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Theoretical Analysis and Performance of NC-PRMA Protocol for Multichannel Wireless Networks

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Abstract. In this paper, we analyze the effect of duplexing schemes on the throughput and the average packet dropping probability of a new multichannel wireless access protocol which allows for non-collision packet reservation multiple access with multiple channel (NC-PRMA/MC). N_C equal-capacity, orthogonal, traffic channels are shared by M mobile users on the uplink. Transmission attempts on the uplink are made by using time-frequency signaling in every frame, which enables transmission attempts of mobile users to be conveyed to the base station without collisions. Two kinds of duplexing schemes, frequency division duplexing and shared time division duplexing, are considered in the performance analysis. Using a discrete-time Markov chain analysis, we derive the analytic expressions for the average per channel throughput and the average packet dropping probability. Computer simulation results verify the analysis. Analytical evaluation and computer simulation show that NC-PRMA/MC with shared time division duplexing improves the channel capacity, which approaches the theoretical upper bound.

Keywords: wireless access protocols, multiple channels, PRMA, NC-PRMA

1. Introduction

As the demand for wireless networks continues to grow, how to increase channel capacity and spectrum utilization under limited spectral resources has become increasingly relevant issues. A major technical issue related to efficiently arbitrating multiple mobile users on a common shared air interface is the selection of a suitable multiple access protocol. The flexibility of packet reservation multiple access (PRMA) systems, which were first proposed in 1989 by Goodman [1], makes such systems an attractive option for wireless applications. Since the PRMA protocol was originally proposed, it has been strongly recommended for mobile users and entails using speech activity detection, by which the status of each mobile user is classified into talkspurts and silent periods. At the beginning of each talkspurt, a mobile user attempts to make reservations for a continuous transmission. When the talkspurt concludes, the mobile user has to give up the occupation of the radio resource. PRMA increases the channel capacity of time division multiple access (TDMA) by exploiting the silence periods and allocating the radio resource to mobile users only during their talkspurts. However, the throughput goes down and the packet dropping probability rapidly goes up during high traffic loads, because of the inherent contention mechanism in PRMA.

To overcome this problem, non-collision PRMA (NC-PRMA) protocol has recently been proposed [2–5]. In NC-PRMA, the channel is time partitioned into frames, as in PRMA. The difference between PRMA and NC-PRMA is that each frame in NC-PRMA is further divided into several information slots and one control slot. The uplink control slot is further divided into m control mini-slots, where each control mini-slot serves as a time interval for time-frequency signaling. During each control mini-slot period, up to n mobile users can transmit their transmission attempts to the base station using different tones. Since there are m control mini-slots in the uplink control slot, the time-frequency signaling can constitute $(m \times n)$ different signatures each being uniquely recognized by the base station. Therefore, each pair of (i, j), where $1 \leq i \leq m$ and $1 \leq j \leq n$, can identify a specific mobile user for the purpose of slot allocation at the base station without incurring collisions.

High-capacity wireless networks may be realized either by assigning a single wide-band channel or by using multiple narrow-band channels that are orthogonal to each other. The latter approach, which has drawn a lot of attention [6–9], is particularly attractive when contiguous wide-bandwidth spectrum is not available. This gives us the suggestion to design and extend the NC-PRMA protocol to utilize multiple, orthogonal, traffic channels, that is, to design the NC-PRMA/MC protocol. Furthermore, both frequency division duplexing (FDD) and shared time division duplexing (STDD) are considered in the design of NC-PRMA/MC. By preventing the mobile users from using radio resources during their silent periods, a higher statistical multiplexing gain can be achieved. Apart from the silent detection technique, using the STDD scheme instead of the FDD scheme is also considered to be quite appropriate for improving channel capacity. This is because the STDD scheme allows the traffic of both the uplink and the downlink to share a common channel, thereby achieving a high statistical multiplexing gain [10, 11]. With regard to the quality of the reconstructed traffic, evidence suggests that speech distortion due to a 1% packet drop is rarely audible and, hence, a packet dropping probability of 1% is considered to be an acceptable level. It is convenient to define $M_{0.01}$ as the maximum number of simultaneous mobile users that can be supported such that the packet dropping probability is below 1%. Hence, the value of $M_{0.01}$ directly reflects the channel capacity. Estimating the corresponding $M_{0.01}$ for the proposed NC-PRMA/MC protocol with either FDD or STDD under different number of multiple channels is evaluated in the paper.

The rest of this paper is organized as follows. NC-PRMA/MC with either the FDD or STDD schemes is described in Section 2. Section 3 introduces the system model that uses a discrete-time Markov chain. The derivation of the analytical expression of the average per channel throughput and the average packet dropping probability are provided in Section 4. Analytical and computer simulation results are presented in Section 5. Finally, conclusions are given in Section 6.

2. Descriptions of NC-PRMA/MC Protocol

2.1. NC-PRMA/MC WITH FDD

In the FDD scheme, the uplink and downlink channels are allocated to distinct bands. Both the uplink and the downlink channels are time partitioned into frames and each frame is further divided into N_F information slots and one control slot. The frame structure of the NC-PRMA/MC protocol with FDD is depicted in Figure 1. The notation C_U is used to denote the control slot in the uplink, which is further divided into m control minislots (CMs). In each channel, each CM serves as a time interval for time-frequency signaling [2–5]. With the use of a fast frequency-hopped multiple-level frequency shift keying scheme [12, 13], a receiver that is equipped with an n-frequency filter bank can be implemented at the base station. Consequently,

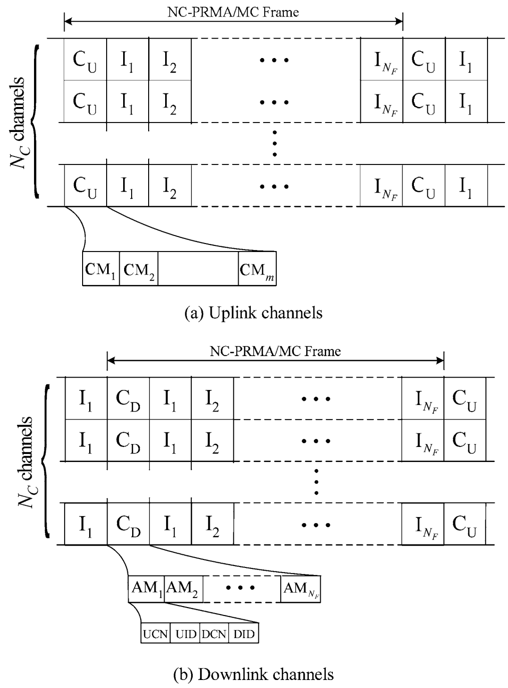

Figure 1. Frame structure of NC-PRMA/MC with FDD scheme.

up to n mobile users can notify the base station of their transmission attempts by transmitting different single tones in each CM. Since there are m CMs in C_U, the time-frequency signaling constitutes $(m \times n)$ different combinations of CMs and single tones with each being uniquely recognized by the base station. Each pair of the ith CM and the jth single tone, (i, j), where $1 \leq i \leq m$ and $1 \leq j \leq n$, denotes a signature which can be assigned to a mobile user for the purpose of notifying the base station of a transmission attempt. As for the control slot in the downlink, C_D, it is partitioned into N_F assignment minislots (AMs). Furthermore, each AM contains four fields, including an uplink channel number (UCN), an uplink identifier (UID), a downlink channel number (DCN), and a downlink identifier (DID) fields.

Each mobile user gets a dedicated signature along with a dedicated channel when he registers with a base station. Once a mobile user generates a talkspurt to be sent to the base station, he first attempts a transmission attempt to the base station via his dedicated channel and signature. Thus, at the end of each C_U, the base station is aware of the demands currently emanating from all dispersed mobile users located in its service area and can then allocate slots accordingly. The base station broadcasts acknowledgments through the downlink control slot C_D of each channel to mobile users. Mobile users should listen to the contents of each AM located on their dedicated channels to know the slot allocation information. Once a mobile user detects that his ID is contained in the UID field of the AM_i, he can transmit information packets to the base station at the ith information slot I_i located on the UCN channel. Similarly, a mobile user should receive information packets from the base station at the ith information slot I_i located on the DCN channel when he becomes aware that his ID is contained in the DID field of the AM_i. Consequently, by monitoring the contents in C_D located on their dedicated downlink channels, mobile users can know which channel and slot are allocated for them to transmit information packets in the uplink and to receive information packets from the downlink. In general, the base station allocates channels and slots on a first-come-first-serve

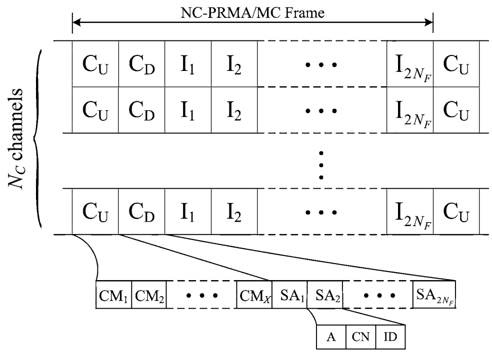

Figure 2. Frame structure of NC-PRMA/MC with STDD scheme.

(FCFS) basis. Upon receiving an acknowledgment, a mobile user can reserve the assigned slots in the successive frames of the assigned channel by continually sending his signature to keep the slot reservation until the end of his talkspurt. On the other hand, if all the $(N_C \times N_F)$ slots are occupied or when the number of active mobile users is larger than the number of idle slots, some mobile users may have no available information slot assigned to them. In such a situation, a mobile user continues his attempt at transmission and queues the packets in a local buffer, with the constraint of the packet delay being no more than $d_{\max}$. Once the delay time of a packet is more than $d_{\max}$, it is discarded.

2.2. NC-PRMA/MC with STDD

STDD duplexing enables both the uplink and the downlink traffic to share a common channel. Figure 2 displays the frame structure of the NC-PRMA/MC protocol with the STDD scheme. There are N_C synchronous channels slotted as in FDD, and the traffic of both the uplink and the downlink traffic share a common radio channel. Therefore, the channel rate of the STDD scheme is designed to be twice as high as that of FDD and the frame duration is identical to that of FDD. As a consequence, there are $2N_F$ information slots in each frame besides one uplink control slot (C_U) and one downlink control slot (C_D). In each channel, the control slot C_U is also divided into m CMs, with each providing a duration for time-frequency signaling, and it operates in the same way as the uplink control slot in the FDD scheme. The downlink control slot C_D is divided into $2N_F$ AMs. Furthermore, each AM consists of three fields, including the A field, the CN field, and the ID field. In the ith assignment mini-slot AM_i the mobile user whose ID is in the ID field is assigned to the ith information slot I_i, where $1 \leq i \leq 2N_F$, located on the CN channel. The A field specifies that this slot I_i is allocated for uplink or downlink transmissions. In the same manner as in the NC-PRMA/MC with FDD, a mobile user transmits its signature through a dedicated channel once it generates a talkspurt that is to sent to the base station. By monitoring the A, CN, and ID fields of each AM on his own dedicated channel, a mobile user may realize if he is successful in gaining a reservation or if any information packet is transmitted to him.

3. Discrete-Time Markov Chain System Modeling

The NC-PRMA/MC system under consideration consists of M mobile users who access a common uplink channel using the NC-PRMA/MC access protocol to transmit information

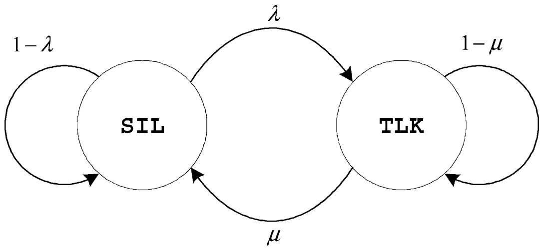

Figure 3. Two-state traffic model for NC-PRMA/MC with FDD.

packets. For analyzing a TDMA system, a continuous-time model is not tractable due to the boundaries of slots and frames. Instead, a discrete-time model is adopted in this paper. The embedded points may be chosen to be the boundaries between time slots or frames. For simplicity of analysis, the embedded points are placed at the beginning of the first information time slot in each frame. This kind of discrete-time method is considered to be a discrete-time Markov chain because the frame duration is much less than the mean holding time of either a talkspurt or a silent period. Furthermore, it is assumed that uplink and downlink channel transmissions are error free and the base station receiver has no packet capturing capability in the proposed approximate model of the real NC-PRMA/MC system.

In the FDD duplexing, a two-state Markov process as shown in Figure 3, including the talk (TLK) state and the silent (SIL) state, is adopted to model the behavior of each mobile user, where the periods of silence gap and talkspurt are exponentially distributed with mean time t_1 and t_2, respectively. For this model, each mobile user is assumed to alternate randomly between TLK state and SIL state, characterized by the transition probabilities λ and μ. Consequently, λ and μ can be obtained by the equations

$$\lambda = \int_0^{T_F} \frac{1}{t_1} \cdot e^{-(t/t_1)} dt = 1 - e^{-(T_F/t_1)} \approx T_F/t_1, \tag{1}$$

$$\mu = \int_0^{T_F} \frac{1}{t_2} \cdot e^{-(t/t_2)} dt = 1 - e^{-(T_F/t_2)} \approx T_F/t_2, \tag{2}$$

where T_F is the frame duration. Furthermore, it is easy to obtain the steady state probability mass function of this two-state Mrakov process, as follows:

$$P(\text{TLK}) = \frac{\lambda}{\lambda + \mu}, \tag{3}$$

$$P(\text{SIL}) = \frac{\mu}{\lambda + \mu}. \tag{4}$$

As for STDD duplexing, the channel is no longer divided into uplink and downlink subchannels. Consequently, the traffic arising from both the uplink and the downlink must be considered together. To do this, a three-state Markov process is used here to model the behavior of both ends for each mobile, as shown in Figure 4. The three states include the SS, TS, and ST states, where the SS state denotes that both the uplink and the downlink are silent, the TS state indicates that a talkspurt is generated by the uplink while the downlink is silent, and the ST state represents the scenario opposite the TS state. Since the probability of a conversation in the TT state is extremely low compared to the probabilities of the SS, TS, and ST states, it is

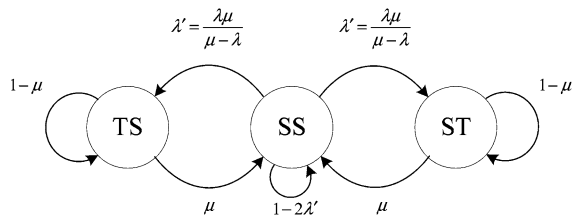

Figure 4. Three-state traffic model for NC-PRMA/MC with STDD.

reasonable to exclude the TT state [10, 11]. From the perspective of the uplink, the talkspurt of the downlink occurs only during the silent period of the uplink because it is assumed that the TT state does not exist. Therefore, the mean time of a mobile user staying in the SS state before transition to the ST state can be obtained by subtracting t_2 from t_1. The transition probability from the SS state to the ST state is given by

$$\lambda' = 1 - \exp[-T_F/(t_1 - t_2)] \approx \frac{T_F}{t_1 - t_2} = \frac{\lambda\mu}{\mu - \lambda}, \tag{5}$$

where λ and μ are given in Equations (1) and (2), respectively. The transition probability from the SS state to the TS state can be obtained through a similar discussion and has the same form as shown in Equation (5). Consequently, the steady state probability mass function of this three-state Markov process can be derived as

$$P(\text{SS}) = \frac{(\mu - \lambda)}{(\mu + \lambda)}, \tag{6}$$

$$P(\text{TS}) = P(\text{ST}) = \frac{\lambda}{(\mu + \lambda)}. \tag{7}$$

The upper bound of the channel capacity is defined as the channel being entirely engaged in the successful transmissions of information packets. There is no bandwidth waste because of packet collisions or idle information slots. The bound value is thus given by

$$M_{\text{UB}} = N_F \times \left(\frac{t_1 + t_2}{t_2}\right). \tag{8}$$

4. Performance Analysis

4.1. Throughput Analysis

Throughput analysis of the NC-PRMA/MC with FDD is dealt first in this section. Since M mobile users share N_C equal-capacity, orthogonal, and traffic channels, and since the behavior of each mobile user is modeled by a two-state Markov process, as mentioned in Section 3, the system state variable $\boldsymbol{S}$ can be defined as the number of mobile users who are in the TLK state when M simultaneous mobile users are operating in the system. Then the steady state probability distribution of the system at each embedded point can be expressed as

$$B(s, M) = \binom{M}{s} p^s (1 - p)^{(M-s)} \tag{9}$$

where $p = \lambda/(\lambda + \mu)$ and $0 \le s \le M$. Since the system is equipped with N_C channels and each frame is partitioned into N_F time slots, the channel throughput can be easily estimated by using

$$T = \frac{1}{N_C N_F} \sum_{s=0}^{M} s \cdot B(s, M). \tag{10}$$

The following is the throughput analysis of NC-PRMA/MC with STDD. Since the TS state represents the uplink in the state of a talkspurt and since both the SS and ST states represent the uplink in a period of silence, we have a two-state Markov process with steady state probabilities equal to those found in Figure 3 when the SS and ST states are merged. From the perspective of the uplink, it is obvious that these two models obtain the same one-way traffic density. This fact provides a fair basis for performance comparison of the FDD and the STDD schemes. Let $\boldsymbol{I}$ and $\boldsymbol{J}$ be the system state variables denoting the number of talkspurts in the uplink and downlink, respectively. With the behavior of each mobile user characterized by this model, the steady state probability of system state (i, j) with M simultaneous mobile users at each embedded point can be represented by

$$\pi(i, j, M) = \binom{M}{i+j}\binom{i+j}{i}\left(\frac{1}{2}\right)^{i+j} q^{i+j}(1-q)^{M-i-j}, \quad 0 \le i + j \le M \tag{11}$$

where $q = 2\lambda/(\mu + \lambda)$. According to this distribution, the performance measures for the STDD scheme can be derived. Similar to previous derivations, the channel throughput of NC-PRMA/MC with STDD is estimated by

$$\bar{\eta} = \frac{1}{2N_F N_C}\left\{\sum_{i+j<2N_F N_C} (i + j)\pi(i, j, M) + \sum_{i+j\ge 2N_F N_C} 2N_F N_C \pi(i, j, M)\right\}. \tag{12}$$

4.2. Packet Dropping Probability Analysis

In addition to the analysis of the channel throughput, the packet dropping probability will be analyzed. As described thus far, the system can be viewed as a closed queuing network with M customers, each alternating between talkspurts and silent periods. For this closed queuing network, the steady state distribution that a newly arriving talkspurt discovers is equal to the steady state distribution of a same network with one less mobile user. When this concept is applied and when a specific talkspurt is considered, the mean access delay and the packet dropping probability can be derived as follows.

Let us deal with NC-PRMA/MC with FDD first. The mean access delay, normalized with respect to the frame duration, is defined as the mean number of frames that a given talkspurt must wait before it can get a reservation. For the derivation, we define the conditional mean access delay of the talkspurt when s mobile users are in talkspurts with M simultaneous mobile users operating in the system as $D(s)$, which consists of the following three components:

$D_{\text{cont}}(s)$: the waiting time for a control slot,
$D_{\text{busy}}(s)$: the waiting time for an information slot,
$D_{\text{assi}}(s)$: the waiting time for the first assigned slot.

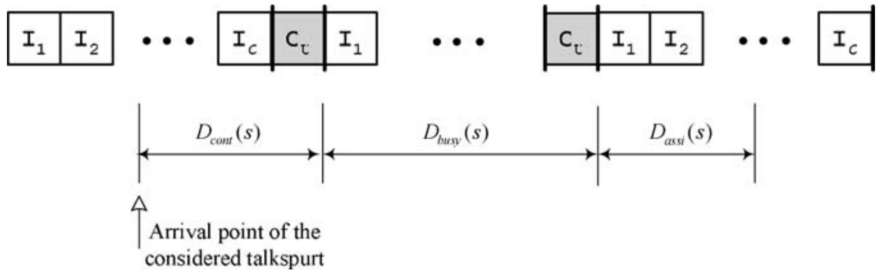

Figure 5. A typical scenario of the waiting time for a talkspurt.

Figure 5 illustrates a typical scenario of the waiting time for a given talkspurt. The first component, $D_{\text{cont}}(s)$, is measured from the time at which the talkspurt was generated to the moment at which an embedded point is first met. Since the talkspurt could be arbitrarily generated within a frame, $D_{\text{cont}}(s)$ is estimated to be 0.5 frames on average.

For the case $s \geq N_C \times N_F$, since the information slots are all busy, a given talkspurt cannot receive a reservation in the first frame and must be queued up until some information slots are available. Obviously, we can see that $(s - N_C \times N_F)$ talkspurts have been queued up ahead of a given talkspurt. Therefore, the talkspurt must wait until $(s - N_C \times N_F + 1)$ talkspurts depart before it can be served. The second component, $D_{\text{busy}}(s)$, is measured from the first embedded point to another embedded point such that during this interval $(s - N_C \times N_F + 1)$ talkspurts depart. Hence, this component can be estimated for dividing $(s - N_C \times N_F + 1)$ by the mean service rate, which is $(N_C \times \mu)$ per frame. It is obvious that $D_{\text{busy}}(s)$ equals zero if the state variable s is smaller than the value of $(N_C \times N_F)$. This leads to the following expression:

$$D_{\text{busy}}(s) = \begin{cases} 0, & s < N_C N_F \\ (s - N_C N_F + 1)/(\mu N_C N_F), & s \geq N_C N_F \end{cases} \tag{13}$$

where we assume that a talkspurt being queued up does not end before receiving a reservation. After waiting for the specified embedded point, a given talkspurt must still wait for the first assigned slot. This delay is referred to as $D_{\text{assi}}(s)$, and is the final component of $D(s)$. It is estimated by

$$D_{\text{assi}}(s) = \begin{cases} 0.5 \times [(s+1)/N_C N_F], & s < N_C N_F \\ 0.5, & s \geq N_C N_F \end{cases} \tag{14}$$

During moments of light demand, $s < N_C \times N_F$, it is assumed that the BS always assumes the former s/N_C slots in each frame per channel for mobile users under talkspurts and levels the latter $(N_F - s/N_C)$ slots idle. When a given talkspurt arrives, the total number of talkspurts in the system is $(s + 1)$. The first assigned slot for the talkspurts is assumed here to be an arbitrary one among the $(s + 1)/N_C N_F$ slots. This accounts for the upper branch of Equation (14). For peak demand moments, $s \geq (N_C \times N_F)$, the first assigned time slot for a talkspurt would be an arbitrary one among all the N_F time slots of a specific frame per channel. Hence, we have the term in the lower branch of Equation (14). From the above derivations, we have

$$D(s) = D_{\text{cont}}(s) + D_{\text{busy}}(s) + D_{\text{assi}}(s). \tag{15}$$

When a talkspurt of length γ is considered, the access delay that a given talkspurt would experience is limited to $(\gamma + d_{\max} - 1)$, because when this constraint is exceeded, all packets of this talkspurt will be totally discarded. Therefore, the actual mean access delay of each talkspurt under system state s is equal to $\min(\gamma + d_{\max} - 1, D(s))$. Hence, $D(s)$ must be weighted by the distribution of the talkspurt length. We denote the modified mean access delay conditioned on the system state s by $\bar{D}(s)$. It can then be written as

$$\bar{D}(s) = \sum_{\gamma=1}^{\tau} (\gamma + d_{\max} - 1) P_{\Gamma}(\gamma) + \sum_{\gamma=\tau+1}^{\infty} D(s) P_{\Gamma}(\gamma), \tag{16}$$

where $\tau = \lfloor D(s) - d_{\max} + 1 \rfloor^{+}$ with $\lfloor x \rfloor^{+}$ represents an integer which is equal to or less than x when $x \geq 0$ and which is equal to zero when $x < 0$. $P_{\Gamma}(\gamma)$ is the probability mass function of the period of a talkspurt, which can be represented as

$$P_{\Gamma}(\gamma) = \mu(1 - \mu)^{(\gamma-1)}. \tag{17}$$

When the steady state probabilities are averaged, the overall mean access delay is

$$\bar{D} = \sum_{s=0}^{M-1} \bar{D}(s) B(s, M-1). \tag{18}$$

When a given talkspurt experiences delay $D(s)$, the number of packets lost equals $\min(\gamma, \tau)$. Hence, if the talkspurt length γ is less than or equal to τ, all the γ packets should be dropped, and otherwise only τ packets are dropped. Therefore, the mean number of packets dropped under the system state s is given by

$$\begin{aligned} L_d(s) &= \sum_{\gamma=1}^{\tau} \gamma P_{\Gamma}(\gamma) + \sum_{\gamma=\tau+1}^{\infty} \tau P_{\Gamma}(\gamma) \\ &= \frac{1 - (\tau+1)(1-\mu)^{\tau} + \tau(1-\mu)^{\tau+1}}{\mu} + \tau(1-\mu)^{\tau+1}. \end{aligned} \tag{19}$$

Therefore, the conditional packet dropping probability is

$$P_d(s) = \frac{L_d(s)}{\bar{\Gamma}}, \tag{20}$$

where $\bar{\Gamma}$ is the mean length of a talkspurt. That is,

$$\bar{\Gamma} = \sum_{\gamma=1}^{\infty} \gamma \mu (1-\mu)^{\gamma-1} = \frac{1}{\mu}. \tag{21}$$

By averaging over the steady state probabilities, the overall packet dropping probability can be obtained by using

$$\bar{P}_d = \sum_{s=0}^{M-1} P_d(s) B(s, M-1). \tag{22}$$

The following is the packet dropping probability analysis of NC-PRMA/MC with STDD. We define $D(i,j)$ as the mean access delay of a given talkspurt under system state (i,j). Let $D_{\text{cont}}(i, j)$, $D_{\text{busy}}(i,j)$, and $D_{\text{assi}}(i,j)$ correspond, respectively, to $D_{\text{cont}}(s)$, $D_{\text{busy}}(s)$, and $D_{\text{assi}}(s)$ used in the analysis of the FDD scheme. Then we have $D_{\text{cont}}(i,j) = 0.5$ and

$$D_{\text{busy}}(i, j) = \begin{cases} 0, & i + j < 2N_F N_C \\ [(i + j) - 2N_F N_C + 1]/(2N_F N_C \mu), & i + j \geq 2N_F N_C \end{cases}, \tag{23}$$

$$D_{\text{assi}}(i, j) = \begin{cases} 0.5 \times [(i + j + 1)/(2N_F N_C)], & i + j < 2N_F N_C \\ 0.5, & i + j \geq 2N_F N_C \end{cases}. \tag{24}$$

With the above equations, the $D(i,j)$ is determined by

$$D(i, j) = D_{\text{cont}}(i, j) + D_{\text{busy}}(i, j) + D_{\text{assi}}(i, j). \tag{25}$$

As the same sake for (16), the conditional mean access delay is obtained by modifying $D(i,j)$, that is,

$$\bar{D}(i, j) = \sum_{\gamma=1}^{\hat{\tau}} (\gamma + d_{\max} - 1) P_\Gamma(\gamma) + \sum_{\gamma=\hat{\tau}+1}^{\infty} D(i, j) P_\Gamma(\gamma), \tag{26}$$

where $\hat{\tau} = \lfloor D(i, j) - d_{\max} + 1 \rfloor^+$. With a few manipulations, Equation (26) can also be expressed as a closed form similar to that shown in Equation (18), except that τ and $D(i)$ are replaced by $\hat{\tau}$ and $D(i,j)$, respectively. Hence, the overall mean access delay is

$$\bar{D} = \sum_{0 \leq i+j \leq M-1} \bar{D}(i, j) \pi(i, j, M - 1). \tag{27}$$

When the same approaches for Equations (19) and (20) are used, the conditional packet dropping probability is

$$P_d(i, j) = \frac{L_d(i, j)}{\bar{\Gamma}}, \tag{28}$$

where $L_d(i,j)$ is similar to that for $L_d(s)$ shown in Equation (19), except that τ is replaced by $\hat{\tau}$. By averaging $P_d(i,j)$ over the steady state probabilities, we have

$$\bar{P}_d = \sum_{0 \leq i+j \leq M-1} P_d(i, j) \pi(i, j, M - 1). \tag{29}$$

5. Results and Discussions

The system performances are evaluated in terms of the average per channel throughput and the average packet dropping probability. In particular, the channel capacity, which is defined as the maximum number of simultaneous mobile users that can be supported per channel under the constraint of the average packet dropping probability is no more than 1%, is provided. The detailed system parameters are listed in Table 1. Extensive computer simulations and

Table 1. System parameters of the NC-PRMA/MC protocol per channel

	Duplexing schemes	
Items	FDD	STDD
Channel rate (kbps)	720	1440
Source rate (kbps)	32	32
Number of information slots per frame, N_F	20	20
Frame duration, T_F (ms)	16	16
Mean duration of a silent period, t_1 (sec)	1.35	1.35
Mean duration of a talkspurt, t_2 (sec)	1.0	1.0
Maximum life time for packets, $d_{\max}$ (ms)	32	32

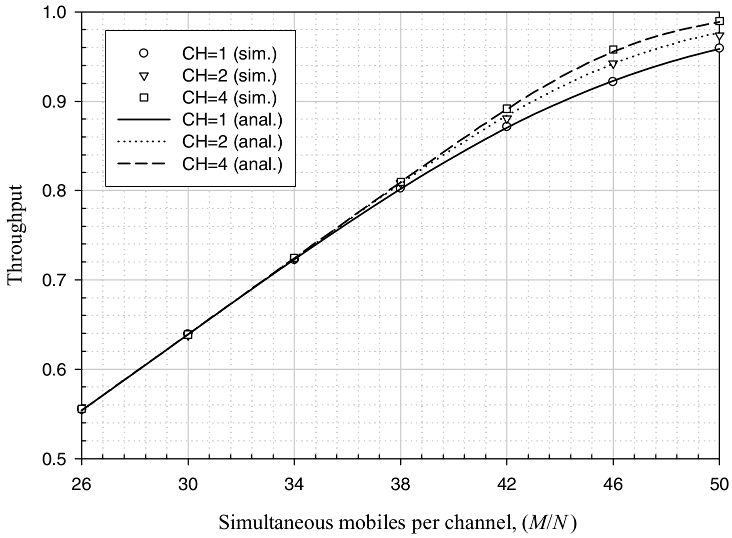

Figure 6. Throughput versus simultaneous mobile users per channel for NC-PRMA/MC with FDD.

numerical results for the average per channel throughput of the NC-PRMA/MC with FDD scheme and the NC-PRMA/MC with STDD scheme with different number of multiple channels are plotted and shown in Figures 6 and 7, respectively. It is expected that the average per channel throughput would increase as the number of simultaneous mobile users per channel increases and approaches unity in heavy traffic loads. The effect of multiple channels on the average per channel throughput is significantly revealed during high traffic loads. With more channels the system gets higher throughput. In addition, when the FDD scheme and the STDD scheme are considered, the latter performs better in terms of throughput than the former does.

Extensive computer simulations and numerical results for the average packet dropping probability of the NC-PRMA/MC with the FDD scheme and the NC-PRMA/MC with the STDD scheme are shown in Figures 8 and 9, respectively. From Figures 8 and 9, it can be seen that the packet dropping probability with either FDD or STDD decreases as the number of channels increases. This means that adopting multiple channels provides higher channel capacity. However, from the figures it can be seen that the improvement of packet dropping probability gets smaller and smaller as the number of channels continuously increases. The most significant improvement occurs when a single channel is extended to double channels.

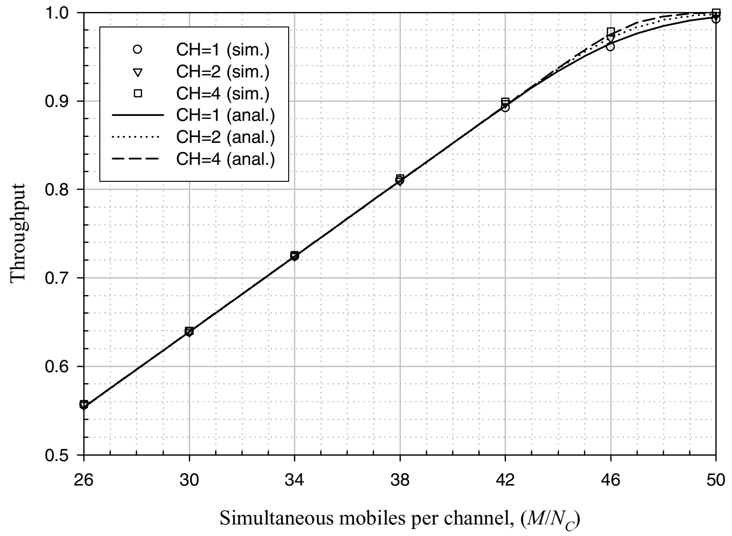

Figure 7. Throughput versus simultaneous mobile users per channel for NC-PRMA/MC with STDD.

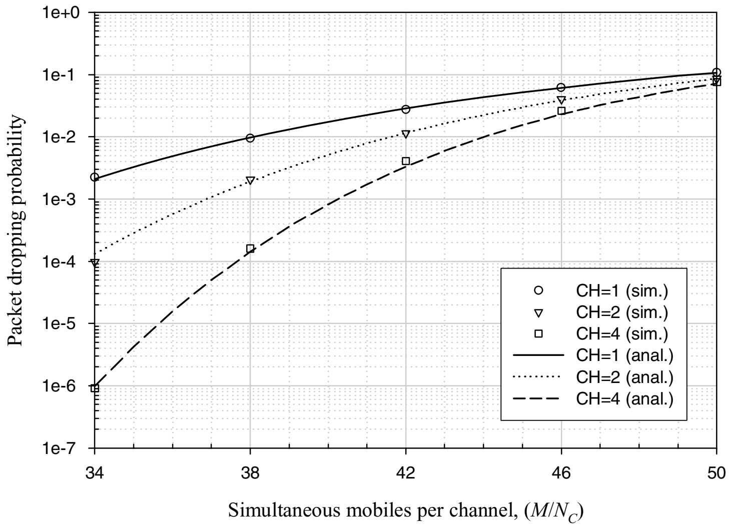

Figure 8. Packet dropping probability versus simultaneous mobile users per channel for NC-PRMA/MC with FDD.

Thus there is a limitation to the number of channels that improve the channel capacity. In addition, from Figures 8 and 9, we further observe that the protocol still provides a larger capacity with the STDD scheme than with the FDD scheme. Table 2 summarizes channel capacities under various values of N_C for the NC-PRMA/MC with either the FDD or the STDD scheme. Our results indicate that the channel capacity ($M_{0.01}$) for NC-PRMA/MC with FDD and $N_C = 1$ is 38 while the channel capacity of the NC-PRMA/MC with STDD and $N_C = 4$ is 46.5. This finding suggests that the NC-PRMA/MC protocol with STDD duplexing significantly improves channel capacity such that theoretical upper bound of $M_{\mathrm{UB}} \approx 47$ is approached.

Table 2. Comparisons of channel capacity ($M_{0.01}$) for NC-PRMA/MC protocols

N_C	$M_{0.01}$ (FDD)	$M_{0.01}$ (STDD)
1	38	45
2	42	46
4	44	46.5
M_{UB}	47	

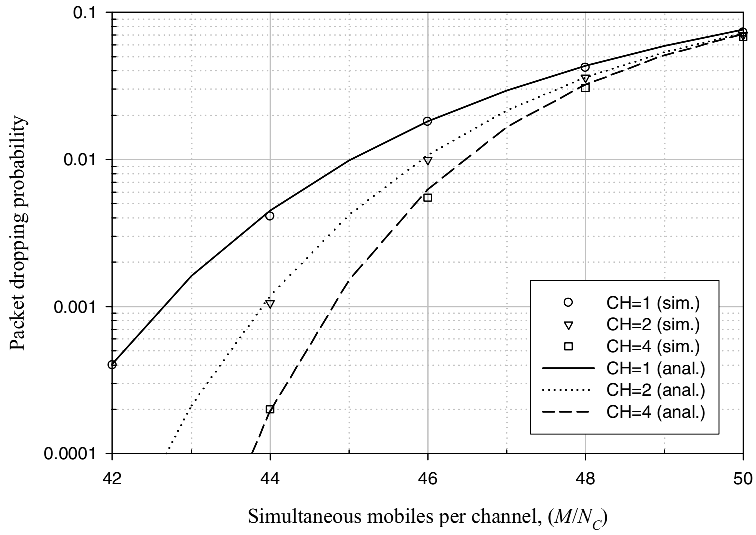

Figure 9. Packet dropping probability versus simultaneous mobile users per channel for NC-PRMA/MC with STDD.

6. Conclusions

We analyzed the effect of duplexing schemes and the number of multiple channels on the channel throughput and packet dropping probability of a multichannel NC-PRMA/MC wireless access protocol. M mobile users shared N_C equal-capacity, orthogonal, traffic channels on the uplink. Transmission attempts can be conveyed to N_C receivers at the base station by using time-frequency signaling without incurring collisions. We modeled the multiple access system with a discrete-time Markov chain. After a discrete-time Markov chain analysis, analytical expressions for the average per channel throughput and the average packet dropping probability were derived. Simulation results were shown to verify the analysis. It was observed that the multiple channel protocol performed better than the single channel protocol. It was further shown that the NC-PRMA/MC protocol with STDD benefited from highly multiplexing gain, and thus, it can offer higher average per channel throughput and lower average packet dropping probability. Noticeably, NC-PRMA/MC protocol with STDD and four channels almost provides an optimum channel capacity.

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