ABSTRACT

HANDOFF EFFECT ON PRMA(PACKET RESERVATION MULTIPLE ACCESS) IN MICRO-CELLULAR SYSTEM

by
Dongsuk Park

PRMA(Packet Reservation Multiple Access) has been proposed for third generation wireless information network by Goodman et al. [5] [4]. Due to small micro cell radius mobile initiated handoff has been proposed to disperse the burden of BS(Base Station) [14]. Even though these frequent handoffs will not burden on BS, increased contends due to handoff will affect the over all performance of PRMA.

In this paper, we analyze the handoff effect on PRMA performance under micro-cellular system. Steady state speech terminal model with handoff is proposed. Stabilities are derived based on proposed steady state terminal model[$F(c_s)$=M] and also increased contend [$F(c_h)$=M] due to handoff. The multiple EPA(equilibrium) points change with handoff. Packet dropping probability and data packet delay are calculated using both Markov Analysis and backlog b from $F(c_s)$=M and $F(c_h)$=M. The changes of performance under handoff show the need of handoff schemes at PRMA.

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by
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APPROVAL PAGE

HANDOFF EFFECT ON PRMA(PACKET RESERVATION MULTIPLE ACCESS) IN MICRO-CELLULAR SYSTEM

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To my country and my family

ACKNOWLEDGMENT

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CHAPTER 1

INTRODUCTION

PRMA(Packet Reservation Multiple Access) is combination of slotted ALOHA and TDMA(Time Division Multiple Access) which is designed for wireless micro-cellular network[4]. The mobile can receive ACK before beginning of next slot because of it's small micro-cell radius. However, there will be frequent hand off due to mobility of mobile. PRMA speech-only, integrated voice and data system have been studied before but without any consideration of hand off effect on performance evaluation[5][7]. In [15][14], mobile initiated hand off in micro-cellular system has been proposed. Hand off will occur frequently in a PRMA micro-cell which may be characterized as having small cell radius. Even though these frequent hand off will not burden on BS(Base Station), increased contends due to hand off will affect the overall performance of PRMA.

In this paper, we analyze the performance of PRMA by means of measuring hand off weight W_h with respect to mean talk spurt duration under hand off and also Markov Analysis of the system. It is shown in this paper that the overall performance of PRMA changes resulted from hand off. We propose speech terminal models both voice only and combined voice and data considering hand off. State based System Equilibrium Function $F(c_s)$=M from speech terminal model with hand off and Increased Contend based System Equilibrium Function $F(c_h)$=M are derived and show the changes of system stability and multiple EPA(equilibrium) point due to increased contend. These increased contends multiply both packet dropping probability and delay.

This paper is organized as follows. Hand off probability is calculated in chapter 2 based on both boundary crossing rate and previously proposed PRMA hand off procedures [18]. Then hand off weight W_h is derived based on speech terminal model

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with hand off. The probability that talk spurt end or handed off in a most recent frame under hand off ζ_e and mean contend c_h under hand off are calculated in chapter 2 and used to find both system stability and performance in chapter 4. In chapter 3, State based System Equilibrium Function $F(c_s) = M$ which is from steady state speech terminal model under hand off and Increased contend based System Equilibrium Function $F(c_h) = M$ which is from both increased contend c_h and F(c)=M are derived. We use Markov Analysis to find steady state probability distribution. Chapter 4 presents Markov model to analyze the steady state probability of the system. We evaluate PRMA packet dropping probability, throughput and data packet delay under hand off based on both Morkov Analysis and ζ_e.
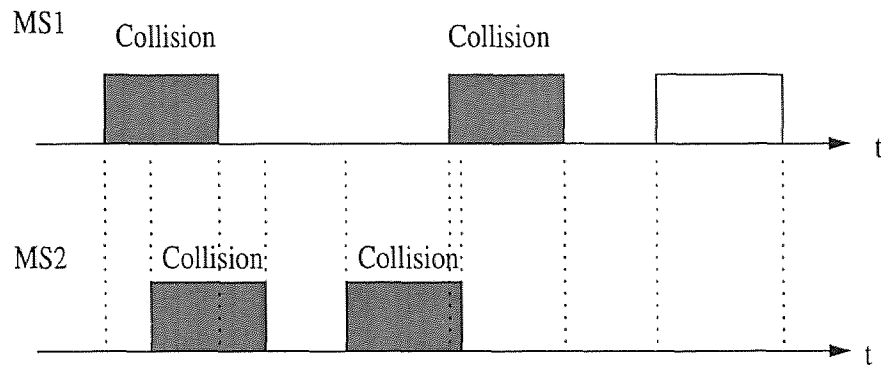
Figure 1.1 Pure ALOHA

1.1 ALOHA

1.1.1 Pure ALOHA

The pure ALOHA protocol was proposed by Norman Abramson for ALOHA system at university of Hawaii in 1970 [20][21]. It was designed for random access protocol which is used for packet data transfer. The users transmit when messages are ready without any consideration for other users. Thus, collisions occur when multiple users transmit at same time slot. In pure ALOHA, the achievable maximum throughput is as low as 18 % at most due to frequent collision and idle channel time.

MS1

Collision

t

MS2 : Collision:

t

time slot
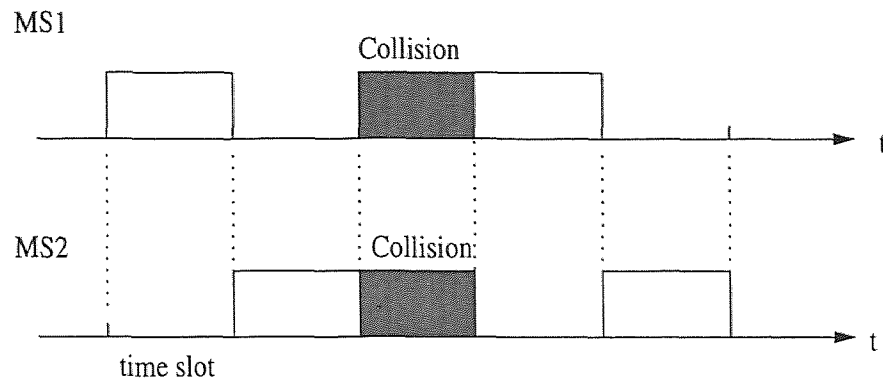
Figure 1.2 Slotted ALOHA

1.1.2 Slotted ALOHA

Slotted ALOHA has been introduced by Roberts in 1972 due to low throughput of pure ALOHA [22] [23]. Time is divided as slots with pips(synchronized clocks) and each mobile is allowed to transmit only at the beginning of slot. The probability of collisions are decreased compare to pure ALOHA. The maximum throughput that can be achievable is twice that of pure ALOHA.

FRAME

RESERVED   AVAILABLE

time
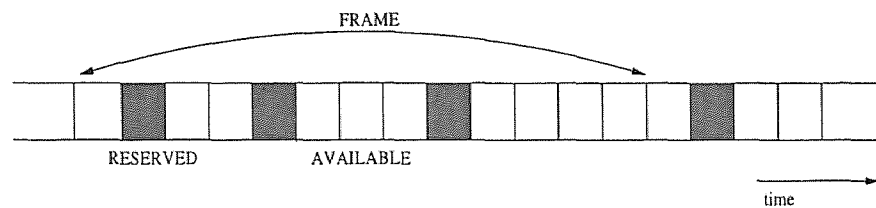
Figure 1.3 Reservation ALOHA

1.1.3 Reservation ALOHA

In reservation ALOHA, mobile can get reservation at a slot if it succeed at contending [24]. The mobile which succeed at contend automatically has the right to use a slot in next frame to the end of it's data transmission. The BS broadcast it's slot status whether it is reserved or available at each frame. Reservation ALOHA is better throughput under high congested situation.

8 bits	24 bits	8 bits	10 bits	14 bits	16 bits	472 bits
DQDB Media Access	Virtual Circuit or Interface Unit Identifier	Packet Control Field	Base Station Identifier	Wireless Channel Sync	Frame Check Sequence	Speech or User Data With Channel Coding

DQDB Header(40 bits)

PRMA Header(80 bits)
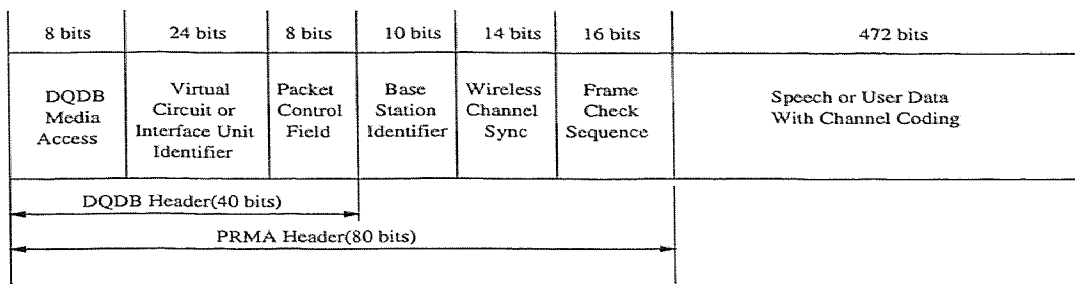
Figure 1.4 Proposed packet structure

1.2 PRMA(Packet Reservation Multiple Access)

PRMA has been designed for contention based uplink MAC protocol from mobile to BS where information is distributed to all of the mobile. Each mobile can get access to available channel using contend. Down link traffic can be transmitted using TDMA/TDD(Time Division Duplex) or TDMA/FDD(Frequency Division Duplex). Both channels are assumed as error free.

PRMA characteristics are

- SAD(Speech Activity Detector) is used to exploit the idle speech period and give advantage over TDMA

- There is no hard limit at PRMA(the voice quality degrades proportionally to mobile number in system)

- Packetized voice permits seamless hand offs

- PRMA achieves acceptable multiple access delays with delay limit

Packets: The proposed packet structure [4] is shown as Figure 1.4. There are two kind of packets, Voice and data, within PRMA. Voice packet can get reservation in a slot. If voice packet gets reservation at a slot it automatically can access at a slot in next frame until the end of talk spurt. However, data packets have to contend every time to send a packet to BS.
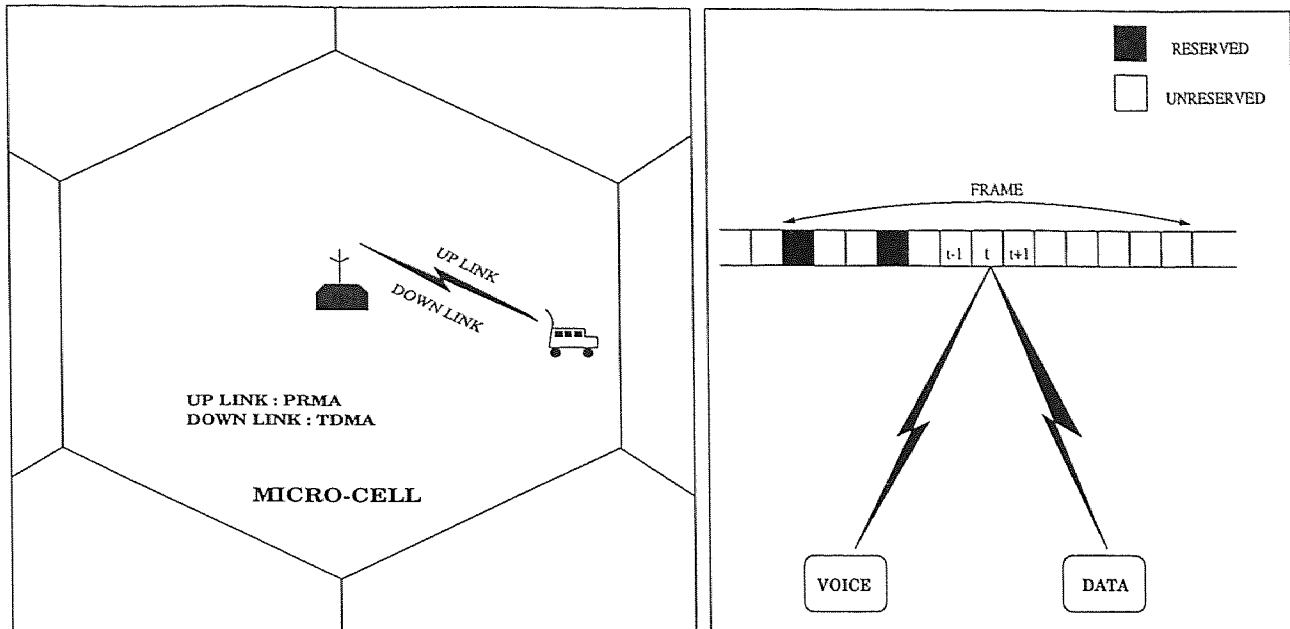
Figure 1.5 PRMA

Frame and Slot: PRMA frame consists of slots which carry information one by one at each frame. There are two slot status in a frame either reserved to a mobile or available for contend. Also, the number of slots in a frame can be calculated as in [5]

$$N = [\frac{R_c T}{R_s T + H}]$$

where τ : Slot duration, T : Frame duration, H : Header length

R_c : Channel rate, R_s : Source rate

Channel Access: As mentioned before, there are two types of information packets, voice and data, in PRMA. These information packets access to channel by contending with different probabilities. Voice packet gets reserved at a slot if it succeeds at contend while data packets have to contend every time to send data packet. The mobile which contend at a slot can receive feedback before beginning of next slot because of it's small cell radius. Not like reservation ALOHA, PRMA copes with congestion by dropping voice packet which exceed a certain delay limit

D_{max}. The required buffer size B in a mobile is

$$B = [\frac{D_{max}}{T}]packets$$

1.2.1 Speech and Speech Terminal Model

The speech model can be shown as Figure 1.6.   Talk spurt is generated exponentially
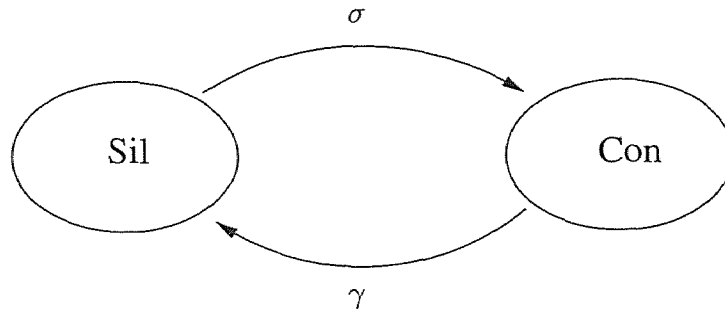
Figure 1.6 Speech model

with mean t_1. The probability that silent end in a time slot σ and the probability that talk-spurt end in a time slot γ are

$$\gamma = 1 - exp(\frac{-\tau}{t_1})$$

$$\sigma = 1 - exp(\frac{-\tau}{t_2})$$

with t_1 : mean talk spurt duration

   t_2 : mean silence duration

   τ : slot duration

From Figure 1.7

N : number of slots in a frame, p : contend permission probability

R : number of mobiles in Reservation,   C : number of mobiles in Contending

γ : probability that talk spurt end in a time slot

γ_f : probability that talk spurt end in a most recent frame $[1 - (1 - \gamma)^{20}]$

Speech only terminal model is shown in Figure 1.7.   The successful contending conditions for voice only model are
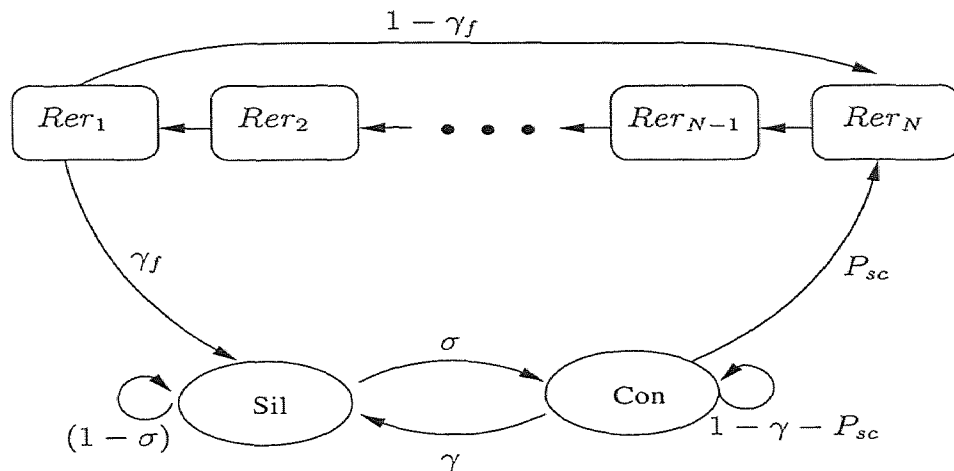
Figure 1.7 Speech terminal model

- mobile have permission to contend : p

- other terminals are not permitted to contend : $(1-p)^{C-1}$

- no talk spurt end during contend : $(1-\gamma)$

- the slot is available : $(1-R/N)$

So, the probability of successful contend is

$$P_{sc} = p(1-p)^{C-1}(1-\gamma)(1-R/N)$$

The successful contending conditions for combined voice and data model are

- mobile have permission to contend : p

- other terminals are not permitted to contend : $(1-p)^{C-1}$

- no talk spurt end during contend : $(1-\gamma)$

- the slot is available : $(1-R/N)$

- no other data terminals are not permitted to contend : $(1-p_d)^{b}$

  where b is data packet backlog

So, the probability of successful contend is

$$P_{sc-d} = p(1-p)^{C-1}(1-\gamma)(1-R/N)(1-p_d)^b$$

Also, the probability that talk spurt end in a most recent frame in both cases is

$$\gamma_f = 1 - (1-\gamma)^N$$

1.2.2 Data Terminal Model
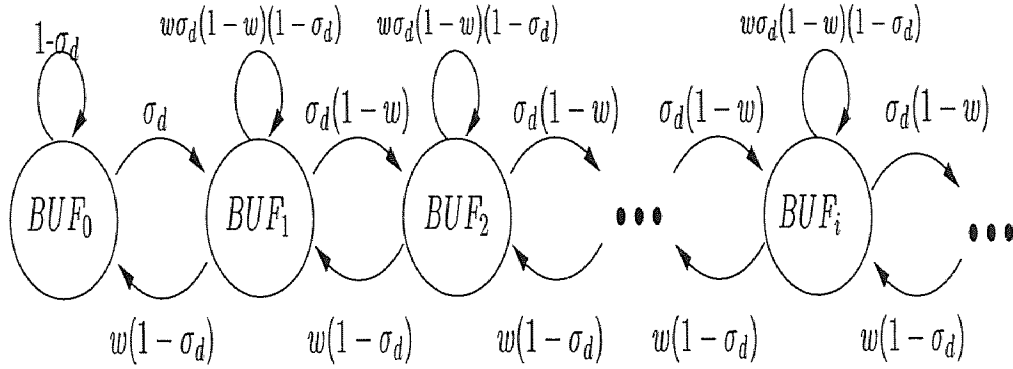
Figure 1.8 Data subsystem model

Data terminals can be assumed either speech terminal which generates system control message, location update, call set-up or e-mail messages. These data sources are assumed to be generated at a low average bit rate. Data terminal model can be shown as in Figure 1.8 as in [5]. If we select average data rate in a mobile as R_d bps and number of information bit in a slot as $R_s T$ then the probability that a packet is generated at a data terminal in a slot σ_d is

$$\sigma_d = \frac{R_d T}{R_s T N} = \frac{R_d}{R_s N}$$

We assume data packet buffer as infinitely long. Data terminals contend with probability p_d but don't get reservation while voice packet gets reserved after successful contention. The successful data packet transmission conditions are

- Permission to contend : p_d

- No voice terminal permission to contend : $(1 - p)^c$

- No other data terminal has permission to contend : $(1 - p_d)^{b-1}$

- The slot is available : (1-R/N)

So, the probability of successful data packet transmission is

$$w = p_d(1 - p)^C(1 - p_d)^{b-1}(1 - R/N)$$

CHAPTER 2

PRMA HANDOFF AND HANDOFF WEIGHT W_H

2.1   PRMA Handoff

2.1.1   Proposed Handoff in PRMA

PRMA micro-cell radius allows short propagation delay in a cell and the mobile can receive feedback information before beginning of the next slot [5]. However, there will be frequent hand offs in PRMA because of it's small cell radius as mentioned before. These frequent hand off will not burden on BS but the increased contend will deteriorate the packet dropping rate and capacity.

Figure 2.1 shows proposed overall structure of Cellular Packet Network. Mobile initiated hand off and distributed network architecture have been proposed to alleviate the burden of BS through whole of the network [14],[18]. Not like current cellular system which require the switch to move a circuit-switched connection from one base station to another as the mobile moves through the network, hand off in PRMA is initiated by mobile which continuously checks received signal [15]. Mobile which decide to be handed off to new BS contend again to new BS if it's signal level can be handled better by new BS. If the mobile gets successful reservation to new BS the new BS just routes the call to the receiving interface TIU(Trunk Interface Unit) which is connected to PSTN(Public Switch Telephone Network). The TIU will update routing table after packet is received from new BS based on the new BS address(Virtual Circuit Identifier). Due to high speed of the MAN(Metropolitan Area Network), the TIU can receive quickly the packet from new BS. There is no additional role on BS with hand off at PRMA which is based on micro-cellular network. The detail mobile initiated intra-MAN hand off procedure is shown in Figure 2.2. We calculate hand off probability using both boundary crossing rate and

10
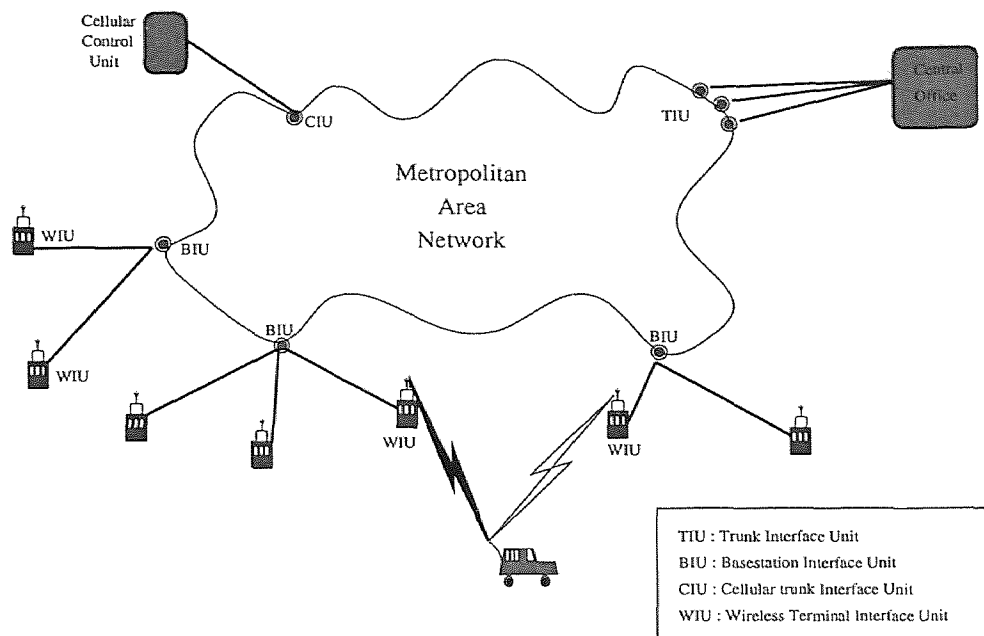
Figure 2.1 Cellular Packet Network

average hand off times. However hand off probability from boundary crossing rate is used at performance evaluation.

2.1.2 Handoff Probability using Boundary Crossing Rate

Boundary crossing rate is used to find hand off probability without any priority in hand off contend as in [1][2]. To calculate boundary crossing rate, we select the maximum mobile number that can be supported in one cell as 37 users within 1 % of packet dropping rate[5]. Also, let Cell radius(r)=150m, Velocity(v)=10Km/h then the boundary crossing rate γ_b during one slot τ is

$$
\begin{aligned}
\gamma_b &= \int_L \frac{\rho v}{\pi} dL = 2\rho v r \\
&= 3.849 \times 10^{-4} mobiles/slot
\end{aligned}
\tag{2.1}
$$

where $\rho = \frac{M}{\pi r^2} = 5.234 \times 10^{-4}$.

Voice gets reservation at a slot in each frame after successful contention and Voice
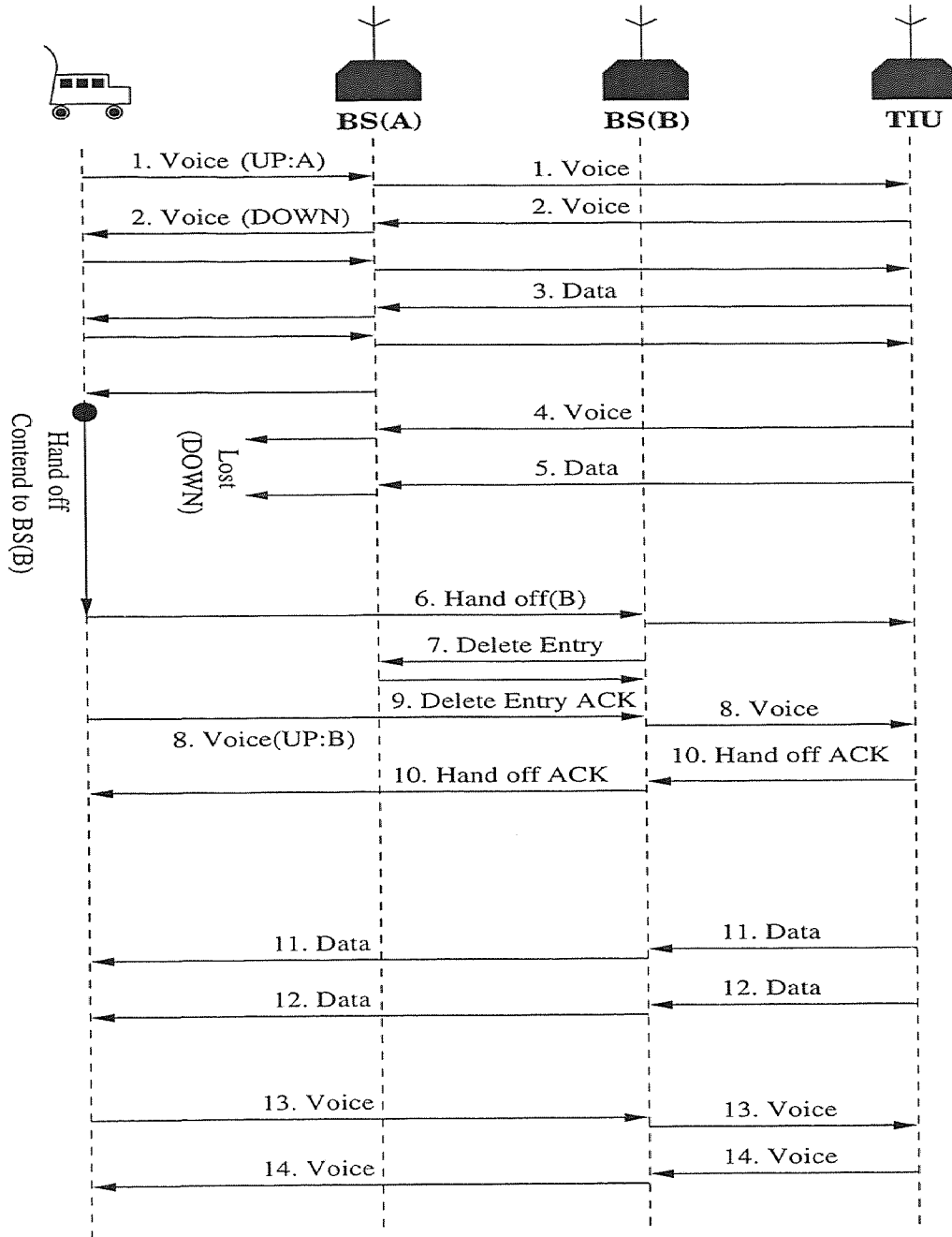
Figure 2.2 Intra-MAN PRMA Hand off

Table 2.1 Boundary crossing rate with different radius and speed

Micro Cell Radius(m)	Mobile Speed(Km/h)	Handoff probability
150	40	1.509×10^{-2}
	60	2.264×10^{-2}
	80	3×10^{-2}
300	40	7.545×10^{-3}
	60	1.13×10^{-2}
	80	1.51×10^{-2}
500	40	4.526×10^{-3}
	60	6.789×10^{-3}
	80	9.05×10^{-3}

packets are generated one by one at voice terminal. So, hand off will occur during one frame duration. The hand off probability at each slot P_s is calculated based on one frame duration.

$$P_s = 20 \times \frac{\gamma_b}{M} = 1.88 \times 10^{-4} \qquad (2.2)$$

Finally handoff probability in a most recent frame "P_h" is summation of the probability that handoff occurs during one slot in a most recent frame duration.

$$P_h = 1 - (1 - P_s)^{20}$$
$$\simeq 20P_s = 3.773 \times 10^{-3} \qquad (2.3)$$

Several different cell radii and mobile speeds are proposed in table1 and used to find the effect on PRMA performance in Chapter 4. We can find that handoff probability is increased proportionally to the speed of mobile and inverse of the cell radius. So, the cell radius and mobile speed are key factors in handoff probability.

2.1.3   Handoff Probability using Handoff Times

Also we can approximate handoff probability using handoff times as in [1]. From [1] the probability that a call goes through at least n handoffs is

$$P_{\geq nH} = \int_0^\infty P[t_n \leq t]s(t)dt$$

where $P[t_n \leq t]$ is n-th boundary crossing take place before time t and s(t) is service time density function.

The average number of handoff is

$$\overline{h} = \frac{(3 + 2\sqrt{3})V}{9R\mu} = \frac{0.7182V}{R\mu}$$

where R : micro cell radius

   μ : average call duration

   V : mobile speed

Since the handoff time interval is very short we can roughly approximate the hand off probability with $\overline{h}$.

2.2   Speech Terminal Model and Handoff Weight W_h

2.2.1   Speech Terminal Model

The speech terminal model under handoff can be shown as Figure 2.3. The handed off calls contend again to new BS if it is handed off during talk spurt duration. We can consider the handoff as flow from reservation to contend at steady state model. From Figure 2.3

P_h : probability of handoff in a most recent frame

γ : talk spurt end in a time slot

γ_f : talk spurt end in a most recent frame $[1 - (1 - \gamma)^N]$

N : number of slots in a frame

p : contend permission probability
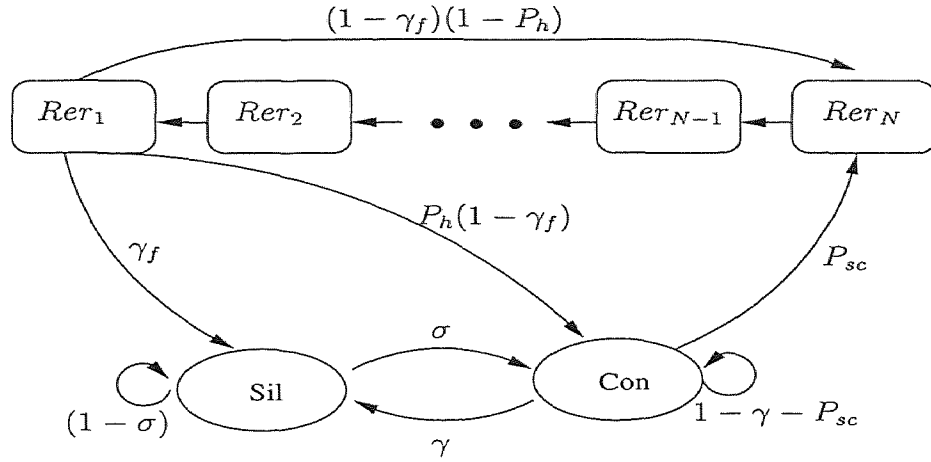
Figure 2.3 Speech terminal model

R : number of mobiles in Reservation

C : number of mobiles in Contending

The successful contending conditions for voice only model are

- permission to contending under handoff: p

- other terminals are not permitted to contend : $(1-p)^{C-1}$

- no talk spurt end during contend : $(1-\gamma)$

- the slot is available : $(1-R/N)$

- no handoff : $(1-P_h)$

So, the successful contend probability is

$$P_{sc} = p(1-p)^{C-1}(1-\gamma)(1-R/N)(1-P_h)$$

The successful contending conditions for combined voice and data model are

- permission to contending under handoff: p

- other terminals are not permitted to contend : $(1-p)^{C-1}$

- no talk spurt end during contend : $(1 - \gamma)$

- the slot is available : $(1 - R/N)$

- other data terminals are not permitted to contend : $(1 - p_d)^b$

- no handoff : $(1 - P_h)$

So, the successful contend probability is

$$P_{sc} = p(1 - p)^{C-1}(1 - \gamma)(1 - R/N)(1 - p_d)^b(1 - P_h)$$

We define mean talk spurt duration under handoff as t'_1 as shown in Figure 2.4. Also, we define H_γ as the probability that t'_1 end in a slot and ζ_e as the probability that t'_1 end in a most recent frame. The values γ and γ_f without handoff have been increased under handoff. We will prove this result in section 2.2.3. In chapter 4, we can find that ζ_e strongly affect the packet dropping probability of PRMA.

2.2.2 Handoff Weight W_h

We define handoff weight W_h as the change of the probability that talk spurt end or handed off in a most recent frame at steady state. To find handoff weight W_h, we focus on change of the probability that talk spurt end or handed off in a most recent frame in steady state speech terminal model. Based on the speech terminal model, we can find that γ_f has been changed to $\gamma_f(1 - P_h) + P_h$. So, handoff weight W_h can be found as follows.

$$\gamma_f W_h = \gamma_f(1 - P_h) + P_h \tag{2.4}$$

$$
\begin{aligned}
W_h &= \frac{\gamma_f(1 - P_h) + P_h}{\gamma_f} \\
&= (1 - P_h) + \frac{P_h}{\gamma_f}
\end{aligned}
\tag{2.5}
$$

$$\zeta_e = 1 - (1 - H_\gamma)^N$$
$$H_\gamma = 1 - e^{\tau/t_1'}$$

CSP/CSP_h

t_1'

CSP_h

$$\gamma_f = 1 - (1 - \gamma)^N$$
$$\gamma = 1 - e^{\tau/t_1}$$

Talk spurt duration(t_1) ——————— Silence(t_2)

Hand off

t_1' t_1''

Talk spurt duration(t_1)   Silence(t_2)

HAND OFF(PRMA)

t_1'' Silence(t_2'') t_1'' Silence(t_2'')

Talk spurt duration(t_1')   Talk spurt duration(t_1')

Shorter mean talkspurt
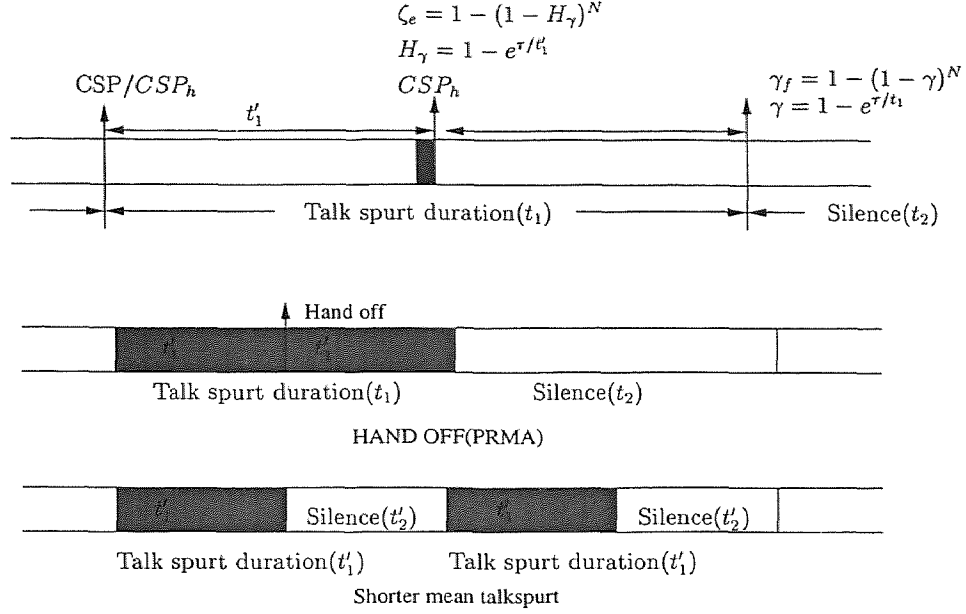
Figure 2.4 mean talk spurt duration under handoff

Also, the minimum value of W_h is

$$
\begin{aligned}
W_h &= (1 - P_h) + \frac{P_h}{\gamma_f} \\
&= P_h(\frac{1}{\gamma_f} - 1) + 1 \geq 1
\end{aligned}
\tag{2.6}
$$

with constraints $0 \leq P_h \leq 1$ and $0 \leq \gamma_f \leq 1$.

The mean talk spurt length L and the number of contending mobile at equilibrium c have been changed proportionally to W_h under handoff. We will prove this in next section.

2.2.3 Mean Talk-spurt Duration t_1' and Mean Talk-spurt Length L' under Handoff

We define t_1' which is mean CSP_h(Contend Start Point) duration in a talk spurt under handoff as mean talk spurt duration under handoff. Also, we define L' which mean CSP_h length under handoff as mean talk spurt length under handoff. The

terminal starts contend if talk spurts are generated. So, t_1' without handoff is same as mean talk spurt duration t_1. However t_1' with handoff is changed proportionally to handoff times n as shown in Figure 2.4. So, t_1' can be shown as

$$t_1' = \frac{kt_1}{n+1}$$

where k is some constant and n is handoff times. Also, t_1' can be expressed as follows if we think $\frac{n+1}{k}$ as handoff weight.

$$
\begin{aligned}
t_1' &= \frac{t_1}{W_h} \\
&= \frac{\gamma_f}{\gamma_f(1 - P_h) + P_h} t_1
\end{aligned}
\tag{2.7}
$$

Mean talk spurt duration under handoff t_1' is a same random variable as t_1 except shorter mean. This t_1' is function of t_1 and handoff weight W_h which is related to mobile speed, cell radius and mobile direction as in [2]. Also t_1 which is measured value of speaking voice without handoff as in [5] is changed under handoff. H_γ can be found as

$$
\begin{aligned}
H_\gamma &= 1 - e^{-\tau/t_1'} \\
&= 1 - e^{-\tau/t_1 W} \simeq \frac{\tau}{t_1} W \\
&= [(1 - P_h) + \frac{P_h}{\gamma_f}]\frac{\tau}{t_1}
\end{aligned}
\tag{2.8}
$$

where 1-$e^{-\alpha t} \simeq \alpha t$ for small αt.

If we use variables from table 4.2 for simplicity

$$H_\gamma \simeq [(1 - P_h) + \frac{P_h}{\gamma_f}]\gamma \tag{2.9}$$

where $\tau \simeq \gamma$.

The probability that talk spurt end or handed off in a most recent frame ζ_e is

$$
\begin{aligned}
\zeta_e &= 1 - (1 - H_\gamma)^{20} \simeq 20 H_\gamma \\
&= 20\Big[(1 - P_h) + \frac{P_h}{\gamma_f}\Big]\gamma \\
&= \Big[(1 - P_h) + \frac{P_h}{\gamma_f}\Big]\gamma_f \\
&= W_h \gamma_f
\end{aligned}
\tag{2.10}
$$

where $1 - (1 - H_\gamma)^{-20} \simeq 20 H_\gamma$ and $\gamma_f \simeq 20\gamma$.

From above we can find that mean talk spurt length L which is $\frac{1}{\gamma_f}$ without handoff is changed as L' which is $\frac{1}{\zeta_e}$ under handoff. We will use $\frac{1}{\zeta}$ as mean talk spurt length under handoff instead of $\frac{1}{\gamma_f}$ to find packet dropping probability under handoff in chapter 4.

2.2.4 Mean Contend under Handoff c_h

Handoff make reserved talk spurt re-contend to new BS. So, contend under handoff c_h is increased proportionally to inverse of t_1' with some constant k. The increased contends can be calculated as

$$
C = k\frac{1}{t_1} = k\frac{1}{W_h t_1'}
\tag{2.11}
$$

where k is constant. By using $c_h = k\frac{1}{t_1'}$

$$
\begin{aligned}
k\frac{1}{W_h t_1'} &= \frac{c_h}{W_h} \\
c_h &= W_h C
\end{aligned}
\tag{2.12}
$$

Therefore, the contend under handoff c_h is increased proportionally to W_h. We can derive Increased Contend based System Equilibrium Function $F(c_h)=M$ using c_h instead of c with $F(c)=M$ which is System Equilibrium Function from without handoff.

CHAPTER 3

SYSTEM STABILITY

We can find System Equilibrium Function from both steady state terminal model with handoff and increased contend c_h. We define $F(c_s)=M$ as State based System Equilibrium Function and can be found from steady state speech terminal model considering handoff as in [5]. Also due to the fact that System Equilibrium Function is a relationship between contend c and mobile M at steady state, we can approximate the stability using both increased contend c_h and $F(c)=M$ which is System Equilibrium Function without handoff. We define $F(c_h)=M$ as Increased Contend based System Equilibrium Function. We will evaluate system stability and performance of combined voice and data system using both $F(c_s)=M$ and $F(c_h)=M$. Figures 3.1, 3.2, 3.3, 3.4 show the system stability which is a result from $F(c_s)=M$ and $F(c_h)=M$. The curves from Figures 3.1, 3.3 show that the multiple EPA point degraded from 60 to 52 mobiles for voice only and 44 to 40 mobiles for combined voice and data using $F(c_s)=M$. Therefore, we can use $F(c_h)=M$ up to 50 and 40 mobiles with analysis parameters from Table 4.2.

3.1   Voice Only

3.1.1   Steady State Based $F(c_s)=M$

We can find $F(c_s)=M$ from speech terminal model as shown in Figure 1.6. To analyze the system state at equilibrium with handoff, we denote c_s,s,r as

c_s : equilibrium number of terminals in state Con

s : equilibrium number of terminals in state Sil

r : equilibrium number of terminals in state Rer

where $r = \sum_{i=0}^{N} r_i$
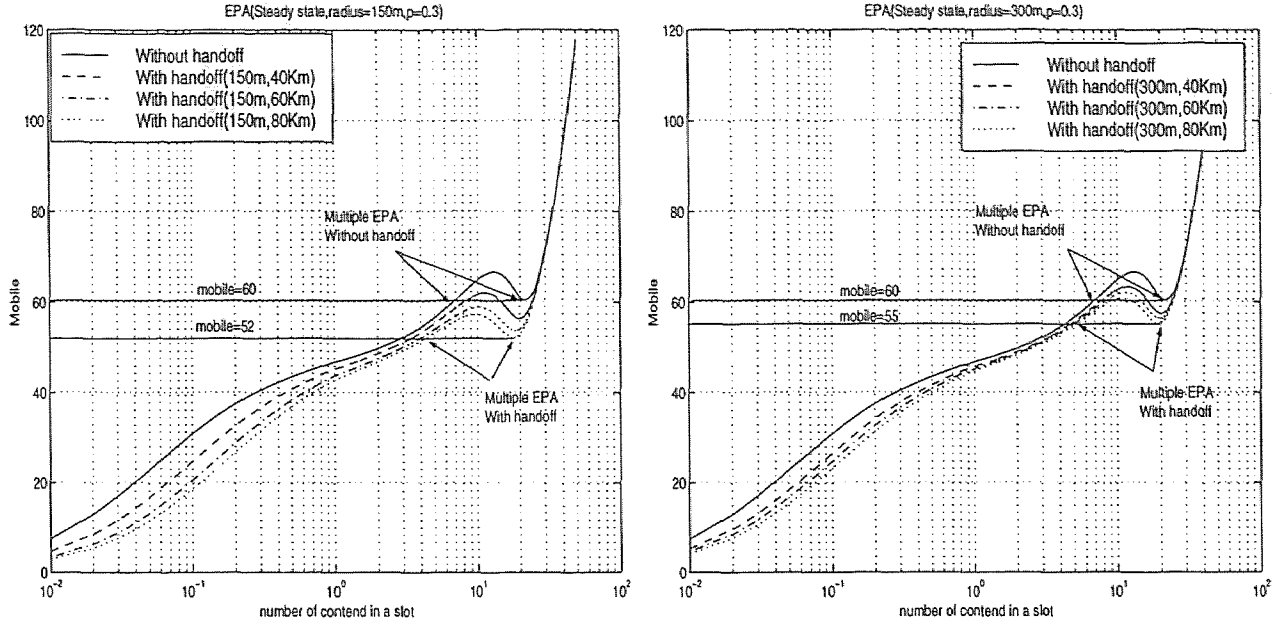
Figure 3.1 Stability($F(c_s)$=M : Voice only)

These values are real not integer. This equilibrium with handoff can be analyzed by solving follow equations as in [5].

$$At\ Rer_N\ :\ r(1 - \gamma_f)(1 - P_h) + c_s P_{sc} = r \tag{3.1}$$

$$At\ Sil\ :\ c_s \gamma + r \gamma_f = s\sigma \tag{3.2}$$

and summation of all terminals are M

$$c_s + s + Nr = M \tag{3.3}$$

The equation of EPA is finally reduced function of between c_s and M

$$c_s(1 + \frac{\gamma}{\sigma}) + r[N + \frac{\gamma_f}{\sigma}] = M \tag{3.4}$$

where

$$r = \frac{c_s p (1-p)^{c_s-1}(1-\gamma)(1-P_h)}{c_s p (1-p)^{c_s-1}(1-\gamma)(1-P_h) + (\gamma_f + P_h - \gamma_f P_h)}$$

This is a System Equilibrium Function from steady state speech terminal model with handoff and we define this equation as $F(c_s)$=M. Figure 3.1 show the stability from $F(c_h)$=M. The multiple EPA point degraded and the number of contend in a slot is increased proportionally to handoff.
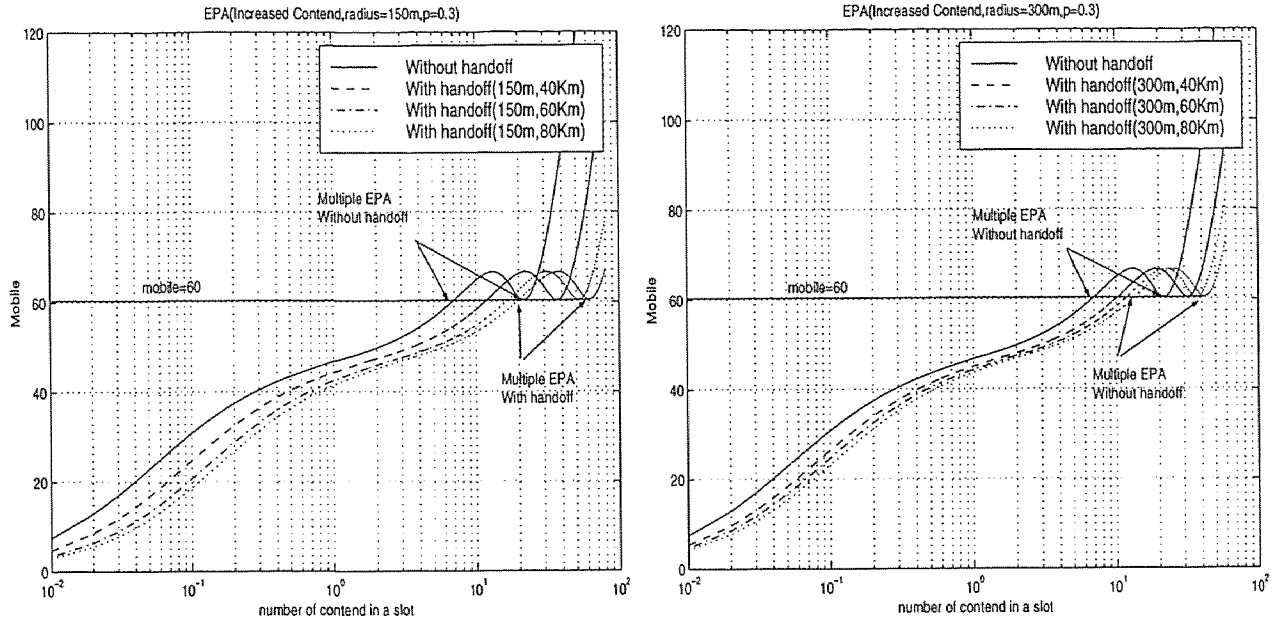
Figure 3.2 Stability($F(c_h) = M$: Voice only)

3.1.2   Increased Contend Based F(c_h)=M

The stability of voice only system also can be derived using increased contend c_h instead of c with F(c)=M as mentioned before. The Increased Contend based System Equilibrium Function F(c_h)=M is

$$c_h(1 + \frac{\gamma}{\sigma}) + r[N + \frac{\gamma_f}{\sigma}] = M \tag{3.5}$$

where

$$r = \frac{c_h p (1-p)^{c_h-1}(1-\gamma)}{c_h p (1-p)^{c_h-1}(1-\gamma) + \gamma_f}$$

Figure 3.2 show the stability from $F(c_h)$=M. The multiple EPA point doesn't change but the number of contend in a slot is increased proportionally to handoff.

3.2 Combined Voice and Data

System Equilibrium Functions both $F(c_s)$=M and $F(c_h)$=M are derived like Voice only case. Figures 3.3 and 3.4 show stability of combined voice and data system for different handoff probability.
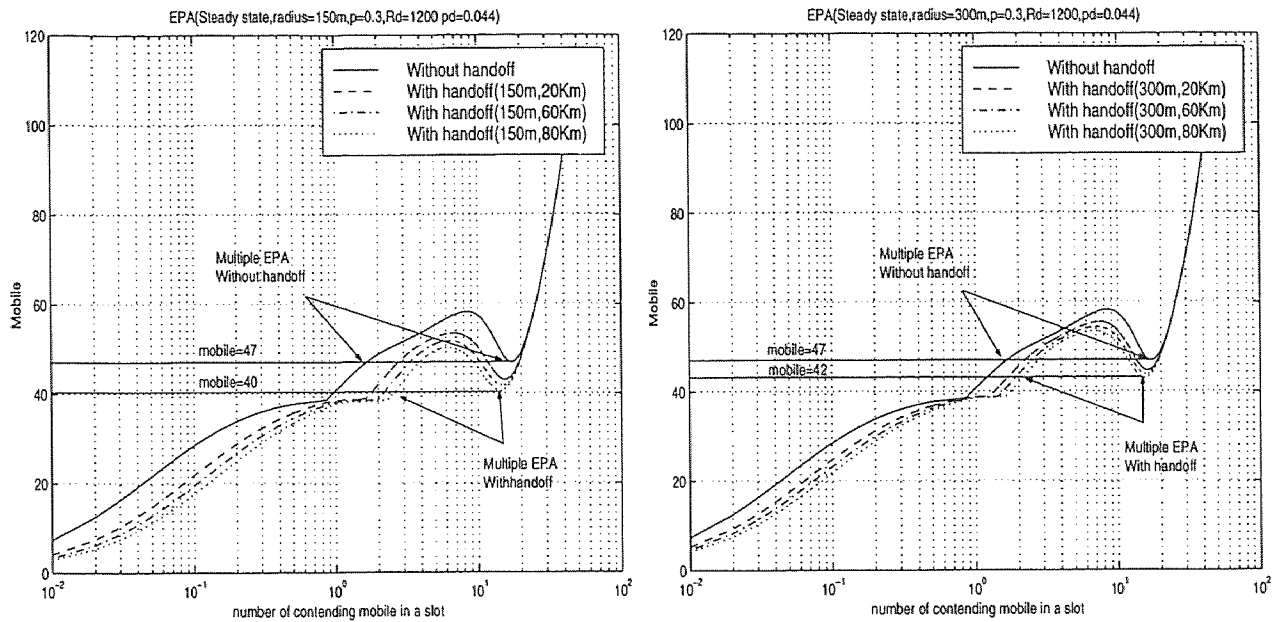
Figure 3.3 Stability($F(c_s)$=M : Voice+data)

3.2.1 Steady State Based $F(c_s)$=M

To find $F(c_s)$=M, same procedures as in [5] can be applied.

$$At\ Rer_N\ :\ r(1 - r_f)(1 - P_h) + c_s P_{sc-d} = r \tag{3.6}$$

$$At\ Sil\ :\ c_s\gamma + r\gamma_f = s\sigma \tag{3.7}$$

and summation of all terminals are M

$$c_s + s + Nr = M \tag{3.8}$$

The equation of EPA is finally reduced function of between c_s and M

$$c_s(1 + \frac{\gamma}{\sigma}) + r[N + \frac{\gamma_f}{\sigma}] = M \tag{3.9}$$

$$h_1 c + h_2 r = M \tag{3.10}$$

where

$$r = \frac{c_s p(1-p)^{c_s-1}(1-\gamma)(1-p_d)^{b_s}(1-P_h)}{c_s p(1-p)^{c_s-1}(1-\gamma)(1-p_d)^{b_s}(1-P_h) + (\gamma_f + P_h - \gamma_f P_h)}$$

This is a System Equilibrium Function $F(c_s)$=M and nonlinear function of b_s, c_s and M. The backlog b_s can be found as in appendix A.

$$b_s = min\left[\frac{c_s p(1-p_d)}{p_d(1-p)}\sigma_d M_d \frac{1-\gamma}{\gamma_f + P_h - \gamma_f P_h}(\frac{h_2}{M - h_1 c_s}), \ M_d\right] \tag{3.11}$$

3.2.2 Increased Contend Based $F(c_h)$=M

We can find $F(c_h)$=M using both F(c)=M and increased contend c_h instead of c. The $F(c_h)$=M is

$$c_h(1 + \frac{\gamma}{\sigma}) + r[N + \frac{\gamma_f}{\sigma}] = M \tag{3.12}$$
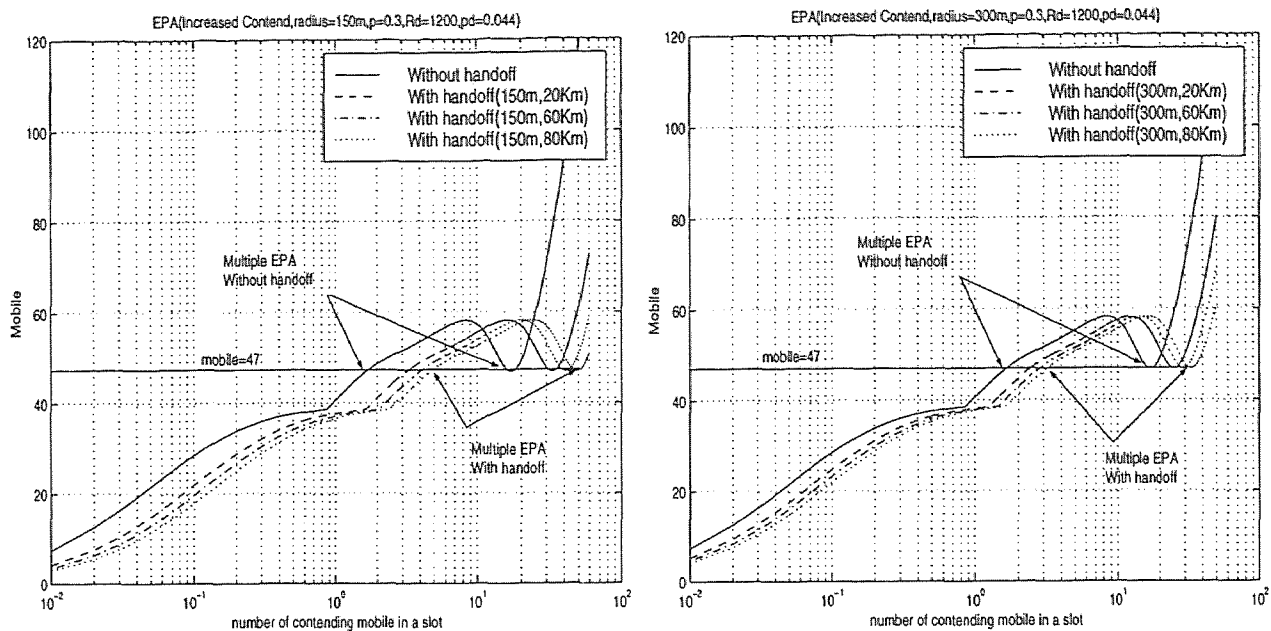
Figure 3.4 Stability(F(c_h) : Voice+data)

$$h_1 c_h + h_2 r = M \tag{3.13}$$

where

$$r = \frac{c_h p (1-p)^{c_h - 1} (1 - P_d)^{b_h} (1 - \gamma)}{c_h p (1-p)^{c_h - 1} (1 - P_d)^{b_h} (1 - \gamma) + \gamma_f}$$

and backlog b_h at equilibrium is

$$b_h = min \left[\frac{c_h p (1 - p_d)}{p_d (1-p)} \sigma_d M_d \frac{1 - \gamma}{r_f} (\frac{h_2}{M - h_1 c_h}), \ M_d \right] \tag{3.14}$$

Figures 3.4 show stability of combined voice and data system for different mobile speed under handoff using F(c_h)=M. The multiple EPA point doesn't change but the number of contend in a slot is increased proportionally to handoff.

CHAPTER 4

PERFORMANCE ANALYSIS

4.1   Steady State Probability

4.1.1   Embedded Markov Chain
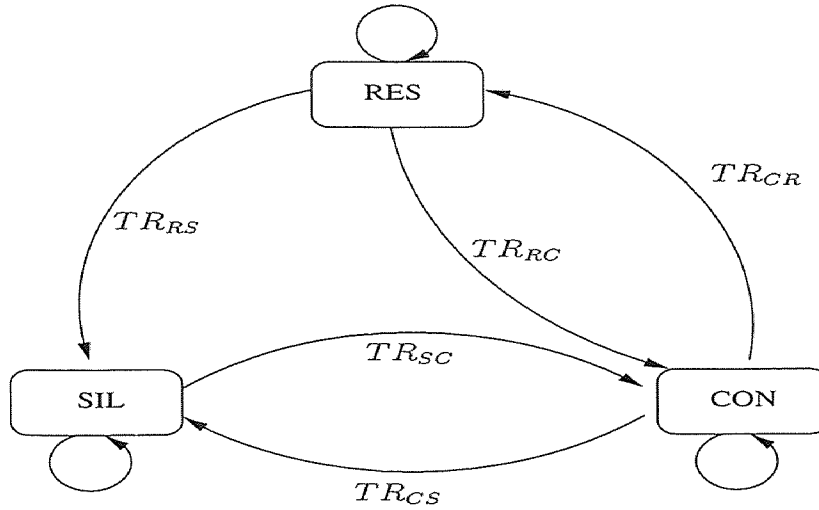
Figure 4.1 Simplified speech terminal model

To analyze the system, MA process can be used as in [11][12]. If N is the number

of slots in a frame then the system can be modeled as an N+2 dimensional Markov

process as in [5],[11].

$$(Sil, Con, Rer_0, Rer_1, \cdots, Rer_N)$$

Since there are two states in each reservation(Rer) the number of possible states are

$2^N M^2$. The precise analysis of this N+2 dimensional MA is prohibitively complex

and difficult to solve ordinary MA. We then simplify this model considering all of

R_i as one Rer state as in figure 4.1. There are 4 state transition random variables

in system with constraint "S+C+R=M" where S is silence, C is contend and R

is reservation. If we set the mobile M as time invariant and select C,R as system

variables then the system state ψ can be defined as function of C and R. The total

possible states are (M-N/2+1)(N+1). We can think this system as embedded Markov Chain with the state t+1 only depend on t as in figure 4.2. This system can be
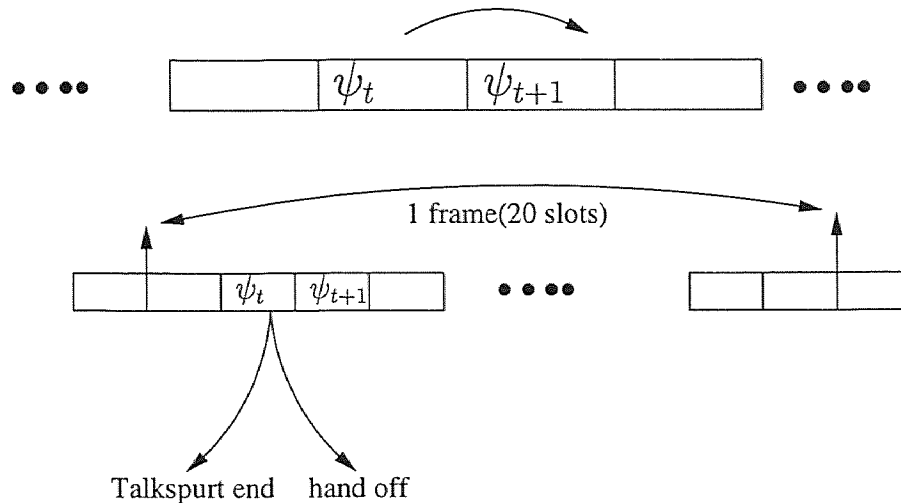
Figure 4.2 Markov Analysis

characterized by using these equations.

$$Pr(\psi_j) = \sum_{i=1}^{\infty} Pr(\psi_j \mid \psi_i)Pr(\psi_i) \tag{4.1}$$

$$\sum_{j=1} Pr(\psi_j) = 1 \tag{4.2}$$

where $i = C_t, R_t, \quad j = C_{t+1}, R_{t+1}$

C_t : number of mobile in Contend at time t

R_t : number of mobile in Reservation at time t

C_{t+1} : number of mobile in Contend at time t+1

R_{t+1} : number of mobile in Reservation at time t+1

4.1.2 Transition Matrix and Steady State Probability

To find transition matrix $Pr(\psi_j \mid \psi_i)$ of system state changes, first think about transition from t to t+1. The state t+1 depends on state t with the 5 changes of 5 TR random variables.

Table 4.1 Probability of event

event	Probability	symbol
No TR_{SC}	$(1-\sigma)^S$	b_0
One TR_{SC}	$1-(1-\sigma)^S \simeq S\sigma$	b_1
No TR_{CS}	$(1-\gamma)^c \simeq 1 - C\gamma$	
One TR_{CS}	$C\gamma$	
One TR_{CR}	$Cpu(1-\frac{R}{N})$	
One TR_{RS}	$\gamma_f \frac{R}{N}$	
One TR_{RC}	$\frac{R}{N}P_h(1-\gamma_f)$	
No $TRCR, RS, RC$	$\frac{R}{N}[(1-\gamma_f)(1-P_h)]+(1\text{-}Cpu)(1-\frac{R}{N})$	
One $TR_{CR,CS}$	$C(C-1)pu(1-\frac{R}{N})\gamma$	
One $TR_{CR}, NoTR_{CS}$	$Cpu(1-\frac{R}{N})(1-(C-1)\gamma)$	

$$C^{t+1} = C^t + TR$$

$$R^{t+1} = R^t + TR \tag{4.3}$$

We can find state transition matrix with combination of these 5 TR random variables as in [3]. The probability of events are shown in table 4.1 with S=M-C-R, $u = (1-p)^{C-1}(1-P_d)^b(1-\gamma)(1-P_h)$. We can assume each of these TR random variables as Poisson with rate α because talk-spurts are generated exponentially with mean t_1'. Also these events can be considered counting process of TR random variables during one slot time with $P[TR] = \alpha\tau$.

$$
\begin{aligned}
TR_{ij} &= Pr("j-i" \; TR \; events \; during \; one \; slot) \\
&= \frac{(\alpha\tau)^{j-i}}{(j-i)!}e^{-\alpha\tau}
\end{aligned}
\tag{4.4}
$$

Table 4.2 Transition probability $Pr(\psi_j \mid \psi_i)$

State t+1	TR Probability
$C_t - 2, R_t + 1$	$b_0 C(C-1)pu(1-\frac{R}{N})\gamma$
$C_t - 1, R_t - 1$	$b_0\frac{R}{N}\gamma_f C\gamma$
$C_t - 1, R_t$	$b_0[(1-\gamma_f)\frac{R}{N}(1-P_h) + (1-Cpu)(1-\frac{R}{N})]C\gamma$
$C_t - 1, R_t + 1$	$b_0 Cpu(1-\frac{R}{N})(1-(C-1)\gamma) + Cb_1(C-1)pu(1-\frac{R}{N})\gamma$
$C_t, R_t - 1$	$b_0\frac{R}{N}\gamma_f(1-C\gamma) + b_1\frac{R}{N}\gamma_f C\gamma + b_0\frac{R}{N}(1-\gamma_f)P_h C\gamma$
C_t, R_t	$[(1-\gamma_f)(1-P_h)\frac{R}{N} + (1-Cpu)(1-\frac{R}{N})][b_0(1-C\gamma) + b_1 C\gamma]$
$C_t, R_t + 1$	$b_1 Cpu(1-\frac{R}{N})(1-(C-1)\gamma)$
$C_t + 1, R_t - 1$	$b_1\frac{R}{N}\gamma_f(1-C\gamma) + \frac{R}{N}(1-\gamma_f)P_h[b_1(C\gamma) + b_0(1-C\gamma)]$
$C_t + 2, R_t + 1$	$[(1-\gamma_f)\frac{R}{N}(1-P_h) + (1-Cpu)(1-\frac{R}{N})]b_1(1-C\gamma)$
$C_t + 2, R_t - 1$	$b_1\frac{R}{N}(1-C\gamma)P_h(1-\gamma_f)$

Then the above matrix show that the TR random variable probabilities which are changes of mobile states from one of states to the other state. The probability that TRs can be happened more than two mobiles is almost zero [6].

$$
\mathbf{P(t)} = \begin{pmatrix}
e^{-\alpha\tau} & (\alpha\tau)e^{-\alpha\tau} & (\alpha\tau)^2 e^{-\frac{\alpha\tau}{2!}} & \cdots & \cdots \\
0 & e^{-\alpha\tau} & (\alpha\tau)e^{-\alpha\tau} & (\alpha\tau)^2 e^{-\frac{\alpha\tau}{2!}} & \cdots \\
\vdots & \vdots & \vdots & \vdots & \ddots \\
0 & 0 & 0 & 0 & e^{-\alpha\tau}
\end{pmatrix}
$$

$$
= \begin{pmatrix}
1-\alpha\tau & \alpha\tau & 0 & \cdots & \cdots \\
0 & 1-\alpha\tau & \alpha\tau & 0 & \cdots \\
\vdots & \vdots & \vdots & \vdots & \ddots \\
0 & 0 & 0 & 0 & 1-\alpha\tau
\end{pmatrix}
$$

We can find state transition matrix with combination of these 5 TR random variables as in [3]. The possible transition cases are shown in Table 4.3. So the transition probability matrix can be found from 4.2 using Table 4.3. Finally, we can get steady state probability $\psi_{C,R}$ with transition matrix and formula 4.1,4.2. These equations can be solved by "LU" factorization in matlab.

Table 4.3 Changes of State with TR variables

TR_{SC}	TR_{CR}	TR_{CS}	TR_{RS}	TR_{RC}	Occurrence	State t+1
1	0	0	0	0	◯	$C^t + 1, R^t$
1	0	0	0	1	◯	$C^t + 2, R^t - 1$
1	0	0	1	0	◯	$C^t + 1, R^t - 1$
1	0	0	1	1	×	
1	0	1	0	0	◯	C^t, R^t
1	0	1	0	1	◯	$C^t + 1, R^t - 1$
1	0	1	1	0	◯	$C^t, R^t - 1$
1	0	1	1	1	×	
1	1	0	0	0	◯	$C^t, R^t + 1$
1	1	0	0	1	×	
1	1	0	1	0	×	
1	1	0	1	1	×	
1	1	1	0	0	◯	$C^t - 1, R^t + 1$
1	1	1	0	1	×	
1	1	1	1	0	×	
1	1	1	1	1	×	
0	0	0	0	0	◯	C^t, R^t
0	0	0	0	1	◯	$C^t + 1, R^t - 1$
0	0	0	1	0	◯	$C^t, R^t - 1$
0	0	0	1	1	×	
0	0	1	0	0	◯	$C^t - 1, R^t$
0	0	1	0	1	◯	$C^t, R^t - 1$
0	0	1	1	0	◯	$C^t - 1, R^t - 1$
0	0	1	1	1	×	
0	1	0	0	0	◯	$C^t - 1, R^t + 1$
0	1	0	0	1	×	
0	1	0	1	0	×	
0	1	0	1	1	×	
0	1	1	0	0	◯	$C^t - 2, R^t + 1$
0	1	1	0	1	×	
0	1	1	1	0	×	
0	1	1	1	1	×	

4.2 Performance Analysis

We use parameters as follows in our analysis

Table 4.4 Analysis parameters

Channel rate	720 Kbps
Source rate (R_s)	32 Kbps
Packet size	576 bits
Packet header(H)	64 bits
Data rate (R_d)	1200 bps
Delay limit (D)	32 msec(40 slots)
Buffer size (B)	2 packets
Handoff probability (P_h)	Table 1
Probability of permission to contend (Voice : p)	0.3
Probability of permission to contend (Data : p_d)	0.044
Mean talk spurt duration (t_1)	1 sec
Mean silence duration (t_2)	1.35 sec
Number of slot in a frame (N)	20 slots
Frame duration (T)	16 msec
Slot duration (τ)	0.8 msec

4.2.1 Voice Only

4.2.1.1 Packet Dropping Probability

The probability of packet dropping can be calculated as in [5] with mean reservation length under hand-off L'. The mean reservation length L' which is mean number of packets in a talk spurt under handoff is.

$$L' = \frac{1}{\zeta_e} = \frac{1}{\gamma_f(1 - P_h) + P_h}$$

The probability of mean packet dropping is

$$P_{drop}(C, R) = \frac{v^D}{1 - v^N}\zeta_e(1 - \zeta_e)^{B-1}\left[1 - \frac{\zeta_e[1 - v^{2N}(1 - \zeta_e)]}{[1 - (1 - \zeta_e)v^N]^2}\right]$$
$$+ \frac{\zeta_e^2 v^N}{[1 - (1 - \zeta_e)v^N]^2} + \frac{\zeta_e^2(1 - \zeta_e)^{B-1}(v^D - v^{NB})}{[1 - (1 - \zeta_e)v^N]^2} \tag{4.5}$$
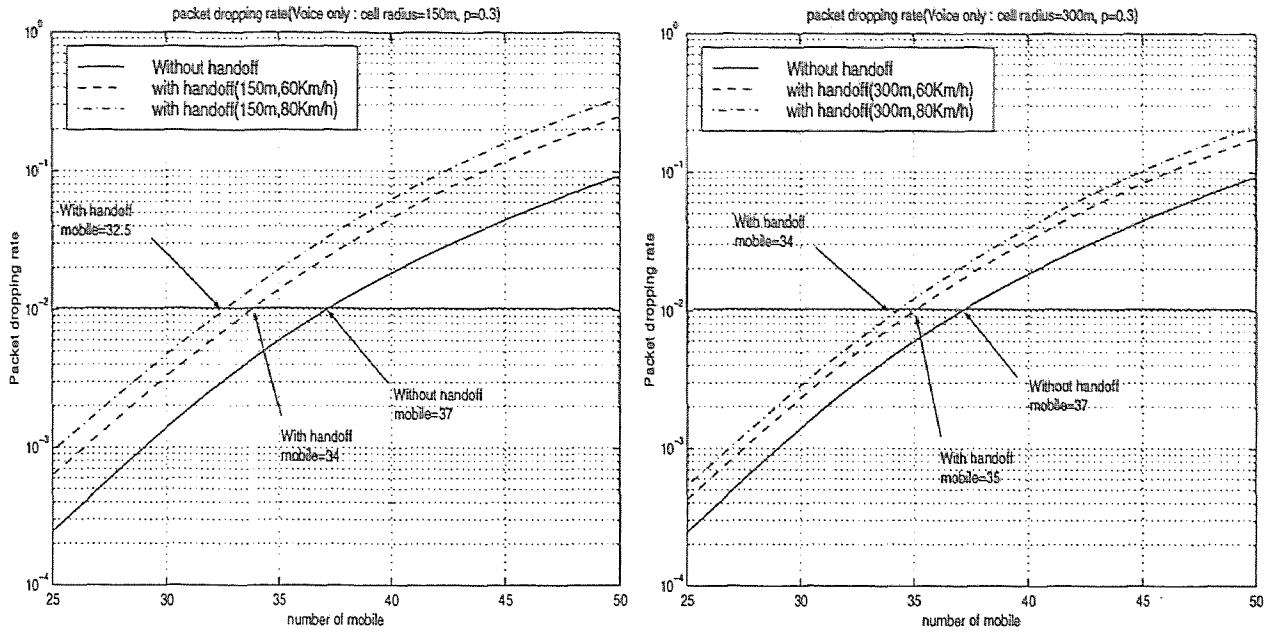
Figure 4.3 P_{drop}(Voice only)

with unsuccessful contention probability $v = 1 - P_{sc}$

$$P_{drop} = \sum_{R=0}^{N} \sum_{C=0}^{M-R} Pr(C,R)\psi(C,R) \tag{4.6}$$

Figure 4.3 shows packet dropping probability of voice only case with cell radius 150, 300m. The capacity with 1 % is decreased from 37 users to 34, 32.5 users and 35, 34 proportionally to mobile speed.

4.2.1.2 Throughput

The throughput is summation of both probability of continuing reservation and successful contention. The mean throughput is

$$\eta(C,R) = R/N(1 - \gamma_f)(1 - P_h) + CP_{sc} \tag{4.7}$$
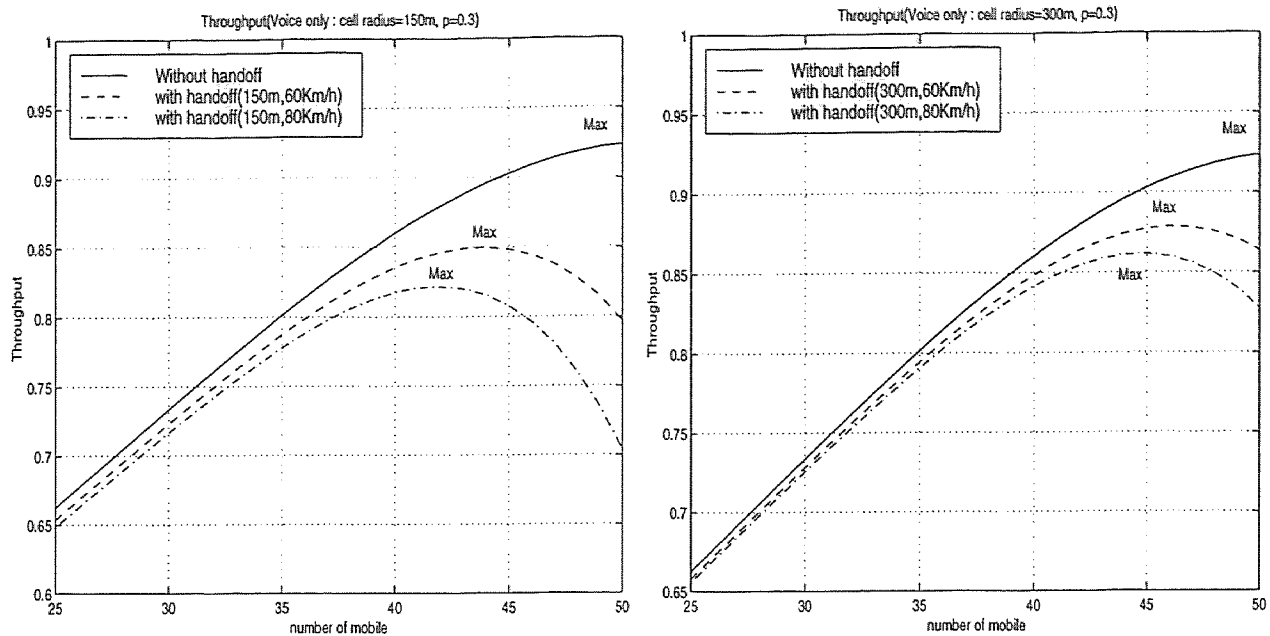
Figure 4.4 Throughput(Voice only)

The average throughput is

$$\eta = \sum_{R=0}^{N} \sum_{C=0}^{M-R} \eta(C,R)\psi(C,R) \tag{4.8}$$

4.2.2 Combined Voice and Data

4.2.2.1 Packet Dropping Probability

We can find performance of combined voice and data with mean talk spurt length under handoff $\frac{1}{\varsigma}$ and backlog b which are from both $F(c_s)$=M and $F(c_h)$=M. Figures 4.5, 4.6 show packet dropping probability of both cases. The capacity with 1 % packet dropping probability is decreased from 34 users to 30.5, 29.5 users and 31.6, 31.4 proportionally to mobile speed and inverse of cell radius. Figures 4.9,4.10 show data packet delay. The data packet delay become unbounded from 36 to 35 with proportional to mobile speed and inverse of cell radius.
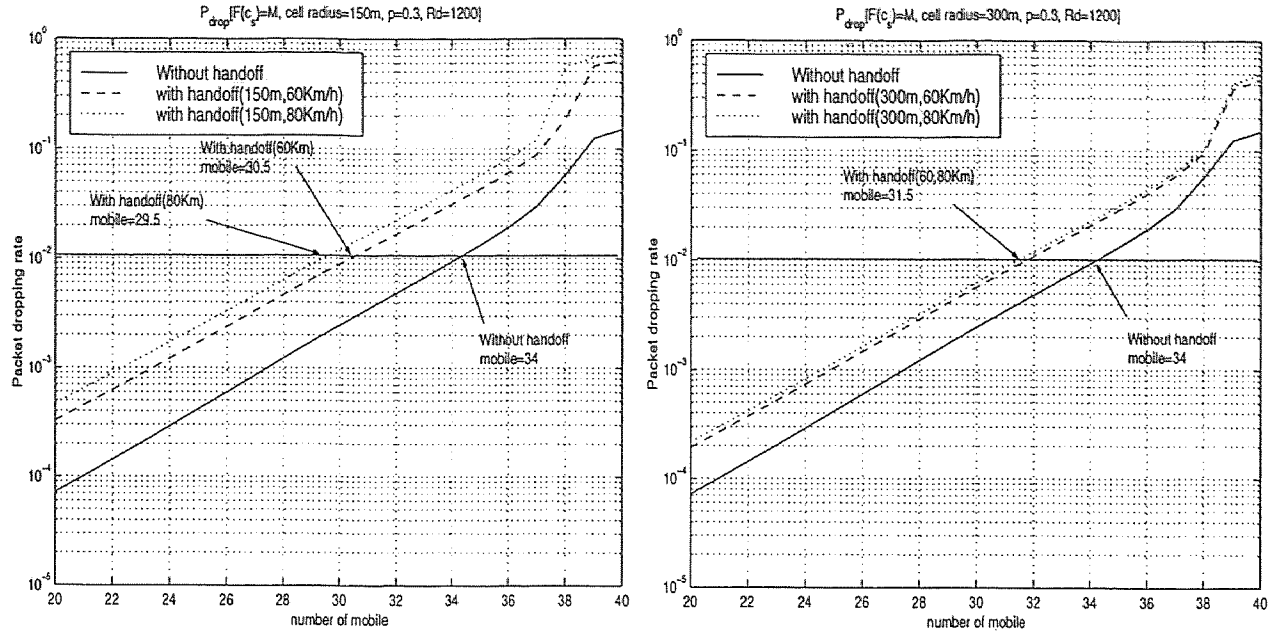
Figure 4.5 $P_{drop}(\mathrm{F}(c_s){=}\mathrm{M} : \text{Voice+data})$

F(c_s)=M: Using MA and backlog b_s from F(c_s)=M, we can calculate packet dropping probability. The mean packet dropping probability with ζ_e is

$$P_{drop}(C, R, b_s) = \frac{v^D}{1 - v^N}\zeta_e(1 - \zeta_e)^{B-1}\left[1 - \frac{\zeta_e[1 - v^{2N}(1 - \zeta_e)]}{[1 - (1 - \zeta_e)v^N]^2}\right]$$
$$+ \frac{\zeta_e^2 v^N}{[1 - (1 - \zeta_e)v^N]^2} + \frac{\zeta_e^2(1 - \zeta_e)^{B-1}(v^D - v^{NB})}{[1 - (1 - \zeta_e)v^N]^2} \qquad (4.9)$$

with $v = 1 - P_{sc-d}$

$$\zeta_e = \gamma_f(1 - P_h) + P_h$$

The average packet dropping rate is

$$P_{drop} = \sum_{R=0}^{N}\sum_{C=0}^{M-R} Pr(C, R, b_s)\psi(C, R, b_s) \qquad (4.10)$$

Figure 4.5 shows packet dropping probability of voice+data with F(c_s)=M.

Figure 4.6 $P_{drop}(F(c_h) = M$: Voice+data)

F(c_h)=M: Also, we can calculate packet dropping probability using both MA and backlog b_h from F(c_h)=M. The mean packet dropping rate with ζ_e is

$$P_{drop}(C, R, b_h) = \frac{v^D}{1 - v^N}\zeta_e(1 - \zeta_e)^{B-1}\left[1 - \frac{\zeta_e[1 - v^{2N}(1 - \zeta_e)]}{[1 - (1 - \zeta_e)v^N]^2}\right]$$
$$+ \frac{\zeta_e^2 v^N}{[1 - (1 - \zeta_e)v^N]^2} + \frac{\zeta_e^2(1 - \zeta_e)^{B-1}(v^D - v^{NB})}{[1 - (1 - \zeta_e)v^N]^2} \qquad (4.11)$$

with $v = 1 - P_{sc-d}$

$$\zeta_e = \gamma_f(1 - P_h) + P_h$$

The average packet dropping probability is

$$P_{drop} = \sum_{R=0}^{N}\sum_{C=0}^{M-R} Pr(C, R, b_h)\psi(C, R, b_h) \qquad (4.12)$$

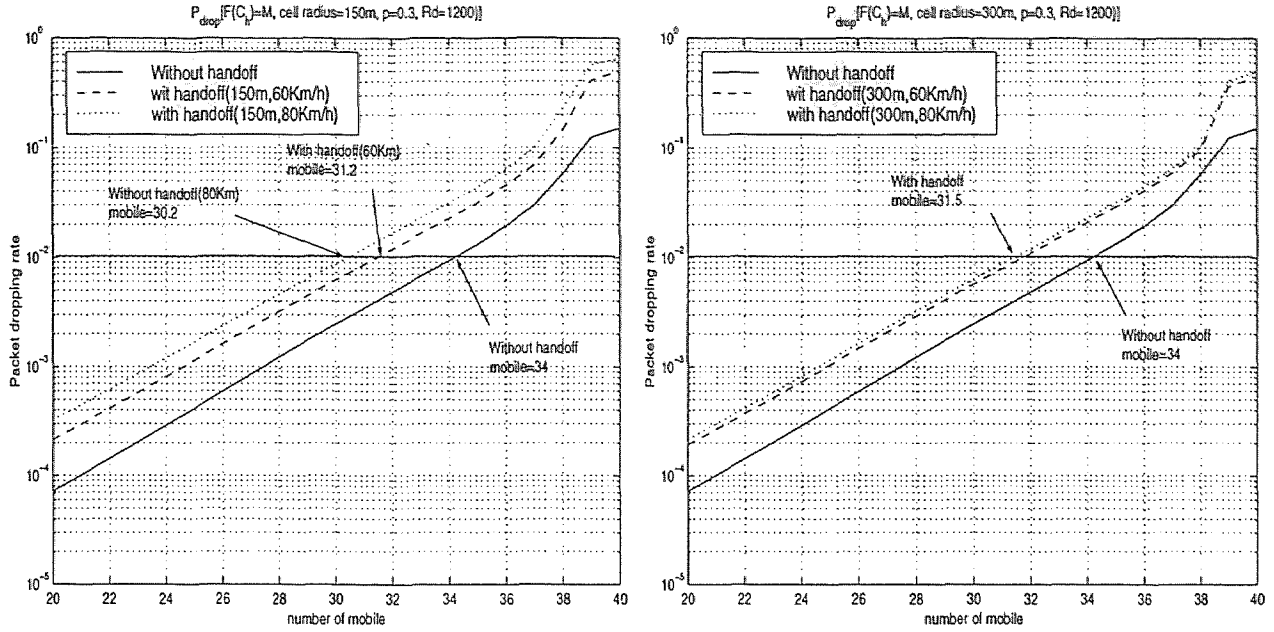Figure 4.6 shows packet dropping probability of voice+data F(c_h)=M.
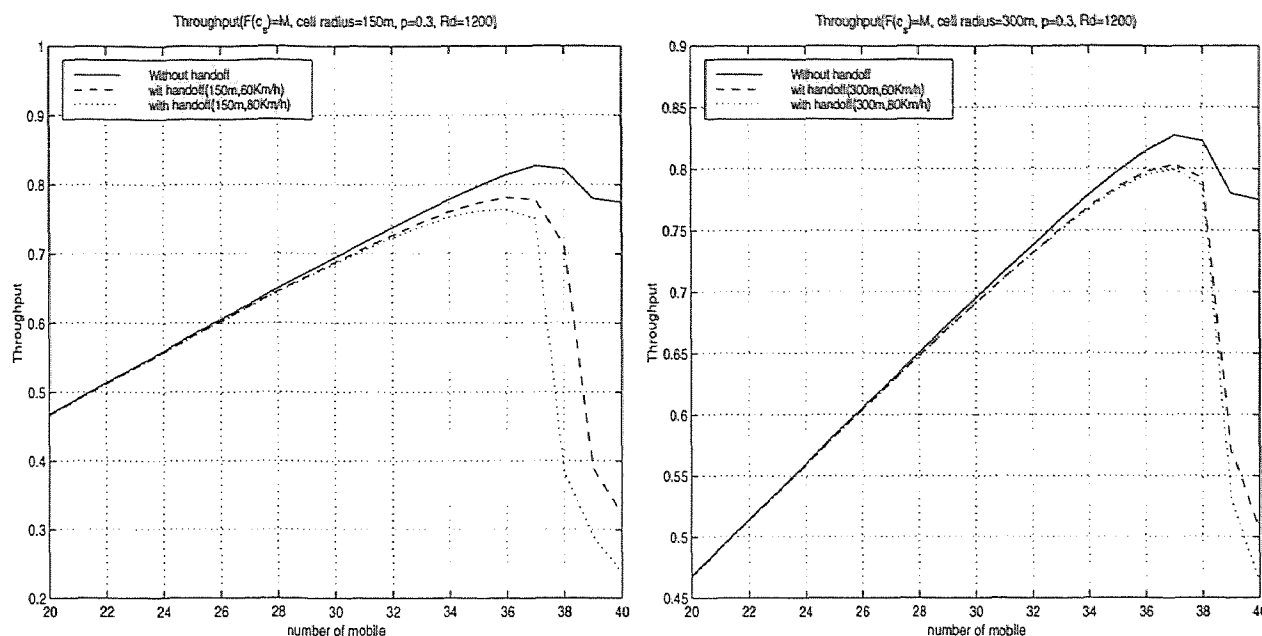
Figure 4.7 Throughput($F(c_s)$=M : Voice+data)

4.2.2.2 Throughput

F(c_s)=M: The throughput is summation of the probability that both continuing reservation and successful contention of voice and data. The mean throughput using b_s from F(c_s)=M is

$$\eta(C, R, b_s) = R/N(1 - \gamma_f)(1 - P_h) + [CP_{sc-d} + b_s P_{sc-dd}] \tag{4.13}$$

with $P_{sc-dd} = p_d(1 - p)^C(1 - p_d)^{b_s-1}(1 - R/N)$.

The average throughput is

$$\eta = \sum_{R=0}^{N} \sum_{C=0}^{M-R} \eta(C, R, b_s)\psi(C, R, b_s) \tag{4.14}$$

Figure 4.7 shows throughput using F(c_s)=M.

F(c_h)=M: If we use b_h from F(c_h)=M then throughput can be found as follows
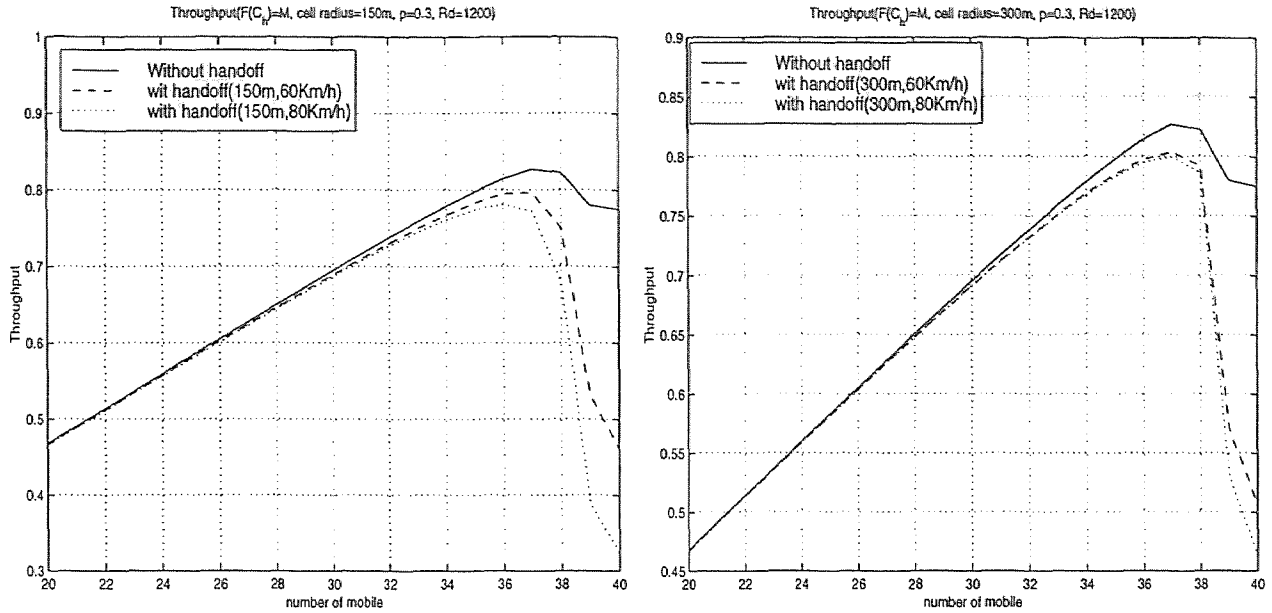
Figure 4.8 Throughput(F(c_h)=M : Voice+data)

$$\eta(C,R,b_h) = R/N(1-\gamma_f)(1-P_h) + [CP_{sc-d} + b_h P_{sc-dd}] \tag{4.15}$$

with $P_{sc-dd} = p_d(1-p)^C(1-p_d)^{b_h-1}(1-R/N)$ and b_h which is backlog from F(c_h)=M. The average throughput is

$$\eta = \sum_{R=0}^{N} \sum_{C=0}^{M-R} \eta(C,R,b_h)\psi(C,R,b_h) \tag{4.16}$$

Figure 4.8 shows throughput from of F(c_h)=M.

4.2.2.3 Data Packet Delay

F(c_s)=M: Delay can be found as in [3] using F(c_s)=M. The probability of successful data packet transmission at state (C,R,b_s) is

$$w = w(C,R,b_s) = p_d u_d(1-R/N)$$

The waiting time for data packet is

$$T = \sum_{j=0}^{\infty} \frac{j+1}{w} Pr_j \tag{4.17}$$
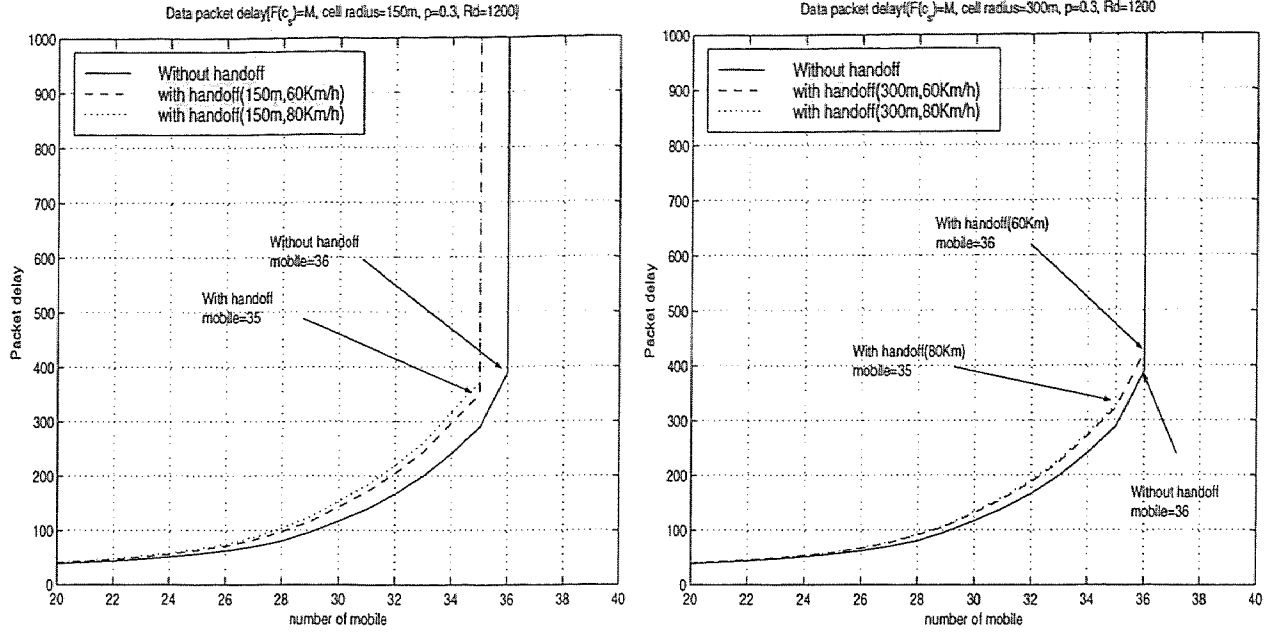
Figure 4.9 Delay(F(c_s)=M : Voice+data)

From global balance equation

$$\begin{cases} Pr_0 = w(1 - \sigma_d)Pr_1 \\ Pr_0\sigma_d + w(1 - \sigma_d)Pr_2 = [\sigma_d(1 - w) + w(1 - \sigma_d)]Pr_1 \\ \sigma_d(1 - w)Pr_{j-1} + w(1 - \sigma_d)Pr_{j+1} = [\sigma_d(1 - w) + w(1 - \sigma_d)]Pr_j, \quad j = 2,3,\bullet\bullet\bullet \infty \\ \sum_{j=0}^{\infty} Pr_j = 1 \end{cases}$$

Pr_j, the probability at state 'j' is

$$Pr_j = \left[\frac{\sigma_d(1 - w)}{w(1 - \sigma_d)}\right]^{j-1} Pr_1 \quad j = 2,3,\cdots \infty \tag{4.18}$$

The mean average waiting time is

$$T(C, R, b_s) = \frac{w - \sigma_d^2}{w(w - \sigma_d)} \tag{4.19}$$

The average waiting time is

$$T_{avg} = \sum_{R=0}^{N} \sum_{C=0}^{M-R} T(C, R, b_s)\psi(C, R, b_s) \tag{4.20}$$

Figure 4.9 shows data packet delay using F(c_s)=M. The delay unbounded point changes from 36 to 35 mobiles in case of cell radius 150m, mobile speed 60,80Km/h and cell radius 300m, mobile speed 80Km/h.
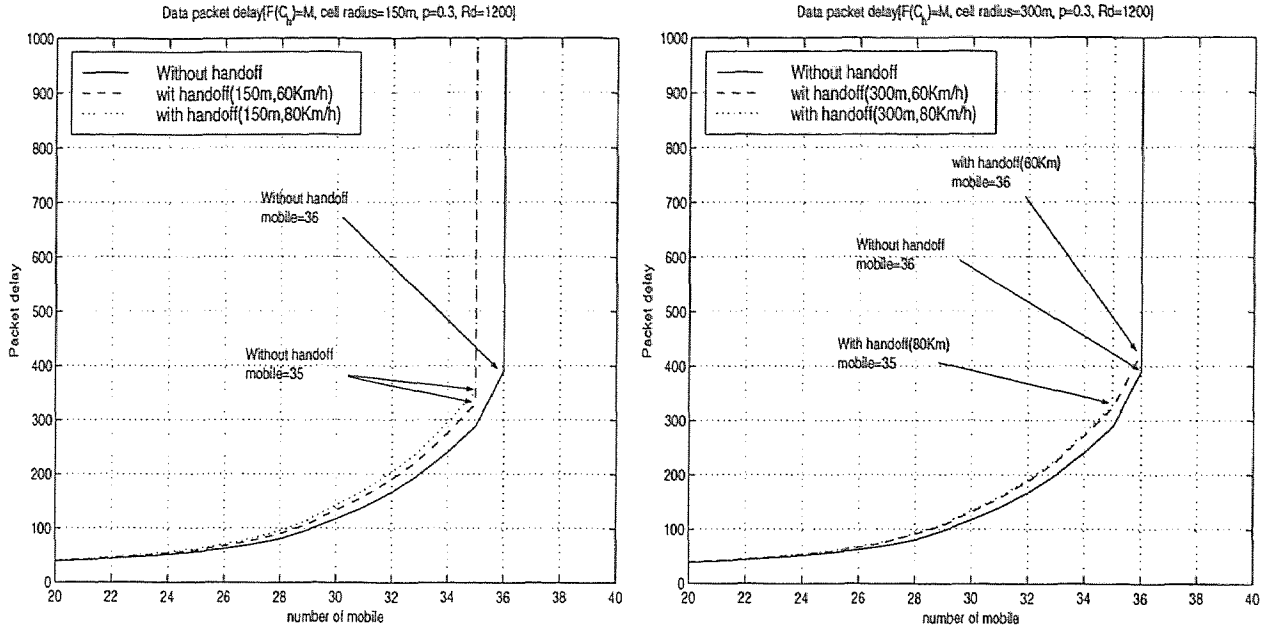
Figure 4.10 Delay(F(c_h)=M : Voice+data)

F(c_h)=M: Delay also can be found using b_h which is from F(c_h)=M. The probability of successful data packet transmission at state (C,R,b_h) is

$$w = w(C, R, b_h) = p_d u_d (1 - R/N)$$

The mean average waiting time is

$$T(C, R, b_h) = \frac{w - \sigma_d^2}{w(w - \sigma_d)} \tag{4.21}$$

The average waiting time is

$$T_{avg} = \sum_{R=0}^{N} \sum_{C=0}^{M-R} T(C, R, b_h)\psi(C, R, b_h) \tag{4.22}$$

Table 4.5 Capacity

System type	Cell Radius(m)	Speed (Km/h)	M_{max}	ν (%)	delay limit (mobile)	C_{max}
Voice only	150	0	37	78.7		47
		60	34	72.3		
		80	32.5	69.1		
	300	0	37	78.7		
		60	35	74.5		
		80	34	72.9		
Combined voice and data	150	0	34	72.34	36	
		60	30.5	64.9	35	
		80	29.5	62.8		
	300	0	34	72.34	36	
		60	31.6	67.6		
		80	31.4	66.8	35	

Figure 4.10 shows data packet delay using F(c_h)=M. The delay unbounded point changes from 36 to 35 mobiles in case of both cell radius 150m(mobile speed 60,80Km/h) and cell radius 300m(mobile speed 80Km/h).

4.2.3 Capacity

The capacity of the system is the % of mobile that can be supported with 1% packet dropping rate. The maximum capacity ν can be obtained by dividing the portion of voice to the whole of the speech duration.

$$C_{max} = \frac{t_1 + t_2}{t_1} \times 20 \qquad (4.23)$$

$$\nu = \frac{M_{max}}{C_{max}} \qquad (4.24)$$

ν : Capacity, C_{max} : Maximum number of mobile that can be supported

M_{max} : The maximum number of mobile with 1% packet dropping rate

Table 4.5 show the capacity of PRMA with respect to micro-cell radius and mobile speed. The maximum capacities are decreased as much as 9.5 %(150m, 80Km), 5.8 % (300m, 80Km) in voice only and 9.54 %(150m, 80Km), 5.54 %(300m, 80Km) in combined voice and data than without handoff.

4.3 Conclusions

This paper has proposed handoff effect on PRMA performance using mean talk spurt duration and Markov Analysis. We find that the mean talk spurt duration under handoff t_1' is same distribution random variable as t_1 with shorter mean duration as in chapter 2. This new mean talk spurt duration affects the overall performance of PRMA. In Figure 3.1 and 3.3, the system stability of Voice only and combined Voice and data decreased due to increased contend under handoff. Also these increased contend affect the performance of PRMA. We compare the capacity with 1 % packet dropping rate which is normally audible level in voice system. The capacity decreased from 37 users to 32.5(150m,80Km/h), 34(300m,80Km/h) users in Voice only case and decreased from 34 users to 29.5(150m,80Km/h), 31.4(300m,80Km/h) users in combined Voice and data system model as in Figure 4.5,4.6.

PRMA has advantage that it can spread the load of BS in future cellular system. We know that handoff effect in PRMA should not be underestimated if we want to design more realistic PRMA system. We can improve the performance of PRMA using several handoff schemes. These handoff schemes can be priority, waiting(queuing), handoff signaling, reverse link and others while optimizing the performance and load of BS.

APPENDIX A

BACKLOG DATA

To find backlog b_s under hand off, same procedures as in [5] can be applied. From global balance equation with data terminal model

$$[w(1 - \sigma_d) + \sigma_d(1 - w)]b_{j-1} = w(1 - \sigma_d)b_j + \sigma_d(1 - w)b_{j-2} \tag{A.1}$$

$$b_j = \left[\frac{\sigma_d(1 - w)}{w(1 - \sigma_d)}\right]^{j-1} \frac{\sigma_d}{w(1 - \sigma_d)} b_0 \tag{A.2}$$

Using $b = \sum_{j=1}^{\infty} b_j$, the backlog data terminal b at equilibrium

$$b = \sum_{j=1}^{\infty} b_j = \frac{\sigma_d}{w - \sigma_d} b_0 \tag{A.3}$$

The backlog b from formula A.3 and $b_0 + b = M_d$

$$b = \frac{\sigma_d}{w} M_d = \rho_d M_d \tag{A.4}$$

where $\rho_d = \frac{\sigma_d}{w}$ and $0 \leq \rho_d \leq 1$ for stable.

from formula A.4 and w

$$bw = \sigma_d M_d, \quad b p_d(1 - p)^C (1 - p_d)^{b-1}(1 - R/N) = \sigma_d M_d \tag{A.5}$$

then this equation can be shown as

$$\frac{bp_d(1-p)}{cp(1-p_d)(1-\gamma)}[cP_{sc-d}] = \sigma_d M_d \tag{A.6}$$

If we replace cP_{sc-d} as $r(\gamma_f + P_h - \gamma_f P_h)$ from formula 3.10

$$b = \frac{cp(1-p_d)}{p_d(1-p)}\sigma_d M_d \frac{1-\gamma}{(\gamma_f + P_h - \gamma_f P_h)}(\frac{h_2}{M - h_1 c}) \tag{A.7}$$

Finally, with constraint that backlog can't exceed mobile number

$$b = min\left[\frac{cp(1-p_d)}{p_d(1-p)}\sigma_d M_d \frac{1-\gamma}{(\gamma_f + P_h - \gamma_f P_h)}(\frac{h_2}{M - h_1 c}),\ M_d\right] \tag{A.8}$$

APPENDIX B

LU FACTORIZATION

The equation can be solved as in [8]. The balance equation and boundary condition are

$$Pr(\psi_j) = Pr(\psi_j \mid \psi_i)Pr(\psi_i) \tag{B.1}$$

$$\sum_{j=1}^{\infty} Pr(\psi_j) = 1 \tag{B.2}$$

These equations can be shown as

$$\overline{x} = A\overline{x} \tag{B.3}$$

$$\overline{U}\overline{x} = 1 \tag{B.4}$$

where transition matrix A is rank n and $\overline{U}$ is a array which is consisted by 1 of n elements.

The $\overline{x} = A\overline{x}$ is changed as

$$(A - I)\overline{x} = 0 \tag{B.5}$$

where A-I is rank n-1.

We can get matrix C which rank is n from formula B.4 and B.5.

$$C\overline{x} = \overline{e}$$

Where C is (A-I) except all of the nth row are 1 and $\overline{e}$ is column vector which elemants are 0 except 1 at nth position. This equation can be solved by LU factorization

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$$LU(C)\overline{x} = \overline{e} \tag{B.6}$$

$$L_C U_C \overline{x} = \overline{e} \tag{B.7}$$

$$U_C \overline{x} = L_C^{-1} \overline{e} \tag{B.8}$$

$$U_C \overline{x} = \overline{V} \tag{B.9}$$

where L_C : low part of C

U_C : upper part of C

use iteration technique and find steady state solution $\overline{x}$

APPENDIX C

PACKET DROPPING RATE

As mentioned before we can derive packet dropping rate with L' instead of L as in [5]. L' is mean reservation length which is number of packets in a reservation under hand off.

$$L' = \frac{1}{\zeta_e} = \frac{1}{\gamma_f(1 - P_h) + P_h}$$

where ζ_e is the probability that reservation end in a most recent frame. The unsuccessful contending probability is $v = 1 - P_{sc}$. Also, the probability that reservation length is L' and waiting probability

$$
\begin{aligned}
Pr(L') &= [\gamma_f(1 - P_h) + P_h][1 - (\gamma_f(1 - P_h) + P_h)]^{L'-1} \\
P_w(j) &= (1 - v)v^{j-1}, \; j = 1, 2, \ldots
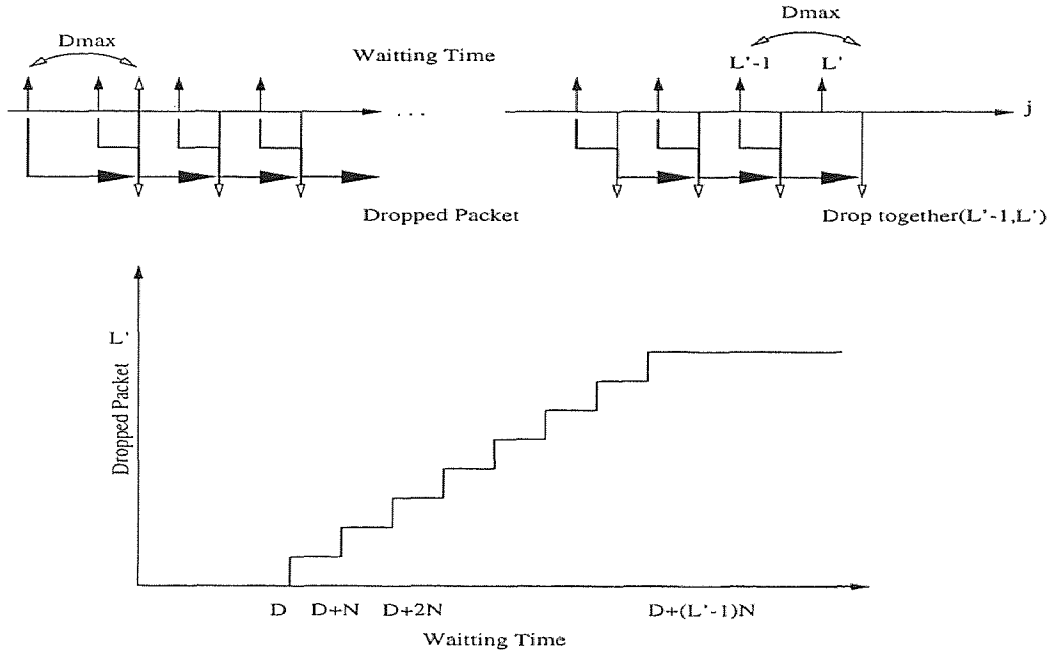\end{aligned}
\tag{C.1}
$$

Figure C.1 Packet dropping

We use same procedures as in [5]. The number of dropped packet

When $L'N > D$

$$
\begin{cases}
n_{drop}(j|L'N > D) &= 0, & 1 \leq j \leq D \\
n_{drop}(j|L'N > D) &= k, & D + (k-1)N + 1 \leq j \leq D + kN \\
& & k = 1, 2, \bullet\bullet, (L' - B) \\
n_{drop}(j|L'N > D) &= L' - B + 1, & D + (L' - B)N + 1 \leq j \leq L'N \\
n_{drop}(j|L'N > D) &= L', & L'N + 1 \leq j
\end{cases}
$$

When $L'N < D$

$$
\begin{cases}
n_{drop}(j|L'N < D) &= 0, & j \leq L'N \\
n_{drop}(j|L'N < D) &= L', & j \leq L'N + 1
\end{cases}
$$

Conditional probability of packet dropping

When $L'N > D$

$$
\begin{cases}
Pr(n_{drop} = 0|L', L'N > D) &= 1 - v^D \\
Pr(n_{drop} = k|L', L'N > D) &= v^{D+(k-1)N} - v^{D+kN}, \\
& \quad k = 1, 2, \ldots, (L' - B) \\
Pr(n_{drop} = L' - B + 1|L', L'N > D) &= v^{D+(L'-B)N} - v^{L'N} \\
Pr(n_{drop} = L'|L', L'N > D) &= v^{L'N} \\
Pr(n_{drop} = L'|L', L'N > D) &= 0
\end{cases}
$$

When $L'N < D$

$$
\begin{cases}
Pr(n_{drop} = 0|L', L'N < D) &= 1 - v^{L'N} \\
Pr(n_{drop} = k|L', L'N < D) &= 0, \ k = 1, 2, \ldots, (L' - 1) \\
Pr(n_{drop} = L'|L', L'N < D) &= v^{L'N}
\end{cases}
$$

Conditional mean

When $L'N > D$

$$
\begin{cases}
E[n_{drop}|L', L'N < D)] \\
\quad = \sum_{k=0}^{L'} k Pr(n_{drop} = k|L', L'N > D) \\
\quad = \sum_{k=1}^{L'-B} k (v^{D+(k-1)N} - v^{D+kN}) \\
\qquad\qquad + (L' - B + 1)(v^{D+(L'-B)N} - v^{L'N}) + L'v^{L'N} \\
\quad = \frac{v^D}{1-v^N}[1 - v^{(L'-B+1)N}] + (B - 1)v^{L'N}
\end{cases}
$$

When $L'N < D$

$$E[n_{drop}|L', L'N < D) = L'v^{L'N} \tag{C.2}$$

so, mean dropping rate $E[n_{drop}]$ is

$$E[n_{drop}] = \sum_{k=1}^{L'-B} E[n_{drop}|L', L'N \le D]Pr(L') +$$
$$+ \sum_{k=B}^{\infty} E[n_{drop}|L', L'N \le D]Pr(L')$$
$$= \frac{v^D}{1 - v^N}(1 - \zeta_e)^{B-1}\left[1 - \frac{\zeta_e[1 - v^{2N}(1 - \zeta_e)]}{[1 - (1 - \zeta_e)v^N]^2}\right]$$
$$+ \frac{\zeta_e v^N}{[1 - (1 - \zeta_e)v^N]^2} + \frac{\zeta_e(1 - \zeta_e)^{B-1}(v^D - v^{NB})}{[1 - (1 - \zeta_e)v^N]^2} \tag{C.3}$$

with $v = 1 - P_{sc-d}$

$$\zeta_e = \gamma_f(1 - P_h) + P_h$$

The mean number of dropped packet is

$$P_{drop} = \zeta_e E[n_{drop}]$$

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