Packet Reservation Multiple Access (PRMA) for Joint Speech and Data Systems

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Abstract. Packet Reservation Multiple Access (PRMA) can be viewed as a combination of TDMA and slotted ALOHA protocols. In PRMA, there are speech and data terminals that communicate with a base station. Downlink packets are scheduled by the base station, but for uplink access (first packet of a talkspurt or any data packet), terminals use slotted ALOHA. Speech terminals (and some data terminals, too) can make slot reservations for future frames. PRMA can also be seen as a kind of statistical multiplexing scheme. Statistical multiplexing gain comes from the fact that speech terminals are equipped with speech activity detectors and thus they transmit packets only during talkspurts.

1 Introduction

Packet Reservation Multiple Access (PRMA) was first introduced in 1988 in IEEE Vehicular Technology Conference. Several papers on PRMA and its variants (from the original authors and other researchers) have emerged since then.

PRMA combines contention and reservations: after gaining access to a channel, “periodic” sources are able to reserve subsequent time slots while “random” sources have to contend for every packet. Both periodic and random sources use contention (basic slotted ALOHA) to gain access.

This report does not present any new research results – it only tries to cover the fundamentals of Packet Reservation Multiple Access and the most important enhancements to the scheme. The rest of the report is organized as follows: section 2 explains the basic mechanisms that are used in PRMA and where they come from, section 3 gives performance figures both in ideal conditions and with slow & fading channels, section 4 introduces Integrated Packet Reservation Multiple Access (IPRMA), sections 5 and 6 present some analysis on PRMA and a few suggested modifications, while section 7 concludes the report with discussion.

2 Packet Reservation Multiple Access (PRMA)

Slotted ALOHA

Before going into PRMA, it may be a good idea to go through the basic operation of slotted ALOHA protocol. A good description can be found, for example, in [1].

The pure ALOHA protocol is very simple; a newly generated packet is transmitted immediately hoping that there is no interference. If a collision occurs, every terminal with a collided packet, schedules a retransmission to a random time in the future. Randomness is needed to ensure that the same set of packets doesn’t keep on colliding indefinitely [1].

The slotted ALOHA variation is just the pure ALOHA protocol with a slotted channel. The slot size equals the duration of a packet transmission. Terminals can send packets only at slot boundaries.

PRMA Basics

There are two kinds of traffic sources: voice and data terminals. Voice terminals do not use channel resources all the time, but they have sensitive voice activity detectors and they only transmit packets during “talkspurts”. Since a voice terminal is usually actively transmitting only 40 to 60 percent of the call duration (of course, depending on both the speaker and the voice activity detector), we can use our resources more effectively if we give up using “line reservations” (as in circuit-switched networks).

In Packet Reservation Multiple Access (PRMA) [2, 3, 4], all terminals use a single channel to transmit information packets to a base station. This upstream channel is slotted, and after each upstream transmission (from any terminal), the base station broadcasts an acknowledgment packet (in addition to downstream information packet). We can use either FDMA (Frequency Division Multiple Access – using a different frequency band) or TDMA (Time Division Multiple Access – sharing the channel with upstream traffic) for transmitting downstream traffic (see Fig. 1). In both cases, the base station schedules the downstream traffic and thus no contention is needed.

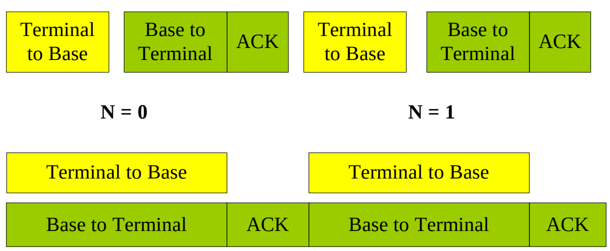

Fig. 1. Both TDMA (upper drawing) and FDMA (lower drawing) can be used for multiplexing upstream and downstream packets.

In PRMA, time slots at a speech terminal are grouped in frames. A slot in a frame can be either “reserved” or “available”. This information is given in the acknowledgement messages sent by the base station. When a talkspurt begins, the terminal uses the well-known slotted ALOHA protocol to contend for an available time slot. After a speech packet is successfully sent in a given slot, this time slot is reserved for future speech packets coming from the same terminal. Thus, there won’t be any collisions with packets from other terminals. After the last packet of the talkspurt is sent, the terminal releases the reservation by leaving the next slot empty.

We have two kinds of information packets in PRMA: periodic information packets and random information packets. The packet type is expressed in packet header using one bit. Speech packets and certain data packets (e.g., those involved in file transfers) are marked as periodic packets while other data packets (e.g., telnet packets) are marked as random packets. Random packets don't make reservations for future packets. With random data only, PRMA is almost identical to slotted ALOHA protocol [1].

Time slots in each terminal are organized in frames with N slots per frame. All terminals use the same N value – it is a system parameter. However, it is not mandatory to agree between all terminals which slot shall be the first in the frame. All terminals have a frame reservation register, which contains the reservation state, represented with one bit, for each slot. Zero stands for unreserved slot while one stands for reserved slot. As said before, this information is broadcasted by the base station.

Contention Scheme and Reservations

Independent of the packet type (periodic or random), all terminals have to first use slotted ALOHA protocol (see e.g., [1]) for contention with other terminals. If the first transmission is unsuccessful (there is a collision), the packet is retransmitted in the subsequent unreserved slots with a certain probability. For speech packets, this probability is q and for data packets r. It is possible to favor speech packets by setting $q > r$ (or vice versa). The contention process continues until the base station sends an acknowledgment about successful reception of the packet. When a periodic packet is successfully transmitted, the terminal obtains a time slot reservation for future packets. Random packets just have to contend for subsequent unreserved time slots.

Terminals refrain from using reserved slots in future frames – a terminal with a reservation has uncontested use of the time slot. When a terminal stops sending periodic information in the reserved slot, the base station broadcasts this event in the acknowledgment packet, and all terminals may contend for that slot in future frames.

Example from [5] nicely illustrates PRMA operation. We present here a modified version of that example (see Fig. 2). We have six time slots per frame, and base station feedback packet for frame (I - 1) tells us that there are four reserved slots in frame I (reserved for terminals 11, 5, 3 and 2). Two slots are still available. At the beginning of frame I, voice terminals 6 and 4 are contending for access to the channel. Since both terminals decide[1] to transmit

[1] A contending voice terminal sends the first packet of a talkspurt in the next available slot with probability q.

in the next available slot (2), there will be a collision. Thus, neither terminal 6 nor terminal 4 obtains a reservation.

	Slot 0	Slot 1	Slot 2	Slot 3	Slot 4	Slot 5
Frame *I*	R11	R5	A	R3	A	R2
Active terminals	11	5	6, 4	-	-	2
Frame *I* + 1	R11	R5	A	A	A	R2
Active terminals	11	5	-	4	6	2
Frame *I* + 2	R11	R5	A	R4	R6	R2
Active terminals	11	5	12	4	6	2

Fig. 2. Speech reservations in PRMA protocol; *Rx* denotes a slot reserved for terminal *x* and *A* denotes an available slot. Active terminals are either contending or using a reserved slot [5].

In slot 5 of frame *I*, both terminals 6 and 4 fail to obtain the permission to send. Thus, they remain in the contending state. While terminals 6 and 4 were contending, terminal 3 released its reservation by sending nothing. The base station feedback packet for slot 3 indicates that there are three available slots in frame (*I* + 1). In frame (*I* + 1), terminals 6 and 4 keep on contending. Terminal 4 obtains a permission to send in slot 4 and terminal 6 in slot 5. Both terminals reserve their slots in the next frame (*I* + 2). In that frame, voice terminal 12 gets lucky – it obtains a permission to send a packet immediately, and since there are no other terminals transmitting in the same slot (2), terminal 12 sends its packet and reserves the slot in the next frame.

Buffers and Packet Loss

While contending for unreserved time slots, a terminal holds packets in a FIFO (First In, First Out) buffer. In case of speech packets, the buffer size is limited to a relatively small value (e.g., 32 ms), because speech is very delay sensitive. Front dropping is used instead of usual tail dropping, because it has been considered less harmful in several listening tests. For random packets, the buffer size can be considerable bigger.

Relation to *R*-ALOHA

PRMA has its roots in (or at least it is closely related to) the reservation ALOHA protocol, *R*-ALOHA [6]. The main difference between *R*-ALOHA and PRMA is that *R*-ALOHA is an explicit reservation protocol (i.e. a portion of the channel capacity is used for making reservations by sending reservation packets) and PRMA is an implicit reservation protocol, which means that the reservation channel is not allocated [7]. Moreover, in *R*-ALOHA, we don't make a difference between voice and data sources – they can all make reservations.

Reservation ALOHA consists of two phases. In the reservation phase, the terminals use slotted ALOHA to transmit small (relative to data[2] packets) reservation packets. A terminal that is able to transmit its reservation packet successfully (no collision) reserves the channel for subsequent data packet transmission. The reservation phase lasts as long as it takes to transmit a reservation packet successfully. In the data transfer phase, the terminal can transmit the data packet without contention because the channel is reserved for it.

Suzuki *et al*. have made a performance comparison [7] between PRMA and a variant of *R*-ALOHA (ALOHA-Reservation protocol). According to their results, the difference in performance (maximum number of terminals that can share a channel) is small.

3 PRMA Performance

PRMA Performance in Ideal Conditions

The performance of PRMA in ideal conditions has been studied at least in [2, 3, 4]. These studies included speech terminals only. PRMA parameter values in the initial study [2] are listed in Table 1.

Table 1. Initial PRMA parameters [1]

Parameter definition	Notation	Value
Channel rate	R_C	720 kbps
Voice source rate	R_S	32 kbps
Frame duration	T	16 ms
Overhead	H	64 bits
Speech activity detector	slow/fast	fast
Maximum delay	D_{max}	32 ms
Voice permission probability	q	0.1
Conversations	M	variable

[2] In this context, "data" can be voice, too.

The follow-up paper [3] examined the effect of several parameters on PRMA performance. The conclusion was that parameters such as voice permission probability (q = 0.3 was adopted) and frame duration have a substantial effect on PRMA bandwidth efficiency.

According to the results of [4], PRMA is able to support 26 to 39 (depending on the strength of the capture phenomenon) simultaneous conversations (speech coded at 32 kbps) on a 720 kbps channel. This was compared with the performance of TDMA system without speech detectors and no overhead. With these assumptions, TDMA can support 720/32 = 22.5 simultaneous conversations.

The performance of PRMA with both speech and data terminals has been studied in [8]. The system parameters used are listed in Table 2. Simulations show that the channel considered in earlier PRMA studies (720 kbps) is able to carry 33 speech conversations (32 kbps) along with 33 random data signals each having an average rate of 1.2 kbps and maximum tolerable delay of 250 ms. Of course, these results depend on the permission probabilities for speech (p_s, q in earlier publications) and data (p_d, r in earlier publications).

Table 2. PRMA parameters for speech and data [7]

Parameter definition	Notation	Value
Channel rate	R_C	720 kbps
Voice source rate	R_S	32 kbps
Data source rate	R_D	1.2 kbps
Frame duration	T_p	16 ms
Overhead	H	64 bits
Maximum voice delay	D_{max}	32 ms
Voice permission probability	p_s	0.3
Data permission probability	p_d	Variable

With random data only, PRMA has performance very close to slotted ALOHA with an infinite number of terminals (throughput of 0.358). With speech only, a result similar to earlier studies was observed: 37 simultaneous conversations (equivalent to a throughput of 0.79).

PRMA Performance with Slow and Fading Channels

In [9], the ideal conditions are abandoned and the effect of channel impairments (i.e. slow and fast fading channels) on PRMA performance is taken into account. The study was done with speech terminals only.

Moreover, it was assumed that the downlink acknowledgments (from base station) were always received correctly.

When the uplink header error rate was 10^{-2}, the number of carried conversations dropped from 36 to 35. However, when the error rate increased to 10^{-1}, only 22 conversations could be carried with the required 1% packet dropping probability. This is mostly due to base station's inability to decode the packet header correctly. When such an event happens, the base station doesn't know whether zero, one or multiple terminals just transmitted packets and thus it announces the current slot available in the next frame. This can lead into lost reservations.

In section 6 of this paper, the proposed solution for this problem is to (slightly) modify the PRMA protocol. However, the authors of [9] (Jalloul, Nanda and Goodman) show that it is possible to achieve the desired packet header error rate of less than 10^{-2} with relatively simple error correction coding and selection diversity. Thus, no changes to PRMA protocol are necessary.

4 Integrated Packet Reservation Multiple Access (IPRMA)

Papers [10], [11] and [12] (all co-authored by Goodman, the first author of the early PRMA papers) describe an enhanced version of PRMA – Integrated Packet Reservation Multiple Access (IPRMA).

Integrated Packet Reservation Multiple Access protocol provides a reservation mechanism for both speech and data packets. In IPRMA, speech terminals are allowed to contend for reservation slots on a frame-by-frame basis while data terminals may reserve multiple slots across a frame to increase throughput. Since speech packets have stricter delay requirements than data packets, IPRMA has a priority mechanism, which ensures that speech terminals have easier access to idle slots. According to authors (Wong and Goodman), these enhancements lead into fewer collisions, which results in improvements in overall system performance while significantly increasing data throughput compared to a system without data packet reservation (basic PRMA) [10].

The assumptions that were used with PRMA (multiple terminals communicating with a base station, base station schedules downstream traffic etc.) hold also for IPRMA.

Speech Packet Reservations

The reservation mechanism for speech packets is identical to the one used in PRMA [2, 3, 4]: when a speech terminal produces a talkspurt, slotted ALOHA is used for contending the next idle slot. After a successful attempt, the base station reserves a time slot for this terminal to be used for subsequent packets. The reservation is released when the terminal does not have any more packets to send.

The probability that a packet is retransmitted in the subsequent unreserved slots has a new name: permission probability, p_s (vs. q in early PRMA papers).

Data Packet Reservations

When a data terminal has packets to send, it contends idle slots in the same manner as a speech terminal. Permission probability for data packets, p_d (r in early PRMA papers), can be different from permission probability of speech packets.

In the basic PRMA, each data packet must contend for access. The primary goal of IPRMA is to use idle slots in a more effective manner in order to increase throughput of data sources.

Each terminal knows the locations and number of idle slots in the frame, because this information is broadcasted by the base station. Thus, it is possible for a data terminal having several packets ready for transmission to indicate the number of idle slots it wants to reserve in the contending packet (cannot exceed the number of buffered packets in the terminal). In order to ensure fairness and give priority to speech terminals, the number of slots that a data terminal can reserve is limited.

In the example given in [10], we have a frame of N slots and k ($k \leq N$) idle slots. If we have a speech priority of M ($M \leq N$) slots, a data terminal cannot reserve more than (k - M - 1) slots excluding the currently contending data packet. This reservation mechanism uses a “sliding window” principle, where the current idle slot in contention is the first of a window of N slots.

If there are no other terminals contending for the currently idle slot, the data terminal has succeeded. It will transmit its first data packet and reserve the next (k - M - 1) idle slots (or less than that, if the number of buffered packets is smaller). When the slots are consumed (and there are still packets in the buffer), the above procedure has to be repeated.

This mechanism provides higher throughput for data terminals – particularly under light load – while ensuring access to speech terminals.

The presented reservation scheme is illustrated in Fig. 3 [10]. The scheme can be seen as a one that provides "vertical reservations" to speech terminals and "horizontal reservations" to data terminals. Each frame has six slots and somewhere in the past, slots 1, 2 and 3 have been reserved for speech packets. At frame *I*, a data terminal reserves two horizontal slots for data packets (slots 4 and 5). At frame (*I* + 1), another data terminal reserves three horizontal slots for data packets (slots 1, 4 and 5). At frame (*I* + 2), yet another data terminal reserves a single horizontal slot for data packets (slot 5).

	Slot 0	Slot 1	Slot 2	Slot 3	Slot 4	Slot 5
Frame *I*	Rs	A	Rs	Rs	Rd	Rd
Frame *I* + 1	Rs	Rd	Rs	Rs	Rd	Rd
Frame *I* + 2	Rs	A	Rs	Rs	A	Rd

Fig. 3. Speech and data reservations in IPRMA protocol; *Rs* denotes a speech reservation, *Rd* denotes a data reservation and *A* denotes available and idle.

According to Wong and Goodman, IPRMA should lead into more efficient utilization of resources; data terminals should experience better throughput while speech terminals would compromise only little – depending on the number of time slots allocated to speech packets only (*M*).

5 Analysis on PRMA/IPRMA

G. Wu *et al*. have performed a thorough analysis of an integrated voice and data transmission system using PRMA [13]. Markov analysis has been used for evaluating the system performance. This means that the analytic models are constructed so that the system transition can be expressed with a Markov chain (see simple example in Fig. 4). After this, the entries of the one step state transition matrix are calculated using an iterative method.

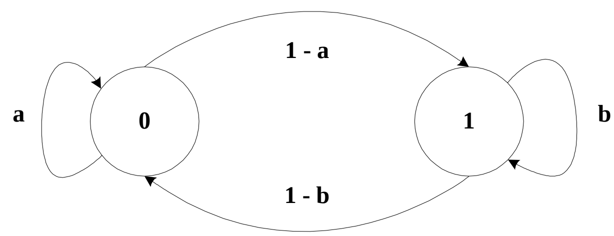

Fig. 4. Simple two-state speech model expressed as a Markov chain; 0 denotes a talkspurt while 1 denotes a silence period.

System performance measures, such as throughput and delay, were evaluated and the analytical model was verified with simulations, which indicated that the proposed method is appropriate to analyze PRMA systems.

6 Suggested Modifications to PRMA/IPRMA

K. Chua and W. Tan have proposed modified PRMA – MPRMA [14]. They are concerned that the effect of noise and fading errors in real radio channels might be very negative on PRMA.

Channel impairments can make a speech terminal to lose a reservation prematurely. If the base station does not detect the terminal's packet due to uplink errors, it releases the reservation. Moreover, if there are errors in the downlink, other contending terminals fail to recognize the reserved slots, which can lead into collisions. Uplink errors were already considered in [9], but downlink was still assumed to be ideal.

MPRMA is similar to PRMA except for the following enhancements, which aim to solve the aforementioned problems:

1. Each uplink packet carries an end-of-talkspurt (EOT) bit in its header. The base station will release the reservation when the EOT bit is turned on. Also, if the base station fails (due to uplink errors) to decode the EOT bit in two successive frames, it will release the reservation. As an additional benefit, the EOT bit allows reservations to be released one frame earlier than in basic PRMA.

2. Each downlink packet (acknowledgement) carries information whether the corresponding uplink packet was correctly received or not. It also tells the status of the present slot in the next frame: free

or reserved. All terminals, excluding the one that transmitted the corresponding uplink packet, will refrain from transmitting into this slot in the next frame if (due to downlink errors) they did not detect the header of the feedback packet and thus are uncertain whether the slot is free or reserved.

The analysis and simulation results of [14] confirm the expected outcome: MPRMA is more robust than PRMA.

7 Discussion

Is PRMA implemented anywhere? Probably not, but PRMA and especially IPRMA (with its data packet reservation scheme) have surely had an effect on GPRS[3] – see e.g., [5], where Goodman proposes PRMA for 3G systems, and [15] (Cai and Goodman on GPRS).

Of course, now we know that CDMA (Code Division Multiple Access) is the chosen technology in most third generation systems. However, GSM/GPRS with EDGE (Enhanced Data Rates for Global Evolution) will also be used by some operators (e.g., those who didn't get the 3G licenses) and some ideas of PRMA could possibly be adapted to these TDMA based systems. We could accept considerably more voice connections, if we would replace TDMA with PRMA [2, 3, 4]. On the other hand, this may not be worth the effort, because it is expected that the share of voice calls in the traffic mix will go down and data traffic will dominate in the future.

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[3] General Packet Radio Service, which is the packet data mode in GSM (Global System for Mobile Communications; originally Groupe Spéciale Mobile). GPRS is often referred to as generation 2.5 of mobile communication systems.

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