $f_i; i = 0, 1, 2, \ldots, N$. Alternatively, to calculate them by means of simulation he assumed that the users are spread uniformly over the whole region, and that their distances from the receiver are random variables with a common distribution function given by $G(x) = x^2 \cdot 1 [0,1]$. If the level of power $E_i$ caused by a transmitting mobile $M_i$ at the receiver due to path loss is proportional to $1/x^m$, the base station will be able to capture this transmission if $E_i > c x^m$, for some constant $c > 1$ and the probabilities $f_i$ can be determined using Monte Carlo simulation. Note that the exponent $m$ is between 2 and about 5, depending on the geography of the region.

The simulation experiment assumes that $k$ idendical ready mobile users are uniformly spread in a circular area of radius 1, which approximates the cell, with the base station located at the centre of the circle. It is also assumed that shadow or Rayleigh fading effects are neglected ($m = 2$). Then:

- Compute the Cartesian distances $d_i$ and the level of power $E_i = 1/d_i^2$; $i = 1, 2, \ldots, k$ of all the mobiles $M_i$ from the base station.
- Check if $\max_j |E_i| > c \sum_{j=1}^{N} E_i; i \neq j$ (e.g. with $c = 2.0$ the corresponding signal-to-noise ratio is 3dB).
- Repeat the algorithm.

Then, the capture probabilities $f_i$ are given as the relative number of times the above condition is satisfied.

**PERFORMANCE MEASURES**

In the following some measures of prime interest are calculated. These measures are the throughput, the mean busy and mean idle times of the channel, the mean backlog, the delay and the rejection probability. As is shown, the derivation of these measures is based on the mean length of each one period and on the mean cycle length. The analysis further requires the conditional mean length of the idle and contention periods given the number of ready users at the beginning of the corresponding period. No analysis is needed for the transmission period.

**Idle period mean length**

To calculate the mean idle period length $\bar{C}_{idle}$, let $C_i$ be a $(N + 1) \times 1$ column vector with elements of the conditional mean idle period lengths, given that the system had $i (i = 0, 1, 2, \ldots, N)$ ready users at the beginning of the idle period. Obviously, the only non-zero element of this vector corresponds to the state $i = 0$. Since $[H^{-1} H_\alpha]_i$, is the conditional probability that the idle period length is $k$ slots, given there were $i$ packets at the beginning of this period and $j$ packets at its end, the $i$th element $[C_i]_i$ of the column vector $C_i$ is obtained as:

$$[C_i]_i = \sum_{k=1}^{N} \sum_{j=0}^{k} [H^{-1} H_\alpha]_{ij} = \sum_{k=1}^{N} [kH^{-1} H_\alpha]_i = [(1 - H_\alpha)^{-1}] [H_\alpha]_i = [(1 - H_\alpha)^{-1} H_\alpha]_i = [(1 - H_\alpha)^{-1} 1],$$

where $1$ is a column vector with $N + 1$ elements, all equal to 1. Note that since $\|E(H_\alpha)\| < \infty$, the matrix $(1 - H_\alpha)^{-1}$ always exists. Thus, the mean idle period length is given by $\bar{C}_{idle} = \pi C_i = \pi (1 - H_\alpha)^{-1} 1$.

**Contention period mean length**

In a similar manner let $\bar{C}_{con}$ be the mean length of the contention period and $C_K$ be a $(N + 1) \times 1$ column vector with elements of the conditional mean contention period lengths, given that the system had $i (i = 0, 1, 2, \ldots, N)$ ready users at the beginning of the contention period. Obviously, the element corresponding to the state $i = 0$ is
protocols

zero. Since \([R_{m-1}^{-1}R_1]_i\) is the conditional probability that the contention period length is \(m\) single time slots given there were \(i\) packets at the beginning of the period and \(j\) packets at its end, the \(i\)-th element \([C_R]_i\) of the column vector \(C_R\) is obtained as:

\[
[C_R]_i = \sum_{m=1}^{N} \sum_{j=0}^{N} k \sum_{m=1}^{N} m[R_{m-1}^{-1}R_1]_i = \sum_{m=1}^{N} [(I - R_-)^{-1}]_i = [(I - R_-)^{-1}]_i
\]

Note that since \(|t(R_-)| < +\infty\), the matrix \((I - R_-)^{-1}\) always exists. Therefore, the mean contention period length is given by \(C_{con} = \pi C_R = \pi (I - R_-)^{-1}\).

**Mean cycle length**

The mean cycle length \(\overline{C}\) consists of the mean idle period length \(C_{idl}\), the mean contention period length \(C_{con}\) and the fixed transmission period of \(\theta\) time slots. If \(C\) is a \((N + 1) \times 1\) column vector such that \(C = C_1 + C_R + \theta 1\), then:

\[
\overline{C} = \pi C = \pi (C_1 + C_R + \theta 1) = \pi C_1 + \pi C_R + \theta \pi 1
\]

\[
= \pi [(I - H_-)^{-1} + (I - R_-)^{-1} + \theta 1]
\]

**Throughput**

Each cycle carries a successful transmission of \(\theta\) time slots. Therefore, the throughput of the system is defined as the ratio between the packet transmission time and the mean cycle length, \(S_1 = \theta/\overline{C}\). Alternatively, the throughput can be defined as \(S_2 = \theta/\overline{C} - C_{idl}\), namely the ratio between the packet transmission time and the mean cycle length of the cycle the channel is actually busy (mean busy period length).

**Mean busy and mean idle time**

The mean busy time of the system, \(U_{bus}\), say, is defined as the ratio between the mean busy (contention and transmission) period length and the mean cycle length. It consists of two parts: the first of which, \(U_{con}\), say, is the proportion of the time spent in the contention period, while the second part is the throughput \(S_1\) of the system. Therefore:

\[
U_{bus} = U_{con} + S_1 = \overline{C}_{con}/\overline{C} + \theta/\overline{C}
\]

\[
= \pi [(I - R_-)^{-1} + \theta]/\pi [(I - H_-)^{-1}]
\]

\[
+ (I - R_-)^{-1} + \theta 1
\]

Alternatively, the proportion of the time spent in the contention period can be defined by excluding the mean idle period length. In this case it will be:

\[
U_{con} = C_{con}/(\overline{C} - C_{idl})
\]

\[
= \pi [(I - R_-)^{-1} + \theta\theta]/\pi [(I - R_-)^{-1} + \theta 1
\]

and:

\[
U_{con} + S_2 = 1
\]

Finally, the mean idle time of the system, \(U_{idl}\), say, is obtained as:

\[
U_{idl} = 1 - U_{bus} = \overline{C}_{idl}/\overline{C}
\]

**Rejection probability**

The rejection probability \(P_{rej}\) is obtained as the percentage of users that are not entered into the system. Therefore, \(P_{rej} = (N_0 - 1)/N_0 = 1 - 1/\overline{C}\).

**Mean backlog**

The mean backlog is defined as the mean number of ready users in the system, and it corresponds to the mean queue length, or equivalently, to the mean number of packets in the system. It is computed either as the ratio between the expected number of ready users, \(B_{bus}\), say, over all slots in the busy period of a cycle, and the mean cycle length \(\overline{C}\), or as the ratio between the \(B_{bus}\) and the mean busy period length \(C_{bus} = \overline{C} - C_{idl}\). Therefore:

\[
N_1 = B_{bus}/\overline{C} = B_{bus}/C_{bus}
\]

\[
N_2 = B_{bus}/(C_{bus} - C_{idl})
\]

\[
B_{bus} = B_{con} + B_{tra} = \pi B_R + \pi B_X
\]

\[
= \pi (B_R + B_X)
\]

\[
= \pi (B_R + B_X)
\]

\[
= \pi (B_R + B_X)
\]

\[
= \pi (B_R + B_X)
\]

\[
= \pi (B_R + B_X)
\]

\[
= \pi (B_R + B_X)
\]

Note that \(B_{con} = \pi B_R\) and \(B_{tra} = \pi B_X\) are the expected number of ready users in the contention and transmission periods, respectively. Moreover, \(B_R = \{[B_R]_q\}_{q=0}^{N}\) and \(B_X = \{[B_X]_q\}_{q=0}^{N}\) are \((N + 1) \times 1\) column vectors with elements the average number of ready users over all slots in the contention or transmission period, respectively, given that the system had \(i\) users ready at its beginning. Thus, if \(i = (0,1,2,\ldots, N)\) is a \((N + 1) \times 1\) column vector with elements the number of ready users corresponding to the state \(i\) then:

\[
[B_R]_i = \sum_{q=0}^{N} [H]_{iq} \sum_{m=1}^{N} [R_{m-1}]_q
\]

\[
= [H \sum_{m=1}^{N} R_{m-1}]_i
\]

\[
[B_X]_i = \sum_{q=0}^{N} [H]_{iq} \sum_{r=0}^{\theta} \sum_{j=0}^{N} [R]_r \sum_{n=1}^{\theta} [X_n^{r-1}]_j
\]

\[
= [HR \sum_{n=1}^{\theta} X_n^{r-1}]_i
\]
Note that the number of ready users during the idle period is zero. The expected number of ready users during the contention and the transmission periods is given, respectively, as:

\[ B_{con} = \pi B_R = \pi H(I - R_\text{-})^{-1}I \] and

\[ B_{tra} = \pi B_x = \pi H R \sum_0^\theta X_n^{-1}j \]

while the mean backlog in the contention, \( \bar{N}_{con} \) say, and the transmission, \( \bar{N}_{tra} \) say, periods can be obtained, respectively, as:

\[ \bar{N}_{con} = B_{con}/C_{bus} \text{ and } \bar{N}_{tra} = B_{tra}/C_{bus} \text{ with} \]

\[ \bar{N}_2 = \bar{N}_{con} + \bar{N}_{tra} \]

**Mean packet delay**

The mean packet delay, \( \bar{D} \) say, can be derived through Little's formula. Since \( N_1/S_1 = N_2/S_2 = B_{bus}/\theta \) the mean delay is given by:

\[ \bar{D} = B_{bus}/\theta = \pi H(I - R_\text{-})^{-1}[I + R_\text{+}] \sum_0^\theta X_n^{-1}j/\theta \]

with mean backlogs given, respectively, by:

\[ \bar{N}_1 = \pi[H(I - R_\text{-})^{-1}[I + R_\text{+}] \sum_0^\theta X_n^{-1}j/C \]

\[ = \pi[H(I - R_\text{-})^{-1}[I + R_\text{+}] \sum_0^\theta X_n^{-1}j]j/C \]

\[ \bar{N}_2 = \pi[H(I - R_\text{-})^{-1}[I + R_\text{+}] \sum_0^\theta X_n^{-1}j]/C_{bus} \]

\[ = \pi[H(I - R_\text{-})^{-1}[I + R_\text{+}] \sum_0^\theta X_n^{-1}j]j/C_{bus} \]

**NUMERICAL RESULTS**

The scheme analysed above is tested in a system with \( N = 19 \) mobile users and a signal-to-noise ratio value of 3dB. All measures defined in the previous section are examined, and the most important results are reported. The steady-state probabilities are obtained by solving a linear system, using the direct approach of the Gaussian elimination method. The matrix \( (I - H_\text{-})^{-1} \) is found analytically, while the matrices \( (I - R_\text{-})^{-1} \) and \( X_0^{-1} \) are calculated by using standard NAG routines.

In Figures 2 to 7 all the measures discussed in the previous section, with packet length \( \theta = 5 \) and attempt probability \( \delta = 1.0 \), are plotted against the arrival rate. Thus, in Figure 2 and (and Figure 3) the throughput \( S_1(S_2) \) and the proportion of time spent in the contention period

![Figure 2](image-url)

**Figure 2.** Arrival rate \( \sigma \) versus the proportion of the time spent in the transmission (throughput \( S_2 \): ---) and the contention (Ucon \(_1\): - - -) period (\( N = 19, \delta = 1.0, \theta = 5, S/N = 3dB \))

![Figure 3](image-url)

**Figure 3.** Arrival rate \( \sigma \) versus the proportion of the time spent in the transmission (throughput \( S_2 \): ---) and the contention (Ucon \(_2\): - - -) period (\( N = 19, \delta = 1.0, \theta = 5, S/N = 3dB \))
Figure 4. Arrival rate $\sigma$ versus the proportion of the time spent in the busy (Ubus: ---) and the idle (Uidl: ----) period ($N = 19$, $\delta = 1.0$, $\theta = 5$, $S/N = 3dB$)

Figure 6. Arrival rate $\sigma$ versus the mean queue length of the backlogged mobile users during the busy ($N_{b}$: ---), the contention ($N_{c}$: ---) and the transmission ($N_{t}$: ---) period ($N = 19$, $\delta = 1.0$, $\theta = 5$, $S/N = 3dB$)

Figure 5. Arrival rate $\sigma$ versus the rejection probability ($N = 19$, $\delta = 1.0$, $\theta = 5$, $S/N = 3dB$)

Figure 7. Throughputs $S_{1}$: --- and $S_{2}$: ---- versus the mean delay $D$ ($N = 19$, $\delta = 1.0$, $\theta = 5$, $S/N = 3dB$)
In both graphs all the measures involved are stable under overload. The values of $S_2$ and $\text{Ucon}_2$ are higher than those of $S_1$ and $\text{Ucon}_1$, respectively, due to the time spent in the idle period. Note that $S_2$ ($\text{Ucon}_2$) approaches its maximum (minimum) value as $\sigma \to 0$. This means that almost every incoming packet is transmitted successfully. As the traffic increases, $S_2$ decreases ($\text{Ucon}_2$ increases) at the expense of the other periods.

In Figure 4 the proportion of the time spent for the busy $\text{Ubus}$ and idle $\text{Uidl}$ periods against the arrival rate is presented. In the sequel the throughput-delay performance for various values of the packet length $\theta$ and attempt probabilities $\delta$ is considered. The throughput $S_1$ versus the mean delay $\bar{D}$ is considered in Figures 8, 10, 12 and 14, while the throughput $S_2$ versus $\bar{D}$ is considered in Figures 9, 11, 13 and 15. Note that in Figures 8, 9, 10 and 11, five values of the packet length ($\theta = 1, 5, 10, 15, 30$) are examined, keeping the attempt probability fixed at $\delta = 1.0$ and $0.05$, respectively. Similarly, in Figures 12, 13, 14 and 15, five values of the attempt probability ($\delta = 0.01, 0.05, 0.1, 0.2, 1.0$) are examined, keeping the packet length fixed at $\theta = 5$ and 30 slots, respectively.

It appears that as the users transmit longer (but fixed) packets, the throughputs $S_1$ and $S_2$ increase significantly at the expense of the idle and contention periods. Although the attempt probability $\delta$ plays an important role, especially when the traffic is light, it seems that it has no further effect under overload. In particular, if the packet length $\theta$ is long and as the attempt probability increases, the obtained throughput is almost the same.

Lastly, for small values of the attempt probability $\delta$ and as the traffic increases, packets seem to suffer to an excessive delay. The magnitude of this delay depends on the packet length. The smaller the packet length is the longer the corresponding delay, and vice versa. Although in a microcellular environment small packets are more (almost every packet is successfully transmitted). However, as the arrival rate increases the situation is reversed. It is expected that as the packet length increases the throughputs $S_1$ and $S_2$ tend to obtain the same values.

The values of $S_1$ tend to obtain the highest values for low traffic and as the traffic increases the situation is reversed. It is expected that as the packet length increases the throughputs $S_1$ and $S_2$ tend to obtain the same values.
Figure 10. Throughput $S_1$ versus mean delay $\bar{D}$ for
(a): $\theta = 1$: ——; (b): $\theta = 5$: ——; (c): $\theta = 15$: ....;
(d): $\theta = 30$: ——; and (e): $\theta = 50$: ——. (N = 19, $\delta = 0.05$, $\theta = 5$, S/N = 3dB)

Figure 11. Throughput $S_2$ versus mean delay $\bar{D}$ for
(a): $\theta = 1$: ——; (b): $\theta = 5$: ——; (c): $\theta = 15$: ....;
(d): $\theta = 30$: ——; and (e): $\theta = 50$: ——. (N = 19, $\delta = 0.05$, $\theta = 5$, S/N = 3dB)

Figure 12. Throughput $S_1$ versus mean delay $\bar{D}$ for
(a): $\delta = 0.05$: ——; (b): $\delta = 0.20$: ——; (c): $\delta = 0.10$: ....;
(d): $\delta = 0.05$: ——; and (e): $\delta = 0.01$: ——. (N = 19, $\theta = 5$, S/N = 3dB)

Figure 13. Throughput $S_2$ versus mean delay $\bar{D}$ for
(a): $\delta = 0.05$: ——; (b): $\delta = 0.20$: ——; (c): $\delta = 0.10$: ....;
(d): $\delta = 0.05$: ——; and (e): $\delta = 0.01$: ——. (N = 19, $\theta = 5$, S/N = 3dB)
Learning from the above results, the values which seem to be the most suitable for the packet length ($\theta = 5$ slots) and the attempt probability ($\delta = 0.2$) are chosen, in order to study the capture effect. Thus, in Figure 16, three values for signal-to-noise ratio are examined corresponding to 3dB, 20dB and no capture. The results are remarkable, in the sense that the throughput is substantially higher and the risk of instability is lower as the capture effect becomes more significant.

CONCLUSION

In this work the capture effect in a p-CSMA protocol suitable for a mobile radio telephone network, without hidden users, fading effects and propagation delay, was investigated. A Markov model was constructed by assuming that the packet collision does not necessarily destroy all the packets involved. It was shown that with a long packet length and a suitable reattempt probability, such a network increases its possibility of being stable, and it can throughput significantly more traffic than the corresponding p-persistent CSMA schemes without capture.
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