Two Medium Access Control Schemes for DS-CDMA Personal Communication Networks *

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Abstract

Code Division Multiple Access (CDMA) has become an attractive technique for media access control in Personal Communication Networks (PCN). In this paper, two MAC schemes are defined and studied for DS-CDMA PCNs, namely Preamble Signaling Access (PSA) and Mini-islot Signaling Access (MSA). PSA uses preamble-packet slot structure while MSA is applying mini-slot techniques to solve the problems of code assignment and MAI control. Markovian chain models have been developed to analyze the performance of these two protocols for voice-only systems as well as data-only systems. The analytical model is shown to be very close to simulation results. Based on the results obtained from the analysis, it is shown that, for many cases, MSA protocol performs better than PSA protocol, especially for voice services.

Keywords: Personal Communication Network (PCN), CDMA, medium access control (MAC).

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1 Introduction

Recently, Code Division Multiple Access (CDMA) has become an attractive technique for medium access control in cellular networks and Personal Communication Systems (PCS). In a CDMA system, the symbols which carry information bits occupy a bandwidth more than the minimum needed for the transmission [14]. The spreading employs a spread spectrum waveform, which is termed as a *code*. Previous research has shown that, comparing with its counterparts such as Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA), CDMA enjoys advantageous features such as efficient spectrum utilization, simple frequency planning, soft handoff, graceful degradation, and tight security [4, 13]. A second-generation system standard IS-95 [13] and a third-generation system testbed CODIT [1] have been proposed or built, which demonstrates the feasibility of applying CDMA technology to personal communications.

A CDMA personal communication network (PCN) consists of multiple *cells*, each of which is an area covered by the transmission range of a *base station* (BS). As a large number of *mobile hosts* (MH) are supported within a cell, one of the most important issues is how to control their uplink access to the shared wireless spectrum.

In this paper, we are only concerned with a receiver-oriented Direct-Sequence CDMA (DS-CDMA) PCN, in which a BS have several receivers, each of which listens to a specific code [10]. Only the receiver which listens to this code can recover the bits from the symbols; other receivers perceive them as noise. It is important that two MHs should use different codes for transmission at the same time; otherwise, the receiver cannot distinguish them. For simplicity, the effect of capture [10] is not considered in this paper.

Even if a bit transmitted by an MH is spread with a code different from any other code used at the same time, it may still be corrupted because the bits simultaneously transmitted by other MHs generate some level of noise on the intended receiver. This is called *multiple-access interference* (MAI). The more the MHs transmit together, the higher the probability of bit error. A function $P_b(z)$ can be used to approximate the probability of bit error, where z is the number of MHs transmitting at the same time.

In [6, 7], Liu *et al* proposed two MAC protocols for DS-CDMA wireless network based on Slotted-ALOHA. During a time slot, an MH uses preamble to contend for a code to transmit its packets. The BS decides whether to grant the MH a code based on consideration of satisfying the QoS of all the MHs. Based on Liu *et al*'s work, Yang *et al* [16] proposed a MAC protocol which integrates data and voice traffic.

Meanwhile, for a long time, there have been many MAC protocols designed for time-division-based mobile communication systems, one of the best known is Packet Reservation Multiple Access (PRMA) [3]. When an MH becomes active, it randomly transmits the first packet in a nonreserved slot. Once its transmission is successful, the MH will keep that slot in subsequent frames till the current "burst" of message transmission is completed. This scheme is good for voice services but not quite suitable for data/voice integration. Another scheme, idle-signal multiple access for integrated services (I-ISMA) [15], derived from PRMA, takes data services into consideration. In I-ISMA, all data packets and the first packet of voice talkspurt contend to access the channel. Another more general and flexible version of PRMA, namely mini-slot PRMA [8], is designed to overcome some of the PRMA limitations. In each slot, a number of "mini slots" are dedicated to the transmission of reservations. If necessary, this number can be increased by assigning extra reservation channels and thus increase the the reservation capacity. A different scheme is C-PRMA in [2]. Each slot is divided into at least two parts: command and data transmission part. The reservation procedure is carried out during the command period.

MAC protocols for DS-CDMA wireless networks proposed in [6, 7, 16] are very similar to C-PRMA as its counterpart in CDMA environment. We call them Preamble Signaling Access (PSA) as they all use preamble-data slot structure, in which a preamble is a minislot used by MHs to contend for CDMA codes. It enjoys many good features but at least has following two shortcomings. First, the preamble is an overhead and will waste some system capacity. Second, the introduction of preamble-data structure is not appropriate for a unified medium access control structure if considering the system signaling, *e.g.*, handover, connection establishment and connection termination.

In this paper, we design another protocol in order to overcome these drawbacks. Preambles are no longer used in the slot structure. Instead, special codes are used specifically for code contending. These codes are divided into minislots, similar to the protocol presented in [8]. We compare this protocol, namely Minislot Signaling Access (MSA), with PSA protocol. Our research shows that MSA protocol performs better than PSA protocol under many circumstances, especially for voice services. This research is useful in designing a third-generation CDMA PCN, in which both data and voice services have to be provided in an efficient and integrated manner. Although data and voice integration is not considered in this paper and is left for future work, the results we obtained from both the theoretical analysis and simulation show that our MAC protocol (MSA) provides a good solution in supporting multi-class wireless services in CDMA PCNs.

The rest of the paper is organized as follows. In Section 2, the main features of these two

MAC protocols for DS-CDMA wireless network are introduced. Markovian models are developed and solved for these two protocols in Section 3. Section 4 presents numerical results both from the analytical model and by simulation, highlighting our new protocol's (MSA) advantages over traditional DS-CDMA MAC scheme (PSA). We apply both the protocols to voice-only and data-only systems respectively. Finally, conclusions are given in Section 5.

2 Two MAC Protocols for CDMA PCNs

In this section, two MAC protocols, namely, Preamble Signaling Access protocol (PSA) and Minislot Signaling Access (MSA) protocol will be presented. Their basic features will be discussed and compared.

2.1 System Architecture and Basic Assumptions

We consider a single micro-cell in a receiver-oriented CDMA PCN. We assume that the uplink (MH to BS) and downlink (BS to MH) transmissions are physically separated by means of Frequency Division Duplex. In this paper, only the uplink transmission in the CDMA network is considered and investigated. This is because the downlink access control is carried out solely by the BS while the uplink control depends on the "snapshot" status of the MHs and its control design is much more challenging. Two kinds of MHs, voice MHs and data MHs, are in the cell, which generate voice and data packets, respectively. Voice and data packets have the same size. The activities of voice MHs follow a pattern of interleaved talkspurts and silence gaps. Only during talkspurts can voice MHs generate packets, at a rate of one per slot. Voice packets can tolerate some loss but have stringent delay requirement, which prohibits retransmissions. In this paper, we assume the tolerable loss rate is 1% and the allowed delay is one slot. On the other hand, data packets have no delay constraint, and will be retransmitted until correctly received. Throughout this paper, we apply our proposed protocols and algorithms to either voice-only system or data-only system. The integration of voice and data traffic will be studied in further work.

2.2 Signaling and Packet Transmission

An uplink transmission in a CDMA wireless packet network can be summarized as following 4 stages: (1) The MH sends a REQUEST signal to the BS, asking for a CDMA code to transmit its packets with; (2) The BS, after receiving the REQUEST from an MH, decides whether to grant the MH a code; (3) The MH, whose REQUEST is acknowledged by the BS, uses this code to transmit

its packets; (4) The BS informs the MH whether the transmission is successful; If not, the MH might try to retransmit the packets.

We call stages (1), (2), and (4) *signaling*, the radio channels a BS or an MH use to send signaling information are called *signaling channels*. In step (3), the MH is doing *packet transmission*, using the radio channels called *packet transmission channel*. We will see the difference between these two types of radio channels in next subsection.

Flowcharts of the underlying procedures in our CDMA systems are shown in Figure 1, Figure 2, and Figure 3 for data MH, voice MH and BS, respectively. These flowcharts contain the operations in one slot while the dashed lines indicate the transitions into the next slot.

At the beginning of each slot, the BS will inform all the MHs the set of signaling channels which can be used in the next slot. The set is called S_{dc} for data-only system and S_{vc} or voice-only system. For a data MH (Figure 1), once a packet is generated, it will send out a REQUEST with probability p_d in the subsequent slots, asking for a CDMA code to transmit its data packet. The signaling channel used is randomly selected from S_{dc}. The data MH will transmit its data packet when the REQUEST is acknowledged by the BS. It will try to retransmit the data packet unless both the REQUEST acknowledgment (QACK) and the data packet acknowledgment (DACK) have been received.

As to a voice MH (Figure 2), it does nothing during a silence gap. Once a talkspurt starts, the voice MH sends REQUEST using randomly selected signaling channel in S_{vc} with probability p_v in every slot. The code associated with the first REQUEST which is acknowledged (by QACK) is reserved for the voice MH during the whole talkspurt. A voice packet is lost if it is not transmitted in the next slot after its generation or corrupted in transmission due to MAI.

The BS (Figure 3) is the central point of control. It takes the responsibilities of determining which acquired signaling channels to acknowledge and updating the regarding signaling channel sets. A limit $\mathcal{L}$ is imposed on the number of packets transmitted in one slot. Let x be the numbers of the acquired signaling channels, and n_r the number of reserved codes. If x and n_r add up to less than $\mathcal{L}$, all acquired signaling channels are acknowledged. Otherwise, only $\mathcal{L} - n_r$ signaling channels will be acknowledged. As pointed out in [16], this limit is used to reduce the MAI during packet transmission and thus enhance the system performance.

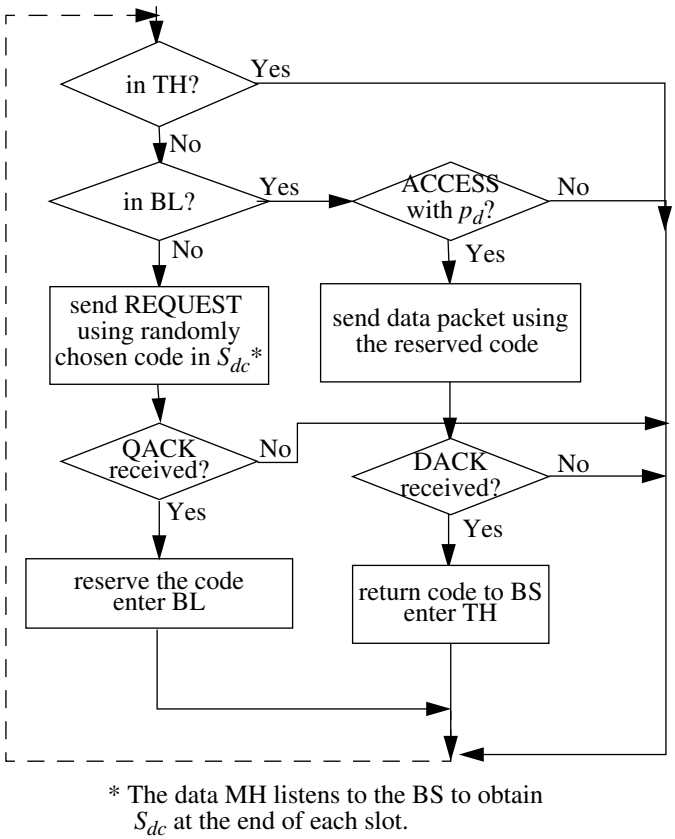


Figure 1: Flowchart for Data Terminal

2.3 Two Protocols for CDMA Medium Access Control

In this section, we present two types of CDMA MAC schemes, namely, Preamble Signaling Access (PSA) and Minislot Signaling Access (MSA).

2.3.1 Preamble Signaling Access (PSA) Scheme

The first one, Preamble Signaling Access scheme, is similar to the MAC protocols proposed in [7, 16] as depicted in Figure 4(a). Each slot of the CDMA system has a preamble part for the purpose of signaling and a packet transmission part for the packet content transmission. Using the preamble, a BS informs MHs which codes are available in next slot. An MH randomly picks up one of these codes and contends for it for packet transmission. For PSA scheme, the preamble is what we call *signaling channel*. It corresponds to one of the CDMA codes. The format of the preamble

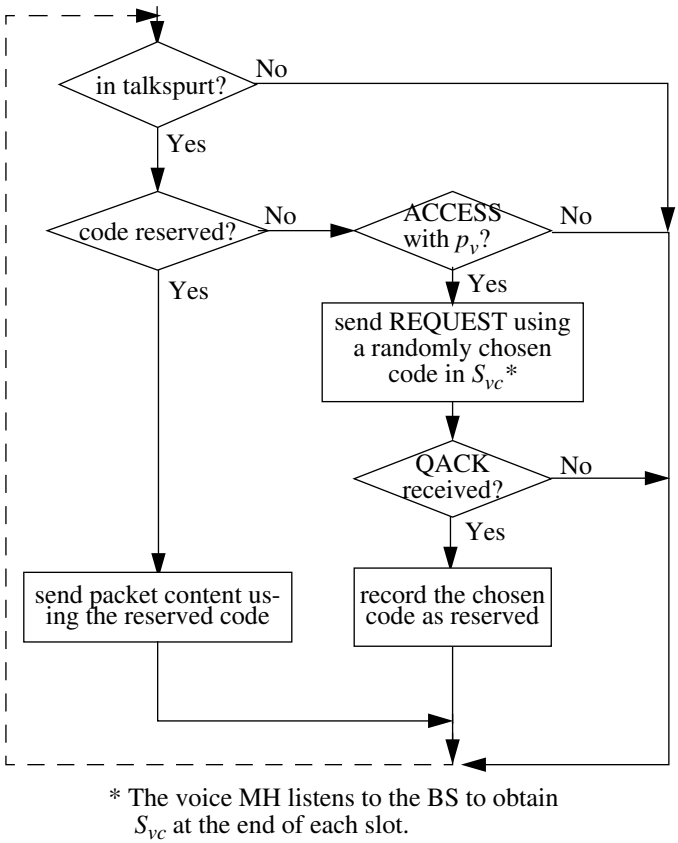


Figure 2: Flowchart for Voice Terminal

is as

$$Preamble = (MHid, EC),$$

where $MHid$ is the identification of the MH assigned to it when it is registered to the CDMA cell during setup or handover. EC is the error correcting code. In our research, we use BCH code for packet error protection.

If its REQUEST is acknowledged by the BS, an MH uses the same CDMA code as the preamble to transmit its packets. In contrast to previous research, in PSA, instantaneous REQUEST acknowledgment is not assumed. A REQUEST can only be acknowledged to the mobile host in the next time slot, as shown in Figure 4(a).

2.3.2 Minislot Signaling Access (MSA) Scheme

As depicted in Figure 4(b), in Minislot Signaling Access scheme, the system slot is no longer divided into preamble and packet transmission parts. Instead, during each slot, some of the CDMA codes

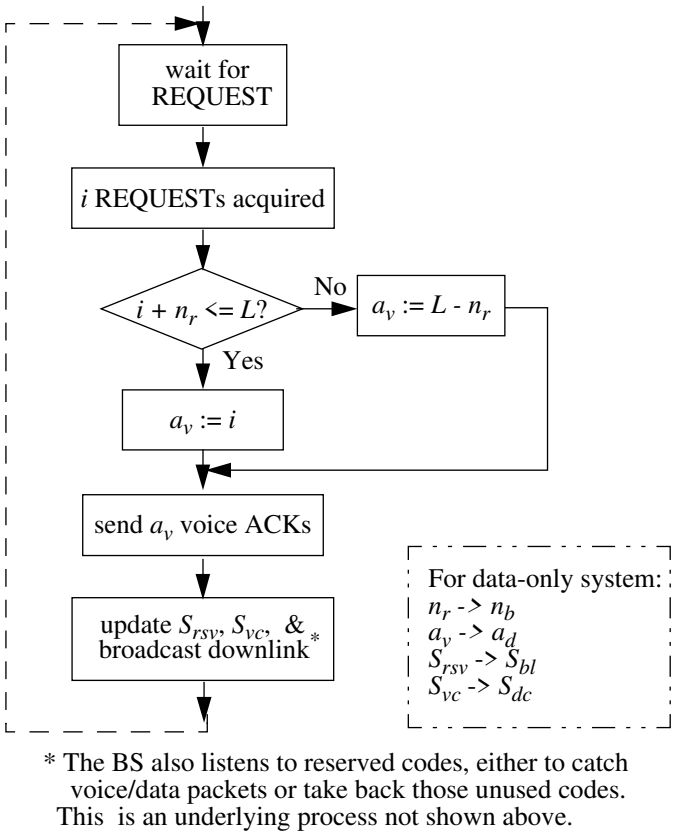


Figure 3: Flowchart for BS

are assigned by the BS as *signaling codes*. If a code is specified as *signaling code*, it is further partitioned into a number of *minislots*, each of which is associated with one of the available codes currently in the system.

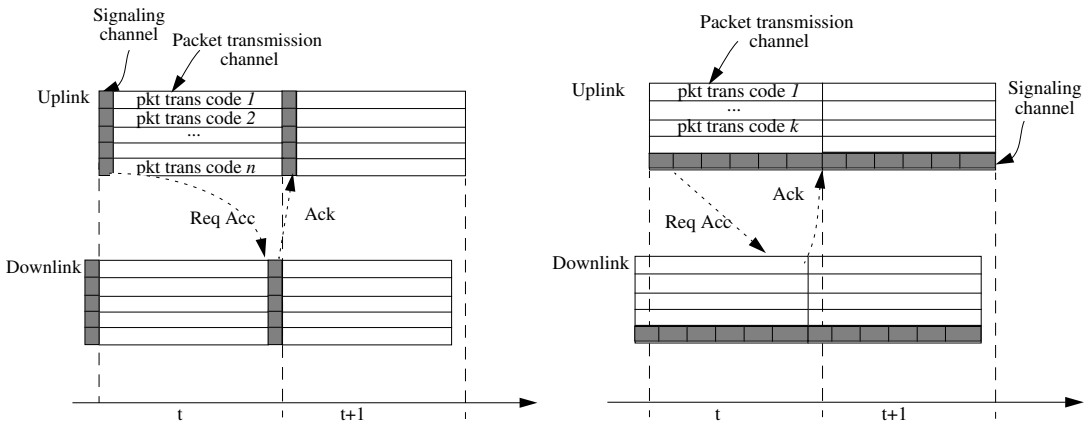
In MSA scheme, a minislot is a *signaling channel*. An MH randomly chooses one of these minislots to contend for packet transmission.

If a code is assigned as signaling code, it will be well error-protected. Throughout this paper, we assume the signaling code for MA scheme is so well protected that no MAI error will occur for signaling.

During different time slots, BS can specify different number of *signaling codes*. When the traffic is light, the BS can assign more *signaling codes* , and vice versa. This is because that, if there are more *signaling codes*, the MHs' contention will be more possible to succeed.

The format of a minislot is the same as that of preamble in PSA protocol.

When an MH's REQEUST is acknowledged, it will use the CDMA code associated with the



(a) Preamble Signaling Access (b) Minislot Signaling Access

Figure 4: Two approaches in CDMA MAC

signaling channel to transmit its packet. A look-up table is maitained in the BS to mapping each signaling channel to its associated CDMA code.

As can be observed by intuition, the overhead cost is smaller in MSA comparing with PSA. However, the MAI during the packet transmission is larger since there are more (*i.e.*, the signaling codes) codes transmitting in one slot than PSA protocol. A comprehensive study and analysis of the comparative performance of PSA and MSA will be presented in following section.

3 Analytical Model

In this section, analytical models will be developed to evaluate the performance of the MAC protocols proposed in Section 2. First, we establish the voice and data traffic models and define the system parameters. Then, Markovian models are developed for voice-only and data-only CDMA system, respectively. Several performance measures are defined based on these analytical models.

3.1 Traffic Models for Voice-only and Data-only System

The voice traffic and data traffic models are depicted in Figure 5. A voice MH stays in the Silence State (SS) without generating any packet. Upon the arrival of a talkspurt, it enters the Contention State (CS), where it sends its packets in the following slots with probability p_v. It moves into the Reservation State (RS) once an acknowledgment to a signaling channel is received, regardless of whether the packet is correctly received or not. In the RS, the MH continuously generates and transmits packets, which may be lost due to MAI. The probabilities of transitions from SS to CS

and from RS to SS can be calculated as $p_a = 1 - e^{-\lambda\tau}$ and $p_s = 1 - e^{-\mu\tau}$, respectively.

A data MH is in the Thinking State (TH) if it has no packet to transmit. It generates data packets following the Bernoulli distribution with the rate of p_o. After a packet is generated, the MH moves into Acquiring State (AC) and contends for a CDMA code. It moves to the Backlogged State (BL) after obtaining a code from the BS. In the BL, the data MH keeps on transmitting the packet in subsequent slots with probability p_d until an acknowledgment is received. Then it moves back to the TH.

3.2 Analysis of the Voice-only System

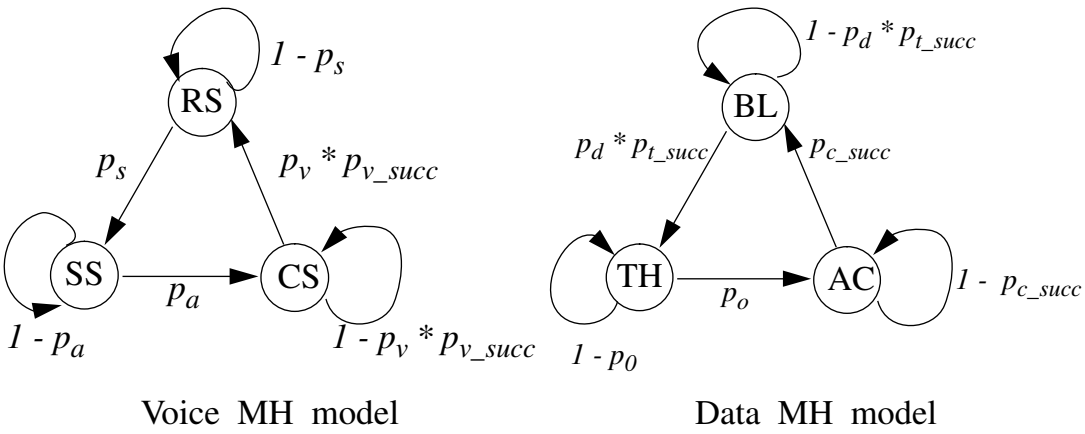


Figure 5: Models of voice MHs and data MHs

System design parameters for the CDMA network care listed in Table 1.

K is a system parameter which can be chosen between 60 and 80, depending upon the tradeoff between the BS complexity and system capacity [16]. L is the limit imposed on the number of packets transmitted in one slot. For PSA scheme, C is chosen as $C = K - n_r$. For MSA scheme, C can be expressed as

$$C = W \times H$$

where W is the number of minislots per signaling code. When W is smaller, the size of a signaling minislot can be larger and thus the MAI loss for the REQUEST will be also less. H is the number of codes which are assigned by BS to be the signaling code. What will be the optimal value of C, for each of the schemes, is one of the interesting questions to be investigated.

Traffic parameters of a voice-only system are listed in Table 2. Given N_v voice MHs in a cell,

Variable	Description
K	number of codes associated with the BS
L	limit of simultaneous packet transmission
C	maximum number of codes for packet contention
W	number of minislots per signaling code (for MSA)
H	number of signaling codes (for MSA)
τ	slot duration

Table 1: CDMA system parameters

Variable	Description
N_v	number of voice MHs in the cell
N_r	number of voice MHs in the Reservation State
N_s	number of voice MHs in the Silence State
N_c	number of voice MHs in the Contention State
$1/\lambda$	average of talkspurt duration
$1/\mu$	average of silence gap duration
p_v	access probability of voice MHs in the CS

Table 2: Traffic parameters for voice-only system

the system can be described by two-state variables $\{N_r, N_s\}$ [11, 16]. In order to find the stationary distributions of these variables, a Markov chain embedded at the slot boundary is considered. This Markov chain is ergodic since it is irreducible, aperiodic and with finite states. To solve this two-dimension Markov chain, a simplification can be made [11] to split it into two sub-processes: a speaking-silence process and a reservation process. The first process has one-state variables $\{N_s\}$. Its stationary distribution can be calculated as follows [11]:

$$\pi(n_s) = \binom{N_v}{n_s} \frac{(\frac{\lambda}{\mu})^{n_s}}{(1+\frac{\lambda}{\mu})^{N_v}}$$

The second process is an one-dimension process with state variables $\{N_r\}$. Its evolvement depends on N_s. The stationary distribution of this process, $\{\Pr[N_r = n_r \mid N_s = n_s]\}$ or $\{\pi(n_r \mid n_s)\}$, is assumed to exist [11]. The stationary distribution of the original two-dimension Markov chain, $\Pr[N_r = n_r, N_s = n_s]$, can be calculated as follows:

$$\pi(n_r, n_s) = \pi(n_r \mid n_s)\pi(n_s) \tag{1}$$

In order to obtain the solution to $\{\Pr[N_r = n_r \mid N_s = n_s]\}$, we first list two functions defined in [11] for our later discussion.

- $B(n, m, p)$: Binomial distribution,

$$B(n, m, p) = \binom{n}{m} p^m (1-p)^{n-m}$$

- $\Phi(a, m, q)$: the probability that q REQUEST acquired given a packets make access to m codes in a slot.

$$\Phi(a, m, q) = \frac{(-1)^q m! a!}{q! m^a} \sum_{k=q}^{\min(m,a)} (-1)^k \frac{(m-k)^{a-k}}{(k-q)!(m-k)!(a-k)!}$$

Based on the description of our protocol, following three functions can be addressed.

- $P_E(z)$: probability of packet loss due to MAI when z packets are simultaneously transmitted in one slot. Suppose the packet size is n bits and at most t error bits are correctable. If we assume the bit errors are *i.i.d.* within a packet,

$$P_E(z) = \sum_{k=t+1}^{n} B(n, k, P_b(z))$$

  $P_b(z)$ is the average bit error probability when there are z packets being transmitted simultaneously.

- $\Psi(c_v, a_v, n_r)$: the probability that a_v REQUEST of voice packets are acknowledged given that c_v voice packets made access to the medium in a slot while n_r voice users are in RS. This function's parameters should satisfy the following constraints: $a_v < c_v$, $a_v < L - n_r$, and $a_v < C$.

$$\Psi(c_v, a_v, n_r) = \begin{cases} \Phi(c_v, C, a_v) & \text{if } (a_v < L - n_r) \\ \sum_{i=a_v}^{c_v} \Phi(c_v, C, i) & \text{if } (a_v = L - n_r) \\ 0 & \text{else} \end{cases}$$

- $\Gamma(n_c, n_s, i)$: the probability that i REQUEST of voice packets are acknowledged given $N_c = n_c$ and $N_s = n_s$. The parameters of the function are subject to the following constraints: $i \leq n_c$, $i \leq C$, and $i \leq (L - (N_v - n_c - n_s)$.

$$\Gamma(n_c, n_s, i) = \sum_{k=i}^{n_c} \Psi(k, i, N_v - n_c - n_s) B(n_c, k, p_v)$$

  The first item is the probability that i REQUEST be acknowledged given k voice contend. The second is the probability of k voice contend given that $N_c = n_c, N_s = n_s$;

Using the above functions, the one-step transition probability of the contending process, conditioned on $N_s = n_s$, can be evaluated by

$$\Pr[N_r(t+1) = i' | N_r(t) = i, N_s = n_s] = \sum_{l=max(i'-i,0)}^{N_v - n_s - i} \Gamma(N_v - n_s - i, n_s, l) B(i, i' - l, 1 - p_s)$$

In the first item inside the $\sum$, l is the number of REQUEST which are acknowledged, $N_v - n_s - i$ is the actual number of contending packets. For the second item, since l codes will be newly reserved, $i' - l$ is the number of MHs that remain in RS from slot t through slot $t+1$.

With this probability, we can first construct the one-step transition matrix $\mathbf{P}$ and then solve the equations of $\Pi = \Pi\mathbf{P}$ and $\sum \pi_i = 1$ to get $\{\pi(n_r \mid n_s)\}$.

Once $\{\pi(n_r \mid n_s)\}$ is obtained for every value of N_s, the stationary distribution $\{\pi(n_r, n_s)\}$ can be calculated by Eq. (1). It can be used to derive following system performance measures,

- $E(N_c)$: expected value of the number of voice users in CS.
  $E(N_c) = \sum_{n_r=0}^{N_v} \sum_{n_s=0}^{N_v - n_r} (N_v - n_r - n_s)\pi(n_r, n_s)$
- $E(N_r)$: expected value of the number of voice users in RS.
  $E(N_r) = \sum_{n_r=0}^{N_v} \sum_{n_s=0}^{N_v - n_r} n_r \pi(n_r, n_s)$
- $E(L_{CONT})$: expected value of voice packet loss due to REQUEST contention.
  $E(L_{CONT}) = \sum_{n_r=0}^{N_v} \sum_{n_s=0}^{N_v - n_r} \left(\sum_{k=0}^{N_v - n_r - n_s} B(N_v - n_r - n_s, k, p_v) \sum_{i=0}^{k} (n_c - i)\Psi(k, i, n_r) \right) \pi(n_r, n_s)$
- $E(L_{MAI})$: expected value of voice packet loss due to MAI.
  $E(L_{MAI}) = \sum_{n_r=0}^{N_v} \sum_{n_s=0}^{N_v - n_r} \left(\sum_{k=0}^{N_v - n_r - n_s} B(N_v - n_r - n_s, k, p_v) \sum_{i=0}^{k} n_r P_E(n_r + H)\Psi(k, i, n_r) \right) \pi(n_r, n_s)$
  (note: for PSA scheme, $H = 0$.)
- VLR_{CONT}: Voice Loss Rate due to REQUEST contention.
  $VLR_{CONT} = \dfrac{E(L_{CONT})}{E(N_c) + E(N_r)}$
- VLR_{MAI}: Voice Loss Rate due to MAI.
  $VLR_{MAI} = \dfrac{E(L_{MAI})}{E(N_c) + E(N_r)}$
- VLR: total Voice Loss Rate.
  $VLR = VLR_{CONT} + VLR_{MAI}$

Variable	Description
N_d	number of data MHs in the cell
N_t	number of data MHs in the Thinking State
N_a	number of data MHs in the Acquiring State
N_b	number of data MHs in the Backlogged State
p_o	data packet generation rate
p_d	data packet transmission rate

Table 3: System variables for data-only system

3.3 Analysis of the Data-only System

Traffic parameters for data-only system are listed in Table 3.

Similar to voice-only system, given N_d data MHs in a cell, the system can be described by two-state variables $\{N_t, N_b\}$. A Markov chain embedded at the slot boundary can also be applied in order to find the stationary distributions of these variables. This Markov chain is ergodic if we constrain $N_t + N_b \leq N_d$.

We borrow the functions $B(n, m, p)$, $\Phi(a, m, q)$ and $P_E(z)$ from Section 3.2. The Ψ function will be redefined as

- $\Psi(c_d, a_d, n_b)$: the probability that a_b REQUEST of data packets are acknowledged given that c_d data packets made access to the medium in a slot while n_b data users are in BL. This function's parameters should satisfy the following constraints: $a_d < c_d$, $a_d < L - n_b$, and $a_d < C$.

$$\Psi(c_d, a_d, n_b) = \begin{cases} \Phi(c_d, C, a_d) & \text{if } (a_d < L - n_b) \\ \sum_{i=a_d}^{c_d} \Phi(c_d, C, i) & \text{if } (a_d = L - n_b) \\ 0 & \text{else} \end{cases}$$

Now, the one-step transition probability of the data conditioned on $N_s = n_s$, can be calculated by

$$Pr[N_t(t+1) = i', N_b(t+1) = j' | N_t(t) = i, N_b(t) = j] = \sum_{l=0}^{i} B(i, l, p_o) \Psi(N_d - i - j, i' + j' - i - j + l, j) \sum_{k=i'-i+l}^{j} \Big(B(k, i' - i + l, 1 - P_E(k + H)) B(j, k, p_d) \Big)$$

The first item inside the out-most $\sum$ is the probability that l data MHs generate data packets during slot t. The second item is the probability that $i' + j' - i - j + l$ data MHs acquire code to transmit their data packets. For the two items inside the inner $\sum$, the first is the probability that $i' - i + l$ data packets are correctly received if k packets are transmitted. The second stands for the probability that k MHs are transmitting data packets given j MHs in BL state. Note that, during slot t, the number of data MHs that transit from AC to BL, y, can be derived using $N_d - i - j - y + l = N_d - i' - j'$, *i.e.*, $y = i' + j' - i - j + l$. Similarly, the number of data MHs transiting from BL to TH, x, can be obtained using $i + x - l = i'$, *i.e.*, $x = i' - i + l$.

Again, after solving this Markovian chain and getting its stationary distribution $\{\Pr[N_t = n_t, N_b = n_b]\}$ or $\{\pi(n_t, n_b)\}$, we can derive following system performance measures for the data-only system:

- $E(N_t)$: expected value of the number of data users in TH.
  $$E(N_t) = \sum_{n_t=0}^{N_d} \sum_{n_b=0}^{N_d - n_t} n_t \pi(n_t, n_b)$$
- $E(N_b)$: expected value of the number of data users in BL.
  $$E(N_b) = \sum_{n_t=0}^{N_d} \sum_{n_b=0}^{N_d - n_t} n_b \pi(n_t, n_b)$$
- $E(R_{cv})$: expected value of data packets which are correctly received per slot.
  $$E(R_{cv}) = \sum_{n_t=0}^{N_d} \sum_{n_b=0}^{N_d - n_t} \left(\sum_{i=0}^{n_b} i \times (1 - P_E(i + H)) B(n_b, i, p_d) \right) \pi(n_t, n_b)$$
- Data packet throughput = $E(R_{CV})$.
- Data packet average delay = $\dfrac{N_d - E(N_t)}{E(R_{CV})}$.

4 Numerical Results

The purpose of this section is three folds: (1) to evaluate the performance of the two CDMA MAC protocols proposed in Section 2, (2) to verify the correctness of the Markovian chain model proposed in Section 3, and (3) to investigate impacts of some of the system design parameters. As we have mentioned in previous sections, the system performance evaluation will be conducted for voice-only and data-only CDMA systems respectively.

4.1 Performance Evaluation Configurations

The configurations for performance evaluation are depicted in Table 4.

We consider a cell with a number of active voice or data MHs. The processing gain of the system, G, is 31. Time is divided into slots of 16 ms and 17.9 ms long for MSA and PSA respectively. The average durations of talkspurts and silence gaps are 1.0 and 1.35 seconds, respectively. BCH-codes are used for error correction for both voice and data packets. A packet is taken as a code of 255 bits. A signaling channel uses BCH code (31,11,5) [5] which means the $MHid$ can have 11 bits, which is fairly enough for a microcell. We use Gaussian method to approximate the bit error probability [9, 12]:

$$P_b(z) = \frac{1}{2}\text{erfc}\left(\left(\frac{2(z-1)}{3G} + \frac{N_0}{E_b}\right)^{-\frac{1}{2}}\right)$$

where E_b/N_0 is 10 dB. The voice and data transmission probabilities, p_v and p_d, are both chosen as 0.9 because as pointed out in [7], a fixed retransmission probability of 0.9 can achieve near optimal performance.

For all our configurations, we choose W of value 8, so for MSA, there can be 8 minislots in one code, each minislot occupies $255/8 = 31$ bits.

For voice-only system, we only investigate the cases where $H = 1$ while for data-only system, we consider the cases of different values of H.

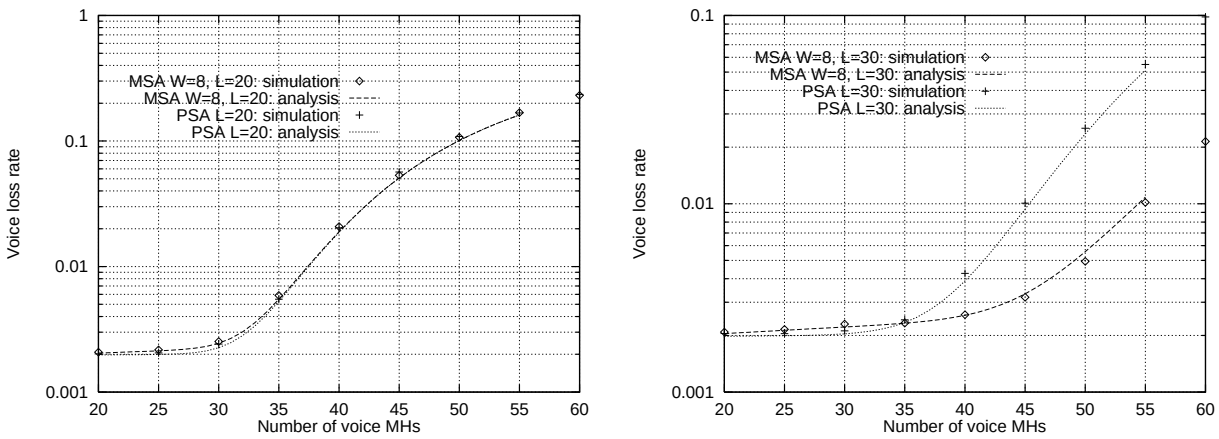
Variable	PSA scheme	MSA scheme
CDMA processing gain G	31	31
CDMA base rate (bps)	16,000	16,000
Voice data rate (bps)	8,000	8,000
Slot length (ms)	17.9	16
Packet length (ms)	15.94	15.94
BCH code (voice)	(255,147,14)	(255,131,18)
BCH code (data)	(255,131,18)	(255,131,18)
BCH code (signaling)	(31,11,6)	(31,11,6)
$1/\lambda$(second)	1.0	1.0
$1/\mu$(second)	1.35	1.35
p_v	0.9	0.9
p_d	0.9	0.9

Table 4: Performance evaluation configurations

4.2 Numerical Results for Voice-only System

Some numerical results are shown in Figure 6 and Figure 7. From these figures we can see that at most of the time, MSA scheme performs much better than PSA scheme. For example, when $L = 30$, 55 voice MHs can be served while satisfying VLR to be less than 0.01 if MSA is used. However, for PSA, only 45 voice MHs can be supported. which means MSA can have performance 22% better than PSA.

Figure 6 and Figure 7 also can be used to verify the accuracy of the Markovian chain model. Each point is an average of 3 runs lasting 5000 seconds. It can be observed that the analytical model indeed provided a good approximation of system performance measures.



(a) Voice loss rate for $L = 20$

(b) Voice loss rate for $L = 30$

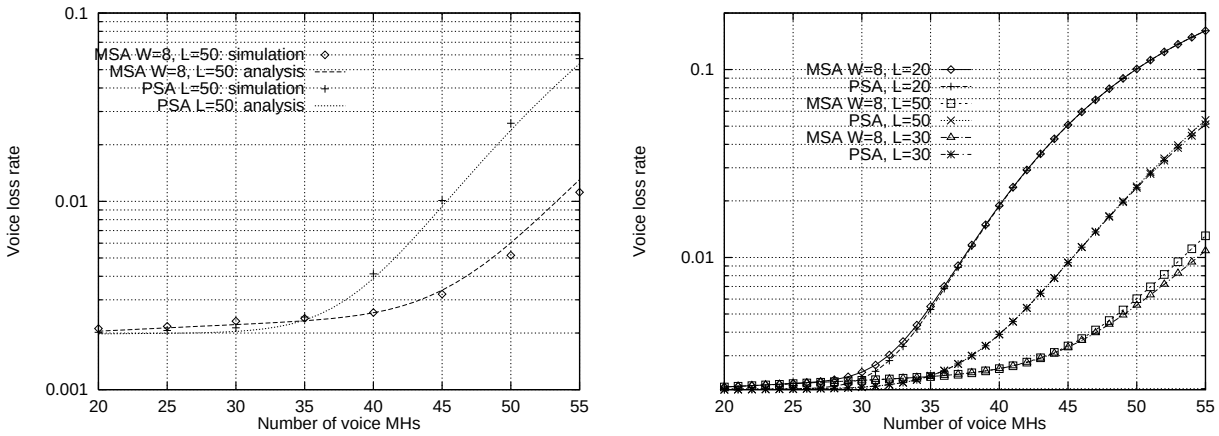
Figure 6: Voice loss for $K = 70$ and $p_v = 0.9$

Also it can be observed that the value of L should be chosen carefully. In Figure 8, we are trying to find out the optimal values of L by which the maximal number of voice users can be served while satisfying the voice loss less than some threshold value. Generally speaking, L can be chosen for value such as 30 to 40.

4.3 Numerical Results for Data-only System

Figure 9 confirms the accuracy of the Markovian model. Again, each point is an average of 3 runs lasting 5000 seconds. It can be observed that the analytical model indeed provides a good approximation of system performance measures, just as the model for voice-only system.

As we have discussed in Section 2.3, in MSA, since some CDMA codes are used for signaling,



(a) Voice loss rate for $L = 50$ (b) Impact of L

Figure 7: Voice loss for $K = 70, L = 50, p_v = 0.9$ and the comparison of all the 3 cases

there should be more MAI error than in PSA; however, for PSA, the preamble is an overhead which also has impact on the system performance. Figure 10 shows that, if we choose $H = 5$ for MSA protocol, MSA will perform better (though not significantly) than PSA protocol, given different values of p_o. It also shows that the throughput of the network has some upperbound. For example, for MSA, when $K = 70, L = 50, p_d = 0.9$, the throughput will decrease at $N_d = 80$ if $p_o = 0.5$.

Figure 11 shows the impact of H, number of signaling codes (for MSA), on the system performance. As can be observed, for different value of p_o, $H = 3$ performs better than $H = 1$. This is because when $H = 1$, there are only 8 codes which can be assigned in one slot, which leads to very high probability of REQUEST contention.

Figure 12 shows the impact of p_o, data packet generation rate, on the system performance. Here we only consider MSA. The figures show that there is a upperbound for the data throughput the system can achieve. For a certain value of p_o, when the number of data terminals comes to some value, the system throughput will begin to decrease as there is too much contention in the system.

5 Summary

In this paper, we have defined and studied two MAC schemes for CDMA PCNs. A new medium access control protocol, MSA, has been proposed using mini-slot techniques to solve the problems of code assignment and MAI control. Another protocol, PSA, is based on those proposed in previous CDMA MAC research. We have used Markovian chain models to analyze the performance of these

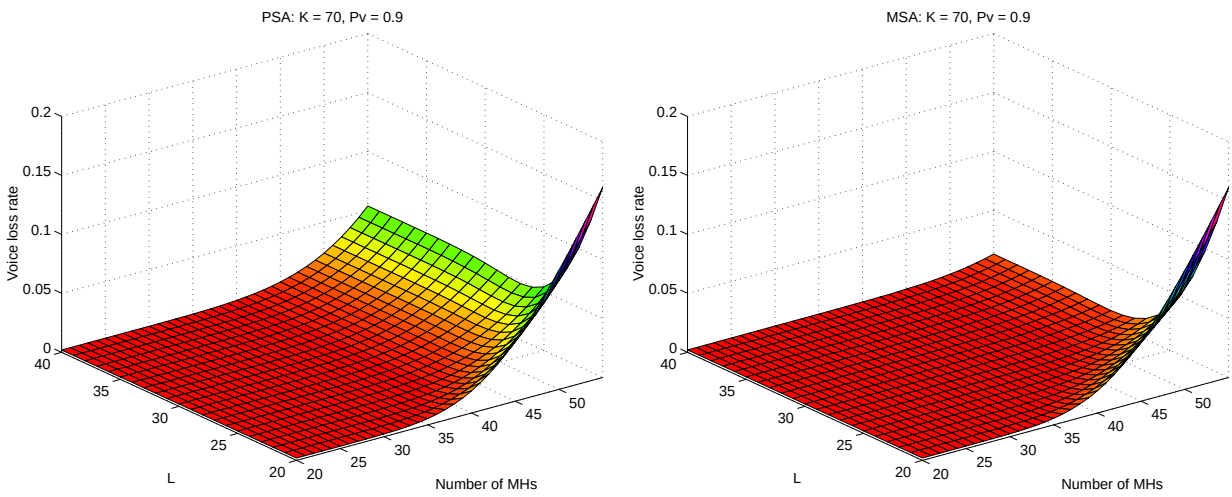


Figure 8: Planar search for voice only system with $K = 70, p_v = 0.9$

two protocols for voice-only and data-only systems, respectively. The analysis is shown to be very close to the simulations we conducted. Based on the results obtained from the modeling, we have compared the performance of these two protocols and found that in many cases, MSA protocol performs better than PSA protocol, especially for voice services. Although data/voice integration has not been dealt with in this paper, we believe our protocol can improve the system performance in a mixed voice/data CDMA wireless network. Future work can be performed on how to integrate data and voice traffic in the new MAC protocol.

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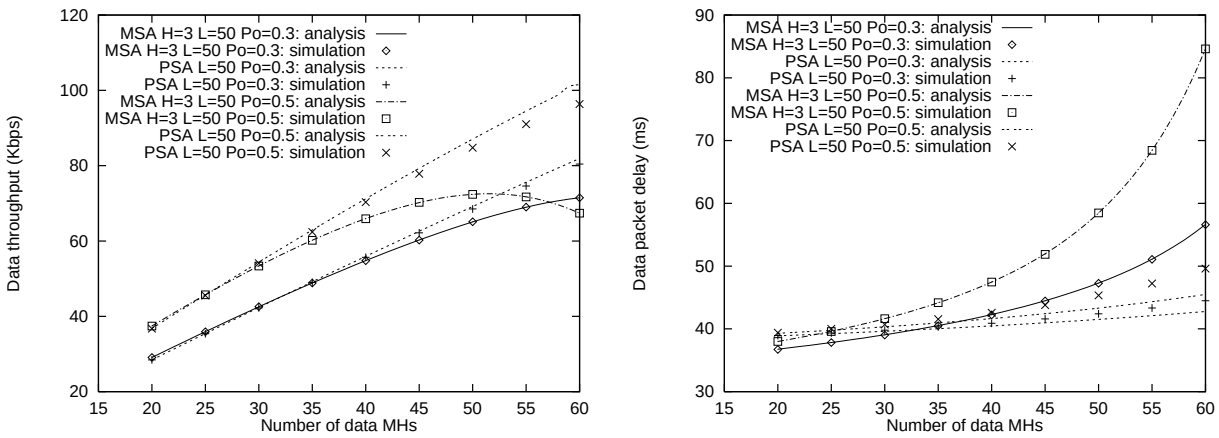

Figure 9: Throughput and delay for data-only system when $K = 70, L = 50, p_d = 0.9$: comparison between simulation and analysis results

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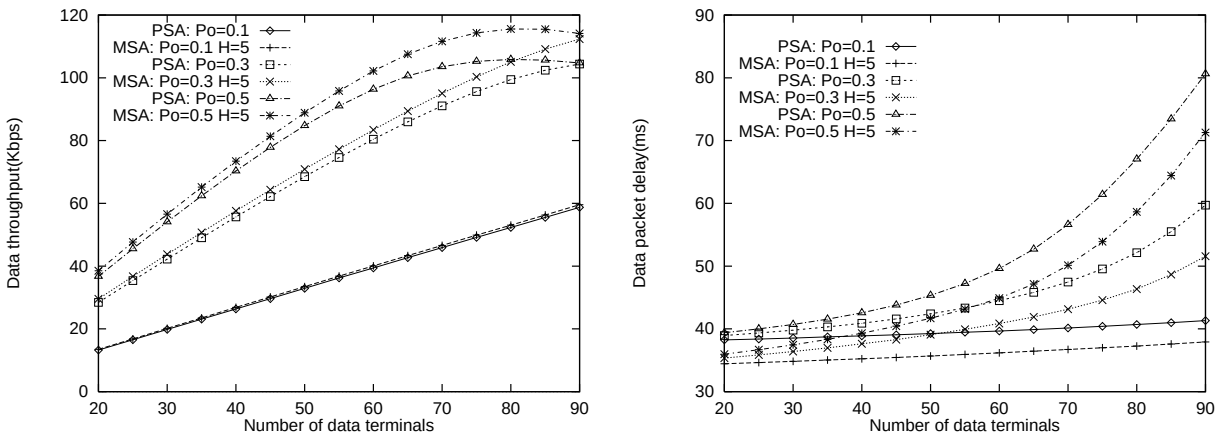

Figure 10: Throughput and delay for data-only system when $K = 70, L = 50, p_d = 0.9$: comparison between PSA and MSA

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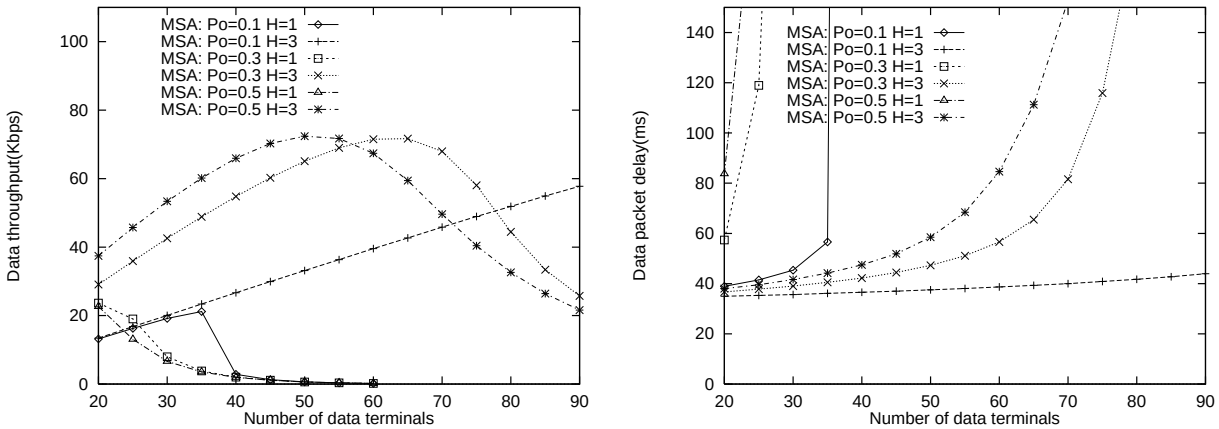

Figure 11: Throughput and delay for data-only system when $K = 70, L = 50, p_d = 0.9$: impact of H on MSA protocol performance

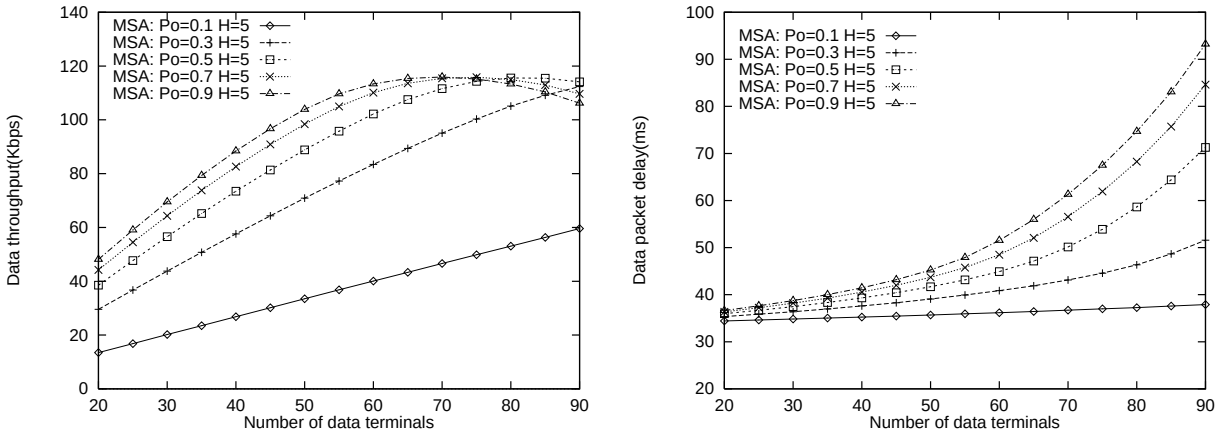

Figure 12: Throughput and delay for data-only system when $K = 70, L = 50, p_d = 0.9$: impact of p_o on MSA protocol performance