Performance analysis of a MAC protocol for wireless IP/CDMA networks

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Abstract - Future wireless networks are expected to provide a broad range of multimedia services including voice, data, and video to mobile users with QoS guarantees. With the growing demand for internet access and the evolution of IP to offer QoS, IP is the best candidate for future broadband wireless access networks. Efficient medium access control (MAC) protocols that can integrate multimedia traffic are required to enhance QoS in the access network. In this paper a novel MAC protocol for wireless IP over CDMA is proposed. The performance of the protocol is analytically evaluated using Markov models.

I. INTRODUCTION

With the increase demand for internet access and multimedia services, next generation wireless networks are envisage to provide a broad range of multimedia services with guaranteed quality of service (QoS) over the IP network. Guaranteeing Quality of Service (QoS) in the Internet has been proposed using two different models, i.e. the Integrated services (IntServ) model and the Differentiated services (DiffServ) model. DiffServ is the promising QoS technology due to its scalability by dealing with aggregates of traffic flows. This architecture provides assured service and premium service classes in addition to best-effort service [1]. Premium service is suitable for traffic which requires minimum guaranteed bandwidth and delay sensitive, while Assured service is suitable for traffic which requires minimum guaranteed bandwidth, but not strict in terms of delays.

To enhance QoS in wireless access networks, it is very important to design an appropriate medium access control (MAC) protocol that offers flexibility to accommodate multimedia traffic within its network and QoS requirements. In 802.11 wireless networks, a new standard called 802.11e is being developed to enhance the original 802.11 MAC layer to support QoS [2]. For cellular wireless networks, several MAC protocols capable of supporting multimedia services have been proposed in literature [3]-[13]. Hybrid time-division/code-division (TD/CDMA) protocols have several advantages such as higher data rates, improved coverage, and capacity. TDD (Time Division Duplex) has advantage over FDD (Frequency Division Duplex) when there is asymmetric traffic between the uplink and downlink. Most of these protocols were design for wireless ATM or simply voice/data integration.

Comparatively, there is little research done on MAC protocols considering IP traffic classes [9] [10] [11] over CDMA.

In this paper a novel TD/CDMA protocol which is a modification of the abovementioned protocols is proposed for integration of premium and assured service traffic. Efficient bandwidth utilization is provided by allowing assured service to utilize remaining capacity from premium service. Markov chains are used to analyze the performance of the protocol. The rest of the paper is organized as follows; in section II we present our network model and traffic model. In section III, we give the overview of the protocol and describe the admission schemes which constitute the protocol. Section IV presents the analytical model. In section V the analytical results are shown. A conclusion is drawn in Section VI.

II. SYSTEM MODEL

A. Network Model

The wireless IP network considered is a single hope star network, where mobile terminals communicate with the base station (BS). A TD/CDMA channel interface is adopted, however only the uplink is considered, since the downlink transmission is easily scheduled by the BS. As in [7], we assume MC-CDMA (multi-code CDMA) to integrate traffic streams with different transmission rates.

B. Traffic model

The traffic for both premium and assured service is assumed to be generated by a finite population of mobile terminals, \( \{N_{PS}, N_{AS}\} \). Premium traffic is modeled as the ON/OFF process generally used for voice traffic [12], whose mean ON and OFF times are geometrically distributed and consists of two states, i.e. silence (SIL) and transmission (TRA). Fig. 1 illustrates the traffic model for premium with transition probabilities.

\[
1 - \sigma_c \quad \eta_R \quad \sigma_c \quad 1 - \eta_R
\]

Fig. 1: Premium traffic model
An assured terminal can be in one of three states as shown in Fig. 2: silence (SIL), permanent state (PM), and temporal state (TM). A mobile in PM or TM state is in ON. Terminals in TM state transmit using capacity unused by premium service. When a call terminates from the PM state, they are converted to PM state. This traffic model is uniquely derived from the assured service MAC scheme as discussed below.

![Traffic Model Diagram](image)

**Fig. 2: Assured traffic model**

### III. PROTOCOL OVERVIEW

#### A. Frame Structure

Fig. 3 illustrates the frame structure employed by the TD/CDMA protocol. Transmission time divided in fixed length frames, which are further divided into time slots. Each time slot supports several code channels which are limited by the BER of service being transmitted. The uplink or downlink consists of a mini-slot used to send reservation requests to the BS and broadcast channel information, respectively.

![Frame Structure Diagram](image)

**Fig. 3: Frame Structure**

#### B. Protocol description

When a premium or assured mobile terminal (i.e., user) wants to transmit packets, it randomly selects a spreading code from a finite code pool and transmit a request packet using spread spectrum ALOHA in the mini-slot. Upon receiving the request the BS performs a call admission control (CAC), to determine whether to admit or reject a call. The BS broadcast successful requests via the downlink of the next frame. A piggyback scheme is used for terminal to inform the BS of the required bandwidth in the next frame. Once the user is admitted it reserves its guaranteed bandwidth for the duration its call, except temporally admitted users.

Temporally admitted are assured terminals admitted on premium capacity, since they are dropped when the premium traffic load increases. If new premium calls are admitted and require the bandwidth used by temporally admitted users, a dropping tone (DT) is broadcasted in the downlink.

When the network is congested, premium terminals transmitting above their minimum guaranteed capacity abort the transmission of the packets corresponding to excess traffic to maintain the required QoS of all admitted users. Since assured service is not delay sensitive, the excess traffic is buffered instead of being dropped and transmitted when extra bandwidth become available.

#### C. Call Admission Control

The total system capacity can be expressed as

\[ C = P^{\text{max}}_s + A^{\text{max}}_a, \]

where \( P^{\text{max}}_s \) is the maximum guaranteed capacity (code channels) for premium service and \( A^{\text{max}}_a \) is the minimum guaranteed capacity for assured service. A new premium call is admitted if after its admission the following criteria is met,

\[ \sum_{i=1}^{R_s} P_i \leq P^{\text{max}}_s \]

where \( P_i \) is the guaranteed number of code channel assigned to the \( i \)th premium service user and \( R_s \) is the number of currently admitted premium users. Since assured service can utilize unused premium capacity a new assured user is admitted if after its admission the following criterion is satisfied:

\[
\sum_{i=1}^{T_a} A_i \leq \left\{ C - \sum_{i=1}^{R_a} G_i \right\}
\]

where \( A_i \) is the minimum guaranteed code channels for the \( i \)th assured service user and \( T_a \) is the number of currently admitted assured users.

### IV. MARKOV ANALYSIS

The analysis of the system is based on the techniques used in [13]. The main noticeable difference is the consideration of VBR nature of the traffic which is addressed through the CAC algorithms and the extension to the three state assured service traffic model.

#### A. Premium service MAC scheme analysis

The premium scheme is completely independent of the assured schemes, which greatly simplifies the analysis. The Premium service subsystem can be fully described by two state variables \( \{ R_{ps}, S_{ps} \} \), namely the number of premium service terminals in transmission state and the number of premium service terminals in silence state. Since the number of mobile terminals is finite, the system can be described by the number of terminals in transmission state. The evolvement of the system is modeled as a 1-D discrete-time Markov chain with the imbedded Markov points at the beginning of the
The stationary distribution of the transmission state is denoted as:

$$\boldsymbol{\pi} = \{ \pi(r_{ps}) \} = \{ P(R_{ps} = r_{ps}) \}$$  \hspace{1cm} (3)

In order to find the stationary distribution, a transition probability matrix is required. The transition probability for the transmitting state $P_{ij}^R$ is obtained as:

$$P_{ij}^R = \left\{ P\left(R_{ps}(t+1) = j \mid R_{ps}(t) = i \right) \right\}$$

$$= \sum_{i=\max(0,j-i) \leq N_{ps}} B(N_{ps} - i, j - (i-k), \sigma_c) B(i,k,\eta_R) \quad j < G_{ps}^\infty$$  \hspace{1cm} (4)

$$= \sum_{i=\max(0,j-i) \leq N_{ps}} \sum_{k=0}^{\min(N_{ps},j-i)} B(N_{ps} - i, j - (i-k), \sigma_c) B(i,k,\eta_R) \quad i \leq j$$

where $G_{ps}^\infty$ is the maximum allowable number of premium calls that satisfy the CAC criteria and $B(m,n,p)$ indicates the Binomial distribution:

$$B(m,n,p) = \binom{m}{n} p^n (1-p)^{m-n}$$  \hspace{1cm} (5)

Given the transition probability the stationary distribution for the reservation state is obtained by solving for:

$$\sum_{r_{ps}} \pi(r_{ps}) = 1 \quad \text{and} \quad \pi(r_{ps}) = \pi(r_{ps}) P_{ij}^R$$  \hspace{1cm} (6)

Once the steady stationary distribution has been obtained, we can calculate the expected number of terminals transmitting terminals per frame, or throughput $\bar{p}$, and the blocking probability. The throughput is defined as

$$\bar{p} = \sum_{r_{ps}} r_{ps} \pi(r_{ps})$$  \hspace{1cm} (7)

The blocking probability is defined as follows:

$$P_{ps} = \frac{E[B_{ps}]}{E[R_{ps}]}$$  \hspace{1cm} (8)

where $E[B_{ps}]$ is expected number of blocked premium service calls in a frame, and $E[R_{ps}]$ is the average number of premium service calls arriving in a frame. $E[R_{ps}]$ is determined as follows:

$$E[R_{ps}] = \sum_{r_{ps}=0}^{G_{ps}^\infty} \sum_{z=0}^{N_{ps} - r_{ps}} z B(N_{ps} - r_{ps}, z, \eta_R) \pi(r_{ps})$$  \hspace{1cm} (9)

$E[B_{ps}]$ is similarly obtained as follows:

$$E[B_{ps}] = \sum_{r_{ps}=0}^{G_{ps}^\infty} \sum_{z=0}^{N_{ps} - r_{ps}} z B(N_{ps} - r_{ps}, z, \eta_R) \pi(r_{ps})$$  \hspace{1cm} (10)

\[B. \text{ Assured service MAC scheme analysis}\]

The assured service is dependent on premium service, since it can utilize unused premium capacity in addition to its minimum reserved capacity. The assured service subsystem can be fully described by four state variables $\{T_{AS}, P_{AS}, S_{AS}, R_{ps}\}$, namely the number of temporally admitted assured service terminals, number of permanently admitted terminals, the number of assured terminals in silence state and the number of premium service terminals in reservation state. The number of mobile terminals in the system is finite, therefore the number of terminals in silence state will be $S_{AS} = N_{AS} - T_{AS} - P_{AS}$. The total number of transmitting assured user is given by the sum of users in permanent and temporally states. The stationary distribution for assured service system states is denoted as:

$$\pi(t_{as}, p_{as}, r_{ps}) = \{ P(T_{AS} = t_{as}, P_{AS} = p_{as}, R_{ps} = r_{ps}) \}$$  \hspace{1cm} (11)

Since the number of transmitting premium terminals in reservation state is independent of assured service processes, the stationary distribution of system states is simplified as follows.

$$\pi(t_{as}, p_{as}, r_{ps}) = \pi(t_{as}, p_{as} \mid r_{ps}) \pi(r_{ps})$$  \hspace{1cm} (12)

The stationary distribution $\pi(t_{as}, p_{as} \mid r_{ps})$ is obtained by evaluating a transition probability matrix denoted by $P_{opt}^{AS} = \{ P\left(t_{as}' = n, p_{as}' = m \mid t_{as} = i, p_{as} = j \right) \}$, conditioned on the number of premium service users $R_{ps} = r_{ps}$ in reservation state. The variables $(t_{as}', p_{as}')$ denote the number of terminals in TM and PM states in the current frame, and $(t_{as}', p_{as}')$ in the next frame. The transition probability matrix for assured call process is determined as follows:

Firstly, consider $m < G_{ps}^\infty$, when all assured terminals from TM state and new calls are admitted, and consequently $n = 0$, where $G_{ps}^\infty$ is the maximum allowed number of assured calls. Then,

$$P_{opt}^{AS} = \sum_{i=\max(0,N_{ps}-m)}^{\min(N_{ps},N_{ps}-m)} \sum_{k=0}^{N_{ps} - i - j + k} B(N_{ps} - i - j + k, \sigma_{as}, B(j,k,\eta_R) \Phi(i,l)$$  \hspace{1cm} (13)

where $k$ is a dummy variable representing the number of calls terminating in frame $t + 1$, and $\Phi(i,l)$ is the probability that among the $i$ terminals in temp state at frame $t$, $l$ terminals are converted from TM state to PM state in frame $t + 1$. In these
case \( l = i \) and \( \Phi(i, l) = 1 \) at this value. It follows that \( P_{\text{new}i}^{\text{AS}} \) can simply be obtained as:

\[
P_{\text{new}i}^{\text{AS}} = \min_{j, N_{\text{AS}} - i - j, m + k - (i + j) \in \sigma_{\alpha}} B(N_{\text{AS}} - \eta_{\text{AS}})B(j, k, \eta_{\text{AS}}) \sum_{i=0}^{N_{\text{AS}} - m - (\eta_{\text{AS}} - 1)} \Pr(a_{i}, a_{j} | i, j).B(j, k, \eta_{\text{AS}}) \tag{14}
\]

For the case, \( j \leq m = G_{\text{max}}^{\text{au}} \) and \( n < E_{\text{max}} \), some of the assured calls in TM state during frame \( t \) are converted to PM state and all new calls are admitted to TM state. \( E_{\text{max}} \) is the maximum number of assured calls that the system can admit under TM state, and is determined as \( E_{\text{max}} = G_{\text{max}}^{\text{au}} - r_{\text{p}} \).

Considering the PM state, the total number of call arrivals from silence and TM states in frame \( t + 1 \) is \( G^{\text{au}}_{\text{max}} - j + k \). Let \( l \) denotes the number of calls from the temp state who are converted to perm state, then the number of call arrivals from silence to perm state is given by

\[
a_{l} = n + l - i \tag{15}
\]

The total call arrivals from silence state is

\[
a_{l} = n + G_{\text{max}}^{\text{au}} + k - (i + j) \tag{16}
\]

Then,

\[
P_{\text{new}i}^{\text{AS}} = \min_{j, N_{\text{AS}} - i - j, m + k - (i + j) \in \sigma_{\alpha}} B(N_{\text{AS}} - \eta_{\text{AS}})B(j, k, \eta_{\text{AS}}) \sum_{i=0}^{N_{\text{AS}} - m - (\eta_{\text{AS}} - 1)} \Pr(a_{i}, a_{j} | i, j).B(j, k, \eta_{\text{AS}}) \tag{18}
\]

where,

\[
\Pr(a_{i}, a_{j} | i, j) = B(N_{\text{AS}} - i - j, n + G_{\text{max}}^{\text{au}} + k - (i + j), \sigma_{\alpha}).
\]

Since \( l \) is deterministic,

\[
\Phi(i, l) = \begin{cases} 
1 & \text{if } l = G_{\text{max}}^{\text{au}} + k - j \\
0 & \text{Otherwise}
\end{cases} \tag{19}
\]

Therefore, for all legal values of \( l \):

\[
P_{\text{new}i}^{\text{AS}} = \min_{j, N_{\text{AS}} - i - j, m + k - (i + j) \in \sigma_{\alpha}} B(N_{\text{AS}} - \eta_{\text{AS}})B(j, k, \eta_{\text{AS}}) \sum_{i=0}^{N_{\text{AS}} - m - (\eta_{\text{AS}} - 1)} \Pr(a_{i}, a_{j} | i, j).B(j, k, \eta_{\text{AS}}) \tag{21}
\]

For \( j \leq m = G_{\text{max}}^{\text{au}} \) and \( i \leq n = E_{\text{max}} \), some of the new calls are blocked. Thus,

\[
P_{\text{new}i}^{\text{new}} = \sum_{i=m}^{j} \sum_{i=0}^{N_{\text{AS}} - m - (\eta_{\text{AS}} - 1)} \Pr(a_{i}, a_{j} | i, j).B(j, k, \eta_{\text{AS}}) \tag{22}
\]

Due to the constraint that the reserved capacity for assured should be fully occupied for terminals to be temporally admitted on premium capacity, the following cases for transition probability will be illegal:

For \( m < G_{\text{max}}^{\text{au}}, n > 0 \) or \( j < G_{\text{max}}^{\text{au}}, i > 0 \)

\[
P_{\text{new}i}^{\text{new}} = 0 \tag{23}
\]

Given the transition probability, the stationary distribution of the temp state and perm state is obtained by solving for:

\[
\pi_{\text{temp}} = \sum_{i=0}^{N_{\text{AS}} - m - (\eta_{\text{AS}} - 1)} \Pr(a_{i}, a_{j} | i, j).B(j, k, \eta_{\text{AS}}) \tag{24}
\]

Using the stationary distribution the following performance metrics are derived, throughout \( \Phi \):

\[
\Phi = \sum_{r_{p}=0}^{G_{\text{max}}^{\text{au}}} \sum_{r_{p}} \sum_{r_{p}=0}^{G_{\text{max}}^{\text{au}}} \pi_{\text{temp}}. \pi_{\text{perm}}. \Phi_{\text{perm}} \tag{25}
\]

The assured service blocking probability is defined as follows:

\[
P_{b}^{\text{AS}}(r_{p}) = \sum_{r_{p}=0}^{G_{\text{max}}^{\text{au}}} \pi_{\text{temp}}. \pi_{\text{perm}}. \Phi_{\text{perm}}(r_{p}) \tag{26}
\]

where, \( P_{b}^{\text{AS}}(r_{p}) \) is the assured service blocking probability given the number of on going premium calls. It can be expressed as follows,

\[
P_{b}^{\text{AS}}(r_{p}) = \frac{E[B_{\text{AS}} | r_{p}]}{E[R_{\text{AS}} | r_{p}]} \tag{27}
\]

where \( E[B_{\text{AS}} | r_{p}] \) is expected number of blocked assured service calls in a frame, and \( E[R_{\text{AS}} | r_{p}] \) is the average number of assured service calls arriving in a frame. \( E[R_{\text{AS}} | r_{p}] \) is determined as follows,

\[
E[R_{\text{AS}} | r_{p}] = \sum_{r_{p}=0}^{G_{\text{max}}^{\text{au}}} \sum_{r_{p}} \sum_{r_{p}=0}^{G_{\text{max}}^{\text{au}}} xB(N_{\text{AS}} - t_{\text{as}} - p_{\text{as}}, x, \sigma_{\alpha}) \pi(t_{\text{as}}, p_{\text{as}}, r_{p}) \tag{28}
\]

While, \( E[B_{\text{AS}} | r_{p}] \) is obtained as follows:
\[ E[B_{AS} | p_{as}] = \sum_{p_{as}} \sum_{t_{as}=0}^{P_{as}} \frac{1}{(t_{as}+p_{as})+k+b} \times \sum_{k=0}^{t_{as}} \Pr(k | p_{as}) \times \sum_{t_{as}=0}^{P_{as}} \sum_{b=0}^{P_{as}} \Pr(b | t_{as}, p_{as}, k) \times \Pr(t_{as}, p_{as}, r_{as}) \]  

(29)

where,

- \[ \Pr(b | t_{as}, p_{as}, k) = \]

- \[ B(N_{ps} - t_{as} - p_{as}, G_{max}^{as} + E_{max} - (t_{as} + p_{as}) + k + b, \sigma_{as}) \]

and \[ \Pr(k | p_{as}) = B(p_{as}, k, \eta_{as}) \]

V. PERFORMANCE RESULTS

A. Protocol Parameters

The performance results are based on the network parameters as shown in Table 1.

Table 1: Simulation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chip Rate</td>
<td>20 MHz</td>
</tr>
<tr>
<td>Spreading Gain</td>
<td>62.5</td>
</tr>
<tr>
<td>Basic rate</td>
<td>32 kbps</td>
</tr>
<tr>
<td>Premium packets/frame</td>
<td>1,2,3,4,5,6,7,8</td>
</tr>
<tr>
<td>Assured packets/frame</td>
<td>1,2,3,4,5</td>
</tr>
<tr>
<td>Frame duration</td>
<td>20 ms</td>
</tr>
<tr>
<td>Average call holding time</td>
<td>3 mins</td>
</tr>
<tr>
<td>Time slots/frame</td>
<td>4</td>
</tr>
<tr>
<td>Code channels/time slot</td>
<td>20</td>
</tr>
<tr>
<td>Capacity (code channels)</td>
<td>80</td>
</tr>
<tr>
<td>(N_{ps}, N_{as})</td>
<td>30, 50</td>
</tr>
</tbody>
</table>

B. Results

Fig. 4 shows the throughput for premium versus arrival rate for various maximum guaranteed capacities \(G_{max}^{ps}\). The throughput increases as the arrival rate increase (or offered traffic load increases). For heavy premium traffic load, the throughput reaches saturation, since most new calls are blocked.

In Fig. 5, the blocking probability for new premium calls due to the CAC procedures is shown versus call arrival rate. As the call arrival rate increases, the expected call blocking probability increases. To maintain the admitted calls below the allowable channel limit, the blocking probability will be high for high traffic loads. From the results it is also noticed that when the maximum capacity available for premium service is minimized, the blocking probability increases. Analytical results are compared with simulation results to justify the correctness of the analytical model.

Fig. 6 shows the premium blocking probability vs. \(G_{max}^{ps}\) considering three call arrival rates which are \(1 \times 10^{-5}\), \(5 \times 10^{-5}\) and \(10 \times 10^{-5}\). As the maximum guaranteed capacity increases more calls are admitted and therefore low blocking probability.

The performance of assured service derived from the analytical model is illustrated in Fig. 7 and Fig. 8. Assured service MAC scheme is partly depended on premium service, therefore we illustrate the performance considering three premium call arrival rates which are \(1 \times 10^{-5}\), \(5 \times 10^{-5}\) and \(0.2 \times 10^{-5}\). For low premium service load, more capacity is available to assured service, therefore higher throughput.
Similarly to premium service, throughput increases with traffic load and saturates at high traffic loads. In Fig. 8 the assured service blocking probability due to CAC is shown vs. call arrival rate.

![Fig. 7: assured service throughput vs. call arrival rate](image)

![Fig. 8: assured service blocking probability vs. call arrival rate](image)

**VI. CONCLUSION**

A novel MAC protocol for wireless IP networks was proposed. Since bandwidth is a scarce resource in wireless communication systems, our emphasis is to design a bandwidth efficient protocol. The protocol performance in terms of throughput and call blocking probability was evaluated through Markov analysis.

Results show the expected throughput and blocking probability as the traffic load increases.

**REFERENCES**


Simon B. Mahlaba completed his BScEng degree in December 2002 in the School of Electrical and Information Engineering at the University of the Witwatersrand, Johannesburg. He is currently doing his Masters degree, researching on MAC protocols for wireless IP networks in the Radio Access Technology Research Centre at the University of KwaZulu-Natal.

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