Chapter 2

Random Access Protocols for Wireless Personal Communications

2.1 Introduction

This thesis is concerned with the ability of packet based random access protocols to operate in high capacity, interference-limited wireless systems. In this chapter the concept of random access is described, with special regard given to the slotted ALOHA (S-ALOHA) and Packet Reservation Multiple Access (PRMA) protocols. The descriptions presented in this chapter assume a single cell, simple channel system in which cochannel interference is not considered. Such an operating environment has commonly been considered in previous analyses of these protocols. By a 'simple' channel it is assumed that packets are only received correctly by the base station when received in the absence of other competing packets.

Random access techniques rely on packetisation whereby the information is segmented into discrete length blocks. Appropriate models that represent the generation of speech and data packets are presented in §2.2. Section §2.2 also presents the unique characteristics and requirements of speech and data traffic. The appropriate performance measures by which a random access transmission technique can be evaluated are outlined. These measures include the throughput, data packet delay, speech packet dropping probability and system stability.

In §2.3 and §2.4 an overview of the S-ALOHA and PRMA random access protocols are presented, respectively. These descriptions relate to their operation in a single cell, simple channel system. The S-ALOHA protocol is designed specifically for data traffic, whereas the PRMA protocol is optimised for speech traffic. However, the PRMA protocol can also cater for the integrated transmission of speech and data traffic, by allowing the data users to communicate with the base station using a S-ALOHA approach. Section §2.5 presents a detailed literature review of data-only S-ALOHA, speech-only PRMA and speech-data PRMA research. This review considers both single cell and multiple cell systems.

2.2 Transmission of Packetised Speech and Data Information

In a random access wireless communication system, the information transmitted by the terminals is first segmented into discrete length packets. Information packets transmitted from terminals to base stations consist of both a payload (actual information) and a header as illustrated in Fig. 2.1. The header contains the terminal ID, which identifies which terminal the packet originated from, as well as the information type and priority level. It also contains the base station ID which identifies which base station the packet is being sent to. It is assumed that fixed size packets are employed by both speech and data terminals in all the systems considered in this thesis. In particular, it is assumed that each speech or data packet contains an H bit header and an I bit

information field[1]. The random access protocols considered in this thesis are organised according to a Time Division Multiplex (TDM) structure, whereby the uplink channel timescale is partitioned into *frames*, with each frame containing *N timeslots*. Fig. 2.2 presents this structure.

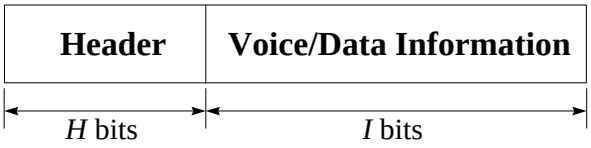

Figure 2.1: *Packet structure for speech and data information.*

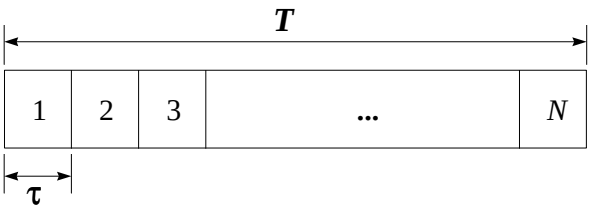

Figure 2.2: *Frame and timeslot organisation.*

The duration, t , of one timeslot is given by

$$t = \frac{T}{N}, \tag{2.1}$$

where T is the duration of a single frame. All the terminals are synchronised such that their packets are transmitted on the leading edge of a timeslot. During a given timeslot no more than one packet can be transmitted from a particular speech or data terminal to its base station. The nature of speech and data packet generation is described in §2.2.1 and §2.2.2, respectively.

2.2.1 Speech Traffic

Speech traffic is inherently bursty, with a typical conversation consisting of a series of *talkspurts* and *gaps*. There are principal spurts and gaps (related to the talking, pausing and listening patterns of a conversation). There are also *mini-spurts* and *mini-gaps* (due to the short silent intervals that punctuate continuous speech). Fig. 2.3 illustrates a recorded speech signal and the corresponding speech activity detection as classified by the speech activity detector presented in [1]. Two models that have been proposed to model the process of speech generation are:

- The “slow” speech activity model which responds only to the principal talkspurts and gaps. It is based on the original Time Assignment Speech Interpolation (TASI) system devised to improve the efficiency of undersea transmissions [2].

[1] The efficiency of random access protocols in fading environments is known to be dependent on packet size, and as such, the size of the packets represents an important design consideration. In this thesis, however, only a fixed packet of size H=576 and I=64 has been considered.

- The more sensitive "fast" speech activity model which also responds to the mini-spurts and mini-gaps. It is based on the behaviour of the speech detector used in an experimental wide-band packet communications system [3].

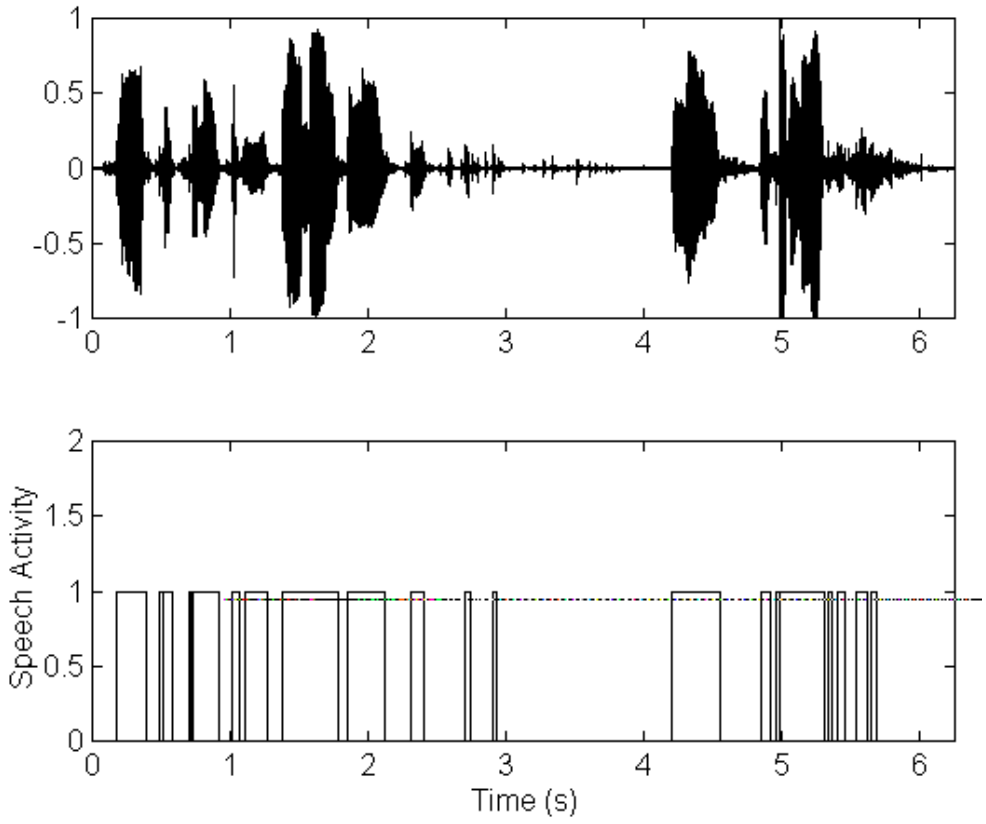

Figure 2.3: *The classification of a recorded speech signal according to an " on-off" process (1 corresponds to speech and 0 corresponds to silence).*

Only the slow speech activity model is used in this thesis. This model, illustrated in Fig. 2.4, consists of a two-state discrete Markov process with exponentially distributed sojourn times. The probability that a silent gap of mean duration t_2 seconds, ends during a t second timeslot is [4]

$$l_s = 1 - \exp(-t / t_2). \qquad \textbf{(2.2)}$$

This is the probability of a transition from the silent state, *SIL* to the talking state, *TLK*. Correspondingly, the probability that a principal talkspurt with mean duration t_1 seconds ends in a timeslot of duration t seconds is [4]

$$g = 1 - \exp(-t / t_1). \qquad \textbf{(2.3)}$$

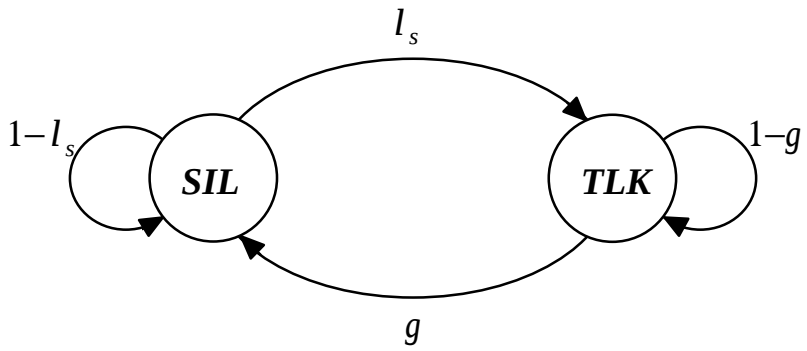

Figure 2.4: *Slow speech activity model.*

Mean values of talkspurt and silent gap durations, as reported in [4], are given in Table 2.1. The corresponding mean speech activity factor (*SAF*), which is the percentage of time that a single speech source is active, is given by

$$SAF = \frac{t_1}{t_1 + t_2} = 0.426 . \qquad \textbf{(2.4)}$$

Condition	Value (s)
Principal Talkspurt, t_1	1.000
Principal Gap, t_2	1.350

Table 2.1: *Parameters for slow speech activity model.*

From Fig. 2.4, it is possible to visualise a speech signal as being composed of a series of talkspurts and silences. A speech terminal operating in a packet-based system will generate a burst of packets corresponding to each talkspurt. In this sense, speech can be considered a source of ‘ long’ information. No packets are generated during the silent periods of speech.

2.2.2 Data Traffic

The characterisation of data traffic is, in many ways, more difficult than the characterisation of speech traffic. This is because the size of a data communication session can vary from a short electronic mail message, carrying only a few bytes of information, up to a long file transfer such as the text of a book, which may be several megabytes long. On the average, the volume of information involved in a data communication session is much smaller than that of a digitised-speech communication session [5, p.2].

Because of this difficulty in uniquely characterising the generation of data traffic, the data traffic model considered in this thesis is relatively simple and is similar to that used in previous analyses of S-ALOHA and PRMA type systems. This tri-state Markov model, illustrated in Fig. 2.5, assumes that the data traffic is a source of ‘short’ information, whereby data messages are

contained within single packets (e.g., email messages). New packets are generated in the origination state (*O*). In the transmission state (*T*), the terminal is busy either transmitting a new packet or re-transmitting a previously unsuccessful packet. The data terminal returns to the *O*-state if it successfully transmits a packet to the base station; otherwise, it enters the retransmission or backlogged state (*RT*). From the latter state, retransmission (i.e., transition into the *T*-state) occurs. A backlogged terminal is blocked in the sense that no new messages can arrive when the terminal is in state *RT*. This implies the absence of a buffer for more than one packet in a data terminal. The specific transition probabilities between the three states depends on the particular system under consideration. Terminal transition probabilities for both S-ALOHA and PRMA data terminals will be presented in later sections of this chapter.

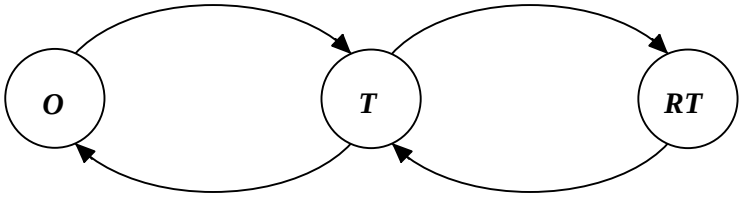

Figure 2.5: *Data terminal model with finite buffer.*

2.2.3 Performance Requirements

In a packetised communication network, speech and data services have different and sometimes contradictory requirements, as summarised in Table 2.2. For example, because of the speech user's expectation of telephone quality speech in the public wired network, packetised speech services must be designed with careful attention to minimising time delays. Inter-packet delays in excess of 30 ms will be noticeable and annoying to the listener[2].

Service	Design Constraint	Performance Targets
Speech	Delay < 30 ms	MOS[3] > 4.0 Decoded BER < 10^{-3} Frame Error Rate < 2%
Low Delay Data	Delay < 30 ms	BER < 10^{-6} Errored Sec. < 10 s/h
High Delay Data	Delay < 300 ms	BER < 10^{-6} Errored Sec. < 10 s/h
Unconstrained Delay Data	Packet Loss < 10^{-6}	Av. Delay < 50 ms 90% Delay < 100 ms

Table 2.2: *Service quality objectives for speech and data services [6].*

[2] In this thesis a packet delay limit of 36 ms is considered in order to accommodate other system parameters and to make the analysis more tractable.
[3] Mean Opinion Score.

In contrast, delay in a data network, while not desirable, is generally acceptable to the data user. Packetised speech can tolerate packet loss rates in the order of 10^{-2}, or bit error rates in the order of 10^{-3} without a noticeable degradation in service quality. An error rate of 10^{-6} is normally accepted for data, but any loss of data packets is totally unacceptable.

2.2.4 Performance Measures

The performance of random access protocols that cater for speech or data traffic can be measured using a number of performance measures. These measures generally relate to the efficiency, delay, accuracy and stability of the system involved. The following performance measures are commonly employed in the analysis of single cell, simple channel S-ALOHA and PRMA systems:

Channel Throughput, h : The channel throughput is defined as the average number of successful packet transmissions per packet transmission time. This measure is used to study the overall efficiency of a random access technique.

Data Packet Delay, W : The data packet delay is the average delay, in slots, that a data packet is held in a terminal's buffer before being successfully transmitted[4]. The delay involved in successful transmission of a data packet depends on how many times it needs to be retransmitted and how long the terminal must wait between retransmissions. Data packets must be retransmitted because loss of data information is normally unacceptable. In S-ALOHA and PRMA, the delay increases significantly when there are a large number of terminals seeking access to the channel.

Speech Packet Dropping Probability, P_{drop} : The speech packet dropping probability is the probability that a speech packet is dropped at a speech terminal due to excessive delay in successfully accessing the base station. Speech packets are dropped to accommodate the delay sensitive nature of speech information. Packets held beyond a certain delay limit are dropped in favour of more recent packets. The probability of packet dropping increases when there are a large number of terminals seeking access to the channel.

Expected Drift, Δ : The expected drift is a measure of the systems dynamic behaviour. With S-ALOHA and PRMA, as with all contention-based random access protocols, there are important issues relating to the stability of the system. The expected drift can be defined as the difference between the expected input traffic and the expected output traffic in a particular system state [7]. The system is expected to operate in a state where the expected drift is equal to zero. These points are referred to as *equilibrium points*.

In Chapter 4 (§4.6.3), additional performance measures are introduced to account for the effect of cochannel interference in multiple cell S-ALOHA and PRMA systems. In particular, the *system utilisation* and *speech packet interference probability* are presented. A further examination of the performance measures, together with analytical expressions are given in Chapters 5-8 of this thesis.

[4] Propagation delays are neglected in this thesis.

2.3 The S-ALOHA Protocol

The S-ALOHA [8] protocol has developed from the original ALOHA[5] protocol. ALOHA derives its name from the ALOHA system, a communications network developed by Abramson and his colleagues at the University of Hawaii and first put into operation in 1971 [9]. The initial system used ground-based UHF radios to connect computers on several of the island campuses with the university's main computer centre at Oahu, by use of a random access protocol which has since been known as the ALOHA protocol.

The concept of S-ALOHA is very simple: users generate information according to a random process, with a terminal generating a new packet in a given timeslot with probability l_d (probability of transition between *O* and *T* states in Fig. 2.5). Once a user has generated a packet, it will attempt to transmit it in the next timeslot. Of course, because multiple users may transmit packets during the same timeslot, there is the possibility of collisions occurring between packets. Thus, after sending a packet, the user waits a length of time equal to the round-trip delay for an acknowledgment from the receiver. If no acknowledgment is received, the packet is assumed lost in a collision and is transmitted again with a randomly selected delay to hopefully avoid repeated collisions. The probability of a data packet being retransmitted in a given timeslot is denoted by p_d (probability of transition between *RT* and *T* states in Fig. 2.5). This procedure continues until the packet is successfully received by the base station. The S-ALOHA process is illustrated in the form of a flow diagram in Fig. 2.6. When a S-ALOHA terminal is attempting to retransmit an unsuccessful packet, no new packets may be generated.

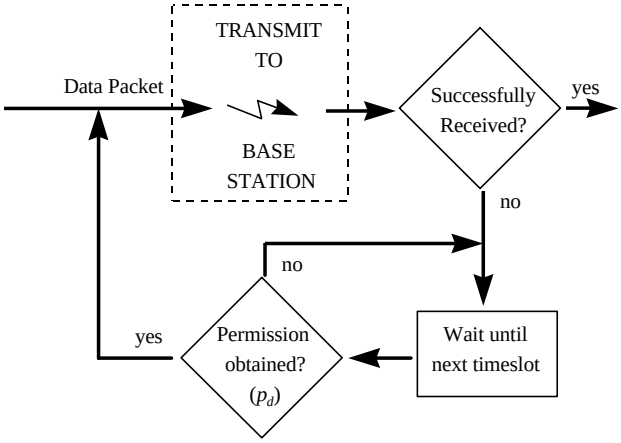

Figure 2.6: *Flow diagram of S-ALOHA operation.*

Fig. 2.7 illustrates a situation where packets are transmitted by three individual terminals. When a collision occurs between terminals 2 and 3 in timeslot 2 (TS2), the individual terminals wait a random time before attempting to retransmit their packets in subsequent timeslots. It is well known that in a single cell simple channel system, the maximum throughput, h, for ALOHA is about 18% (1/*e*) and about 36% (1/2*e*) for S-ALOHA [5, p.466]. This is illustrated in Fig. 2.8.

[5] Also referred to as pure-ALOHA.

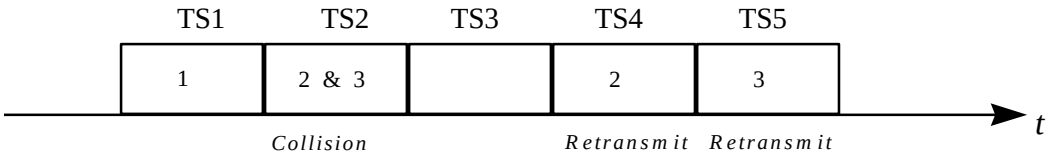

Figure 2.7: *Collision Mechanisms in S-ALOHA.*

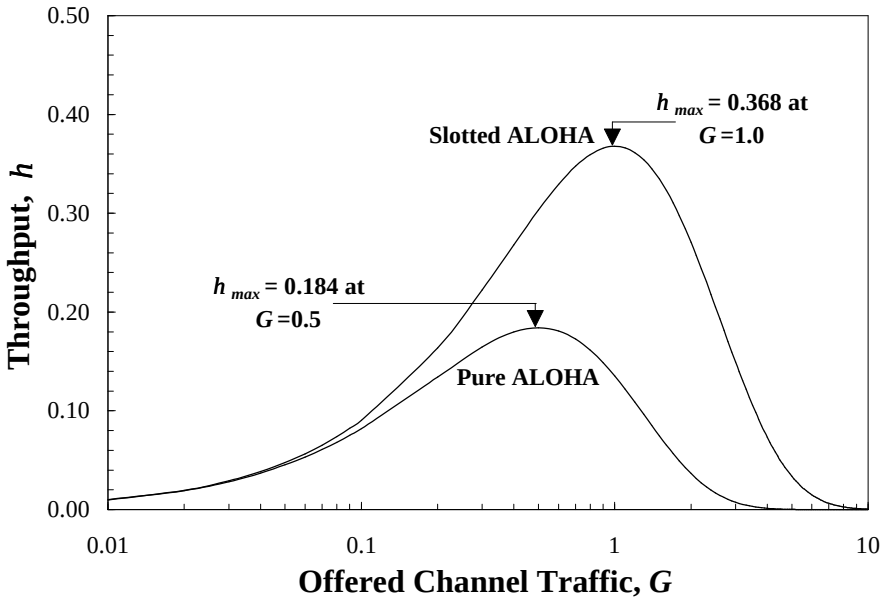

Figure 2.8: *Throughput versus traffic load for Pure and Slotted ALOHA in single cell simple channel systems (from [5]).*

2.4 The PRMA Protocol

The development and analysis of protocols that allow terminals to efficiently transmit packetised speech and data information in a wireless environment was motivated by Goodman in [10], when he proposed the Packet Reservation Multiple Access (PRMA) scheme. PRMA merges characteristics of the S-ALOHA and TDMA protocols. PRMA employs a Time Division Multiplex (TDM) based structure as presented in Fig. 2.2. For a speech terminal source rate of R_s bits/sec, channel rate per cell R_{cell} bits/sec, header size H bits/packet and frame duration T seconds, the number of slots in each frame is given by [11]

$$N = \text{int}\left[\frac{R_{cell}T}{R_sT + H}\right], \qquad \textbf{(2.5)}$$

where int[x] is the largest integer $\leq x$. The frame structure is designed so that speech sources generate exactly one packet per frame. Speech terminals generate bursts of packets corresponding to talkspurts whereas data terminals generate packets randomly. Speech and data terminals recognise timeslots as being either available or reserved. Speech and data terminals with new

packets contend for access during available timeslots. Permission to transmit during an available timeslot is granted if the output of the terminal's uniform random number generator is less than or equal to the permission probability, where the speech permission probability p_s, is normally greater than the data permission probability p_d. Permission to transmit at each terminal is independent of permissions at other terminals.

When a speech terminal contends successfully, it obtains a reservation for exclusive use of that timeslot in subsequent frames until it has no more packets to transmit. In this way, the speech terminals with reservations share the channel as in TDMA. Data terminals on the other hand, must contend each time that they have a packet to transmit. If a contending speech or data packet is unsuccessful in capturing the base station, the terminal involved may retransmit the packet in a future available timeslot. Speech packets, however, cannot be held at a speech terminal indefinitely due to the delay requirements of speech. Therefore, in PRMA any speech packet held beyond a certain number of slots is dropped by its terminal. Data packets, on the other hand, are retransmitted until successful, due to their stringent error requirements which do not allow them to be dropped. Flow diagrams that illustrate the process by which speech and data packets are transmitted in a PRMA system are presented in Figs. 2.9 and 2.10, respectively.

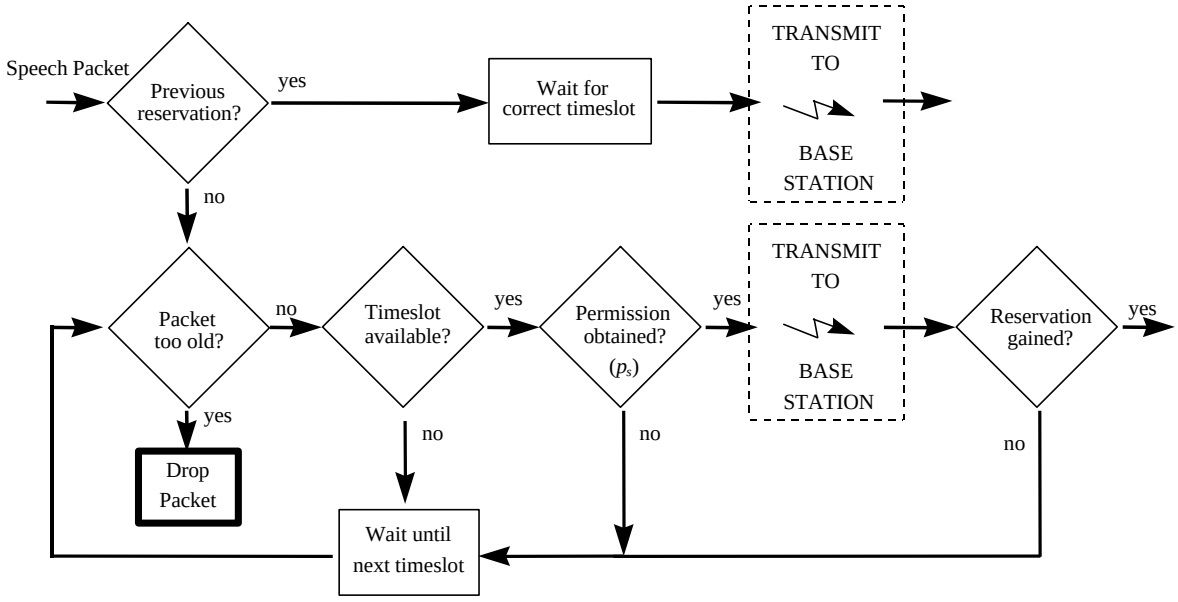

Figure 2.9: *Flow diagram of PRMA operation (speech users).*

A speech terminal contains a first-in-first-out (FIFO) buffer to store packets awaiting transmission. The capacity of the speech buffer is B_s packets. If the buffer is full when a new packet arrives, the terminal drops the oldest packet and stores the new packet. With the packet dropping mechanism, the speech buffer size required is

$$B_s = [D_{max} / T], \qquad \textbf{(2.6)}$$

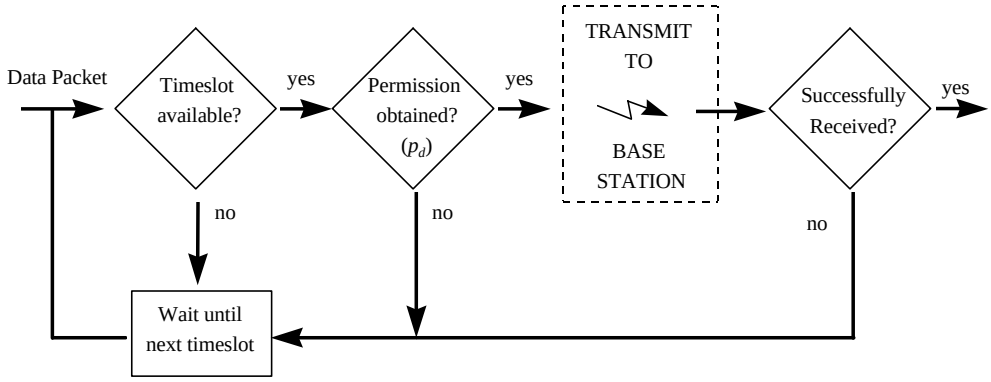

Figure 2.10: *Flow diagram of PRMA operation (data users).*

with $[x]$ denoting the smallest integer $\geq x$. T is the frame duration and D_{max} is the maximum transmission delay for speech. For short speech packets (for example, 16 ms of speech information) packet dropping probabilities, P_{drop}, up to 0.01 are acceptable [12]. Using speech interpolation techniques [13,14], even higher packet dropping rates may be tolerated. In this thesis packet dropping probabilities of either 1% and 5% are considered.

Fig. 2.11 illustrates the operation of a single cell speech-only PRMA system. In this example, there are eight time slots per frame and the base station feedback packets for frame K-1 have established that, in frame K, six slots are already reserved and two slots are available.

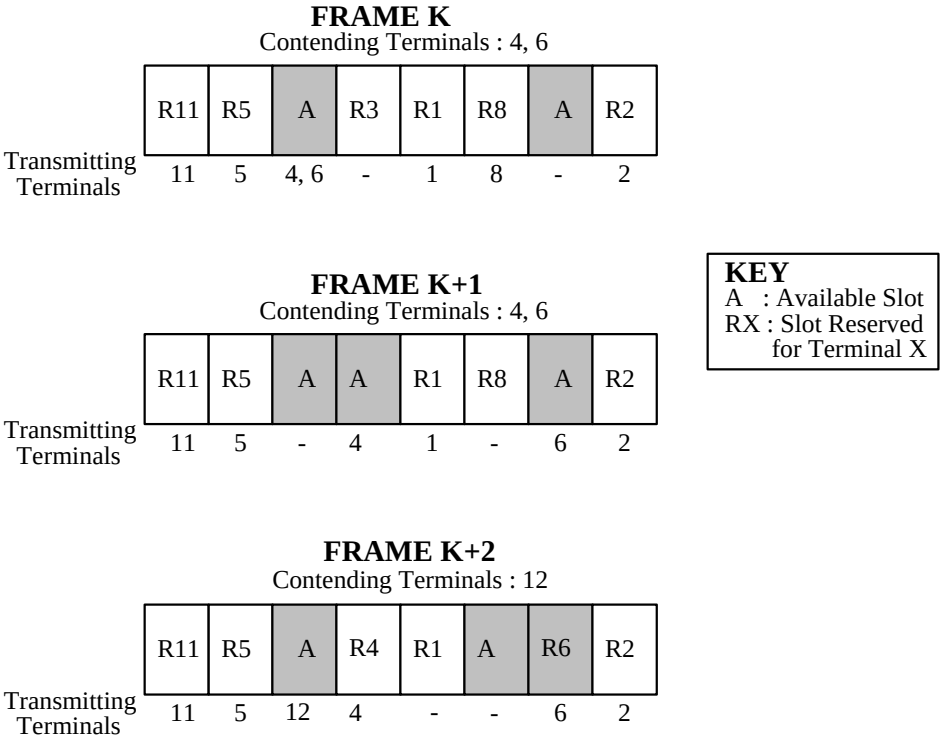

Figure 2.11: *PRMA protocol operation example*

At the beginning of frame K, terminals 4 and 6 are contending for access to the channel. Both of these terminals obtain permission to transmit in slot 3 and, because their packets collide, neither obtain a reservation. In slot 7, both terminals fail to obtain permission to transmit and, thus, remain in the contending state at the beginning of frame K+1. Meanwhile in frame K-1, terminal 3 transmitted the final packet in its talkspurt. Therefore in frame K (slot 4) it does not use its reservation. The base station feedback packet for slot 4 of frame K indicates that slot 4 is available in frame K+1.

In frame K+1, neither terminal 6 nor terminal 4 has permission to transmit in slot 3. In slot 4, terminal 4 has permission but terminal 6 does not. Thus, terminal 4 gains a reservation for slot 4. Terminal 6 obtains permission to transmit in slot 7 and reserves that slot in frame K+2. In frame K+1, terminal 8 gives up its reservation of slot 6, and a talkspurt begins at terminal 12 which enters the contending state. In frame K+2, terminal 12 gains a reservation (slot 3) and terminal 1 releases its reservation (slot 5).

Fig. 2.12 presents the speech packet dropping probability for a speech-only, single cell, simple channel PRMA system. In this particular example the single cell PRMA system is capable of supporting 37 speech terminals at $P_{drop} = 0.01$ and 44 speech terminals at $P_{drop} = 0.05$. This particular system is based on the parameters of [15], in which N=20 timeslots per frame was assumed. This result illustrates the ability of PRMA to support significantly more users compared to the number of timeslots.

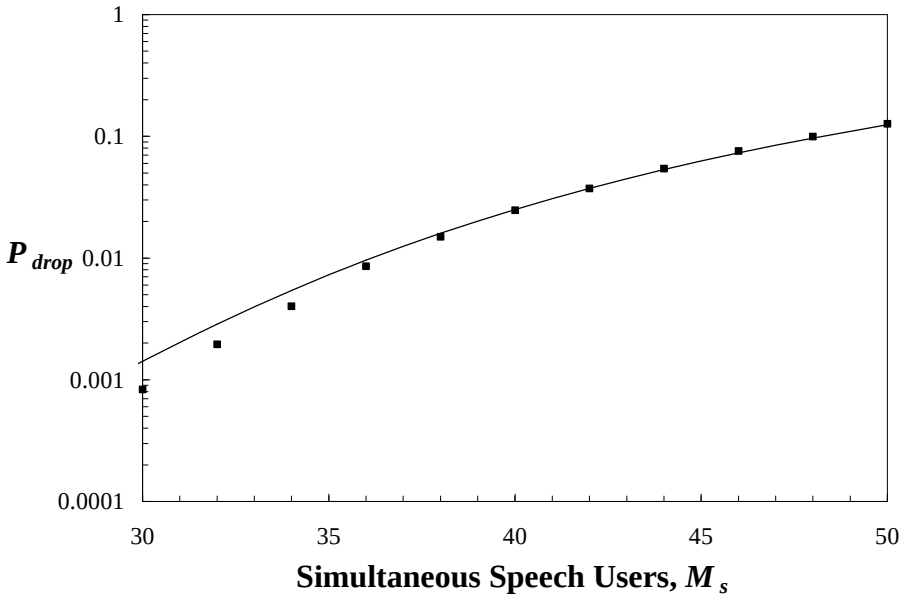

Figure 2.12: *Speech packet dropping probability in a speech-only, single cell, simple channel PRMA system. The parameters assumed are the same as those in [15]. Both Markov analysis results (lines) and simulation results (single points) are presented.*

This is achieved by the statistical multiplexing nature of PRMA, whereby individual speech signals are multiplexed at the talkspurt level as opposed to the call level, as in TDMA. In an equivalent TDMA system without any overheads[6], it would be possible to support only 22.5 speech terminals [15].

2.5 Literature Review

Considerable research has already been undertaken into S-ALOHA and PRMA. A summary of the key research, as it relates to the work examined in this thesis, is presented in this section. This literature review considers research relating to S-ALOHA and PRMA in single cell, simple channel systems. This is then extended to research that has considered single cell S-ALOHA and PRMA systems with variable channels. Finally, multiple cell S-ALOHA and PRMA systems are examined. Unlike the simple channel model described in §2.1, realistic radio channels allow for situations in which a packet may be received successfully by the base station in the presence of other competing packets. This phenomenon is due to the variable nature of the propagation channel, which results in the received powers of individual packets being different. In such a situation, a dominant packet (i.e., a packet with a high power level) may be capable of *capturing*[7] the base station receiver.

2.5.1 S-ALOHA Systems

Single Cell S-ALOHA Systems with Simple Channel

In [7] Carleial and Hellman used Markov analysis [16,17] to study a single cell, simple channel S-ALOHA system. Expressions were developed to describe the throughput, delay and drift for such a system. The bistable nature of S-ALOHA was studied in detail. Bi-stability refers to the situation where the system can, in some circumstances, possess two statistically stable equilibrium points, one in a desirable low-delay region, and the other in an un-desirable high delay region, with the system oscillating between the two equilibrium points. In [18] it was shown that S-ALOHA can possess either one stable equilibrium point or three equilibrium points, with the first and third points stable and the second one unstable. Similar findings were presented by Kleinrock and Lam in [19], also via Markov analysis.

Markov analysis involves formulating a Markovian model of the system and obtaining the state probability distribution of the Markov chain from the state transition probabilities. While Markov analysis is a more involved technique, it provides information regarding the dynamic behaviour and throughput-delay characteristics of the system, which other techniques such as the *infinite population model*[8] and *equilibrium point analysis* (EPA) are unable to provide. The infinite population analysis was devised by Abramson in [9] to evaluate the performance of the ALOHA system. This technique assumes that the system stays in equilibrium and that the traffic source consists of an infinite number of users, who collectively form an independent Poisson source. It can be readily applied to the analysis of complex contention-based systems (e.g. [20]). However, the infinite population model cannot reveal the dynamic behaviour of the system; that is, this technique cannot give any solution to the stability problem which is present in all contention-

[6] i.e., without packet headers.
[7] The concept of receiver capture will be discussed in detail in Chapter 4.
[8] Also referred to as S-G (throughput-delay) analysis, or Poisson analysis.

based systems. EPA analysis represents a simplification of the more complex Markov analysis. EPA assumes that the system is always at an equilibrium point. Under this assumption it is not necessary to calculate the state transition probabilities of the Markov chain. The importance of the equilibrium point in contention-based systems was first noticed by Carleial and Hellman [7] and Kleinrock and Lam [19]. Fukuda introduced an analytical technique based on this result in [21-23].

Single Cell S-ALOHA Systems with Variable Channel

Over more recent years, S-ALOHA has been analysed in single cell systems with more realistic channels. In [24] Namislo carried out a Markov analysis of a single cell S-ALOHA system with receiver capture, although no specific channel or capture model was considered. In [25] Goodman and Saleh considered a channel model based on distance-dependent pathloss, while in [26] Arnbak and Blitterswijk considered a Rayleigh fading channel. The performance of S-ALOHA in a single cell system with Rayleigh fading, shadowing and near-far effect was analysed by van der Plas and Linnartz [27] and Sheikh, Yao and Wu [28]. It was found in both [24] and [27] that receiver capture, aided by a highly variable propagation channel, reduced the bi-stability of S-ALOHA substantially, compared to the case where a simple channel was considered. The central finding of [24-28] was that a variable channel enhanced the overall performance of single cell S-ALOHA systems. Other research into single cell variable channel S-ALOHA systems has been presented in [29-33].

Multiple Cell S-ALOHA Systems

Most recently, several researchers have considered the operation of S-ALOHA in multiple cell systems. In [34] Linnartz investigated the performance of S-ALOHA in a cellular environment using an infinite population model. It was found that frequency reuse distances in packet switched systems, such as S-ALOHA, can be smaller than in circuit switched systems. In this situation, S-ALOHA overcomes the effect of cochannel interference through random retransmission of information. This is as opposed to the spatial isolation of cochannel cells, as is usual in FDMA/TDMA systems. In [35] Zorzi and Pupolin proposed S-ALOHA as a multiple access scheme for voice cellular communications. An analysis of a system with complete frequency reuse was performed using an infinite population model. Other research into multiple cell S-ALOHA systems has been presented in [36-38].

2.5.2 PRMA Systems

Single Cell PRMA Systems with Simple Channel

Initial studies of both speech and joint speech-data PRMA systems focused primarily on the performance in an interference-free, single cell architecture. These studies assume that all packets involved in collisions with other packets at the base station receiver are destroyed; likewise all packets not in collision are received correctly. In [11], Goodman presented an overview of the cellular packet switch and packet reservation multiple access concepts. In [15] Goodman and Wei investigated the performance of PRMA via computer simulation and found the protocol to be capable of supporting 1.64 speech conversations per channel at a packet dropping probability of 1%. The effect of frame duration, speech activity detector and speech permission probability, p_s, on the speech packet dropping probability were determined.

Nanda, Goodman and Timor used equilibrium point analysis (EPA) in [39] to study a speech-only PRMA system. Expressions for the speech packet dropping probability, P_{drop}, and throughput, h, were derived, and the necessary conditions for system stability and efficiency were established. In [40] and [41] the performance of an integrated speech-data PRMA system was determined by Nanda using equilibrium point analysis. It was found that PRMA gracefully accepted low-rate data terminals with moderate data packet delays. The EPA used in this paper required a judicious change of variables to reduce the analysis to a univariate problem of the same form as the speech-only system of [39]. In the analysis of [39], the probability distribution functions were derived when there was a single equilibrium point. It was assumed that the equilibrium value of the state variable was equal to the mean. This method underestimates the system performance since it assumes that the system is always at a stable equilibrium point. In practice, the system state moves to a state space according to some state distribution. The error between analysis and computer simulation results in [39] is too large in some cases to satisfy designer's requirements.

In [42] a modification to the original integrated speech-data PRMA system of [40] and [41] was proposed by Wong and Goodman, whereby data terminals could reserve multiple slots across a frame. From the computer simulation results, this modification was shown to improve slot utilisation without compromising speech transmission performance. In [43], Eastwood, Hanzo and Cheung investigated the ability of PRMA to transport a mixture of speech, data and video information. This investigation was performed using computer simulations. In [44] Wu, Mukumoto and Fukuda determined the performance of a speech-data PRMA system using the theory of Markov analysis. This analysis method appears to be more accurate than methods proposed in earlier papers [39-41], which use an EPA technique. However, [44] did not present any results regarding the speech packet dropping probability. In addition, the analysis of [44] assumed that terminal departures from the various states only occurred at the end of frames, when in practice, they occur at the end of timeslots.

Qi and Wyrwas presented a Markov analysis of a speech-only PRMA system in [45]. Results relating to the speech packet dropping probability, throughput and first exit time (FET) [19] were presented. The agreement between analytical and simulation results was better than the agreement shown in [39], where EPA was employed. Unlike [44], the Markov analysis of [45] assumed terminal departures from the various states occurred at the end of timeslots. The analysis presented in [45] forms the basis for the mathematical analysis of PRMA presented in this thesis. While Markov analysis is more complicated than EPA, it is able to reveal more information about the system's performance and stability than EPA. Other research into single cell, simple channel PRMA systems has been presented in [46-53].

Single Cell PRMA Systems with Variable Channel

In [54], the performance of a speech-only PRMA system in the presence of random packet transmission impairments was investigated using computer simulation. It was assumed that speech terminals that lose reservations early due to transmission errors have to recontend for a new reservation and hence, risk dropping old packets while waiting. In [55], a modified PRMA protocol was proposed to minimise premature loss of reservations when the protocol operates in the presence of random packet transmission impairments. This modification was also suggested as part of the research presented in [56].

In [57] a speech-only PRMA system was studied via Markov analysis. The Markov analysis was an extension of that presented in [45]. A propagation channel which accounted for distance dependent pathloss, lognormal shadowing and Rayleigh fading was considered. It was found that the capture effect was capable of providing considerable improvements to PRMA performance, especially in highly variable propagation environments. In [58] the performance of a speech-only PRMA system was determined via Markov analysis. In this system, the desired terminal was assumed to transmit packets suffering from Rician fading, whereas other contending packets suffered from Rayleigh fading.

In [59] Qi and Wyrwas presented two analysis methods for a joint speech-data PRMA system suffering from random packet transmission impairments. The first was a combined EPA and Markov analysis, while the second was a Markov analysis which used an approximate marginal distribution of backlogged data terminals. Expressions were derived for the speech packet dropping probability, P_{drop}, data packet delay, W, and throughput, h, in the presence of random packet errors. The two methods were found to produce similar results, although the latter method was more complex than the former method.

In [60] the performance of a speech-only PRMA system was determined by Qiu and Li using Markov analysis. A combined Rician-Lognormal channel was considered and the capture effect was incorporated. Other research into single cell, variable channel PRMA systems has been presented in [61-64].

Multiple Cell PRMA Systems

In the simulation studies of [65-68] and [69] the performance of speech-only and speech-data cellular PRMA systems were determined, respectively. A channel model which incorporated distance dependent pathloss and lognormal shadowing was used. In [65-69], it is assumed that a powerful error correcting code protects the packet header, which prevents it from being destroyed even when cochannel interference causes corruption to the packet's information field. By making this assumption, it is implicitly assumed that a terminal's reservation is not lost prematurely due to cochannel interference. Only the packet transmitted in the presence of the cochannel interference is lost, with the following packets of the same talkspurt able to be transmitted. The findings of [69] indicated that the performance of PRMA may be severely affected by cochannel interference. It was suggested that methods should be investigated to reduce the impact of this cochannel interference.

In the simulation study of [70] the concept of Space and Time Reservation Multiple Access (STRMA) was presented. STRMA can be viewed as a dynamic cellular PRMA protocol, whereby terminals not only reserve bandwidth for a certain period of time (as in the original PRMA protocol), but also reserve the bandwidth over a certain geographical space in order to reduce interference to nearby cells. By reserving the bandwidth for a particular user part of the time in part of the network, a frequency reuse pattern is created but this pattern is no longer fixed. In the simulation study of [71], Mastroforti determined the performance of a speech-only PRMA system in a cellular environment. A channel model which incorporated distance dependent pathloss and lognormal shadowing was considered.

2.6 Summary

In this chapter, it has been shown that significant differences exist between the nature and requirements of speech and data traffic. These differences present challenges when designing transmission protocols capable of integrating speech and data traffic in an efficient and accurate manner.

The concept of transmitting speech and data information using packetised random access methods has also been presented in this chapter. In particular, the S-ALOHA and PRMA protocols have been presented in terms of their operation in single cell systems, free from cochannel interference. S-ALOHA is confined to the transmission of data traffic, whereas PRMA is capable of supporting both speech and data traffic. Appropriate performance measures, from which the performance of S-ALOHA and PRMA may be determined, have been presented. These include the throughput, data packet delay, speech packet dropping probability and drift. A detailed literature review that considers not only single cell S-ALOHA and PRMA systems but also multiple cell S-ALOHA and PRMA systems has also been presented.

This chapter has focused primarily on the theoretical considerations of the random access protocols being investigated in this thesis. The aim of this thesis is, however, the consideration of S-ALOHA and PRMA in more realistic situations, namely multiple cell variable channel systems. As a first step to completing this aim, the following chapter will present an overview of radiowave propagation in multiple cell environments.

References

[1] L. Hanzo, J. C. S. Cheung, R. Steele, W. T. Webb, “A packet reservation multiple access assisted cordless telecommunication scheme,” *IEEE Trans. Veh. Technol.*, vol. 43, no. 2, May 1994, pp. 234 - 244.

[2] P. T. Brady, “A model for generating on-off speech patterns in two-way conversation,” *Bell. Syst. Tech. J*., vol. 48, pp. 2445 - 2472, Sept. 1969.

[3] R. W. Muise, T. J. Schonfeld, G. H. Zimmerman III, “Experiments in wideband packet technology,” in *Proc. 1986 Zurich Seminar.*, pp. D4.1 - D4.5.

[4] S. Nanda, D. J. Goodman, U. Timor, “Performance of PRMA: a packet voice protocol for cellular systems,” *IEEE Trans. Veh. Technol.*, vol. 40, no. 3, Aug. 1991, pp. 584 - 598.

[5] K. Pahlavan, A. H. Levesque, *Wireless Information Networks*, John Wiley and Sons Inc., 1995.

[6] D. Grillo, N. Metzner, E. D. Murray, “Testbed for assessing the performance of a TDMA-based radio access design for UMTS,” *IEEE Personal Commun. Mag.*, vol. 2, no. 2, Apr. 1995, pp. 36 - 45.

[7] A. B. Carleial, M. E. Hellman, “Bistable behavior of ALOHA-type systems,” *IEEE Trans. Commun.*, vol. 23, no. 4, Apr. 1975, pp. 401 - 409.

[8] L. G. Roberts, “ALOHA packet systems with and without slots and capture,” *Comput. Commun. Rev*., vol. 5, no. 2, Apr. 1975, pp. 28 - 42.

[9] N. Abramson, “The ALOHA system - another alternative for computer communications,” *Proc. 1970 Fall Joint Comput. Conf.*, AFIPS Press, vol. 37, 1970, pp. 281 - 285.

[10] D. J. Goodman, R. A. Valenzuela, K. T. Gayliard, B. Ramamurthi, "Packet reservation multiple access for local wireless communications," *IEEE Trans. Commun*., vol. 37, no.8, 1989, pp.885-890.

[11] D. J. Goodman, “Cellular packet communications,” *IEEE Trans. Commun.*, vol. 38, no. 8, Aug. 1990, pp. 1272 - 1280.

[12] J. G. Gruber, L. Strawczynski, “Subjective effects of variable delay and speech clipping in dynamically managed voice systems,” *IEEE Trans. Commun.*, vol. 33, no. 8, Aug. 1985, pp. 801 - 808.

[13] N. S. Jayant, S. W. Christensen, “Effects of packet losses in waveform coded speech and improvements due to an odd-even sample interpolation procedure,” *IEEE Trans. Commun.*, vol. 29, Feb. 1981, pp. 101-109.

[14] O. J. Wasem, D. J. Goodman, C. A. Dvorak, H. G. Page, “The effect of waveform substitution on the quality of PCM packet communications,” *IEEE Trans. Commun.*, vol. 36, Mar. 1988, pp. 342-348.

[15] D. J. Goodman, S. X. Wei, “Efficiency of packet reservation multiple access,” *IEEE Trans. Veh. Technol.*, vol. 40, no. 1, Feb. 1991, pp. 170 - 176.

[16] D. L. Isaacson, R. W. Madsen, *Markov Chains: Theory and Applications.* New York, Wiley, 1976.

[17] R. B. Mattingly, C. D. Meyer, “Computing the stationary distribution vector of an irreducible Markov chain on a shared-memory multiprocessor,” *in Numerical Solution of Markov Chains*, W. J. Stewart, Ed., Dekker, 1991, pp. 491 - 510.

[18] Y. -C. Jenq, “On the stability of slotted ALOHA systems,” *IEEE Trans. Commun.*, vol. 28, no. 11, Nov. 1980, pp. 1936 - 1939.

[19] L. Kleinrock, S. S. Lam, “Packet switching in a multiaccess broadcast channel: performance evaluation,” *IEEE Trans. Commun.*, vol. 23, no. 4, Apr. 1975, pp. 410 - 422.

[20] L. Kleinrock, F. Tobagi, “Packet switching in radio channels: Part I - carrier sense multiple access modes and their throughput delay characteristics,” *IEEE Trans. Commun*., vol. 23, no. 12, Dec. 1975, pp. 1400 - 1416.

[21] A. Fukuda, “Equilibrium point analysis of ALOHA-type systems,” *Trans. IECE Japan (in Japanese)*, vol. J61-B, Nov. 1978, pp. 959 - 966.

[22] A. Fukuda, S. Tasaka, "The equilibrium point analysis - a unified analytic tool for packet broadcast networks," *in Proc. 1983 IEEE Global Telecommunications Conf.*, San Diego, California, Nov 1983, pp. 33.4.1 - 33.4.8.

[23] S. Tasaka, "Stability and performance of the R-ALOHA packet broadcast system," *IEEE Trans. Comput*., vol. 32, Aug. 1983, pp. 717 - 726.

[24] C. Namislo, "Analysis of mobile radio slotted ALOHA networks," *IEEE J. Selected Areas Commun.*, vol. 2, no. 4, Jul. 1984, pp. 583 - 588.

[25] D. J. Goodman, A. A. M. Saleh, "The near/far effect in local ALOHA radio communications," *IEEE Trans. Veh. Technol.*, vol. 36, no. 1, Feb. 1987, pp. 19 - 27.

[26] J. Arnbak, W. van Blitterswijk, "Capacity of slotted ALOHA in Rayleigh-fading channels," *IEEE J. Selected Areas Commun.*, vol. 5, no. 2, Feb. 1987, pp. 261 - 269.

[27] C. van der Plas, J. P. M. G. Linnartz, "Stability of mobile slotted ALOHA network with Rayleigh fading, shadowing, and near-far effect," *IEEE Trans. Veh. Technol.*, vol. 39, no. 4, Nov. 1990, pp. 359 - 366.

[28] A. U. H. Sheikh, Y.-D. Yao, X. Wu, "The ALOHA systems in shadowed mobile radio channels with slow or fast fading," *IEEE Trans. Veh. Technol.*, vol. 39, no. 4, Nov. 1990, pp. 289 - 298.

[29] H. H. Tan, S. V. Hung, "Performance analysis of slotted ALOHA over fading communications channels," *in Proc. 9th Annual Joint Conference of the IEEE Computer and Communications Societies, INFOCOM'90*, San Francisco, California, Jun. 1990, pp. 595 - 602.

[30] J.- P. M. G. Linnartz, R. Hekmat, R.- J. Venema, "Near-far effects in land mobile random access networks with narrow-band Rayleigh fading channels," *IEEE Trans. Veh. Technol.*, vol. 41, no. 1, Feb. 1992, pp. 77 - 89.

[31] I. Widipangestu, A. J. 'T Jong, R. Prasad, "Capture probability and throughput analysis of slotted ALOHA and unslotted np-ISMA in a Rician/Rayleigh environment," *IEEE Trans. Veh. Technol.*, vol. 43, no. 3, Aug. 1994, pp. 457 - 465.

[32] M. Zorzi, R. R. Rao, "Capture and retransmission control in mobile radio," *IEEE J. Selected Areas Commun.*, vol. 12, no. 8, Oct. 1994, pp. 1289 - 1298.

[33] M. Zorzi, "Mobile radio slotted ALOHA with capture and diversity," *Wireless Networks*, no. 1, 1995, pp. 227 - 239.

[34] J.- P. M. G. Linnartz, "Slotted ALOHA land-mobile radio networks with site diversity," *IEE Proceedings-I*, vol. 139, no. 1, Feb. 1992, pp. 58 - 70.

[35] M. Zorzi, S. Pupolin, "Slotted ALOHA for high-capacity voice cellular communications," *IEEE Trans. Veh. Technol.*, vol. 43, no. 4, Nov. 1994, pp. 1011 - 1021.

[36] K. Sakakibara, “Performance approximation of a multi-base station slotted ALOHA for wireless LAN's,” *IEEE Trans. Veh. Technol.*, vol. 41, no. 4, Nov. 1992, pp. 448 - 454.

[37] J.- P. M. G. Linnartz, “Imperfect sector antenna diversity in slotted ALOHA mobile network,” *IEEE Trans. Commun.*, vol. 44, no. 10, Oct. 1996, pp. 1322 - 1328.

[38] J. G. Lee, M. Scott Corson, “The performance of an "imbedded" ALOHA protocol in wireless networks,” *in Proc. 7th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC'96*, Taipei, Taiwan, ROC, Oct. 1996, pp. 377 - 381.

[39] S. Nanda, D. J. Goodman, U. Timor, “Performance of PRMA: a packet voice protocol for cellular systems,” *IEEE Trans. Veh. Technol.*, vol. 40, no. 3, Aug. 1991, pp. 584 - 598.

[40] S. Nanda, “Analysis of packet reservation multiple access: voice data integration for wireless networks,” *in Proc. 1990 IEEE Global Telecommunications Conf.,* San Diego, California, Dec. 1990, pp. 1984 - 1988.

[41] S. Nanda, “Stability evaluation and design of the PRMA joint voice data system,” *IEEE Trans. Commun.*, vol. 42, no. 5, May 1994, pp. 2092 - 2104.

[42] W. C. Wong, D. J. Goodman, “A packet reservation multiple access protocol for integrated speech and data transmission,” *IEE Proceedings-I*, vol. 139, no. 6, Dec. 1992, pp. 607 - 612.

[43] M. Eastwood, L. Hanzo, J. C. S. Cheung, “Packet reservation multiple access for wireless multimedia communications,” *Electronics Letters*, vol. 29, no. 13, Jun. 24th 1993, pp. 1178 - 1180.

[44] G. Wu, K. Mukumoto, A. Fukuda, "Analysis of an integrated voice and data transmission system using packet reservation multiple access," *IEEE Trans. Veh. Technol*., vol. 43, no. 2, May 1994, pp. 289 - 297.

[45] H. Qi, R. Wyrwas, “Markov analysis for PRMA performance study,” in *Proc. 44th IEEE Veh. Technol. Conf.*, Stockholm, Sweden, May 1994, pp.1184-1188.

[46] R. Bolla, F. Davoli, M. Taffone, F. Reichert, “The PRMA-ISA protocol for multiple access of mixed voice and data traffic,” *in Proc. 44th IEEE Veh. Technol. Conf.,* Stockholm, Sweden, May 1994, pp. 1213 - 1217.

[47] P. Narasimhan, R. Yates, D. J. Goodman, “Performance analysis of frame reservation multiple access,” *in Proc.1994 3rd Annual International Conf. on Universal Personal Communications*, San Diego, California, Sep. 1994, pp. 26 - 30.

[48] S.T. Chua, K. C. Chua, K. M. Lye, “Minislotted packet reservation multiple access protocol for integrated voice-data transmission,” *in Proc. 1994 IEEE International Conf. on Communication Systems, ICCS'94*, Singapore, Nov. 1994, pp. 320 - 323.

[49] G. Bianchi, F. Borgonovo, L. Fratta, L. Musumeci, M. Zorzi, "C-PRMA: the centralised packet reservation multiple access for local wireless communications," *in GLOBECOM, 94*, San Francisco, California, Nov. 1994, pp. 1340 - 1345.

[50] J. S. Jang, B. C. Shin, "Performance evaluation of fast PRMA protocol," *Electronics Letters*, vol. 31, no. 5, Mar. 2nd 1995, pp. 347 - 349.

[51] P. Narasimhan, R. D. Yates, "A new protocol for the integration of voice and data over PRMA," *IEEE J. Selected Areas Commun.*, vol. 14, no. 4, May 1996, pp. 623 - 631.

[52] P. Taaghol, R. Tafazolli, B. G. Evans, "Burst reservation multiple access techniques for the GSM/DCS and DECT systems," *in Proc. 7th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC'96*, Taipei, Taiwan, Oct. 1996, pp. 412 - 416.

[53] X.-F. Dong, L.-M. Li, "Spread spectrum PRMA and minimum reservation capacity spread spectrum PRMA for microcellular networks," *in Proc. 7th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC'96*, Taipei, Taiwan, Oct. 1996, pp. 633 - 637.

[54] L. M. A. Jalloul, S. Nanda, D. J. Goodman, "Packet reservation multiple access over slow and fast fading channels," *in Proc. 40th IEEE Veh. Technol. Conf.*, Orlando, Florida, May 1990, pp. 354 - 359.

[55] K. C. Chua, W. M. Tan, "Modified packet reservation multiple access protocol," *Electronics Letters*, vol. 29, no. 8, Apr. 15th 1993, pp. 682 - 684.

[56] M. M. Khan, D. J. Goodman, "Effects of channel impairments on packet reservation multiple access," *in Proc. 44th IEEE Veh. Technol. Conf.*, Stockholm, Sweden, May 1994, pp. 1218 - 1222.

[57] H. Qi, R. Wyrwas, "Capture effects on PRMA stability and performance," *Electronics Letters*, vol. 30, no. 7, Mar. 31st 1994, pp. 539 - 540.

[58] C. van den Broek, R. Prasad, "Effect of capture on the performance of the PRMA protocol in an indoor radio environment with BPSK modulation," *in Proc. 44th IEEE Veh. Technol. Conf.*, Stockholm, Sweden, May 1994, pp. 1223 - 1227.

[59] H. Qi, R. Wyrwas, "Performance analysis of joint voice-data PRMA over random packet error channels," *IEEE Trans. Veh. Technol.*, vol. 45, no. 2, May 1996, pp. 332 - 345.

[60] X. Qiu, V. O. K. Li, "On the capacity of packet reservation multiple access with capture in personal communication systems," *IEEE Trans. Veh. Technol.*, vol. 45, no. 4, Nov. 1996, pp. 666 - 675.

[61] R. A. Ziegler, G. P. Pollini, "An experimental implementation of the PRMA protocol for wireless communication," *Proc. 43rd IEEE Veh. Technol. Conf.*, Secaucus, New Jersey, May 1993, pp. 909 - 912.

[62] L. Hanzo, J. P. Woodward, “An intelligent multimode voice communications system for indoor communications,” *IEEE Trans. Veh. Technol.*, vol. 44, no. 4, Nov. 1995, pp. 735 - 748.

[63] L. Hanzo, J. C. S. Cheung, R. Steele, W. T. Webb, “Performance of PRMA schemes via fading channels,” *in Proc. 43rd IEEE Veh. Technol. Conf.*, Secaucus, New Jersey, May 1993, pp. 913 - 916.

[64] L. Hanzo, J. C. S. Cheung, R. Steele, W. T. Webb, “A packet reservation multiple access assisted cordless telecommunication scheme,” *IEEE Trans. Veh. Technol.*, vol. 43, no. 2, May 1994, pp. 234 - 244.

[65] M. Frullone, G. Falciasecca, P. Grazioso, G. Riva, A. M. Serra, “On the performance of packet reservation multiple access with fixed and dynamic channel allocation,” *IEEE Trans. Veh. Technol.*, vol. 42, no. 1, Feb. 1993, pp. 78 - 86.

[66] M. Frullone, G. Riva, P. Grazioso, M. Missiroli, “Comparisons of multiple access schemes for personal communication systems in a mixed cellular environment,” *IEEE Trans. Veh. Technol.*, vol. 43, no. 1, Feb. 1994, pp. 99 - 109.

[67] M. Frullone, G. Riva, P. Grazioso, C. Carciofi, “Self-adaptive channel allocation strategies in cellular environments with PRMA,” *in Proc. 44th IEEE Veh. Technol. Conf.*, Stockholm, Sweden, May 1994, pp. 819 - 823.

[68] M. Frullone, G. Riva, P. Grazioso, C. Carciofi, “PRMA performance in cellular environments with self-adaptive channel allocation strategies,” *IEEE Trans. Veh. Technol.*, vol. 45, no. 4, Nov. 1996, pp. 657 - 665.

[69] D. Grillo, M. Frullone, P. Grazioso, P. Valigi, "A performance analysis of PRMA considering speech/data traffic, co-channel interference and ARQ error recovery," *in Proc. 7th IEE European Conf. on Mobile and Personal Communications*, Brighton, United Kingdom, no. 387, Dec. 1993, pp. 167-172.

[70] C. van den Broek, J.- P. M. G. Linnartz, “A simulation study of space and time reservation multiple access,” *in Proc. 6th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC'95*, Toronto, Canada, Sep. 1995, pp. 527 - 531.

[71] M. Mastroforti, “Up-link capacity evaluation of a PRMA based system in a terrestrial radio mobile environment,” *Centro Studi e Laboratori Telecomunicazioni (CSELT) Technical Reports, Torino, Italy*, vol. 24, no. 4, Feb. 1996, pp. 113 - 130.