Performance Evaluation of a Joint CDMA/NC-PRMA Protocol for Wireless Multimedia Communications

Jyh-Horng Wen, *Member, IEEE*, Jenn-Kaie Lain, and Yu-Wen Lai

***Abstract*—A joint code division multiple access and noncollision packet reservation multiple access (CDMA/NC-PRMA) technique is proposed and investigated as an uplink protocol for the third-generation (3G) mobile systems. Being the underlying time division multiple access (TDMA) architecture of the CDMA transmissions, NC-PRMA enables the base station (BS) to have a centralized control over the slot allocation policy. In order to reduce the multiple access interference (MAI) variation in a CDMA transmission, two different slot assignment schemes, referred to as load-balancing (LB) and power-grouping (PG) schemes, are proposed and evaluated. Simulation results show that considerable improvement can be achieved over the joint CDMA/PRMA scheme, in which the MAI variation is reduced by way of a dynamic permission probability for contending terminals. Especially when an imperfect power control mechanism is considered, the proposed PG assignment scheme achieves significant performance advantages.**

***Index Terms*—CDMA, PRMA, radio resource assignment schemes, wireless multimedia communications.**

I. Introduction

With the development of high-performance devices, such as portable computers, personal digital assistants, and portable videophones, the demand for providing multimedia services over the future wireless personal communication networks (WPCNs) has been rapidly increasing [1]. In the third-generation (3G) mobile systems, a variety of media such as voice, data, and video are coexistent. The system should be capable of multiplexing different media in an effective manner. A key issue in such a system is the design of a suitable multiple access control protocol to efficiently arbitrate multiple terminals on a common shared channel.

Conventional random assignment and fixed assignment multiple access control schemes are unsuitable for the wireless multimedia communications [2]. Random assignment methods, such as ALOHA and carrier-sense multiple access/collision detection (CSMA/CD), are insufficient for real-time information, and fixed assignment schemes, including frequency division multiple access (FDMA) and time division multiple access (TDMA), are inefficient for the transmission of busty traffic. On the other hand, the demand assignment access control scheme, which assigns the bandwidth to users dynamically regarding their demand, is a feasible approach toward heterogeneous traffic environment [2]. Several multiple-access protocols pertaining to the demand assignment catalog have been proposed for wireless multimedia applications. In [1], the dynamic TDMA (D-TDMA) scheme has been modified to support multimedia traffic. In that study, the multiservice-dynamic-reservation time division multiple access (MDR-TDMA) scheme was proposed. This scheme is based on the TDMA architecture, and each frame is divided into request slots and message slots. The request slots are used to convey access requests from dispersed users on the basis of random access scheme, and the message slots are used to carry information traffic. Thus, the base station (BS) can assign slots in response to the request information received from request slots. Another notable TDMA-based protocol, known as packet reservation multiple access (PRMA) [3], [4], achieves its capacity gain by way of multiplexing voice traffic at a talkspurt level rather than permanently allocating resources for voice traffic, as is in the conventional TDMA systems. However, as the traffic is heavily loaded, the PRMA protocol suffers serious performance degradation due to packet collisions.

Several variants of PRMA protocol were proposed to enhance the original PRMA protocol. In [5], a centralized PRMA (C-PRMA) has been proposed, in which the BS plays a central role in scheduling the transmission of mobile terminals. The main evolution of C-PRMA is that the BS uses polling messages to specify whether an uplink slot is “available” or “reserved” and to identify the terminal to which the corresponding slot is assigned. In contrast to fixed place assignment, the slot places in the consecutive frames are dynamically controlled by the base station. In this way, the packet loss due to exceeding the delay constraint is reduced. In addition, the concept of dynamic slot allocation was also adopted in the packet reservation multiple access/dynamic allocation (PRMA/DA) protocol proposed in [6]. In the protocol, the BS also acts as a bandwidth allocation manager and tries to satisfy the anticipated quality of service (QoS) of each medium by way of the operation of its resource allocation algorithm.

Yet, there is another protocol proposed for WPCN called noncollision PRMA (NC-PRMA) [7], [8]. The main idea of NC-PRMA is the use of a time–frequency signaling scheme by which the BS can learn the service requests from all dispersed terminals. Thus, the BS can have a centralized control over the slot allocation policy. Moreover, the signal strengths of signatures from specific users may indicate the current transmitted

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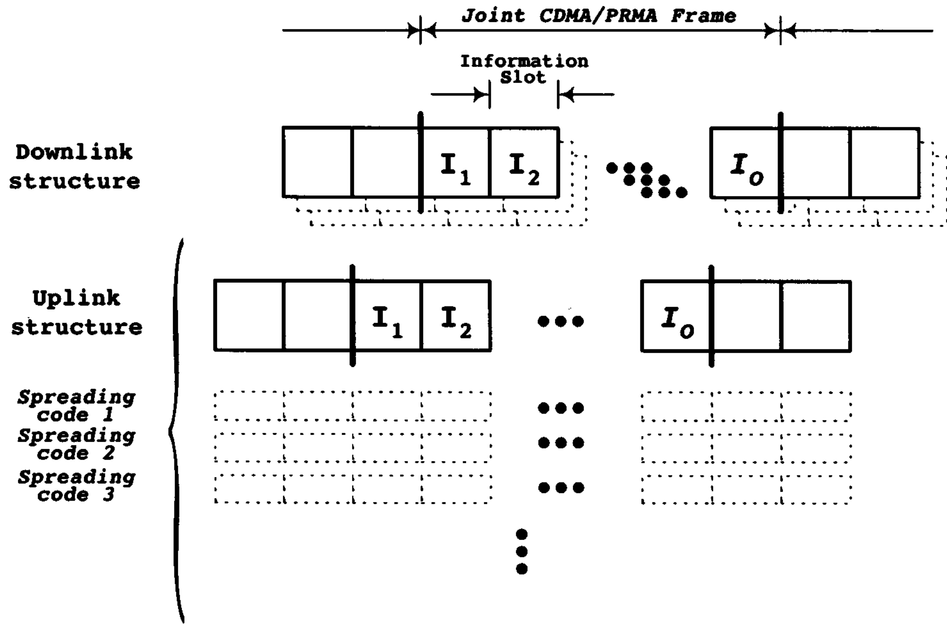

Fig. 1. Frame structure of joint CDMA/PRMA protocol.

power levels in the corresponding information slots. Associated with our proposed slot assignment scheme, knowledge about the power levels of all active terminals can play a vital role in reducing of the multiple access interference variation; thus, in this paper, we adopt NC-PRMA as the underlying TDMA architecture for the proposed joint CDMA/NC-PRMA protocol.

The code division multiple access (CDMA) scheme is another promising candidate for multiple access technique in wireless communication systems because of its ability of frequency diversity, resolution of multipath components, and universal frequency reuses [9]–[12]. With the CDMA scheme, different bit rate media can use the entire channel bandwidth at the same time in a spread-spectrum manner. Thus, there would be a good statistical multiplexing gain for the accommodation of different media. Recently, a joint CDMA/PRMA protocol is proposed to merge the advantages of PRMA-based schemes and CDMA techniques [13]. In joint CDMA/PRMA protocol, multiple access interference variation is reduced by way of an appropriate control of the permission probability for contending users. However, due to the decentralized slot allocation manner, the number of actually transmitting packets on a specific slot is a statistical phenomenon in nature. Thus, it may vary from slot to slot, and a certain amount of resulting multiple access interference variation exists, suggesting some room for further performance improved. Motivated by this fact, we propose using NC-PRMA as the TDMA architecture for CDMA transmissions. By this modification, the slot assignment scheme is changed from a decentralized manner into a centralized one.

By means of the centralized control over slot assignment, the number of transmissions in each slot may be well controlled such that the multiple access interference variation is actually minimized. In this study, we refer to the slot assignment scheme to achieve this goal as load-balancing (LB) scheme. In addition to the effects of different traffic loads among slots, as long as imperfect power control is concerned, the variation of received power levels may play a vital role in bit error rate (BER) performance. In contrast to the issue that different power levels are not dealt with in the joint CDMA/PRMA scheme, we do take it into account in the joint CDMA/NC-PRMA protocol by using a power-grouping slot (PG) assignment scheme on the basis of information about different power levels acquired from signatures. To validate the effectiveness of joint CDMA/NC-PRMA system, its performance will be compared with that of joint CDMA/PRMA protocol.

The remainder of this paper is organized as follows. In Section II, we describe some preliminary work, with emphasis on the basic features of joint CDMA/PRMA protocol. In Section III, we propose the joint CDMA/NC-PRMA protocol, together with two slot assignment schemes referred to as LB slot assignment and PG slot assignment schemes, to reduce the multiple access interference (MAI) variation in the multiple access environment. The relevant system parameters and performance measures for both single- and multicell systems are presented in Section IV. Section V presents simulation results with discussion. Finally, the conclusion is drawn in Section VI.

II. Preliminary Work

A. Basic Features of Joint CDMA/PRMA Protocol

The joint CDMA/PRMA protocol is essentially an extension of the conventional PRMA protocol operating in a DS/CDMA environment. During a time-slot period, a certain group of terminals have their quotas to transmit using the direct sequence (DS) spread-spectrum scheme. Fig. 1 shows its frame structure. The time axis is divided into slots, which are grouped into frames, as in PRMA [3], [4]. The frame rate is identical to the packet arrival rate of voice terminals so that a voice terminal may periodically transmit a packet during a frame interval. On the uplink carrier, a number of information channels, separated by different spreading codes, are dynamically assigned to terminals for information transmissions. As for downlink transmission, each downlink packet is preceded by a feedback message in response to the results of the most recent uplink transmissions. If the BS is able to decode the header of one or more arriving packets, the feedback message identifies the packet-sending terminals, indicating which of the corresponding packets were received successfully, and transmits the available permission probability of the corresponding slot in the next frame.

In the original PRMA, each contending terminal conducts a Bernoulli experiment with a predetermined permission probability as the parameter. If the outcome is positive, the terminal is granted to transmit. The essence of the joint CDMA/PRMA protocol is the use of the CDMA scheme in connection with the PRMA protocol with a dynamic permission probability in response to the variation of the number of reservation users. The BS, obtaining information from the packet headers sent from the reserving terminals in a current slot, calculates the available permission probability of the corresponding slot in the next frame via a channel access function. Thus, the contending terminals can contend for a reservation according to this permission probability.

The purpose of the channel access function is to control the simultaneous conversations K in every slot such that the capacity is maximized under the constraint of the packet loss probability not exceeding the required packet loss probability limit $(P_{\rm loss})_{\rm req}$. Typically, the permission probability decreases with the increase of the number of simultaneous conversations per slot. Giving a constraint of $(P_{\rm loss})_{\rm req}$, the optimal number of simultaneous conversations per slot $K_{\rm opt}$ was calculated in [13].

B. DS-CDMA System Modeling

In this paper, it is assumed that the performance of a CDMA system is measured by the BER [4], [5], [13]. A widely used approximation for the multiple access interference to determine the BER performance on the CDMA channel is the standard Gaussian approximation [16]. Assuming that the multiple access interference is Gaussian distributed, and using the binary phase-shift keying (BPSK) modulation–demodulation and a simple correlation receiver [16], the bit error probability P_e can be obtained from

$$P_e \approx Q(\overline{\rm SNR}). \tag{1}$$

In (1), the average signal-to-noise ratio (SNR) $(\overline{\rm SNR})$ for the ith packet in the case of unequal power reception when considering a single-cell system can be written as [13], [16]

$$\overline{\rm SNR}_i = \sqrt{\frac{P_i}{\frac{1}{3N}\sum_{\substack{k=1\\k\neq i}}^{K} P_k + \frac{N_0}{2T}}} \tag{2}$$

where

K	number of simultaneous transmitting terminals in a given slot;
T	data bit duration;
$N_0/2$	two-sided power spectral density of the additive white Gaussian noise (AWGN) channel;
P_k	power level of the kth user;
N	processing gain.

In a multicell system with $R+1$ equally loaded cells, where R denotes the number of neighboring cells, and each has K active users, including contending and reserving terminals, the average SNR for test cell 0 under perfect power control can also be written as follows [13]:

$$\overline{\rm SNR} = \sqrt{\frac{3P_0N}{(K-1)P_0 + \sum_{k=1}^{K}\sum_{i=1}^{R} P_{(k,\,i)_0}}} \tag{3}$$

where P_0 denotes the desired signal power level while $(K-1)P_0$, and $\sum_{k=1}^{K}\sum_{i=1}^{R} P_{(k,\,i)_0}$ denote the intracell and intercell interference, respectively. Note that the effect of the AWGN is neglected in (3), due to the consideration of the intercell interference. Thus, the bit error probability P_e can be derived in both single and multicell environments, according to (1). Consequently, the bit successful probability is $Q_e = 1 - P_e$.

To compensate the potential channel impairments, various investigations suggest that forward error correction (FEC) code is needed in packet CDMA systems [13], [17]. With K simultaneous conversations, assuming that a packet of L bits is transmitted over a memoryless binary symmetric communication channel with bit successful probability $Q_e[K]$ and employing a linear block code that can correct t errors, the packet successful probability $Q_E[K]$ can be calculated from

$$Q_E = \sum_{i=0}^{L} \binom{L}{i} (1-Q_e)^i (Q_e)^{L-i}. \tag{4}$$

C. Inherent MAI Variation in Joint CDMA/PRMA

It has been shown that the joint CDMA/PRMA protocol can achieve significant capacity gain relative to the random access CDMA scheme [13]. Since the permission probability is always set to unity in the random access CDMA system, the packet transmissions suffer serious variation of multiple access interference. Thus, it can be viewed as a special case of the joint CDMA/PRMA system operating without the constraint of the channel access function. Another scheme, named the optimized *a-posteriori* expectation access scheme, is employed as a good benchmark for efficiency of the joint CDMA/PRMA protocol [13]. When the number of contending terminals K_c is known, the BS sets the permission probability for the contending terminals as

$$p_s = \frac{K_{\rm opt} - K_{\rm res}}{K_c} \tag{5}$$

where $K_{\rm res}$ denotes the number of reserving terminals at this slot. The expectation of the number of terminals K in every slot can be estimated as $E[K] = K_{\rm res} + K_c \cdot p_s$. From the viewpoint of mean value of $K, E[K]$ would approach $K_{\rm opt}$. However, a certain amount of MAI variation still exists due to the dynamic characteristic of statistical behaviors. The main aim of this paper is to reduce the variation inherent in the joint CDMA/PRMA protocol.

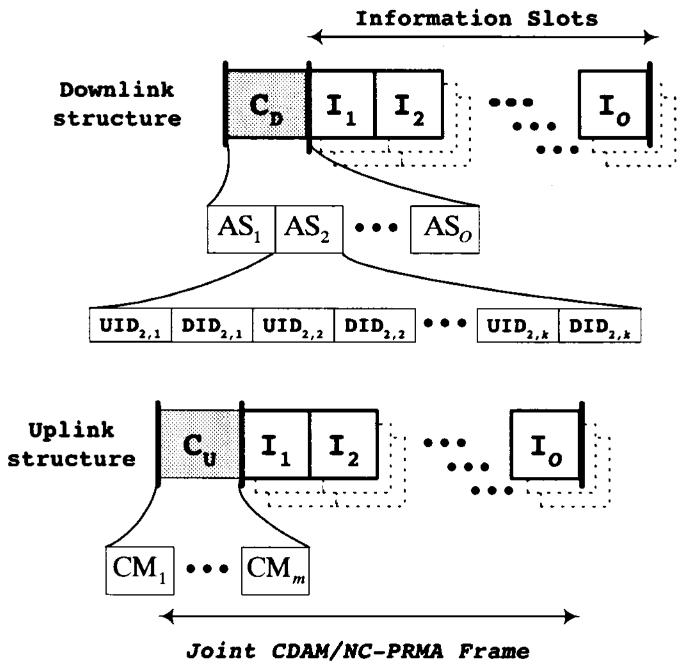

Fig. 2. Frame structure of joint CDMA/NC-PRMA protocol.

III. Description of Joint CDMA/NC-PRMA

A. Protocol with Centralized Operation

The NC-PRMA access scheme is suitable for wireless multimedia communications. The reasons are summarized twofold: One is due to its excellent design of the time–frequency signaling mechanism that offers an easy way for terminals to inform their bandwidth demand to the BS without collision and the other is the operation of centralized control over a slot allocation policy [7]. Thus, using NC-PRMA as the underlying TDMA architecture, joint CDMA/NC-PRMA protocol is a centralized and frame-based protocol, which enables us to design two slot-assignment schemes to further reduce the MAI variation, as described in the following.

B. Frame Structure

Fig. 2 shows the frame structure of the proposed joint CDMA/NC-PRMA protocol. Traffic of uplink and downlink is transmitted on separate radio carrier, i.e., frequency division multiplexing (FDD) mode. The uplink information carrier is time-partitioned into frames, and the frame duration is identical to the packet interarrival time of voice terminals. Each frame contains O information slots and one control slot C. Here, we use $I_m, 1 \leq m \leq O$ to denote the mth information slot in each frame. Since the joint CDMA/NC-PRMA systems are operated in a centralized manner, the address field used by the joint CDMA/PRMA systems in each information packet header can be extracted for the application of control slot. This suggests that there is enough bandwidth for the design of the control slot. The detailed design issues of the control slot will be discussed in Section IV.

C. Time–Frequency Signaling Scheme

The control slot is used to carry the required control messages of terminals. The uplink control slot (C_U) is further divided into m control minislots (CMs), and each CM can contain n single tones, where each CM serves as a time interval for the time–frequency signaling scheme. By using the same idea of a fast frequency-hopped multiple-level frequency shift keying scheme [18], [19], a receiver that is equipped with an n-frequency filter bank is assumed to be implemented in the BS. During each CM period, up to n terminals can transmit to the BS using different single tones. Since there are m CMs in the C_U, thus, the time-frequency signal scheme can constitute $(m \times n)$ different signatures with each being uniquely recognized by the BS, where the signature denotes a pair of (m, n). Therefore, each signature can identify a specific terminal for the purpose of slot assignments in the BS. In this study, we assume that dedicated signatures are assigned only to voice terminals. The voice terminals in the system are classified into silent and active terminals, and the active terminals are further categorized into reserving terminals and requesting terminals. Whenever a terminal has a new talkspurt arrival, it changes from silent state to requesting state and starts to transmit the signature on its dedicated CM to inform the BS about its bandwidth request. Upon receiving the slot assignment command from the downlink control slot, it enters the reserving state and begins to transmit the packets on the assigned information slots. Similar to the joint CDMA/PRMA protocol, each O information slot can be simultaneously used by more than one user using a different spreading code.

As for the downlink carrier, the downlink control slot (C_D) is partitioned into O assignment minislots (ASs). Each AS_n $(1 \leq n \leq O)$ comprises k pairs of uplink terminal identity (UID) and downlink terminal identity (DID) fields. The downlink control slot aims to broadcast the assignment information to the terminals, which have a new talkspurt arrival or need a slot reassignment. The UID field of AS_n specifies the terminal ID who has the right to transmit the packet on the nth information slot of the uplink, while the DID field indicates the terminal ID that needs to receive the packet from the nth information slot of the downlink. Hence, by listening to every AS in each downlink frame, terminals that have a new talkspurt arrival or need a slot reassignment can realize which slot is allocated to them to transmit packets to the BS or to receive packets from the BS. Once the first packet of a talkspurt has been successfully received, the related terminal can transmit the successive information packets on the assigned slot until the talkspurt finishes or a slot reassignment occurs.

D. Channel Access

The BS assigns a unique signature pair (m, n) to each terminal during the call set-up procedure. The active voice terminals use their signatures to indicate the bandwidth demand in every frame while the silent terminals are not required to transmit their signature. Hence, at the end of each uplink control slot, the BS knows the bandwidth demand information and can then make slot assignments or reassignments according to the slot assignment schemes. The BS broadcasts the slot assignment information to the terminals through the downlink control slot. The uplink and downlink terminals IDs about slot allocations and reassignments are carried by the UID and DID fields of ASs. Upon receiving the messages on ASs, the terminal transmits its information packet in an I_m slot until the talkspurt finishes or a slot reassignment occurs. At the end of a talkspurt, the related terminal releases the time slot by ceasing the transmission of its bandwidth-demand indication in its dedicated CM. Thereafter, the BS can assign the corresponding slot to other requesting terminals.

E. Slot Assignment Schemes

In order to reduce the MAI variation, we propose two efficient slot assignment schemes for the joint CDMA/NC-PRMA system, which are described as follows

1) *LB slot assignment scheme*: In this scheme, only the terminals, which have a new talkspurt arrival (not yet become reserving), are assigned a slot by the BS. Since the BS knows the traffic distribution of each slot, it assigns the requesting terminals that have a new talkspurt arrival to the slots with the least reserving terminals while the assigned slots of the reserving terminals are unchanged. The aim of this scheme is to control the number of terminals assigned to the O information slots in a frame as equal as possible. Thus, the load among all slots will approach balance under this operation. In Section V, the joint CDMA/NC-PRMA system with the LB slot assignment scheme will be evaluated and compared with the joint CDMA/PRMA protocol under perfect and imperfect power control assumptions, respectively.
2) *PG slot assignment scheme*: This scheme differs from the previous one in that the received power levels are taken into account and the slot position for each reserving terminal might change from slot to slot. By measuring the current power level of each active terminal from its signature at the beginning of each frame, the BS can learn the current power ordering information of those terminals. Assuming that there are ℓO active terminals in the current frame. The power ordering information can be represented as $(P_0, P_1, P_2, \cdots, P_{\ell O-1})$, where P_i is the signature power level of user i and $P_0 < P_1 < P_2 < \cdots < P_{\ell O-1}$. With the PG slot assignment scheme, the BS assigns the first ℓ terminals with signature power level $P_0, P_1, P_2, \cdots, P_{\ell-1}$, respectively, to the information slot I_1, the next ℓ terminals with signature power level $P_\ell, P_{\ell+1}, \cdots, P_{2\ell-1}$, respectively, to the information slot I_2, and so on. By this way, all the terminals assigned to a specific slot have a comparative power level. This is what the term "power-grouping" implies. As will be seen in Section V, the joint CDMA/NC-PRMA system with PG slot assignment scheme will provide an excellent performance in the presence of power control imperfections.

IV. Performance Evaluation

A. Traffic Models

In order to support wireless multimedia applications, both voice and video media are considered in this investigation. A voice terminal creates a pattern of talkspurts and silent gaps, as classified by a slow voice activity detector [3], [4]. Thus, the silent gaps can be exploited to accommodate more users. The slow voice activity detector is modeled as a two-state Markov process. The periods of talkspurt and silence are exponentially distributed with mean time $t_1 = 1$ s and $t_2 = 1.35$ s, respectively. This yields a voice activity factor α_s that is defined as the fraction of time where voice is detected to be about 0.43. Regarding to the constraint of voice packet delay, the maximum tolerable delay of voice packets $D_{\max}$ is set to be 40 ms [20].

For the video traffic model, we adopt the same video model as used in [13] for the purpose of performance comparison. Video terminals create a new packet in every slot, according to a Bernoulli experiment with parameter $\sigma_d = 0.9$. Once a video packet is produced, it is first queued in the local buffer of video terminals. If there are any packets queued in the buffer, video terminals transmit one packet per slot until the buffer becomes empty. Additionally, video packets have to be retransmitted when they are corrupted due to excessive MAI.

TABLE I
SYSTEM PARAMETERS

Items	Joint CDMA/PRMA (511,229,38)	Joint CDMA/ NC-PRMA (315,185,13)
Information size (bit)	160	160
Symbol size (bit)	229	185
Packet size after coding (bit)	511	315
Frame duration (ms)	20	20
Information slot	20	20
Control slot	-	1
Information slot duration (ms)	1	0.9
Control slot duration (ms)	-	2
CDMA channel rate (kbps)	3577	3577
PRMA channel rate before coding (kbps)	229	205
PRMA channel rate after coding (kbps)	511	350
Processing gain	7	10.22
Number of orthogonal tone	-	25
Duration of single tone (ms)	-	0.09
Duration of guard time (ms)	-	0.01

B. Design Issues for System Parameters

For comparison purpose, the parameters used in the joint CDMA/PRMA protocol are adopted for the joint CDMA/NC-PRMA protocol with a little modification to support the control slot in each frame as mentioned above. As shown in Table I, the control slot duration is 2 ms. Since the joint CDMA/NC-PRMA is a centralized protocol, the address field is not necessary to transmit in the wireless hop. Therefore, the address field of each information packet can be extracted to design the control slot. Assuming the number of uplink control minislots $m = 20$, the duration of each uplink control minislot plus guard time is 0.1 ms. So choosing the duration of each uplink control minislot $T = 0.09$ ms seems enough to take care of the guard time required in practice. On the other hand, with $T = 0.09$ ms, the bandwidth that is required for each signature is at least $1/T \approx 11.11$ kHz. Thus, the total bandwidth required for supporting 25 orthogonal tones is at least 277.75 kHz, which is much smaller than the channel bandwidth 3577 kHz. This statement supports our plan to implement the time–frequency signaling scheme for the joint CDMA/NC-PRMA protocol.

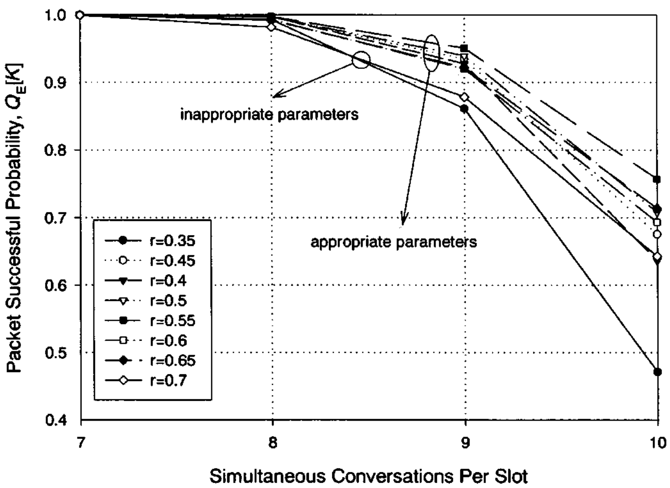

Fig. 3. Packet successful probability versus simultaneous conversations per slot when $M = 229$.

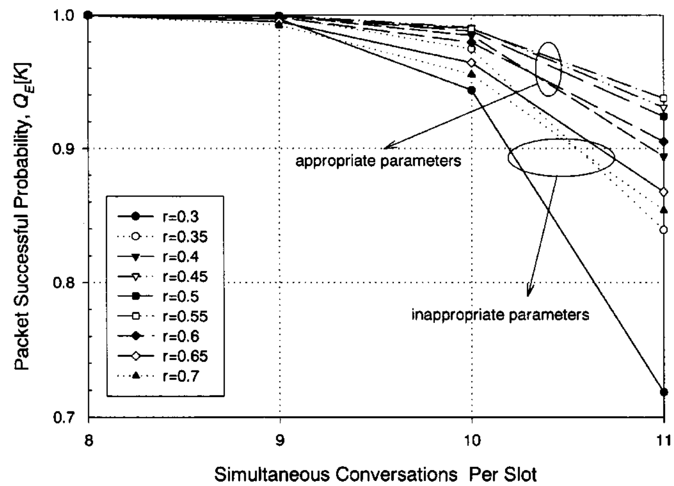

Fig. 4. Packet successful probability versus simultaneous conversations per slot when $M = 185$.

It is well known that each cell uses the whole system bandwidth for information transmission in CDMA systems. In the proposed system, the bandwidth required for the uplink control slot in each cell is about 277.75 kHz for the time–frequency signaling scheme. Therefore, the total system bandwidth can be divided into 12 disjoint bands to support a cluster size of 12 cells to operate the time–frequency signaling scheme in a frequency division manner. Thus, the total bandwidth should be reused for every 12 cells. Obviously, with a cluster size of 12 cells, the reuse distance for the time–frequency signaling scheme is far enough to keep the signal-to-interference ratio (SIR) to no less than 18 dB [25], which is large enough to assure the proper detection of signature in each cell. On the other hand, in order to make sure the correct reception of control slots, the target system of our proposed scheme should be synchronized within one cluster. But it is allowed to be asynchronous in different clusters. In fact, there is no difficulty for us to satisfy this requirement using current techniques.

When operating in a DS-CDMA environment, the packet successful probability in a given slot depends on the number of packets simultaneously transmitted, the correcting ability of FEC code used, and the processing gain. An (L, M, t) BCH-code is considered for FEC code here, where

- L number of packet bits;
- M number of information bits;
- t number of correctable errors.

For a given M, an increment of L may result in an increment of t. Thus, the processing gain decreases if the CDMA channel rate is kept constant. Therefore, a meaningful consideration about system parameters design should be given. Figs. 3 and 4 are given to reveal the relation between the packet successful probability $Q_E[K]$ and the code rate r, defined as M/L. By calculating $Q_E[K]$ with a different code rate while keeping $M = 229$, including 160 information bits and 69 bits header, using the Varsharmov–Gilbert bound to determine t [21], appropriate code rates are in the range of 0.4 to 0.6, as shown in Fig. 3. Therefore, a (511, 229, 38) BCH-code [21], which has a code rate around 0.45, was chosen for the joint CDMA/PRMA system [13]. Following the same approach, appropriate code rates are in the range of 0.45 to 0.65 for $M = 185$, which is equal to the size of the joint CDMA/PRMA packet minus 44 bits of the address field, as shown in Fig. 4. Therefore, a (315, 185, 13) nonprimitive BCH-code [21], which has a code rate around 0.55, is chosen for our proposed joint CDMA/NC-PRMA system. The system parameters for both systems are summarized in Table I.

C. Imperfect Power Control Model

Several studies [22]–[24] showed that system performance can be remarkably degraded in the presence of an imperfect power control. The level of imperfection of this mechanism depends on many causes, such as power control algorithm, power control loop delay, the distribution of the terminals, propagation environment, etc. In this paper, following [22]–[24], the imperfection of power control is modeled as a log-normal distribution, given by

$$P_r(t) = P_d 10^{\xi(t)/10} \tag{6}$$

where

- $\xi(t)$ Gaussian random variable with zero mean and standard deviation σ;
- P_d desired signal power level;
- P_r actual received power level.

The higher values of σ denote a more serious imperfect power control, while $\sigma = 0$ dB means a perfect power control.

D. Performance Measures

As for the performance measures, we consider the maximum number of simultaneous conversations that can be accommodated under the constraint of the loss probability no more than $(P_{\rm loss})_{\rm req}$. Furthermore, there is another benchmark, named perfect scheduling, that is driven as the theoretical maximum capacity in [13]. With the definition of $K_{\rm opt}$ and $Q_E[K]$, we can believe that by achieving the maximum capacity with a given $(P_{\rm loss})_{\rm req}$, each slot should be loaded with either $K_{\rm opt}$ or $(K_{\rm opt} + 1)$ simultaneous conversations. Thus, the packet loss probability $P_{\rm loss}$ can be represented in (7), shown at the bottom

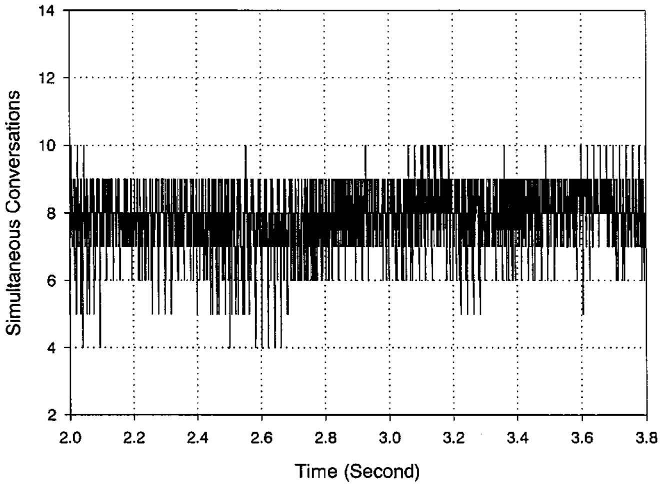

Fig. 5. MAI pattern for joint CDMA/PRMA system under 375 simultaneous conversations.

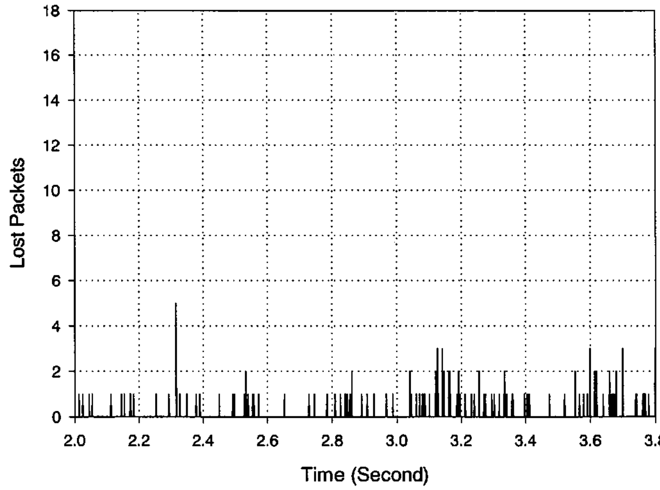

Fig. 6. Packet loss caused by MAI pattern depicted in Fig. 5.

of the page, where $P_E[K] = 1 - Q_E[K]$ is the packet-error probability. The probability that a slot is loaded with $(K_{\rm opt}+1)$ conversations is $p[K_{\rm opt}+1] = 1 - p[K_{\rm opt}]$. This yields

$$p[K_{\rm opt}] = \frac{(K_{\rm opt}+1)\cdot(P_E[K_{\rm opt}+1] - P_{\rm loss})}{(K_{\rm opt}+1)\cdot P_E[K_{\rm opt}+1] - K_{\rm opt}\cdot P_E[K_{\rm opt}] - P_{\rm loss}}. \tag{8}$$

Hence, the maximum number of simultaneous conversations for a given $(P_{\rm loss})_{\rm req}$ is

$$C_{\max} = O\cdot 1/\alpha_s\cdot(p[K_{\rm opt}]\cdot K_{\rm opt} + p[K_{\rm opt}+1]\cdot(K_{\rm opt}+1)). \tag{9}$$

In this paper, we will also evaluate this performance to show how well the proposed system can perform.

V. Simulation Results and Discussions

Computer simulation based on the aforementioned modeling and performance measures is used as the main approach to explore the performance evaluation of our proposed joint CDMA/NC-PRMA scheme. The BS is assumed to be equipped with an omnidirectional antenna. Each BS has a fixed number of terminals under communication, and the terminals are uniformly distributed over its service area. During the entire simulation interval, each voice terminal changes its state between talkspurt and silence according to the two-state Markov process. Therefore, the effect of call arrivals and departures are not considered in our simulation. This situation is identical to that adopted in the joint CDMA/PRMA protocol [13]. The result for each performance measure is obtained by averaging over ten Monte Carlo simulation runs where each run is performed over an interval of 10^6 information slots.

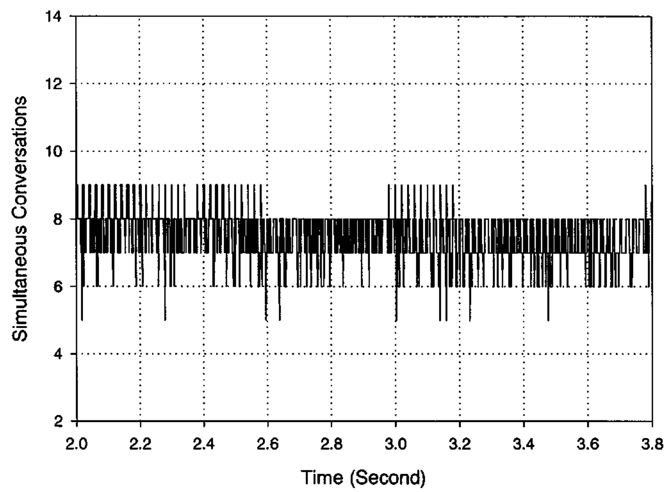

Fig. 7. MAI pattern for joint CDMA/NC-PRMA system with LB scheme under 375 simultaneous conversations.

A. Voice-Only Traffic in Single-Cell System

In this subsection, the simulation results of the joint CDMA/PRMA protocol and the proposed joint CDMA/NC-PRMA protocol with the LB slot assignment scheme operating in a voice-only traffic and single-cell system are compared. The typical multiple access interference patterns are shown in Figs. 5 and 7 for the joint CDMA/PRMA and the joint CDMA/NC-PRMA protocols, respectively, with 375 simultaneous conversations. The packet loss caused by the corresponding MAI pattern are depicted in Figs. 6 and 8 for both protocols, respectively. It is observed that the MAI pattern of the proposed the joint CDMA/NC-PRMA protocol becomes more stationary than that of joint CDMA/PRMA protocol from Figs. 5 and 7. As expected, by balancing the loads among all slots, a less interference variation is achieved. Consequently,

$$P_{\rm loss} = \frac{p[K_{\rm opt}]\cdot K_{\rm opt}\cdot P_E[K_{\rm opt}] + p[K_{\rm opt}+1]\cdot(K_{\rm opt}+1)\cdot P_E[K_{\rm opt}+1]}{p[K_{\rm opt}]\cdot K_{\rm opt} + p[K_{\rm opt}+1]\cdot(K_{\rm opt}+1)} \tag{7}$$

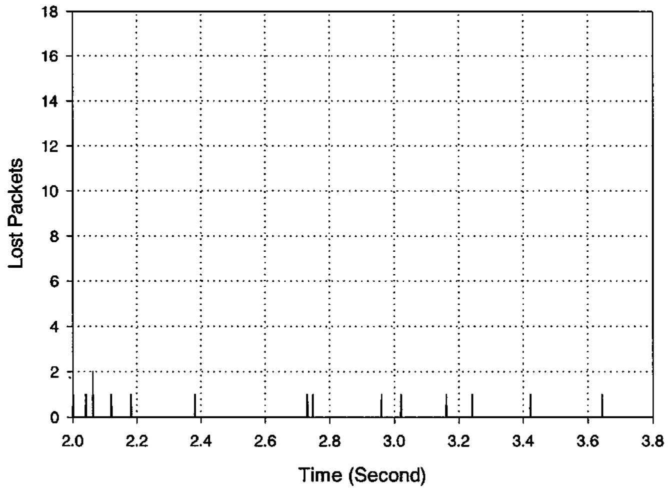

Fig. 8. Packet loss caused by MAI pattern depicted in Fig. 7.

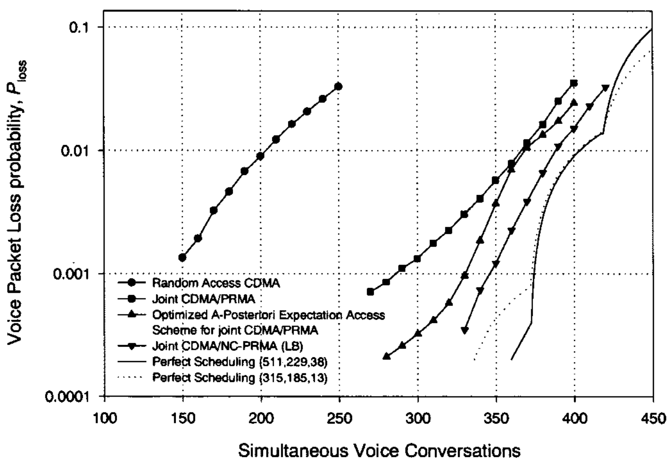

Fig. 9. Voice packet loss probability versus simultaneous voice conversations for different schemes.

TABLE II
SIMULATION RESULTS OF MAXIMUM SIMULTANEOUS VOICE CONVERSATIONS FOR VOICE-ONLY TRAFFIC IN DIFFERENT ENVIRONMENT

Environment	Single Cell		Cellular, $\gamma = 4$		Cellular, $\gamma = 3$	
Protocol	J C/P	J C/NC	J C/P	J C/NC	J C/P	J C/NC
$P_{loss} = 0.01$	358	389	266	288	209	224
$P_{loss} = 0.02$	379	406	280	298	220	234

a smaller portion of transmitted packets is lost for the joint CDMA/NC-PRMA protocol, as shown in Figs. 6 and 8.

Fig. 9 depicts the packet loss probability versus simultaneous conversations for various schemes considered. The maximum number of simultaneous conversations under the constraint of $P_{\rm loss} \leq 0.02$ and $P_{\rm loss} \leq 0.01$ are summarized in Table II. From this table, the number of maximum simultaneous conversations for the joint CDMA/NC-PRMA protocol is superior to those for the joint CDMA/PRMA scheme. Furthermore, the joint CDMA/NC-PRMA scheme even outperforms the joint CDMA/PRMA protocol with the optimized *a posteriori* expectation access scheme, as shown in Fig. 9. As mentioned in the preceding section, the optimized *a posteriori* expectation access scheme tries to reduce the interference variation by controlling the permission probability on the basis of the expected number

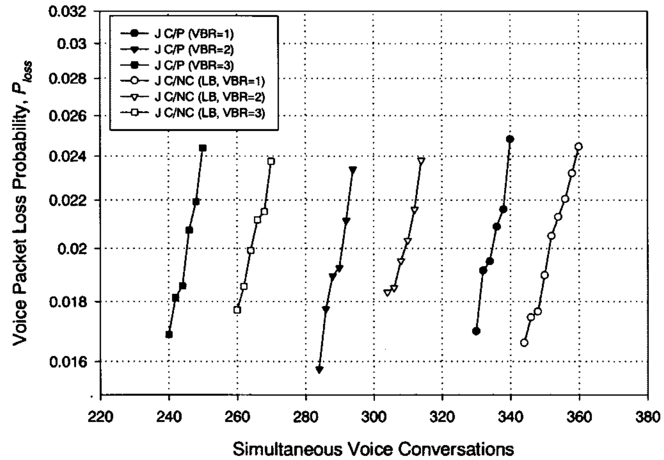

Fig. 10. Voice packet loss probability versus simultaneous voice conversations with one, two, and three video terminals, respectively, in a single-cell system.

TABLE III
SIMULATION RESULTS OF MAXIMUM SIMULTANEOUS VOICE CONVERSATIONS FOR MIXED VOICE/VIDEO TRAFFIC

Num. of Video	1		2		3	
Protocol	J C/P	J C/NC	J C/P	J C/NC	J C/P	J C/NC
$P_{loss} = 0.02$	335	352	291	309	245	264

of simultaneous terminals. However, the statistical behaviors of the Bernoulli permission probability experiments conducted by different terminals render its effectiveness to be limited. On the other hand, the joint CDMA/NC-PRMA protocol minimizes the variation of simultaneous transmission users by the use of the LB slot assignment scheme. In addition, the performance curve for the proposed protocol with the LB slot assignment scheme quite often approaches the theoretical maximum capacity of the perfect scheduling scheme. In summary, the proposed protocol with the LB slot assignment scheme successfully migrates the packet loss due to the MAI variation under the assumption of perfect power control.

B. Mixed Voice/Video Traffic in Single-Cell System

In the joint CDMA/PRMA protocol, video terminals are considered to generate continuous information, hence, they are regarded as permanent reserving and almost transmit one packet per slot [13].

Fig. 10 illustrates voice packet loss probability versus simultaneous voice conversations with one, two, and three video terminals, respectively, for the joint CDMA/PRMA protocol and the joint CDMA/NC-PRMA protocol with the LB scheme. The maximum number of simultaneous voice conversations under the constraint of $P_{\rm loss} \leq 0.02$ is summarized in Table III for both joint CDMA/PRMA and joint CDMA/NC-PRMA protocols. The joint CDMA/NC-PRMA protocol with the LB scheme still outperforms the joint CDMA/PRMA protocol in the mixed voice/video traffic environment. Especially, the joint CDMA/NC-PRMA protocol achieves more capacity gain compared to the joint CDMA/PRMA protocol when there are larger video terminals in the system, i.e., the capacity gain of the join CDMA/NC-PRMA protocol is 17, 18, and 19 more than those of the joint CDMA/PRMA protocol for one, two, and three video terminals, respectively. The reason can be explained as follows. Due to the bursty characteristic of video traffic, the more video terminals there are, the larger the variation of MAI in the joint CDMA/PRMA. So. the performance degradation of voice terminals becomes more serious as the number of video terminals is increased. On the other hand, the joint CDMA/NC-PRMA with LB scheme always assigns the new talkspurt arrivals to the slots with the least MAI; so, it has the ability to alleviate the variation of MAI arising from the video terminals. Hence, the impact of increasing the video terminals on the capacity degradation of voice terminals is less serious than the joint CDMA/PRMA.

C. Voice-Only Traffic in Multicell System

In this subsection, we discuss the performance for the considered protocols in a multicell system. In a multicell system, not only the interference created in the considered cell has to be accounted for but also the interference originated from the other cells, i.e., the intercell interference, should be taken into account for capacity evaluation as well. We consider a regular hexagonal cell layout with BSs in the center of each cell. The average value of an intercell interference level can be obtained from the procedure developed in [14] and [17]. When considering a path-loss law with a distance-independent path-loss exponent, for equally loaded cells, the normalized intercell interference for unit traffic per cell $I_{\text{Intercell}}$ depends only on the value of path-loss exponent. For path-loss exponent $\gamma = 3$ and $\gamma = 4$, $I_{\text{Intercell}}$ (unit traffic/cell) amounts to 0.749 and 0.37, respectively (see [14]). Thus, the second term in the denominator of (3) can be substituted by

$$\sum_{k=1}^{K}\sum_{i=1}^{R} P_{(k,\,i)_0} = P_0 \cdot I_{\text{Intercell}} \cdot \frac{C \cdot \alpha_s}{O} \tag{10}$$

where C denotes the simultaneous conversations in each cell, and O is the number of slots per frame. Simulation results for the voice-only system with both $\gamma = 3$ and $\gamma = 4$ are depicted for the considered schemes in Fig. 11. The slot assignment scheme, adopted in the joint CDMA/NC-PRMA protocol, is the LB scheme. By comparing the joint CDMA/NC-PRMA protocol with the joint CDMA/PRMA protocol, the capacity increases of the simultaneous voice conversations are about 14 and 18 for $\gamma = 3$ and $\gamma = 4$, respectively, under $(P_{\text{loss}})_{\text{req}} = 0.02$. Since the CDMA systems provide the advantages of universal frequency reuses, our proposed system makes a considerable capacity gain for a geographical CDMA system in which every cell uses the same frequency band.

D. Voice-Only Traffic in the Presence of Power Control Imperfections

Previous studies have suggested that imperfect power control does serious performance degradation to CDMA systems [15], [22]–[24]. The joint CDMA/PRMA protocol has the same phenomenon when the imperfect power control is considered [15]. The performance degradation for both joint CDMA/PRMA protocol and joint CDMA/NC-PRMA protocol with the LB slot assignment scheme in single- and multicell systems ($\gamma = 4$) are shown in Figs. 12 and 13, respectively. The capacity loss increases rapidly with the increase in σ. Although the proposed protocol with the LB slot assignment scheme outperforms the joint CDMA/PRMA protocol, its capacity is also degraded obviously when σ increases. This is because that the LB scheme

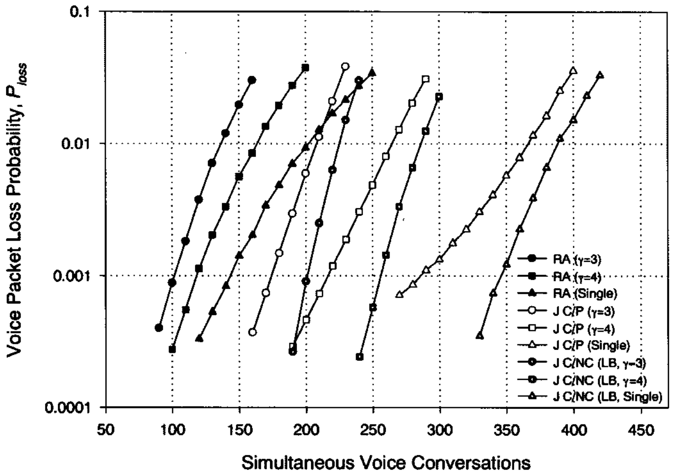

Fig. 11. Voice packet loss probability versus simultaneous voice conversations in a multicell system.

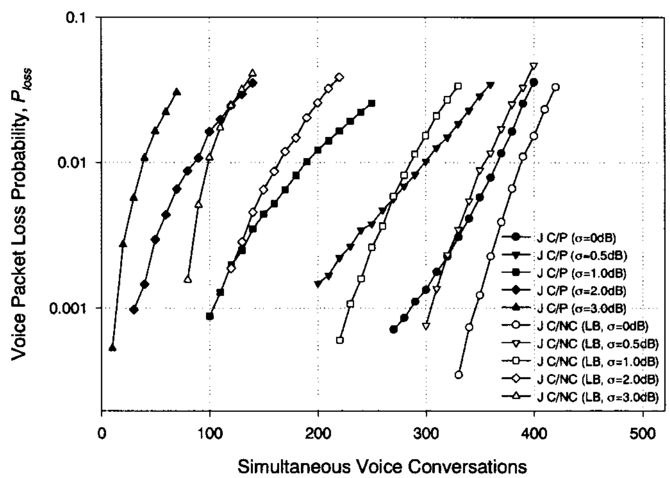

Fig. 12. Voice packet loss probability versus simultaneous voice conversations in a single-cell system under the presence of power control imperfections.

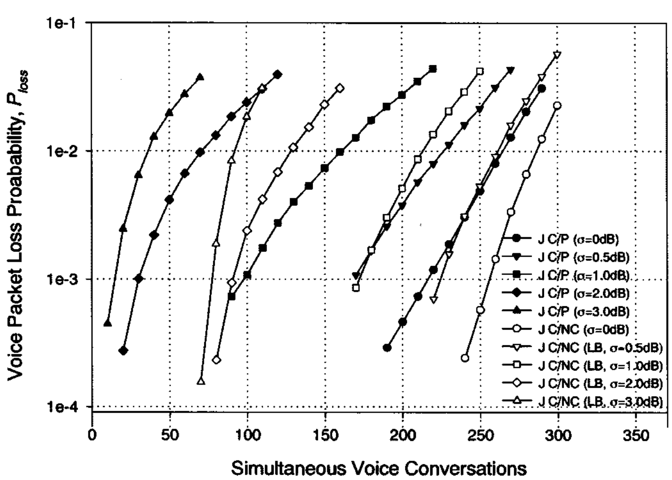

Fig. 13. Voice packet loss probability versus simultaneous voice conversations in a multicell system ($\gamma = 4$) under the presence of power control imperfections.

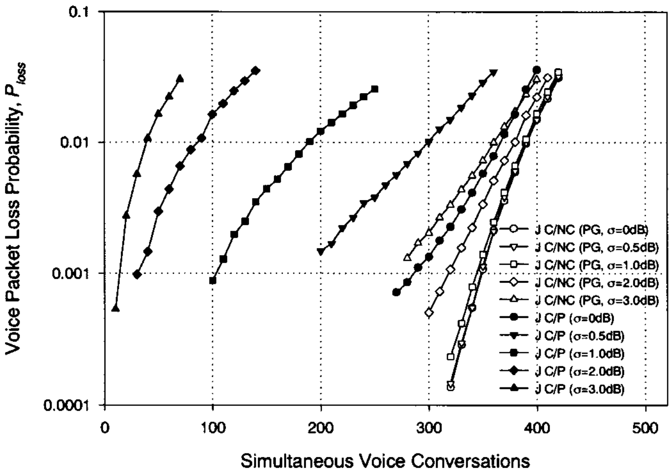

Fig. 14. Voice packet loss probability versus simultaneous voice conversations in a single-cell system under the presence of power control imperfections.

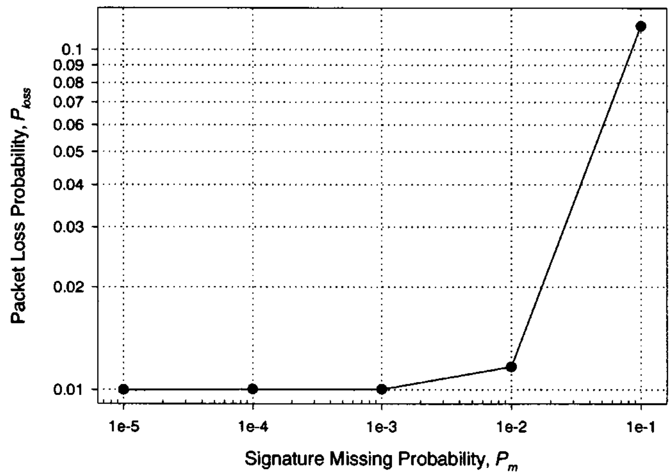

Fig. 16. Voice packet loss probability versus signature missing probability for the joint CDMA/NC-PRMA protocol with the LB scheme under perfect power control.

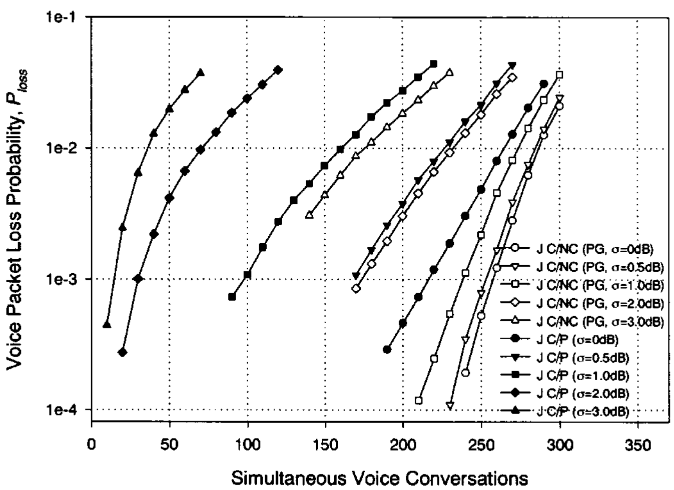

Fig. 15. Voice packet loss probability versus simultaneous voice conversations in a multicell system ($\gamma = 4$) under the presence of power control imperfections.

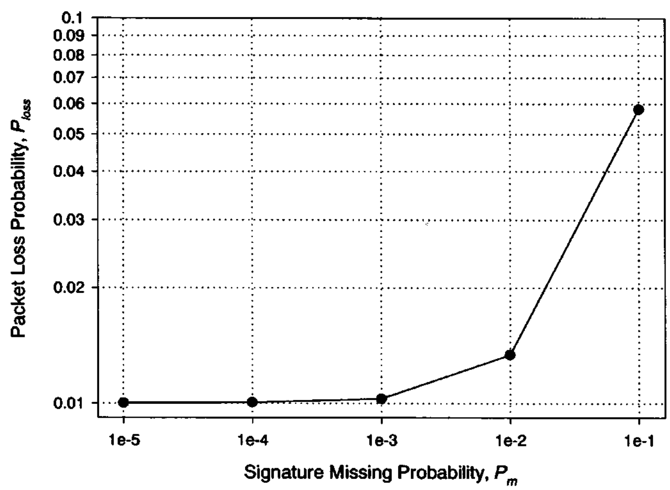

Fig. 17. Voice packet loss probability versus signature missing probability for the joint CDMA/NC-PRMA protocol with the PG scheme under imperfect power control ($\sigma = 0.5$ dB).

just considers the slot with the least reserving terminals as the slot with the least multiple access interference. However, this is not always true when the imperfect power control is considered. The terminals with a small power level might experience serious bit error probability even though they transmit in a slot with a smaller population.

The proposed protocol with the PG slot assignment scheme is emphasized for resisting the impact of imperfect power control. Figs. 14 and 15 depict the packet loss probability versus the simultaneous voice conversations for the joint CDMA/PRMA protocol and the joint CDMA/NC-PRMA protocol with the PG slot assignment scheme in the presence of power control imperfections under single- and multicell systems ($\gamma = 4$), respectively. When the imperfection of power control is small, the performance degradation is slight for the proposed protocol with the PG scheme in both single- and multicell systems. Since the transmitting terminals in the same slot are with a comparative power level, the phenomenon that the terminals with a small power level may experience serious bit error probability even though they transmit in a slot with a smaller population when applying the LB scheme is migrated successfully. Furthermore, the capacity of the proposed protocol with the PG scheme is significantly improved when compared with that of the joint CDMA/PRMA system. Simulation results demonstrate that the proposed joint CDMA/NC-PRMA with the PG slot assignment scheme is a robust and effective multiple access control scheme for the 3G mobile systems.

E. System Performance in the Presence of Signature Missing

Obviously, in the joint CDMA/NC-PRMA system, the signature mechanism plays an important role in slot allocations. In the BS, the traffic load distribution of voice terminals can be known well by the perfect signature mechanism. When the signature mechanism is not perfect, the performance of the joint CDMA/NC-PRMA systems will be slightly degraded. The traffic distribution recognized by the BS might mismatch with the actual traffic distribution due to the error reception of some signatures. In this subsection, we further study the effect of signal missing probability on the system performance. Here, the signature missing probability is defined as the probability that a detection of signature is failed.

Figs. 16 and 17 show the packet loss probability versus the signature missing probability for the joint CDMA/NC-PRMA protocol with LB and PG slot assignment scheme, respectively. Both results of Figs. 16 and 17 are performed under 389 simultaneous conversations, which is the system capacity of the joint CDMA/NC-PRMA system with either the LB scheme in the ideal power control environment or the PG scheme in the presence of imperfect power control with standard deviation $= 0.5$ dB under the constraint of the packet loss probability no more than 1%. Simulation results exhibit that our proposed protocol with either the LB or PG scheme is very robust if the signature missing probability is no more than 0.001. Furthermore, if the signature missing probability ranges from 0.001 to 0.01, the system suffers only a little degradation in packet loss probability.

VI. Conclusion

A joint CDMA/NC-PRMA protocol using the LB slot assignment scheme in a perfect power control assumption and the PG slot assignment scheme in an imperfect power control condition was proposed and evaluated. Under the centralized slot allocation policy, the MAI variation in both perfect power control and imperfect power control environments was significantly reduced. Results showed that the number of simultaneous users can be remarkably increased when compared to that of the joint CDMA/PRMA protocol. Especially, the imperfect power control situation severely degraded the performance of the joint CDMA/PRMA protocol, while it only slightly degraded the performance of the proposed joint CDMA/NC-PRMA system with the PG slot assignment scheme.

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