Using Power Priorities to Improve Slotted ALOHA in Wireless Networks with QoS Guarantees

Jaime Sánchez*, José R. Gallardo, Jorge Flores Troncoso
Electronics and Telecommunications Department, CICESE Research Center
Km. 107 Carretera Tijuana-Ensenada, Ensenada, B.C., México 22860

Abstract – A fundamental part of a wireless system is the MAC protocol, whose main goal is to let the users quickly and orderly gain access to the needed bandwidth to transmit their information. The main problem in wireless communications is to overcome the disadvantage of the hostile characteristics presented by the radio channel. This paper deals with the proposal of a retransmission Algorithm based on Power Priorities (RAPP), to be used along with S-ALOHA for the retransmission of the request packets sent by remote terminals to a base station (BS) in a WATM network. WATM is used in this work as a test platform, but RAPP is general enough to be applied in other scenarios as well. The performance of RAPP is analyzed and compared with that of the Binary Exponential (BE) retransmission algorithm, highlighting the advantages presented by RAPP in a WATM environment.

Keywords: RAPP, S-Aloha, capture effect, MAC, QoS, WATM

I. Introduction

Multimedia services offered to wireless terminals are taking an increasing importance in the world society, creating new challenges to the development of wireless telecommunication systems. The potential increase in the demand for multimedia services, especially those related to the downloading of video, images and huge files, is creating the need for the development of new multiple access techniques and the upgrading of the existing ones; all with the goal of increasing the transmission rate along with obtaining a better spectral efficiency on the radio channels. There are several technologies converging towards this future Broadband Wireless Communications System: Wireless LAN's (IEEE 802.11(a&b), Bluetooth), Wireless ATM (HiperlanII) and, to some extent, 3rd generation cellular networks. Both IEEE 802.11b and Bluetooth use Spread Spectrum techniques in the 2.4 GHz band [1] [2]; the former with DSSS and the latter with FHSS. Hiperlan II and IEEE 802.11a use OFDM, the first operates in the 5.150-5.350 or 5.470-5.725 GHz bands [2], and the second in the 5.150-5.250 or 5.250-5.350 GHz bands [3]. Third generation cellular standards use W-CDMA, CDMA-2000, and TD-SCDMA, all in the 1.8 GHz band [4] [5].

Among the Wireless network options, the Wireless Asynchronous Transfer Mode (WATM) is considered as one of the dominant technological alternatives due to its ability of handle several traffic types, each with its negotiated QoS. One of the main challenges faced by the WATM technology is to be able to share a limited-bandwidth radio channel among the maximum number of users without violating the QoS agreement, especially important for those with real time applications. In addition to the limited bandwidth, the radio channel suffers from interference, fading, shadowing, etc. Several medium access control (MAC) protocols have been proposed regarding this problem [6].

Most of the MAC proposals for Wireless ATM use some form of TDMA, with Slotted ALOHA as the random access protocol for bandwidth reservation from remote terminals to a base station. A very important part of the random access protocol lies on the retransmission algorithm, especially for WATM, due to its direct incidence on the average delay for the terminals to reach the base station and receive an acknowledgement (ACK) to their request.

In this paper, the performance of a new retransmission algorithm based on Power Priorities (called RAPP) is analyzed, and compared with the performance of the well known Binary Exponential retransmission algorithm. The channel model considered is one with Rician fading, since a picocell environment is assumed with line of sight from terminals to base. Furthermore, capture effect is considered in the receiver. Capture refers to the ability of a receiver to successfully receive a transmission from a given station when multiple stations are transmitting simultaneously.

The Capture effect has been thoroughly studied since the development of FM radio broadcast, and a good definition for the case of digital modulation is given by Linnartz in [7], p. 194. The capture probability depends on received power levels, type of modulation, robustness of receiver synchronization, interference characteristics, and channel fading.

The framework for the simulation of the RAPP algorithm is a TDMA/TDD access scheme, with a fixed frame size of 64 slots. The first up-link slot is converted into four mini-slots, from which the first mini-slot is reserved for turnover time, and the remaining 3 mini-slots are used for transmission of request packets in a random access mode. For high traffic conditions, the second up-link slot is also converted into four mini-slots, providing the terminals with seven random access channels. This access scheme is described in detail in [8].

As part of this framework, a scheduling mechanism that assigns slots to the terminals in a frame by frame basis was developed for the basestation; it allows and promotes the satisfaction of QoS guarantees for voice, data, and video services. The scheduler handles the five standardized types of services (CBR, rt-VBR, nrt-VBR, ABR, and UBR), assigning priorities according to table 1, where a bigger number implies a higher priority. These service types are defined in [9]. A fisht stage of service differentiation is done within the RAPP algorithm, as explained in section I-B.

<table>
<thead>
<tr>
<th>Type of Service</th>
<th>CBR</th>
<th>rt-VBR</th>
<th>nrt-VBR</th>
<th>ABR</th>
<th>UBR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Priority</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

TABLE 1

PREFERENCES FOR THE DIFFERENT TYPES OF SERVICES IN ATM

* This paper was developed within a project financed by the Mexican Science and Technology Council (CONACYT) under grant 38833-A.

* Corresponding author. Tel: +(52-646) 175-0555. Fax: +(52-646) 175-0554. E-mail: jasan@cicese.mx

0-7803-7547-5/02/$17.00 © 2002 IEEE

409
A. Establishing priorities using different power levels

The key idea behind RAPP is to help those terminals that have failed to reach the receiver on the request procedure. After each failure, the set of power levels from which a contending terminal may randomly choose is increased, until a predetermined limit. Giving a terminal the opportunity to use a higher transmission power increases its capture probability at the receiver. At the same time, by potentially increasing the power level after each retransmission, the fairness in serving first the earlier requesting terminals is assured to some extent. It is not completely assured due to the randomness of a fading channel (simulation results have shown that the Capture probability approaches 0.9 even with a difference of 12dB favoring the high-priority terminal [8]).

Thus, an important motivation to use the RAPP algorithm is to take advantage of the capture effect, which has been shown to increase the throughput of the S-ALOHA protocol [10]. Using different power levels has the advantage, as compared to backoff mechanisms, that no waiting periods are necessary and still one of the terminals has a very good chance of success. The induction of the capture effect, by means of controlling the transmitter power, has been previously considered by at least two research groups [11], and [12]. However, both pieces of work may be considered to be of general application, since none of them takes into account the QoS restrictions imposed by a Wireless ATM network, such as the need to guarantee a maximum delay, and a Cell Loss Ratio, which may be met by the use of priorities. Another aspect related to QoS is the necessity to limit the maximum number of retransmissions, which is very important for delay-sensitive services.

We propose the following rule to specify the different power levels \( \{ P_1, P_2, \ldots, P_m \} \) to be used in the RAPP algorithm so that contenders that have waited longer still have an advantage over newer ones, regardless of the total number of contenders and the power levels they are using. It agrees with [13] and [14], in which the authors show that the logarithmic spacing of power levels gives a better performance than linear spacing:

\[
P_i = z \cdot P_{i-1} \quad \text{for} \quad 2 \leq i \leq m
\]

(1)

Then the number of available power levels is given by:

\[
m = \log_z \left( \frac{P_m}{P_1} \right) + 1
\]

(2)

This results in a power vector as follows

\[
[ P_1, P_2, \ldots, P_m ] = [ P_1, z \cdot P_1, z^2 \cdot P_1, \ldots, z^{m-1} \cdot P_1 ]
\]

(3)

As an example, if we assume that \( P_1 = 0.625 \) mW, \( P_m = 160 \) mW, and that \( z = 2 \) to achieve capture, the power vector generated is the one shown in table 2. Some results of this analysis have been presented in [15].

<table>
<thead>
<tr>
<th>P1 (mW)</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
<th>P7</th>
<th>P8</th>
<th>P9</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.625</td>
<td>1.25</td>
<td>2.50</td>
<td>5</td>
<td>10</td>
<td>20</td>
<td>40</td>
<td>80</td>
<td>160</td>
</tr>
</tbody>
</table>

The \( m \) power levels are determined according to the minimum \( (P_1) \) and maximum \( (P_m) \) allowed transmission power levels for the terminals in a picocell. The minimum power \( (P_1) \) must satisfy the SNR and BER constraints, while the maximum power \( (P_m) \) is determined by international standards. Assuming a given \( P_1 \) and \( P_m \), the minimum power level to be used by a terminal \( (P_i) \) should be above \( P_1 \), while the maximum power level \( (P_m) \) should be below \( P_m \). \( P_i \) will depend on the distance between the mobile terminal and the base station, and so will the \( m \) power levels to be used by the mobiles. They will be adjusted accordingly by the power control mechanism being used by the mobiles, which can be similar to the one used in CDMA wireless networks.

B. RAPP Algorithm

As mentioned above, this paper deals with the proposal of an algorithm for the retransmission of the request packets sent by remote terminals to a base station in order to reserve bandwidth to send its application information.

Two priorities are defined in this protocol; the higher priority is for real-time applications (CBR, and rt-VBR), and the lower priority is for non real-time applications (nrt-VBR, ABR, and UBR). The set of power levels is divided into two subsets, each corresponding to one of the priorities. Let us say that the subsets are: \( \{ P_1, P_2, \ldots, P_1 \} \) for low-priority and \( \{ P_{\text{1+1}}, P_{\text{1+2}}, \ldots, P_{\text{n}} \} \) for high-priority terminals.

In its first attempt, each terminal will send its request through one of the request slots using the lowest allowable power level corresponding to its priority \( (P_1 \text{ or } P_{\text{1+1}}) \). After each collision, the terminal will select a new power level from among those allowed by the RAPP protocol according to its priority level and the number of failed attempts.

Based on the guidelines in [16], the operation of the retransmission algorithm is as follows:

- If the mobile terminal (MT) corresponds to a high-priority service, it will select between \( P_{\text{1+1}} \) and \( P_{\text{1+2}} \) in its first retransmission. After each new collision, it will add to the allowable set the power level that is right above the highest one the set currently has. When there are no more power levels to add, the MT will limit itself to using one of the two highest power levels \( (P_{\text{1+1}} \text{ and } P_{\text{n}}) \). If the MT fails to reach the BS again, the process is stopped for a random time selected from the set \( \{ T, 2T, 4T \} \), where \( T \) is a frame duration. After this silence, if the packet has not expired, the station will start trying again, choosing between the two highest power levels. If transmission is again unsuccessful after a predetermined number of attempts \((m-k)\), it will stop again for a period selected from the set \( \{ T, 2T, 4T \} \), and so on.

- If the mobile terminal (MT) corresponds to a low-priority service, on the other hand, it will select between \( P_1 \) and \( P_2 \) in its first retransmission. After each new collision, it will shift the allowable set upwards, but still keeping 2 options in the set. When it is not possible to move upwards, \( i.e. \), when \( P_1 \) is already a member of the allowable set, the MT will transmit one last time using \( P_2 \), and then, if the transmission is again unsuccessful, it will stop sending requests for a random time. When this
happens, we say that a cycle has been completed. The process is restarted later, repeating the procedure from the first retransmission. The set from which the random waiting period is selected is defined using the following rule: if the number of cycles \( C \) is odd, then the set is \{27, 4T, \ldots, 2^{C+1} \cdot T\}, whereas if the number of cycles is even, the set has only one option, which is 256 \( T \).

The above procedure is shown in figure 1. In all cases, regardless of the priority the MT belongs to, it will randomly select its power level considering that all the options in the allowable set are equally likely.

![Figure 1. Power levels for the RAPP algorithm](image)

FIGURE 1. POWER LEVELS FOR THE RAPP ALGORITHM

Note that for RAPP there is no differentiation among MTs that correspond to the same priority group. This implies that CBR and rt-VBR users share the same privileges and so do nrt-VBR, ABR, and UBR users. However, RAPP has to do with the delivery of requests to the basestation only. It is the responsibility of the scheduler at the basestation to make sure that the five priorities shown in table 1 are respected when it comes to actually allocating bandwidth.

A more detailed explanation of the RAPP algorithm can be found in the Master of Science thesis reported in [17].

II. Slotted ALOHA in Rician fading

The achievable throughput \( S \) in a Slotted ALOHA environment under traffic generated according to a Poisson process with average arrival rate \( G \) is given by:

\[
S = G \cdot Pr[NC] = G \cdot e^{-G} \tag{4}
\]

where NC is an abbreviation for “No Collision”. When capture is taken into account:

\[
S = G \cdot \left(Pr[NC] + \sum_{n=1}^{\infty} Pr[\text{Capture}\mid C_n] \cdot Pr[C_n]\right) = G \cdot e^{-G} \left(1 + \sum_{n=1}^{\infty} \frac{G^n}{n!} \cdot Pr[\text{Capture}\mid C_n]\right) \tag{5}
\]

In the previous equation the abbreviation \( C_n \) is used to denote collision with \( n \) contenders. According to [15], the capture probability is given by:

\[
Pr[\text{Capture}\mid C_n] = 1 - e^{nk} e^{-Gz} \sum_{i=0}^{\infty} \left(\frac{nK}{k!}\right)^{i} \frac{(A \cdot z)^{i}}{i!} \tag{6}
\]

where \( A \) and \( K \) are parameters of the Rician distribution that governs fading, and \( z \) is the power of the signal transmitted by a single user divided by the capture threshold \( z \). Finally, when several \( (M) \) mini-slots are provided and the users are allowed to choose randomly among them, the total load \( G \) is evenly divided among the mini-slots, which results in the following expression for the throughput per mini-slot:

\[
S = \frac{G}{M} \cdot e^{-G/M} \left(1 + \sum_{n=1}^{\infty} \left(\frac{G/M}{n!}\right)^{n} \cdot Pr[C_n]\right) \tag{7}
\]

III. Performance analysis

The number of simulated scenarios was 18, increasing each time the number of mobile terminals, but keeping the same traffic generating characteristics of each one in order to force a heavier traffic on each successive run. Roughly 70% of the load corresponds to high priority traffic in all cases. The same set of simulations were run using both RAPP and the BE retransmission algorithms in order to fairly compare the performance of both approaches.

A. Simulation Assumptions

The main assumptions for our simulations were that Rician fading and capture effect are present in the wireless channel, that the packet length is equal to that of an ATM cell, and that an ATM cell is always transmitted without error after the corresponding request packet has been acknowledged by the BS. The last assumption is made so that the simulation results reflect only the behavior of the retransmission algorithms.

The following assumptions were made as well:

1. The limit between the up-link and the downlink sub-frame was considered variable, with a dynamic algorithm (DAL) determining the limit at each frame. This algorithm has been reported in [18], and its explanation is outside the scope of this work.
2. The number of contention (mini) slots is variable, equal to 3 or 7, as determined by the DAL.
3. Only the up-link radio communication section was simulated, and we used direct delivery of packets for the downlink (base to terminals) messages.
4. The number of terminals varies between 25 and 250, each generating only one type of traffic (CBR, rt-VBR, nrt-VBR, ABR, or UBR) with a unique WVCI.
5. A pico-cell with radius equal to 200 meters is used for each generating only one type of traffic (CBR, rt-VBR, nrt-VBR, ABR, or UBR) with a unique WVCI.
6. There is line of sight between all terminals and the base.
7. The mean request arrival rates are:
   - CBR = 30 calls/hour
   - rt-VBR = 25 frames/sec (MPEG file)
   - nrt-VBR, ABR, and UBR = 2 requests/sec (exponentially distributed interarrival time)
8. The capture threshold is \( z = 2 \)

B. Simulation Results

We created all of our models using OPNET (OPtimized Network Engineering Tools). Two sets of 18 simulations were run, each 200 seconds long. The first set corresponds
to RAPP and the second corresponds to the binary exponential (BE) retransmission model. The measured parameters are:

- **Offered traffic** is the combined traffic created by the 5 types of traffic generators.
- **Generated traffic** (G) is the combined traffic, created by the 5 types of traffic generators, plus retransmissions.
- **Throughput** (S) is a measure of the effective utilization of the request channels. The maximum throughput (value equal to 1) corresponds to the reception at the BS of 3 or 7 successful request packets per frame.
- **Lost request packets** indicates the percentage of rt-VBR request packets, sent by all the terminals, and lost during the random access request procedure.
- **Average delay of request packets** (D) is the time from the creation of the packet at the mobile to its successful arrival at the base. The average delay was computed separately for packets corresponding to real-time applications and non-real-time applications.

The results of our simulations are summarized in several plots, which are explained next.

**Average throughput.** Figure 2 shows the behavior of the throughput (S) versus generated traffic (G) considering all the terminals during each one of the 18 runs, for both the RAPP and the BE cases. As can be seen from the figure, the throughput achieved with RAPP is greater than that of BE, reaching a maximum value of 0.65 against a maximum of 0.56 for BE. The embedded Dynamic Algorithm assigns 7 mini-slots for most high traffic situations, which means that a throughput of 0.65 corresponds to around 4.5 out of 7 possible packets being correctly received per frame. Figure 2 also shows the theoretical throughput as a function of G, from equation (7), for different values of the number of available mini-slots (M = 3, 6, and 7). It is important to note that there is a remarkable agreement between the maximum throughput achieved with RAPP and the theoretical maximum. Also remarkable is the fact that the theoretical curve for M = 6 (most likely the average number of mini-slots used during each simulation) is almost identical to the RAPP results, up to values of G around 9.

**Delay for high-priority terminals.** Figure 3 shows the plots of the delay versus G for the high-priority terminals (CBR, and rt-VBR), during each one of the 18 runs, for both the RAPP and the BE cases. As can be seen from the figure, the delay for the RAPP algorithm remains very low (between 1.5 and 2.3 msec), while the delay for the BE case increases sharply for load values bigger than 2 pkts/frame, reaching values of up to 9 msec.

**Delay for low-priority terminals.** Figure 4 shows the plots of the delay versus G for the low-priority terminals (nrt-VBR, ABR, and UBR) for both the RAPP and the BE cases. Both plots have very similar behavior since they correspond to the traffic that is not benefited by the priority scheme. It can be seen that the delay remains very low (less than 1 msec) for load values of up to 7 pkts/frame and that beyond this load the delay increases sharply. This behavior is due to the fact that when the number of requests is excessive, collisions occur very often, which means that most of the requests have to be sent more than once before being received successfully.

**Losses for high-priority terminals.** Figure 5 shows the number of request packets lost versus traffic load for the high-priority terminals for both RAPP and BE. In the case of RAPP, the number of lost packets remains at zero for load values of up to 9, while in the BE case the system starts losing packets for a load value of 1 pkts/frame and gets even worse when the load is greater than 3 pkts/frame.
In this paper, the performance of a Retransmission Algorithm based on Power Priorities (RAPP) has been analyzed as a complement to the S-ALOHA random access method. The framework for this project was a TDMA/TDD multiple access scheme proposed for WATM, with a focus on the transmission of up-link request packets. For comparison purposes, a set of simulations with the same parameters but substituting the RAPP with the Binary Exponential (BE) algorithm were also performed.

Simulation results showed that, for real-time terminals, the delay for the RAPP algorithm remains very low (less than 2.3 msec) even for traffic values of up to 12 pkts/frame. However, the delay for BE increases sharply for traffic values bigger than 2 pkts/frame. Moreover, the number of lost packets for RAPP remains at zero even for load values of up to 9 pkts/frame, while in the BE case, the system starts losing packets for a load value of 1 pkts/frame. These results verify the superior performance of RAPP against the BE algorithm regarding the most important parameters for real-time traffic: packet delays and losses.

The QoS parameters related to the application information (cell losses and delays) were not evaluated, since this research focused on the random delay and losses experienced by request packets only.

A possible interesting extension to this work would be the performance analysis of the RAPP algorithm in other environments, such as a CDMA/TDD, CDMA/OFDM, or any of the approaches used by the emerging technologies.

**References**


