Chapter 1 Introduction

In a wireless communication system, especially in a cellular system, a seamless migration from cell-to-cell is a fundamental problem. In third generation and beyond wireless CDMA (code division multiple access) systems, besides the seamless migration, it is critical to manage the use of resources by adapting the non-linear relationship among the connection quality, the overall interference level, and the required radio resources.

In handoff control algorithms, starting with SIR (Signal-to-Interference Ratio) based handoff algorithms[1] and then the pilot strength Ec/Io based CDMA soft/softer handoff controls [2-3], those algorithms are designed to ensure a seamless migration from sector/cell-to-sector/cell and have been proven successfully in the field. Recently, quality-based handoff algorithms, which take the actual connection quality (i.e., aggregate Ec/Io) into consideration [4-6], are proposed to reduce the required connection sectors (legs) that do not contribute significantly to the connection quality. Due to the saving in both the forward-link power budget and hardware resources, quality-based handoff algorithms are adopted by IS-95B[7] and cdma2000[8,9]. Besides those standard-defined algorithms, the idea of controlling the handoff operation region by using interference and CE (channel element) in order to gain better performance is also investigated in [10]. Further more, in [11], the Fuzzy Interference System using the number of pilots of each MS and the remaining channel elements can provide better performance than the IS-95A and IS-95B/cdma2000 with extra complexity involved.

In a CDMA wireless system, all users' connection qualities are tightly coupled. Adding a new leg (connection) to improve one user might cause unstable interference impacts. This non-linear effect is important and should be considered in the handoff control designs. Unfortunately, this effect is not captured in current handoff control algorithms in neither the fixed quality-based handoff algorithm [5] nor the linear dynamic quality-based handoff algorithm used for IS-95B[7] and cdma2000[8,9].

In our believe, the impacts on the overall-interference by changing the number of effective connections will make those non-linear effect. In this thesis, the Multi-Slope Quality Based Handoff Control Algorithm (MSHO) is proposed to meet the design challenges of minimizing the required resources 3G and beyond wireless systems.

The paper is organized as follows: In Chapter 2, currently handoff control algorithms in IS-95A(cdmaOne) and IS-95B/cdma2000 are discussed. In Chapter 3, the advanced multi-slope quality based handoff algorithm is presented and proposed respectively. The architecture in simulation platform for handoff performance studies are stated in Chapter 4. Chapter 5 will discuss the performance results and the reasons.

The final conclusions are included in Chapter 6.

Chapter 2 Background for CDMA Handoff Controls

In this chapter, the prevailing IS-95A(cdmaOne) and IS-95B/cdma2000 soft handoff control algorithms will be introduced. The soft handoff is the key feature in CDMA wireless communication technologies. Using the soft handoff, the connection quality of an on-going call can be more robust during the handoff process. The cdmaOne performs static add/drop threshold and treat all connection quality the same thresholds. In IS-95B/cdma2000, the linear add/drop threshold, is implemented to reduce the unnecessary handoff event and to improve the efficiency of using system radio resources.

2.1 Handoff algorithm in IS-95A

IS-95A is the first implemented cdma-type cellular communication system. The pilot channel used as a reference channel is important for the handoff process in IS-95A system. Basically, all related handoff triggers are base on pilot Ec/Io measurements for the add-leg, drop-leg, and swap-legs trigger. In IS-95A handoff control procedure, there are four important handoff parameters. They are T_ADD, T_COMP, T_DROP, and T_TDROP, listed as follows:

- T_ADD (add-leg threshold): When the active set is filled, the threshold is used to decide whether the pilot should be added to the candidate set. When the active set is not filled, the threshold is used to decide whether the pilot should be added to the active set.
- T_COMP (swap threshold)：The threshold is used to decide whether to swap an existing pilot to a candidate pilot. It is also used as a threshold for a second pilot strength report, if the first pilot report is not accepted by the BS.
- T_DROP (drop-leg threshold)：The threshold is used it to decide whether to move a candidate pilot and/or an active pilot into the neighbor set.
- T_TDROP (drop-leg timer): The timer is used to decide whether to move a pilot from the candidate set and/or the active set to the neighbor set.

All those thresholds are fixed once decided. A Handoff is triggered by the measurement of the pilot strength (Ec/Io). The Ec is the chip energy received from the sector. The Io is the spectral density of total received interference.

2.1.1 Add-Leg Stage

Mobile will detect the pilot strength and use it as the handoff trigger. When the neighbor set pilot strength is greater than T_ADD, the mobile will add the pilot to the candidate set. There are two requirements to move the pilot from the candidate set to the active set: (1) If the active set is not full, the pilot which the strength is larger than

T_ADD will be added to the active set directly. However, if for some reason that system does not add the pilot into active set, then mobile will inform the system when the candidate pilot strength exceeds T_ADD by T_COMP depending on system whether to add the pilot into the active set or not. (2) If the active set is full, the system will base on the received pilot strength report to decide whether to swap the existing pilot in the active set to the new pilot. When the best candidate pilot strength is greater than weakest active pilot strength by T_COMP×0.5, the two pilots will be swapped.

2.1.2 Drop-Leg Stage

When either the active set pilot or the candidate set pilot is lower than T_DROP, the system will start a timer. When the timer expires (after T_TDROP seconds), the system will drop the pilot and move it to the neighbor set. The timer will be reset, if the pilot strength exceeds T_DROP before the expiration of the timer. The mobile maintains an age counter, AGE, for each pilot in the neighbor set. If a pilot moves from the active set or candidate set to the neighbor set, its counter is initialized to zero. If the pilot moves from the remaining set to the neighbor set, its counter is set to the maximum age value. The mobile will update the counter value under the direction of the serving site. The neighbor pilot will be moved to the remaining set only of the number of the neighbor list pilot’s AGE exceed the maximum value of the AGE counter, NGHBR_MAX_AGE or when the number of neighbor pilots exceed the capacity of neighbor set.

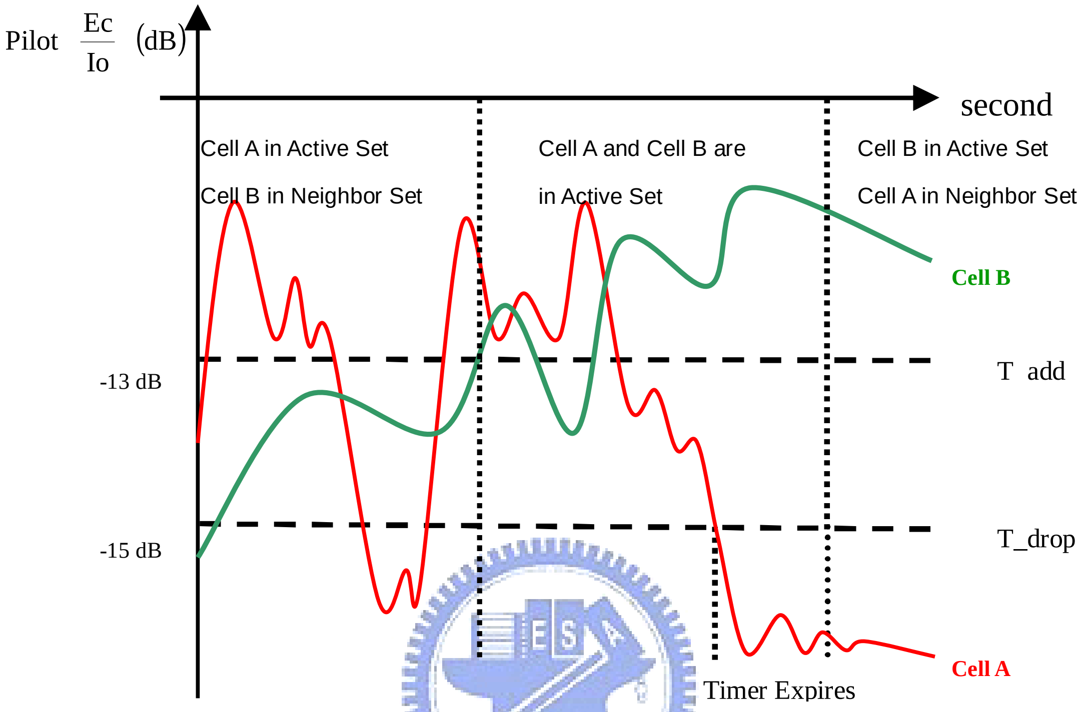

Figure 2.1, IS-95A Handoff Procedure

2.1.3 Handoff Process

To have a better understanding, the handoff procedure is depicted in Figure 2.1. From this figure, the original active set is the pilot from the cell A. Even the pilot A is lower than T_DROP once since the timer is not expired, the pilot A remains in the active set. In other words, the timer is designed to avoid the ping-pong effect due to a quick fading case. When the pilot from the cell B exceeds T_ADD, because the active set is not full, the system adds the pilot B into the active set directly. Handoff starts. Finally, the pilot A is lower than the T_DROP and the timer exceeds T_TDROP seconds, the system moves the pilot A to the neighbor set.

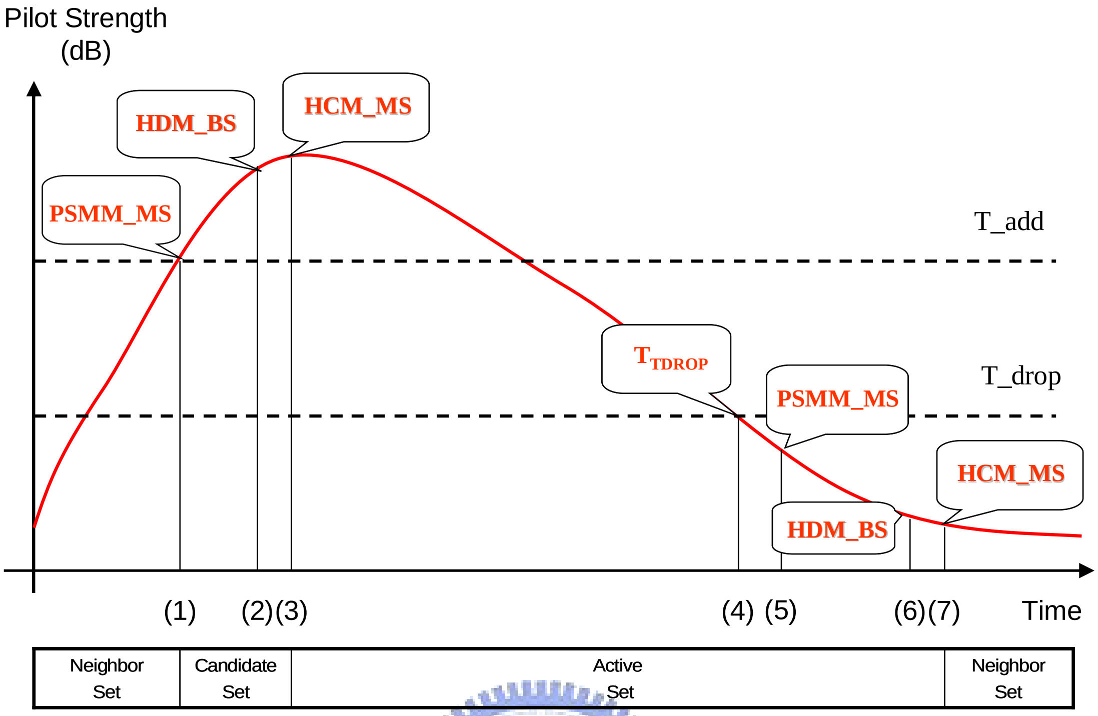

Figure 2.2, IS-95A Handoff Process with Messages

The Figure 2.2 explains the complete process of how and when a handoff is executed. At first, the pilot is in the neighbor set. As shown, the pilot strength is increasing gradually. At time (1) when the pilot strength exceeds T_ADD, the mobile sends PSMM (pilot strength measurement message) to the base station and put the pilot into the candidate set. At time (2), the base station received PSMM and decides to add the pilot. Therefore it sends HDM (handoff direction message) with proper code information to the mobile to execute the handoff process. After the mobile received HDM, it sends a response message to the base station to notice the base station that the mobile has received the message and then add to the new traffic channel, i.e. mobile transfers the candidate pilot to the active set. To complete the handoff process, the final message is HCM (handoff completion message) at time (3). When at the time (4), the pilot strength is lower than T_DROP. The drop timer starts. At (5), when the timer is expired (given the pilot strength is continuously lower than T_DROP), the mobile sends PSMM to the base station to move the weak active pilot to the neighbor set. At (6), the base station received PSMM then sends HDM back to the mobile. At (7), the mobile receives HDM and moves the pilot to the neighbor set. After mobile sends back the HCM, the handoff process is finished.

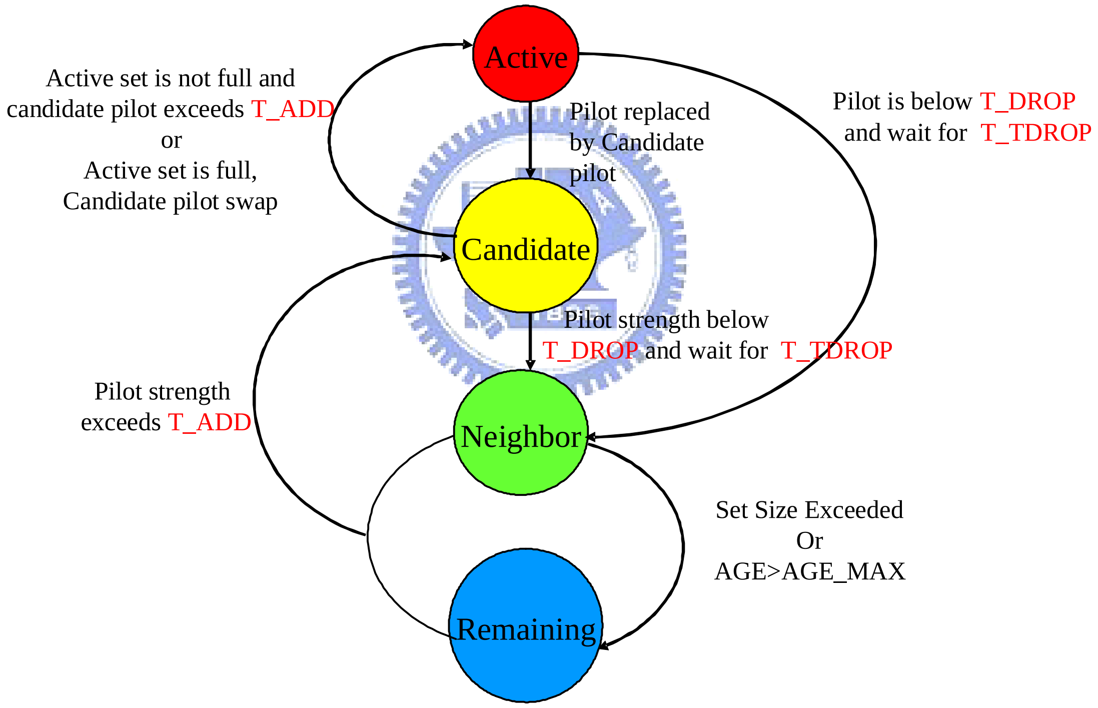

Figure 2.3, Various Handoff Sets in IS-95A

In IS-95A, as shown in Figure 2.3, four different sets are used to describe the handoff process:

- Active set: pilots in this set have RF connections with the mobile
- Candidate set: pilots in this set have the high priority (shorter measurement

interval) in the pilot Ec/Io measurement

- Neighbor set: pilots in this set are the potential pilots for the soft handoff connections. The measurement interval is longer than the pilot in the active sets and candidate sets.
- Remaining set: pilots other than the active, candidate and neighbor sets. The measurement interval is the longest.

2.2 Handoff algorithm in IS-95B and cdma2000

In IS-95B and cdma2000 (the 3G), the handoff control algorithm is focus on reducing the required resources to support a mobile connection. To achieve that, two extra dynamic handoff trigger thresholds are used. In IS-95B/cdma2000, there are four important parameters T_{ADD_95A}, T_{ADD_2000}, T_{DROP_2000}, and T_{DROP_95A} where T_{ADD_95A} and T_{DROP_95A} are fixed and are the same as T_{ADD} and T_{DROP} in IS-95A. T_{ADD_2000} and T_{DROP_2000} are dynamic thresholds calculated by a specific function.

2.2.1 Add-Leg Stage

When the neighbor set pilot strength is larger than T_{ADD_95A}, the pilot will be moved to the candidate set. If the candidate pilot strength is larger than T_{ADD_2000}, the pilot will be added to the active set when the active set is not full. The add-leg threshold, T_{ADD_2000}, is calculated in Equation (2.1):

$$T_{ADD\_2000} = \max\{(\mathrm{SOFT\_SLOPE}) \times 10\log\Big(\sum_{i \in \{\text{active set}\}} (Ec/Io)_i\Big) + \mathrm{ADD\_INTERCEPT}, T_{ADD\_95A}\} \quad (2.1)$$

The new pilot P_j will be added to the active set if $10\log(P_j) \geq T_{ADD\_2000}$. In other words, the dynamic add threshold is calculated based on the aggregate pilot $\sum_{i \in \{active\ \ set\}} (Ec/Io)_i$ but will be bounded by T_{ADD_95A}. Here, the aggregate Ec/Io is used to represent the connection quality. The mobile will report the PSMM again if the new pilot P_j is not accepted at the first report but has $T_{COMP} \times 0.5$ greater than any pilot in the active set.

2.2.2 Drop-Leg Stage

To drop a pilot to the neighbor set, T_{DROP_2000} and T_{DROP_95A} are used, where T_{DROP_2000} is calculated by Equation (2.2).

$$T_{DROP\_2000} = \max\{(SOFT\_SLOPE) \times 10\log(\sum_{i \in \{remaining\ \ active\ \ set\}} (Ec/Io)_i) + DROP\_INTERCEPT, T_{DROP\_95A}\} \quad (2.2)$$

When the pilot in the active set is less than T_{DROP_2000} for T_{TDROP} seconds, the pilot will be moved to the neighbor set. The timer will be reset if the pilot is greater than the T_{DROP_2000} before the expiration of the timer (T_{TDROP} seconds). Same as T_{ADD_2000}, T_{DROP_2000} is calculated based on the aggregate Ec/Io.

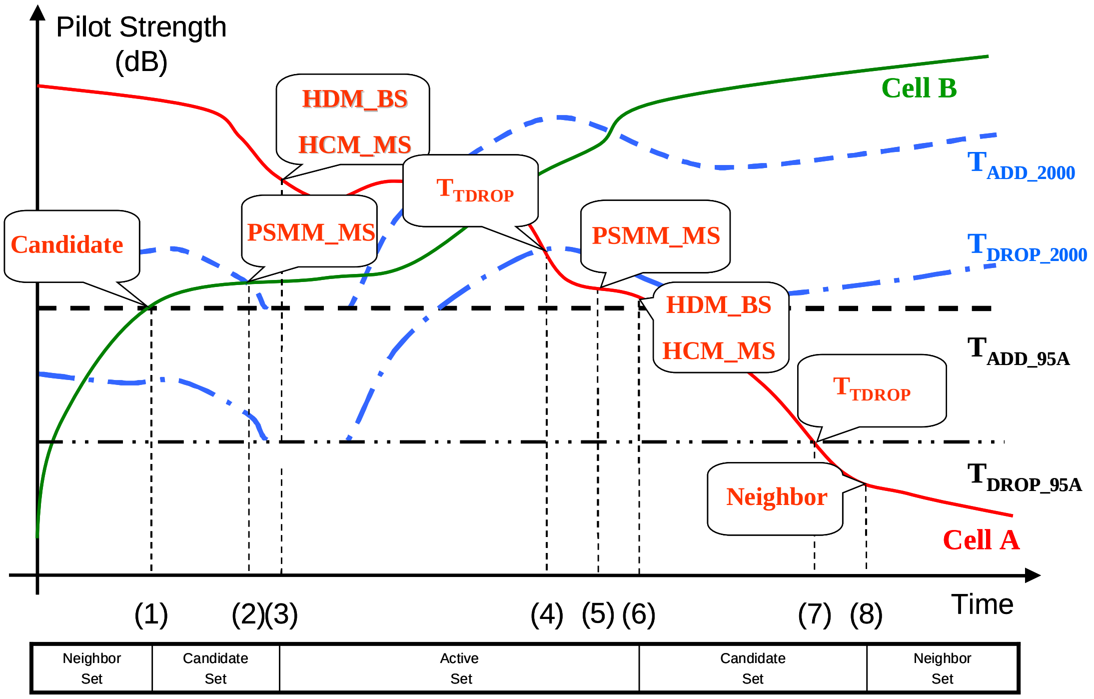

Figure 2.4, IS-95B/cdma2000 Handoff Process

2.2.3 Handoff Process

The handoff process in IS-95B/cdma2000 systems is depicted in Figure 2.4. As shown, P_A is in the active set and P_B is in the neighbor set. As increase of P_B strength, at (1), P_B is larger than T_{ADD_95A} therefore the P_B will be added to the candidate set. At (2), when P_B is larger than dynamic threshold T_{ADD_2000}, the mobile sends PSMM to the base station to start the handoff process. At (3), the mobile receives the HDM from base station and then adds P_B into the active set. Now, there are P_A and P_B in the active set. Therefore the dynamic thresholds are base on P_A and P_B's aggregate Ec/Io. At (4), when P_A is lower than the dynamic threshold $T_{DROP\_2000,}$ the drop timer starts. At (5), the timer expires and P_A does not exceed the T_{DROP_2000} again. The mobile will send PSMM and at (6), the base station sends HDM back to the mobile and removes

P_A from the active set to the candidate set. For now, the active set has P_B only. All related dynamic thresholds are calculated based on P_B's Ec/Io only. At (7), when P_A is lower than T_{DROP_95A}, the timer starts. At (8), when the timer expires, the mobile moves the P_A from the candidate set to the neighbor set.

Chapter 3 Multi-Slope Quality Based Handoff Control Algorithm (MSHO)

In the wireless communication system, how to minimize the required resources is an important issue. The Multi-Slope Quality Based Handoff Control Algorithm is not designing for maintain the connection quality. Instead, with a comparable connection quality the MSHO is proposed to minimize the required resources.

3.1 The Multi-Slope Quality Based Control Algorithm

The pilot signal is used for acquisition, and tracking in each sector/cell. The quality of the pilot signal becomes important in CDMA wireless communication systems. During the handoff operation, mobile detects sector/cell pilot strength, to decide whether there is a pilot to improve the connection quality.

The quality of pilot signal strength received by the mobile station will be affected by the overall interference level and its thermal noise. It can be formulated in Equation (3.1).

$$\left[\frac{\mathrm{E_c}}{\mathrm{I_o}}\right]_{\mathrm{i}} = \frac{m\mathrm{P_i}/\mathrm{W}}{\mathrm{FN_{th}} + \sum_{\mathrm{all\,j}} \mathrm{P_j}/\mathrm{W}} \tag{3.1}$$

where,

- E_c:chip energy received from I-th sector.
- I_o:spectral density of total received interference.
- μ:fraction of sector power allocated to pilot signal,
- P_i:received power from i-th sector,
- W:system bandwidth(1.25MHz),
- F:base station noise figure,
- N_{th}:thermal noise power density.

Because of the non-linear relationship in the pilot signal quality, overall interference level, and the radio resource, the MSHO is proposed to use multiple slopes at various signal qualities, i.e. $T_{Quality}$.

To simply the discussion, two-slope are used to explain the concepts for MSHO, as shown in Figure 3.1. The T_{SLOPE_I} and T_{SLOPE_II} can be the same or different at different aggregate Ec/Io values, and the value, $T_{Quality\_I}$, of aggregate Ec/Io which the slope changed can be various under different packet error rate requirement.

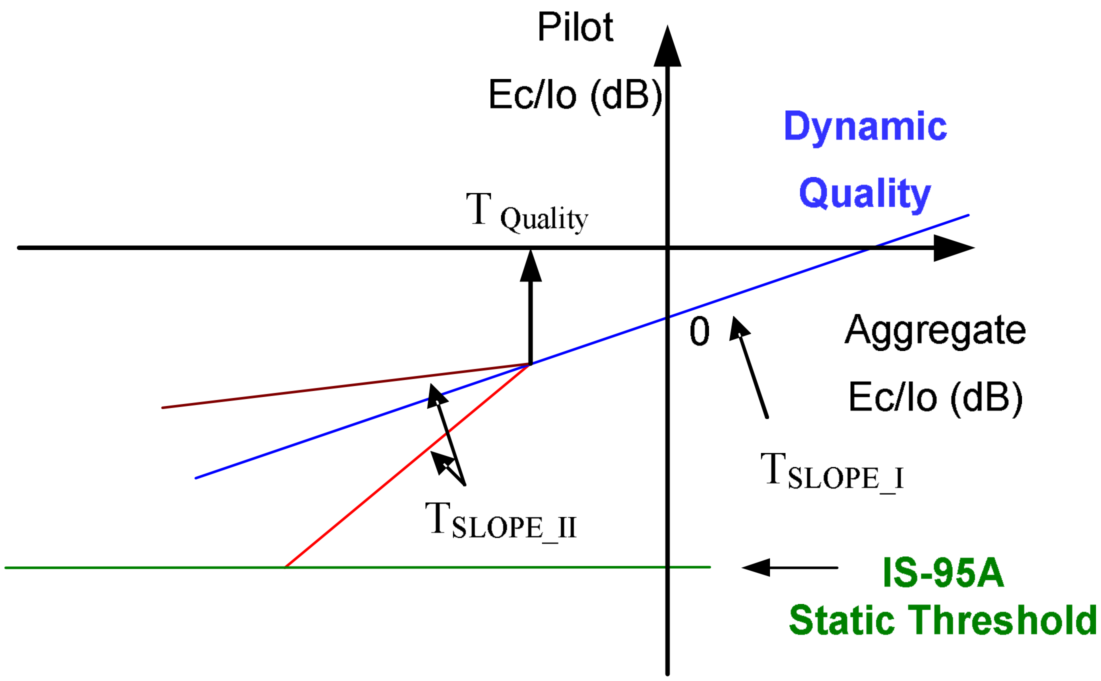

Figure 3.1, Multi-Slope Quality Based Handoff Control Algorithm

Intuitively, the slope value should be increased at a poor RF connection, to allow more connections to be added to rescue the poor connection. But potentially, there exist a negative impact on the overall connection quality by increasing the forward-link power. A positive impact on the poor connection is true only if the added link is stable and can continuously contribute the diversity gain. On the contrary, if the added link is not stable, then adding those links will have negative impacts on all links including the link that need to be improved. This is because the unstable links can not constantly contribute the diversity link during a quick RF changing scenario.

As a result, the proposed MSHO provides the flexible design to the slope value. The slope value can be varied at different aggregate Ec/Io values. Figure 3.2 shows a general MSHO algorithm. The selection of T_{ADD} can be divided into two steps. First, select the minimum value between the strongest active pilot and $T_{ADD\_MulitSlope}$. Second, choose the maximum value between T_{ADD_95A} and the one which is decided in the first step.

$$T_{ADD\_MultiSlope} = A\Big(\sum_{i\in\{active\ \ set\}}(Ec/Io)_i\Big)\times\sum_{i\in\{active\ \ set\}}(Ec/Io)_i + B\Big(\sum_{i\in\{active\ \ set\}}(Ec/Io)_i\Big)$$

$$T_{ADD} = \max\left\{\min\left[\max_{i\in\{active\ set\}}\{i\,|\,(Ec/Io)_i\},\ T_{ADD\_MultiSlope}\right],\ T_{ADD\_95A}\right\}$$

Figure 3.2, Multi-slope Quality based Handoff Algorithm -- T_{ADD}

T_{DROP} threshold mathematical expression is in Figure 3.3. Generally the T_{DROP} value is smaller than T_{ADD} one. There should be a difference between T_{ADD} and T_{DROP} threshold to avoid the exceeded unnecessary handoff direction message to and from the Base Station and Mobile Station.

$$T_{DROP} = \max\left\{A_{DROP}\Big(\sum_{i\in\{remaining active\ set\}}(Ec/Io)_i\Big)\times\sum_{i\in\{remaining active\ set\}}(Ec/Io)_i + B_{DROP}\Big(\sum_{i\in\{remaining active\ set\}}(Ec/Io)_i\Big)\ ,\ T_{DROP\_95A}\right\}$$

for T_{TDROP} Second

Figure 3.3, Multi-slope Quality based Handoff Algorithm – T_{DROP}

A(‧) and B(‧) are chosen to meet the non-linear curve between aggregate Ec/Io and packet error rates. Under different aggregate Ec/Io the slopes and intercepts could be different.

In our example, A(‧) and B(‧) are formulated as follows:

$$A = A_{DROP} = \begin{cases} T_{SLOPE\_I} & \text{if}\quad \text{Aggregate}\,{}^{Ec}\!/\!{}_{Io}\,(dB) > T_{Quality} \\ T_{SLOPE\_II} & \text{if}\quad \text{Aggregate}\,{}^{Ec}\!/\!{}_{Io}\,(dB) \le T_{Quality} \end{cases}$$

$$B = -T_{Quality}\times A + \left(A_{cdma\ \ 2000}\times T_{Quality} + B_{cdma\ \ 2000}\right)\ \ (dB)$$

$$B_{DROP} = -T_{Quality}\times A_{DROP} + \left(A_{cdma\ \ 2000\_DROP}\times T_{Quality} + B_{cdma\ \ 2000\_DROP}\right)\ \ (dB)$$

where $B_{cdma\,2000}$ and $B_{cdma\,2000\_DROP}$ are add and drop intercepts in cdma2000 Handoff parameters and $T_{Quality}$ is the threshold to trigger the change of the second slope. Assuming T_{SLOPE_I} is the same as the soft-slope in cdma2000

3.2 Summary

The key feature of MSHO is using different slope at different aggregate Ec/Io to determine proper add/drop threshold. This design is trying to minimize the required resource during seamless handoff operation in wireless communication systems.

Chapter 4 Simulation Platform

This simulation model is developed in wireless communication system handoff control algorithms studies, with the inputs of the users, fading channels, propagation models, forward link power control, etc. The platform provide the analysis of average aggregate Ec/Io, forward link power budget, channel element usage, handoff event frequency, and the stability of the link connection, etc.

4.1 Simulation Model

Figure 4.1 shows the block diagram for this simulation. With the inputs of propagation model, the fading channel, various interference levels (in terms of number of mobiles), and user mobility, different performance were measured. To capture the dynamic behavior of the mobile RF condition, the number of connection paths, mobile locations, the pilot Ec/Io, transmitted power and hardware usage were calculated every 200 milliseconds. The platform was developed based on the following assumptions:

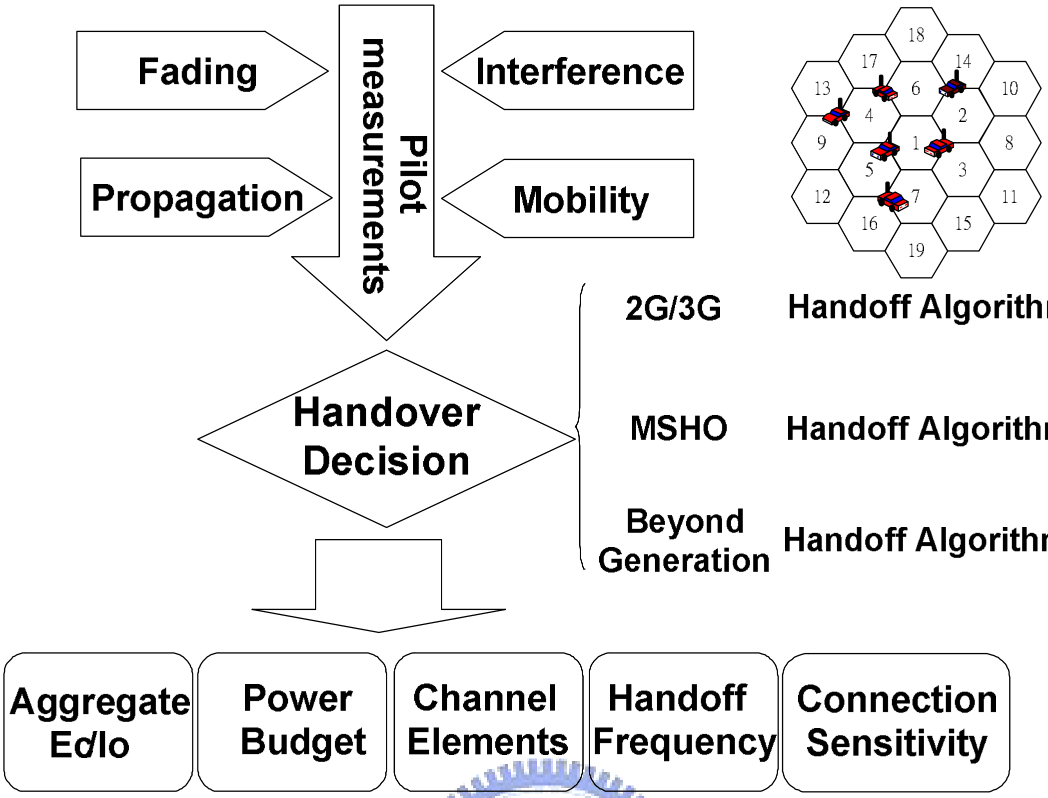

Figure 4.1 Simulation Model

The Simulation System Parameters

- Two-tier, 19 BSs, 3-sector cells were considered.
  - Center cell was used to study the performance statistics
- Propagation model: Cellular Band: Hata Model [12] was used.
- Lognormal fading with the correlation distance of 400 meters and the variance of 8 dB were used
- Traffic loads: various user cases can be dynamic allocated.
- 120° Antenna pattern was used.

The downlink fading environment between each mobile and each sector's pilot strength is different. The log-normal fading expression in Matlab program is generated from Equation (4.1).

$$\mathrm{fad}(m,s) = \mathrm{randn}(1,\mathrm{nbs}) \times \mathrm{sigma} \tag{4.1}$$

where,

- m = mobile index,
- s = sector index,
- nbs= number of base station,
- sigma = variance [dB].

The link budget between each sector and each mobile was calculated from Equation (4.2).

$$\mathrm{L1}(m,s) = [A \times B,\ \ A \times \exp(i \times 2 \times \pi/3) \times B,\ \ A \times \exp(i \times 4 \times \pi/3) \times B] \tag{4.2}$$

where,

- i = image vector,
- m = mobile index,
- s = sector index,
- $A = 69.55 + 26.16 \log f_c - 13.82 \log h_{te} - a(h_{re})$

  $a(h_{re}) = (1.1 \log f_c - 0.7) h_{re} - (1.56 \log f_c - 0.8)$ dB
- $B = 44.9 - 6.55 \log(h_{te})$

- A and B are Hata Model [12] parameters in urban areas.

Each sector's pilot strength in each mobile can be calculated by Equation (4.3).

$$\frac{\mathrm{Ec}}{\mathrm{Io}}(\mathrm{m},\mathrm{s}) = 10 \times \log_{10}\left(\mathrm{pilot} \times \mathrm{L1}(\mathrm{m},\mathrm{s})\right) / \left(\mathrm{power0} \times \mathrm{L1\_sum}(\mathrm{m}) + \mathrm{FNW}\right) \tag{4.3}$$

where,

- m = mobile index,
- s = sector index,
- power0 = forward link transmit power,
- $\mathrm{L1\_sum}(\mathrm{m}) = \sum_{j=1}^{\mathrm{mobile}} \sum_{:=1}^{57} \mathrm{L1}(\mathrm{m},\mathrm{s})$,
- FNW = Thermal Noise.

All sectors will be operated the same as the center sector.

4.2 Forward Link Required Power Calculation

In order to maintain the quality of an on-going call, the purpose of the forward link power control is to provide sufficient power for mobiles to overcome the fading and propagation loss and to maintain 1% FER.

In the simulation platform, the fractional forward link traffic power allocation for mobile receiver was calculated from Equation (4.4) and equation (4.5).

$$\mathrm{x} = \frac{\mathrm{d}}{\mathrm{G}} \times \frac{\mathrm{FN}_{\mathrm{th}}\mathrm{W} + \mathrm{P}_{\mathrm{r,same}} + \mathrm{P}_{\mathrm{r,other}}}{\mathrm{P}_{\mathrm{r,host}}} \tag{4.4}$$

$$\mathrm{Si}(\mathrm{j}) = \frac{10^{\frac{\mathrm{EbNo}(\mathrm{j})}{10}}}{\mathrm{G}} \times \frac{\mathrm{Overhead} + \mathrm{Const} \times \mathrm{B} \times \mathrm{FNW} \times \mathrm{ls}(\mathrm{j}) + \mathrm{FNW}}{(1 - \mathrm{Const} \times \mathrm{A}) \times \mathrm{lcs}(\mathrm{j})} \tag{4.5}$$

where

x = fractional traffic power allocation for mobile receiver,

d = Eb/Io requirement,

G = spread spectrum processing gain (bandwidth normalized by data rate 14.4 kbit/s)

$P_{r,host}$ = received total power at mobile receiver from host sector,

$P_{r,same}$ = received total power at mobile receiver from other same-sector traffic links, and

$P_{r,other}$ = received total power at mobile receiver from surrounding sector.

Overhead= $0.2 \times P_{total\_forward\_link}$,

Const = voice/G,

Voice Activity=0.48,

j = mobile index,

$ls(j) = P_{r,same} + P_{r,other}$,

$lcs(j) = P_{r,host}$.

4.3 Base Station Antenna and Cell Coverage Designs

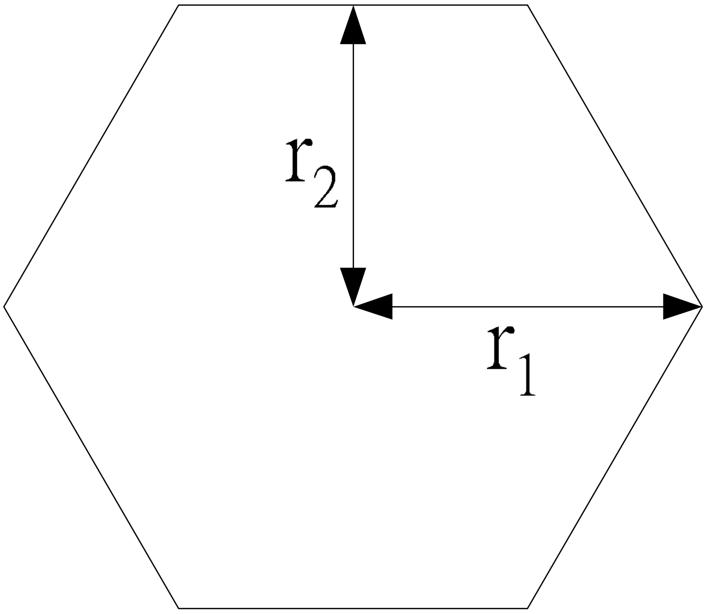

Figure 4.2, Single Cell Topology

In Figure 4.2, r_1 is the unit distance in x-axis and r_2 is that in y-axis. Each parameter was referenced from Hata Propagation model [12] in urban areas as follows：

$$r_1 = 10^{\left[(Lp - A - C)/B \right]} \;;\; r_2 = \sqrt{3}/2 \times r_1 \;;\; r = \left((r_1 + r_2)/2 \right)$$

- $L_p(dB) = A + B$
- $A = 69.55 + 26.16 \log f_c - 13.82 \log h_{te} - a(h_{re})$

  $a(h_{re}) = (1.1 \log f_c - 0.7) h_{re} - (1.56 \log f_c - 0.8)$ dB for urban
- $B = 44.9 - 6.55 \log(h_{te})$
- $C = -\left(2[\log(f_c/28)]^2 + 5.4\right)$
- f_c = frequency, MHz

- h_{te} = effective height of the base station, m (20 m < h_{te} <30 m)
- h_{re} = mobile antenna height (1 m < h_{re} <10 m)

Figure 4.3 shows the topology for three section antennas transmitted at 0°, 120°, and 240° degrees.

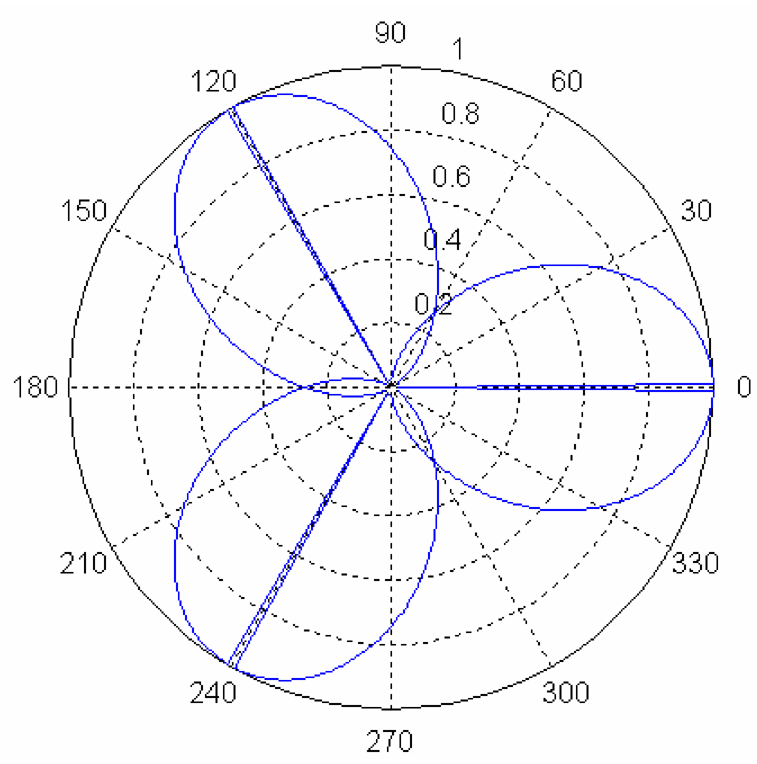

Figure 4.3, Three Antenna Patent in one Cell.

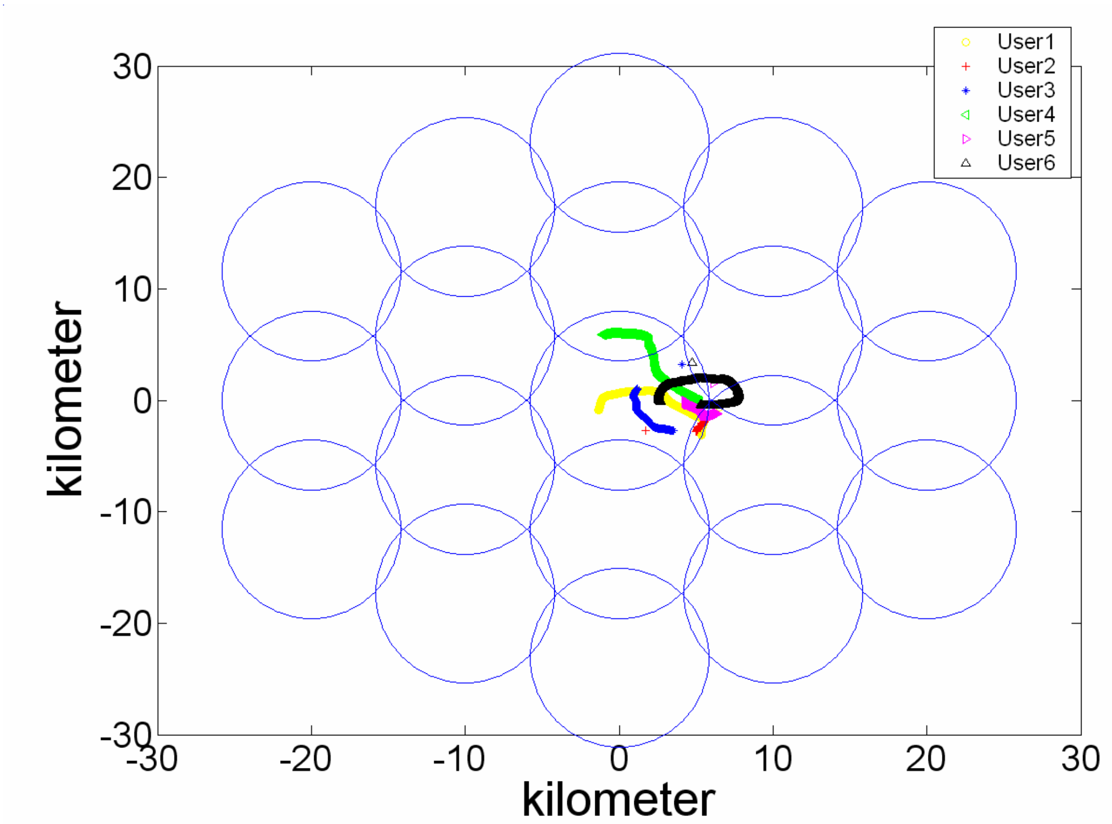

Figure 4.4, 6 Users' Trajectories & 19 BSs Topology

The performance analysis was based on the users in the center sector, including the calculation of connection quality, channel element usage, the required forward link power, handoff event frequency, and the std. of each user connection quality. Figure 4.4 shows the trajectories of 6 moving users in the center sector for 60 seconds.

4.4 The Mobile Required Eb/No Calculation

Table 4.1 and Figure 4.5 show the required Eb/No versus the number of active Leg connections. In this simulation model, the number of path in each leg can vary. Under the different number of connection leg/path, the required Eb/No would be calculated based on Table 4.1 assumptions.

Table 4.1, The required Eb/No versus the number of active Leg Calculation

Number of Leg	Required Eb/No
1 Leg	$14.3+\Delta\times 9.3[\mathrm{dB}],\quad 0\le\Delta\le 1$
2 Legs	$\mathrm{Path}_{12}\_\mathrm{Slope}\times(3.0-\Delta_{12})+\mathrm{Path}_{12}\_\mathrm{Intercept}\ \ [\mathrm{dB}]$ $\Delta_{12}=10\log\left(\dfrac{10^{\frac{\mathrm{Aggregate}\ \ \mathrm{Ec/Io}}{10}}}{10^{\frac{\mathrm{Active\_Max}}{10}}}\right)$ $\mathrm{Path}_{12}\_\mathrm{Slope}=[(7.4+\Delta\times 4.7)-(14.3+\Delta\times 9.3)]/3,\ \ 0\le\Delta\le 1$ $\mathrm{Path}_{12}\_\mathrm{Intercept}=(14.3+\Delta\times 9.3)-(3.0\times\mathrm{Path}_{12}\_\mathrm{Slope}),\ \ 0\le\Delta\le 1$
3 Legs	$\mathrm{Path}_{23}\_\mathrm{Slope}\times(4.8-\Delta_{23})+\mathrm{Path}_{23}\_\mathrm{Intercept}\ \ [\mathrm{dB}]$ $\Delta_{23}=10\log\left(\dfrac{10^{\frac{\mathrm{Aggregate}\ \ \mathrm{Ec/Io}}{10}}}{10^{\frac{\mathrm{Active\_Max}}{10}}}\right)$ $\mathrm{Path}_{23}\_\mathrm{Slope}=[(4.8+\Delta\times 3.0)-(7.4+\Delta\times 4.7)]/(4.8-3.0),\ \ 0\le\Delta\le 1$ $\mathrm{Path}_{23}\_\mathrm{Intercept}=(7.4+\Delta\times 4.7)-(3.0\times\mathrm{Path}_{23}\_\mathrm{Slope}),\ \ 0\le\Delta\le 1$

The calculation of mobile required Eb/No was based on the number of connected legs. First, in this study each connection leg has one path. Table 4.1 shows the required Eb/No versus the number of active leg calculation and in Figure 4.5 the x-axis is the gain of the pilot strength in aggregate Ec/Io. For example, when in two equal pilot strength, the aggregate Ec/Io will have 3 dB gain, while in three equal pilot strength case, there will be 4.8 dB gain in the aggregate Ec/Io. The y-axis is the mobile required Eb/No. In the case of one active leg, the corresponding Eb/No required is $14.3+\Delta\times 9.3[\mathrm{dB}]$, where △ is a normal distribution random variable between [0,1]. In two equal-strength legs case, the required Eb/No is

$7.4 + \Delta \times 4.7[\mathrm{dB}]$. In three equal strength legs case, the required Eb/No is $4.8 + \Delta \times 3.0[\mathrm{dB}]$. However, when the active pilot strengths are not equal, the required Eb/No will be calculated based on the formulas listed in Table 4.1.

For the case of two different-strength legs, the require Eb/No was calculated as,

$$\mathrm{Eb/No} = \mathrm{Path}_{12}\_\mathrm{Slope} \times (3.0 - \Delta_{12}) + \mathrm{Path}_{12}\_\mathrm{Intercept} \quad [\mathrm{dB}]$$

where, $\Delta_{ij}[\mathrm{dB}]$; $i, j \in \{1,2,3\}, i < j$ is the pilot strength difference between the aggregate Ec/Io and the strongest active pilot. Path_{12}_Slope is the slope of 1 leg to 2 leg lines shown in Figure 4.5 which represents the linear relationship between the required Eb/No and the gain of the connection pilot strength. Using the same design concept, the required Eb/No in the case of three pilot strengths is calculated as,

$$\mathrm{Eb/No} = \mathrm{Path}_{23}\_\mathrm{Slope} \times (4.8 - \Delta_{23}) + \mathrm{Path}_{23}\_\mathrm{Intercept} \quad [\mathrm{dB}]$$

where, Path_{23}_Slope is the slope of the 2 leg to 3 leg lines shown in Figure 4.5 and the Path_{12}_Intercept and Path_{23}_Intercept are the intercept points on the y-axis which correspond to 1 leg to 2 leg and 2 leg to 3 leg cases.

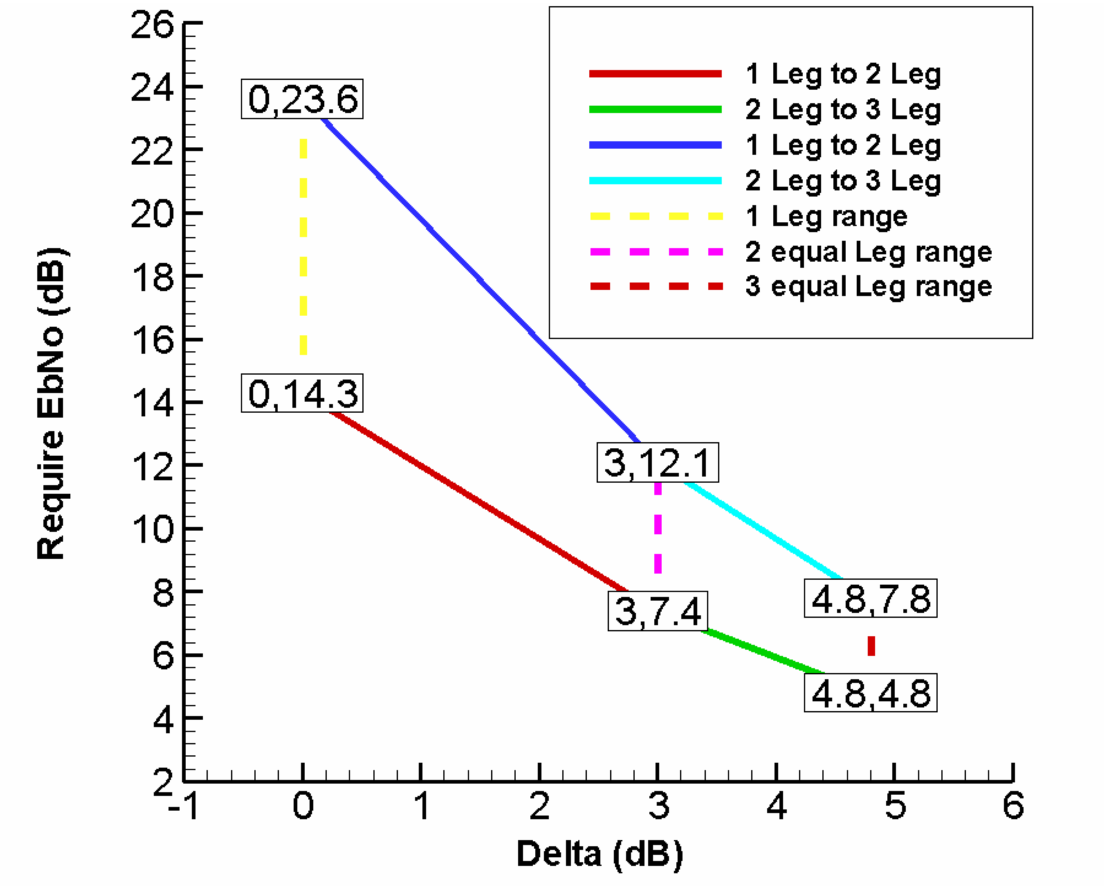

Figure 4.5, The linear-relationship in required Eb/No with different active pilot strength.

4.5 Program State Flow

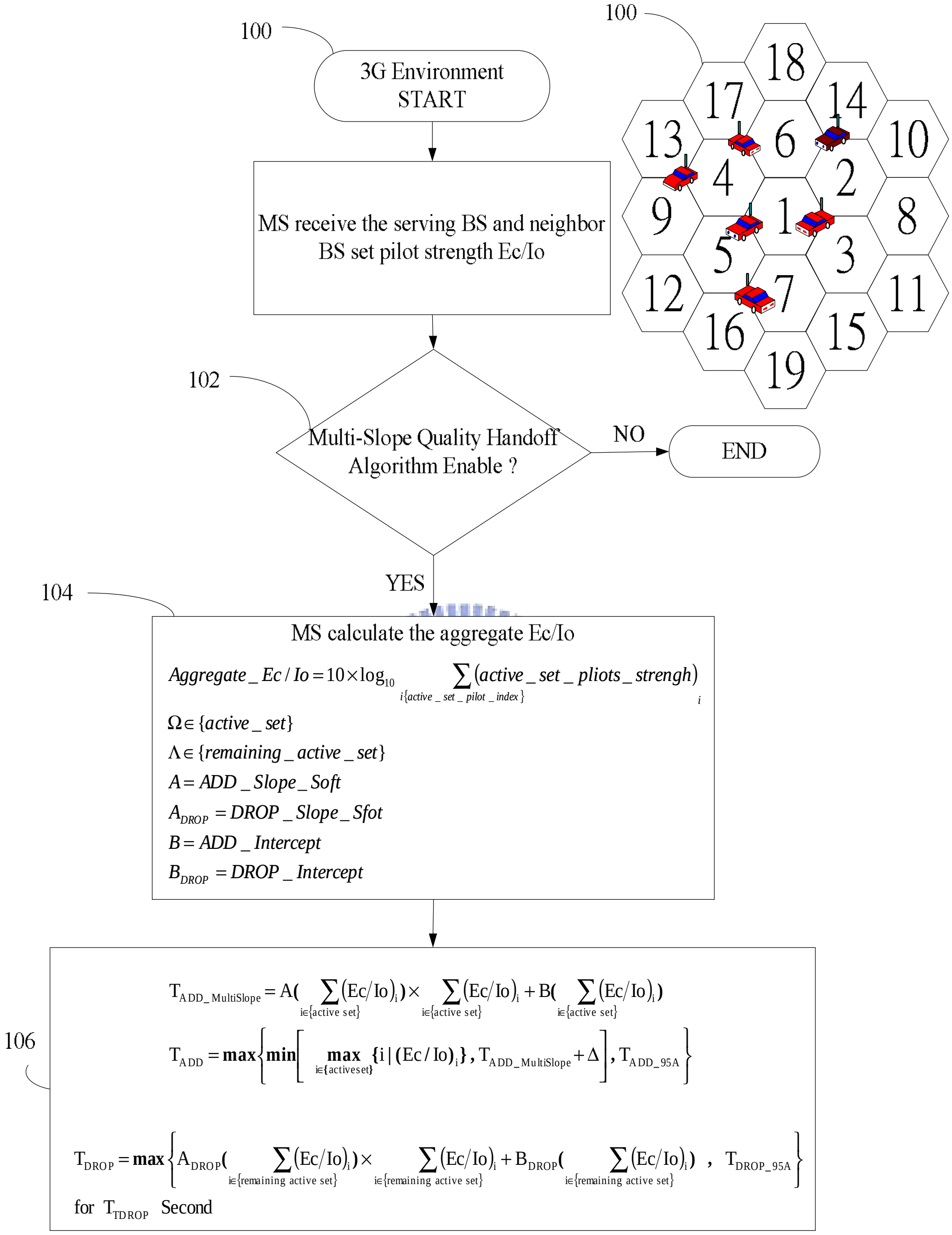

Figure 4.6, Program State Flow Chart_I

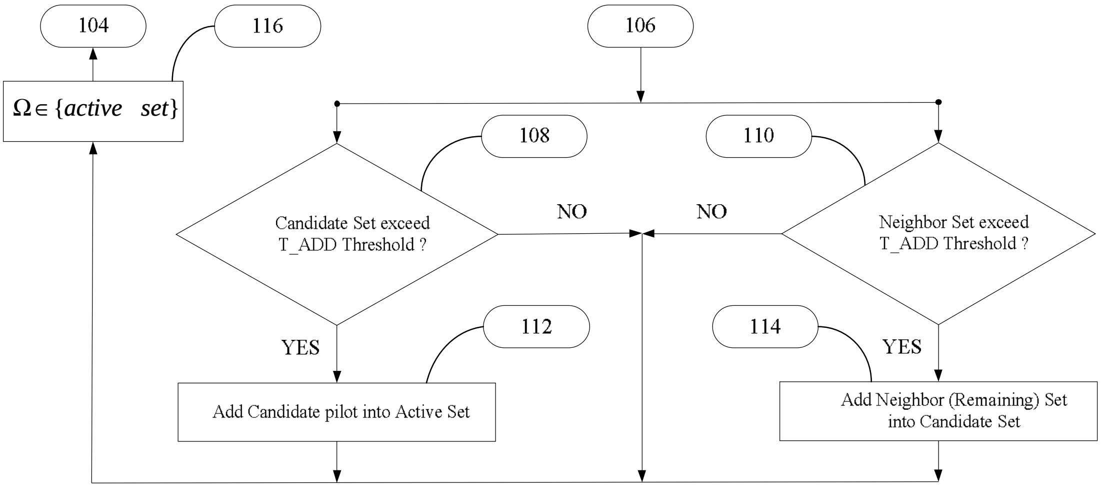

Figure 4.7, Program State Flow Chart_II

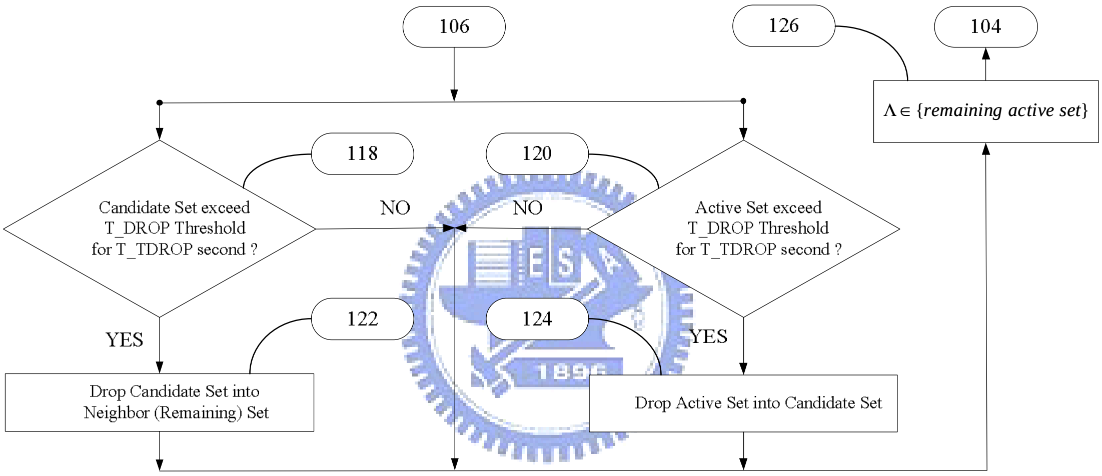

Figure 4.8, Program State Flow Chart _III

Figure 4.6, Figure 4.7 and Figure 4.8 are flow diagrams of an exemplary embodiment of the invention where the system keeps track of mobile location, and speed and the Multi-Slope Quality Based Handoff Control Algorithm. Here is the description of each stack.

Step 100: The cdma wireless communication environment with six users per sector in 19 cells.

Step 102: The Multi-Slope Quality Based Handoff Control Algorithm (MSHO) is triggered or not.

Step 104: Fundamental handoff parameters initial setting, including Add_Slope/Add_Intercept, Drop_Slope/Drop_Intercept and The maximum number of Active Set. The Remaining Set is number of active pilots remaining after an active pilot dropped out from active set.

Step 106: The MSHO Handoff parameters calculations, including T_{ADD}, T_{DROP}, $T_{MultiSlope}$

Step 108: Check if candidate pilot exceeds the T_{ADD} threshold.

Step 110: Check if neighbor pilot exceeds the T_{ADD} threshold.

Step 112: Add the candidate pilot into active set.

Step 114: Add the neighbor pilot into candidate set.

Step 116: Store the active pilots, and go to step 104.

Step 118: Check if active pilot exceeds the T_{DROP} threshold for T_{TDROP} seconds.

Step 120: Check if candidate pilot exceeds the T_{DROP} threshold for T_{TDROP} seconds.

Step 122: Drop the active pilot into candidate set.

Step 124: Drop the candidate pilot into neighbor set.

Step 126: Update the active plot in the active set, i.e. remaining active set, after the dropping of any active pilot, then go back to step104.

4.6 Summary

The simulation platform constructs wireless communication environments for handoff studies. All the channel models, user mobility and power control technologies are built in it. The performance matrix can be used for comparing advantages and disadvantages in traditional and innovated handoff algorithms.

Chapter 5 Simulation Results

The handoff simulation platform described in Chapter 4 is used for analyzing the performance of new handoff control designs. The performance includes, but not limited to (1) connection quality, (2) forward-link power usage (capacity), (3) hardware resources (channel elements), and (4) processing load (handoff frequency).

5.1 The Simulation Assumption

In order to have proper assessment of the results, we first decide a proper loading based on cdmaOne experience. In IS-95A(cdmaOne), the proper average operating aggregate pilot Ec/Io should be around of -8dB to ensure the target FER of 1% to 2%. Here, the multi-slope quality based handoff algorithm is based on the two-slope design only. The assumptions used for different handoff control algorithms are listed in Table 5.1.

Table 5.1, Algorithm Assumptions

	Tadd	Tdrop	Ttdrop	Tquality	SlopeI	SlopeII	Add Intercept	Drop Intercept
IS-95A	-13 dB	-15 dB	1 sec	X	X	X	X	X
IS-95B/cdma2000	D	D	1 sec	X	1	X	D(-3)	D(-5)
Multi-Slope	D	D	1 sec	-6 dB	1	vary	D(-3)	D(-5)

D: Dynamic, X: N/A (not available)

Note: The first slope is set at the value of 1. The performance of IS-95B/cdma2000 is very close to the slope value of 1 for both the slope one and slope two.

As depicted in Figure 3.2, to operate at the average aggregate Ec/Io of -8dB, 6-user case (with continuous transmission) is chosen. It is important to know that the results in Figure 5.1 are the average performance among 100 runs with each run lasting 60 seconds. The intention is to identify the average operating range.

When the traffic loading in each sector gets heavy, the handoff issues will become increasing important. As shown in Figure 5.1, the MSHO helps the connection quality when the traffic loading gets heavier. Based on IS-95A(cdmaOne) experience, aggregate Ec/Io of -8 dB will be the proper operating range. In this case, 6 –user case will be chosen and will be used for the comparison studies.

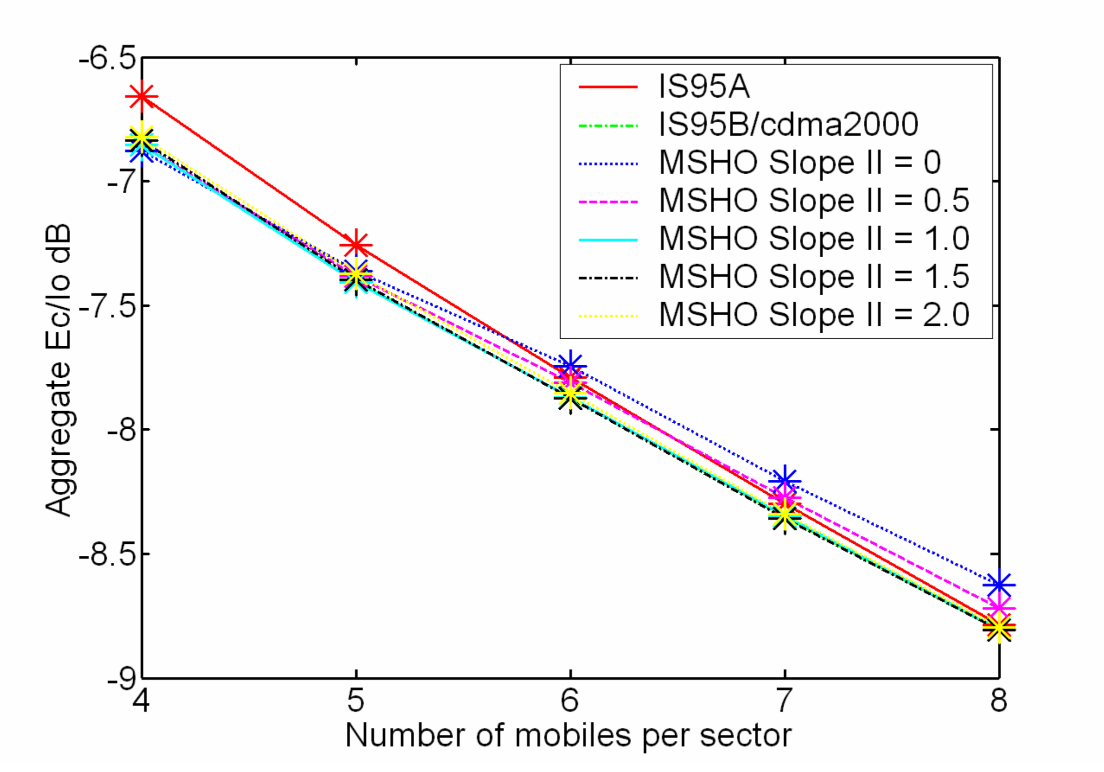

Figure 5.1, Average aggregate Ec/Io vs. number of active users

5.2 Connection Quality

In any control designs, maintaining the connection quality is always the first fundamental objective. To quantify the connection quality, the aggregate pilot Ec/Io is used for evaluating the average aggregate performance and individual performance.

Considering the average aggregate connection quality, as shown in Figure 5.2, the multi-slope quality-based handoff algorithm with the second slope value less than one (up tilt from the slope I) has the improvement in the average connection quality for most Ec/Io operating ranges. But if we selectively examine user’s instant performance (at every 200 msec), plotted in Figure 5.3, the gain (relative to the cdmaOne) are not guaranteed. Figure 5.4 shows the pilot channel variation in aggregate Ec/Io. The variation grows, when the slopeII decreases. Here, it is more important to point out that even implementing a conservative algorithm likes cdmaOne (by adding legs more aggressively), the algorithm does not necessary improve the connection quality. In other words, adding a leg does not necessarily improve the connection quality but instead the leg could increase the interference level which might have a negative impact on the connection quality. As shown in Figure 5.4, with MSHO slopeII decreases, the standard deviation in aggregate Ec/Io has a minor increase. This will have an impact on the connection stability.

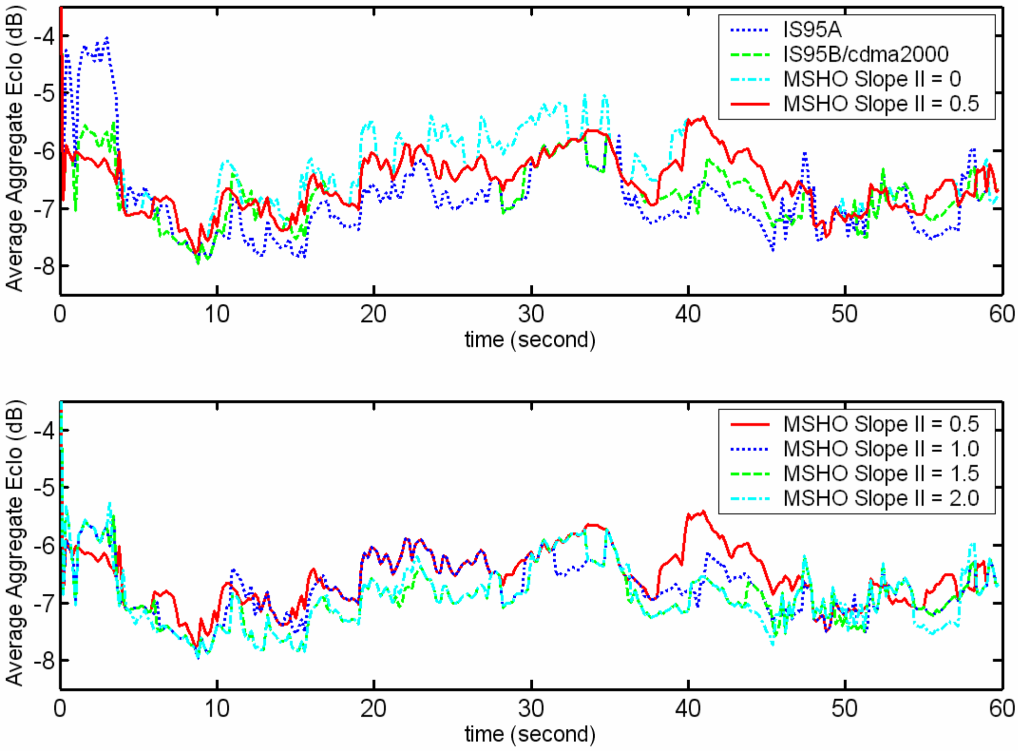

Figure 5.2, Average aggregate Ec/Io at 6-user case

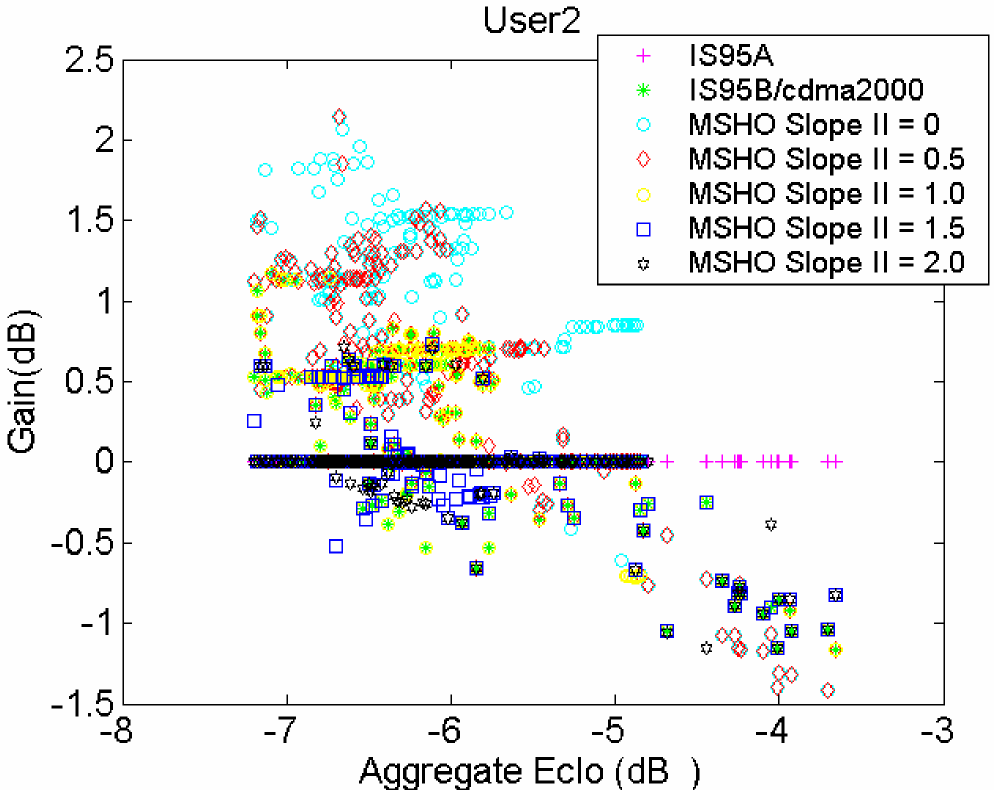

Figure 5.3, Instant Performance (200 msec average) – User 2

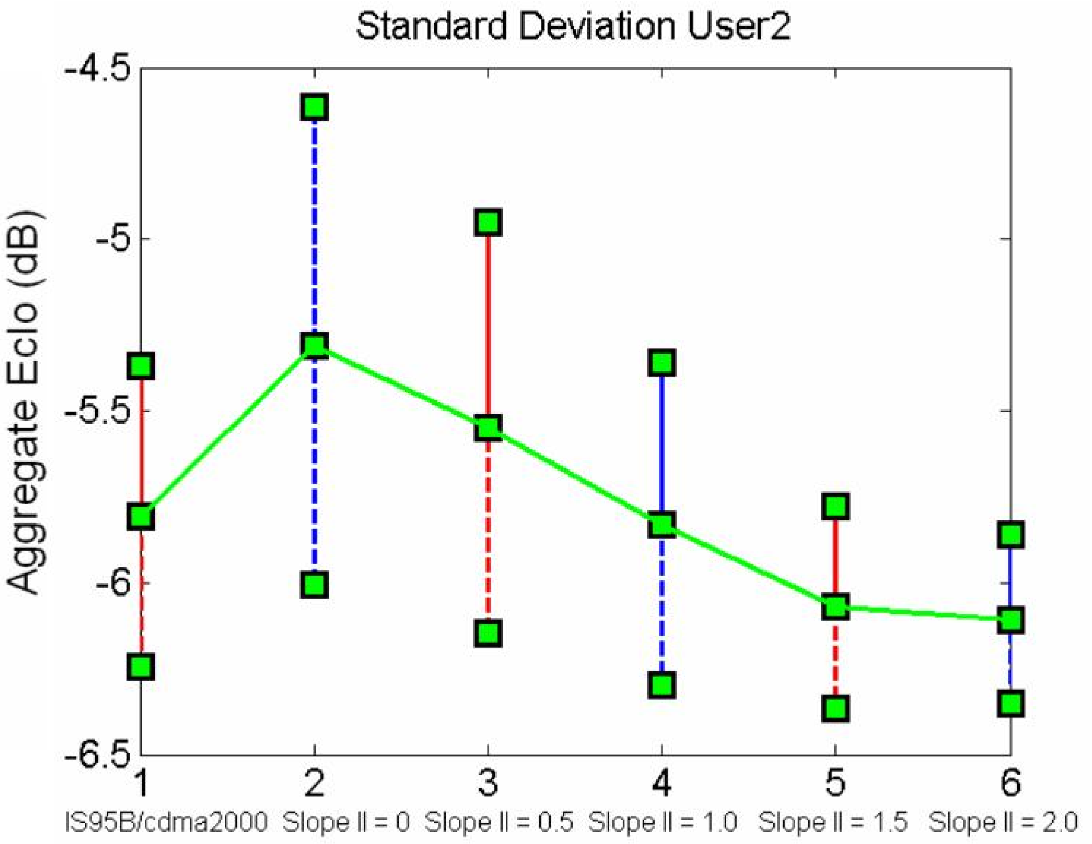

Figure 5.4, The standard deviation in aggregate Ec/Io _User2

5.3 Forward-link Power Budget

In current CDMA system designs, the forward-link power budget is limited. Any controls to reduce the total power can effectively improve the forward-link capacity. In a CDMA system, if a user has multiple connections, it means that multiple sectors need to transmit the same power to the user (if the power synchronization is done properly). In this case, if a leg has only minor contribution to the connection quality, the leg could be eliminated to reduce the transmitted power. In Figure 5.5 and Figure 5.6, to support the same number of users, the multi-slope handoff algorithm needs less power than the baseline algorithm, when slopeII equals to 0 and 0.5 cases. If we compare the correlation between the total transmitted power (Figure 5.5) and the average aggregate pilot Ec/Io (Figure 5.2), we find that there exists a high negative correlation between the average aggregate pilot Ec/Io and the total transmitted power; the reduction of the transmitted power has a positive effect on the average connection quality. Among all, the multi-slope quality-based handoff algorithm with second slope values of 0 and 0.5 need the less forward-link transmitted power with comparable connection quality.

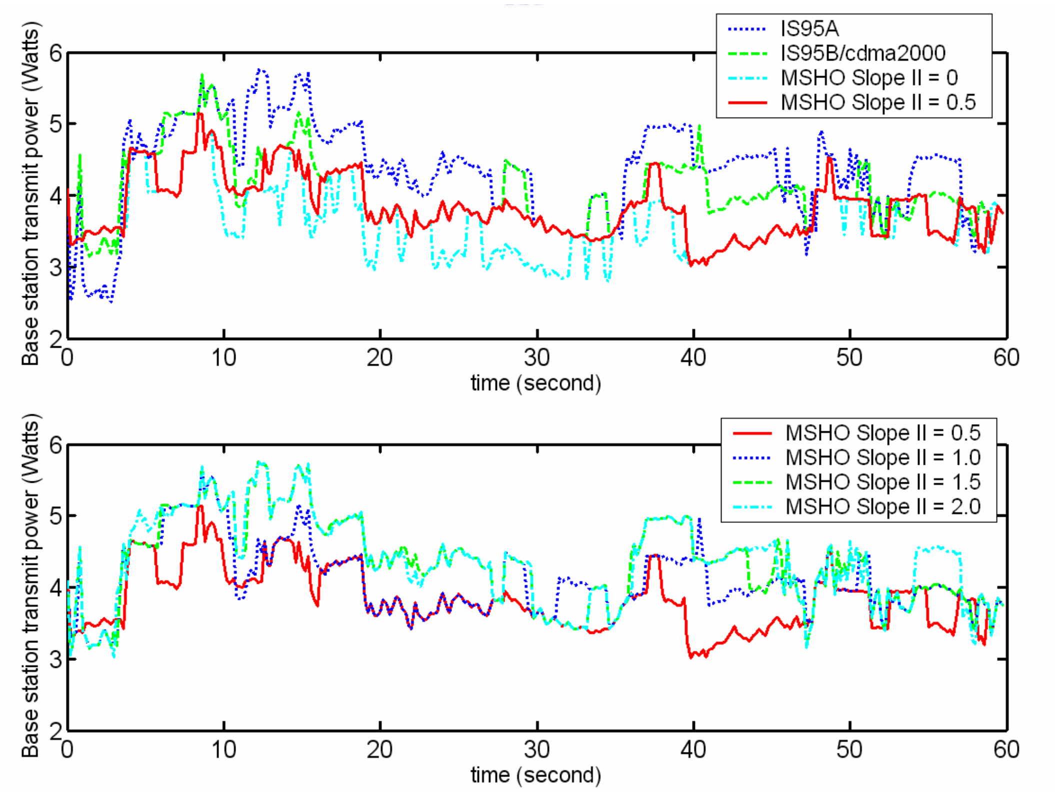

Figure 5.5, Base Station Transmit Power at 6-user Case and the Associated Aggregate Pilot Ec/Io

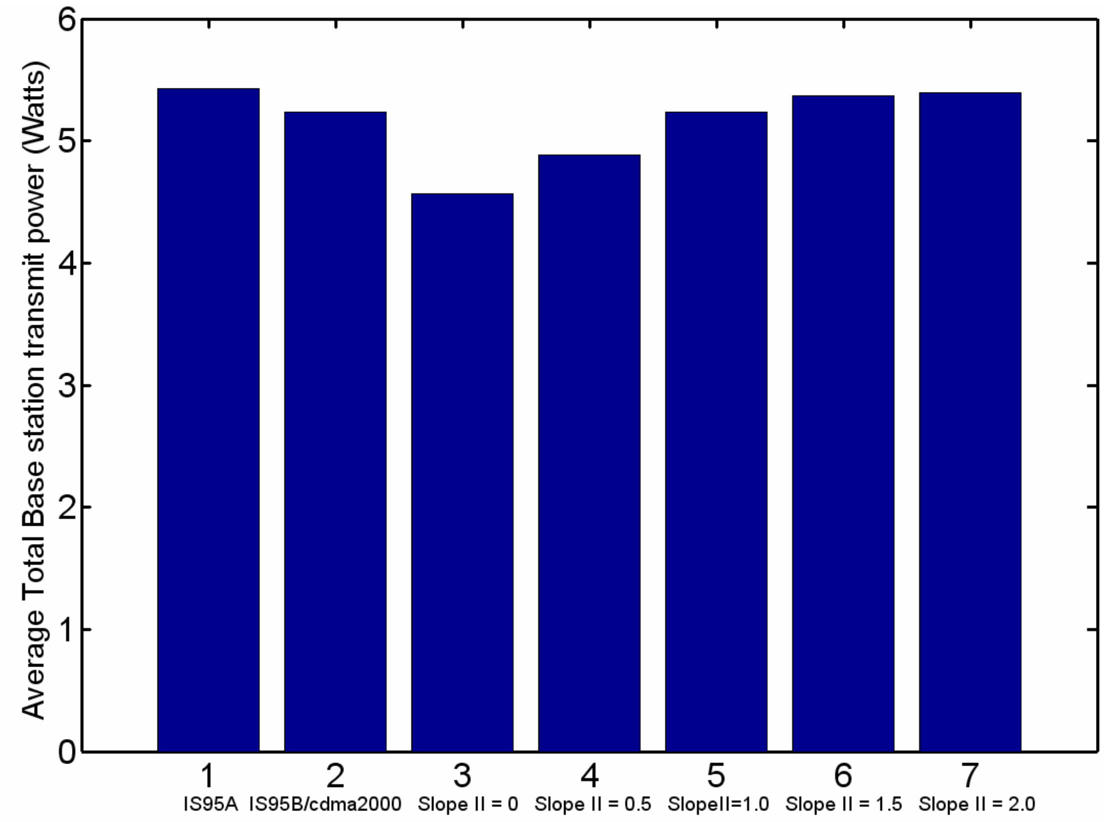

Figure 5.6, Average Total Base Station Transmit Power at 6-user Case

5.4 Channel Elements (Hardware Resources)

In this section, we will quantify the saving on the required channel elements. Figure 5.7 shows the average channel element usage at each sample time in different handoff control mechanisms and Figure 5.8 shows its average channel element usage in histogram. In Table 5.2, the saving in channel elements (CEs) is significant at the normal traffic loading situation, when slopeII=0 and 0.5. Without compromising the connection quality, this reduction in CEs is very important especially the purchasing of CEs will occupy the most portion of the capital investment. Besides, the provisioning on the backhaul to accommodate the CEs' traffic is even more critical for the daily operation cost.

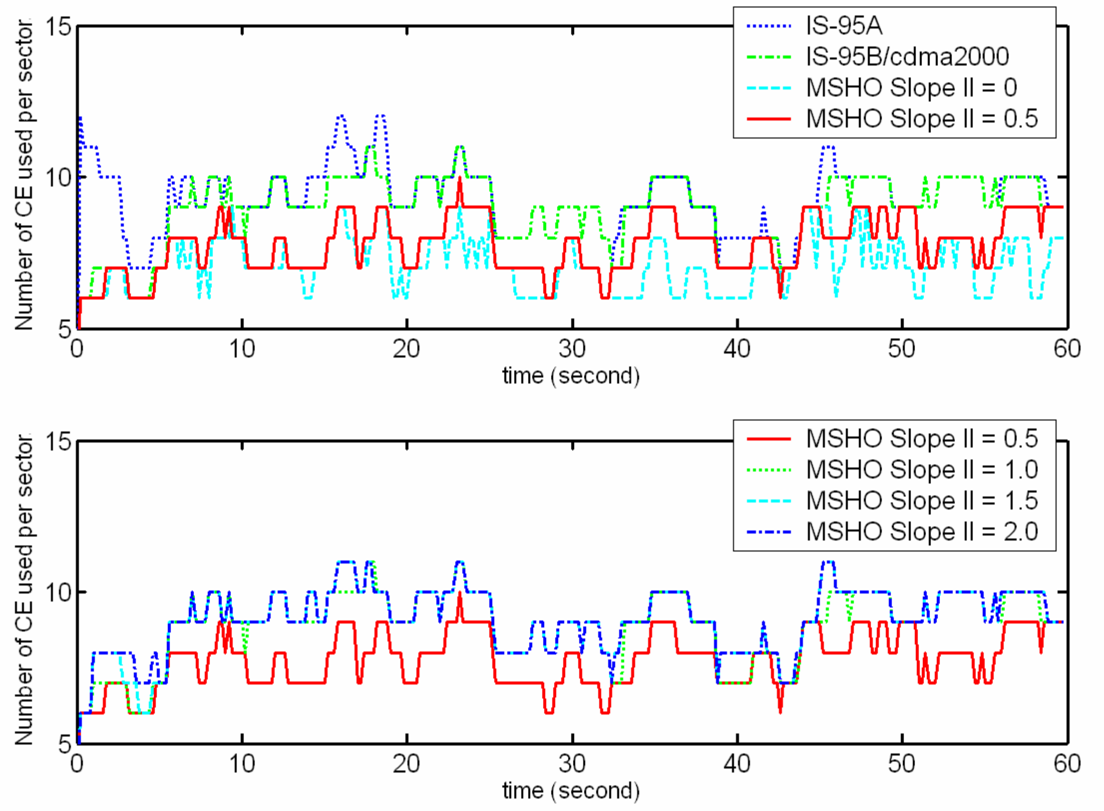

Figure 5.7, Channel Element (hardware) Usage at 6-user case

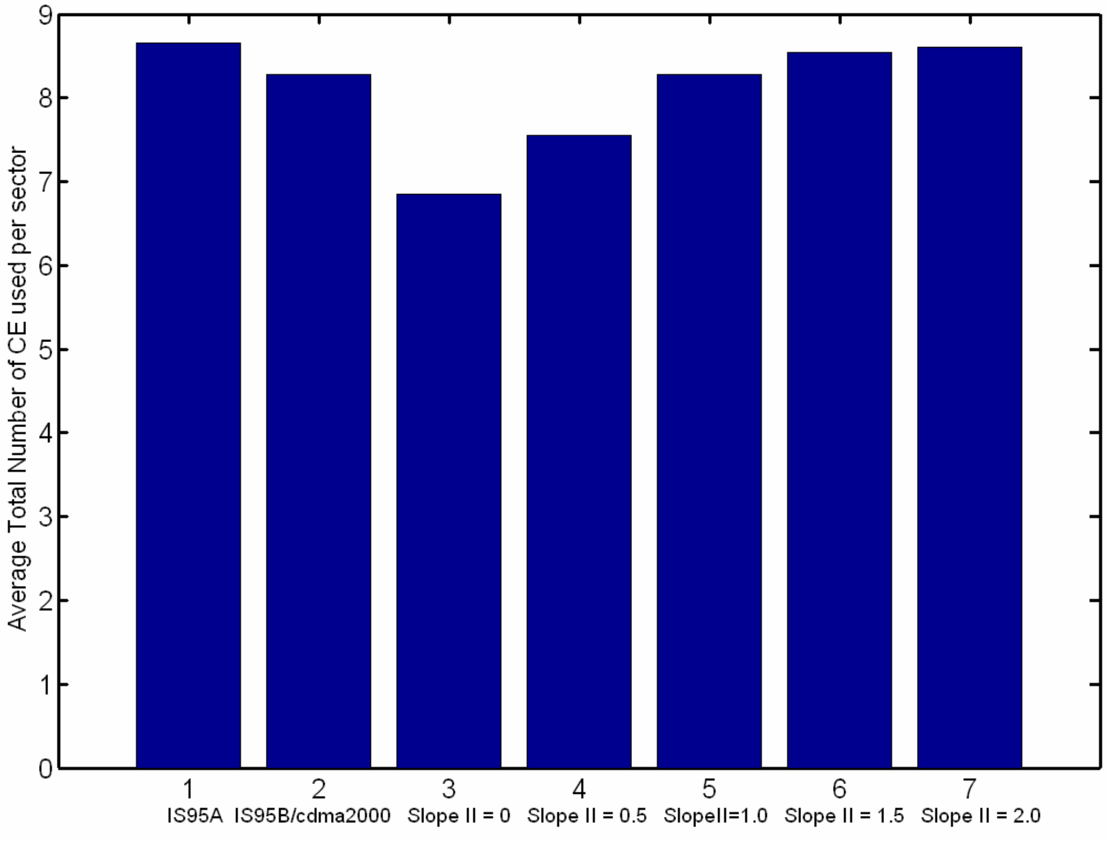

Figure 5.8, Average Total Channel Element Usage at 6-user case

Table 5.2, Channel Element (hardware) Usage Percentage at 6-user case

	Channel Element Usage Percentage
IS-95A(Based-Line)	100.00%
IS-95B/cdma2000	95.11%
Slope II = 0.0	78.72%
Slope II = 0.5	86.45%
Slope II = 1.0	95.11%
Slope II = 1.5	98.50%
Slope II = 2.0	99.29%

Table 5.3, Handoff Leg connection distribution

Handoff Distribution	1_way	2_way	3_way
IS-95A	49.15%	42.82%	8.02%
IS-95B/cdma200	62.74%	33.55%	3.71%
Slope II = 0.0	84.55%	13.96%	1.48%
Slope II = 0.5	73.58%	24.81%	1.61%
Slope II = 1.0	62.51%	33.67%	3.82%
Slope II = 1.5	58.88%	35.73%	5.38%
Slope II = 2.0	56.42%	37.48%	6.10%

Consistently, in Table 5.3, the increases of the slope II value increase the probability of multiple-leg connections that explain the increase of the CEs. for the same number of users.

5.5 Processing Load (Handoff Frequency)

For each handoff process, there is a set of call processing messages sent back-and-forth between the base station and the user. This processing load will reduce the capacity of the processor for handling other calls (if the processors have reached the processing limit). From a design perspective, any reduction of unnecessary processing load is always important, especially when the processing power is limited or when the relative power consumption is a major concern. In Figure 5.9, the number of handoff frequency is plotted with different algorithms. As shown, the multi-slope quality-based handoff algorithm has less handoff events in a 60-sec call duration. Among all settings, the second slope of 0.5 provides the most saving in the handoff trigger events and the associated processing power.

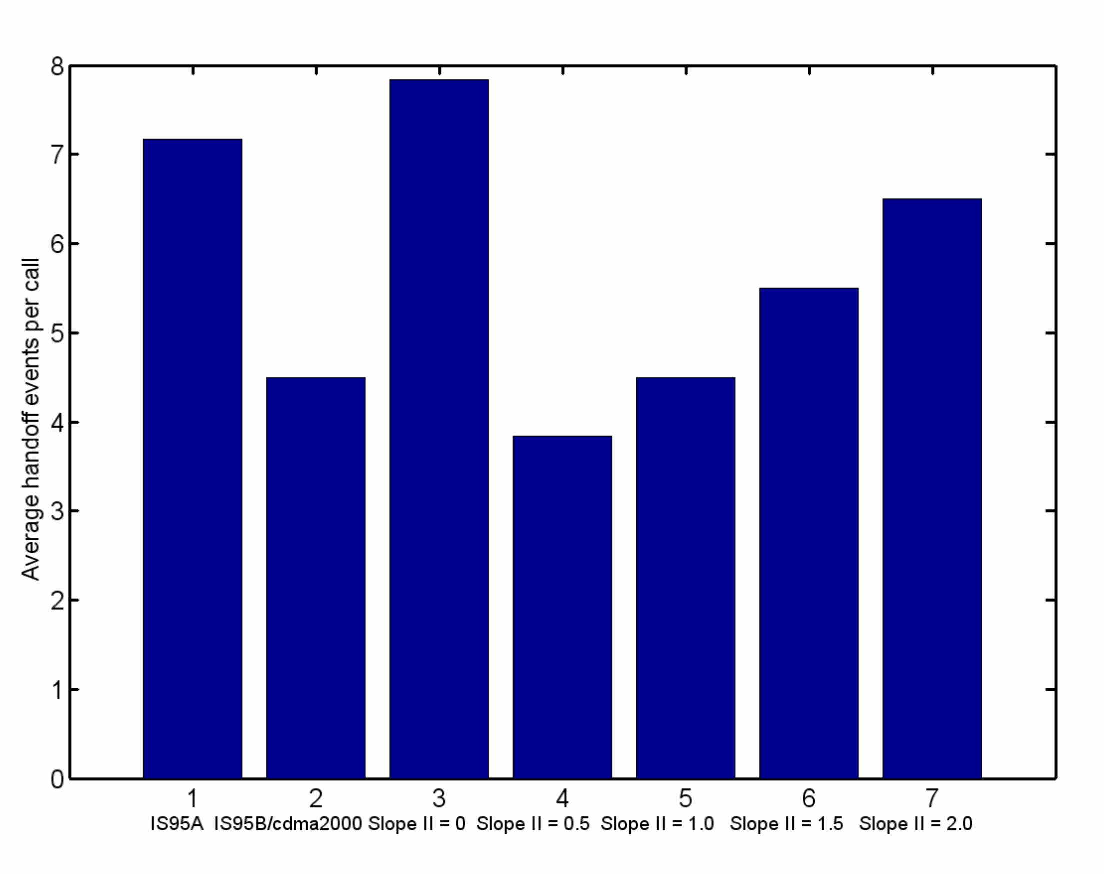

Figure 5.9, Handoff Events per 60-sec Call

Whenever a pilot connection is added into active set or an active pilot is dropped from active set to candidate/neighbor set, it represents a handoff event. As seen in Figure 5.9, handoff events would double when slopeII equals 0 as compared to slopeII of 0.5. As shown in Figure 5.10, the handoff event grows as a concave curve in between slopeII of 0 to 1 in 10 minutes call. In our cases, setting stringent control at a poor connection reduces the required resources but increases the number of early drop that increase the number of handoff events. From Figure 5.10, slopeII of 0.8 provides the most saving in the handoff events.

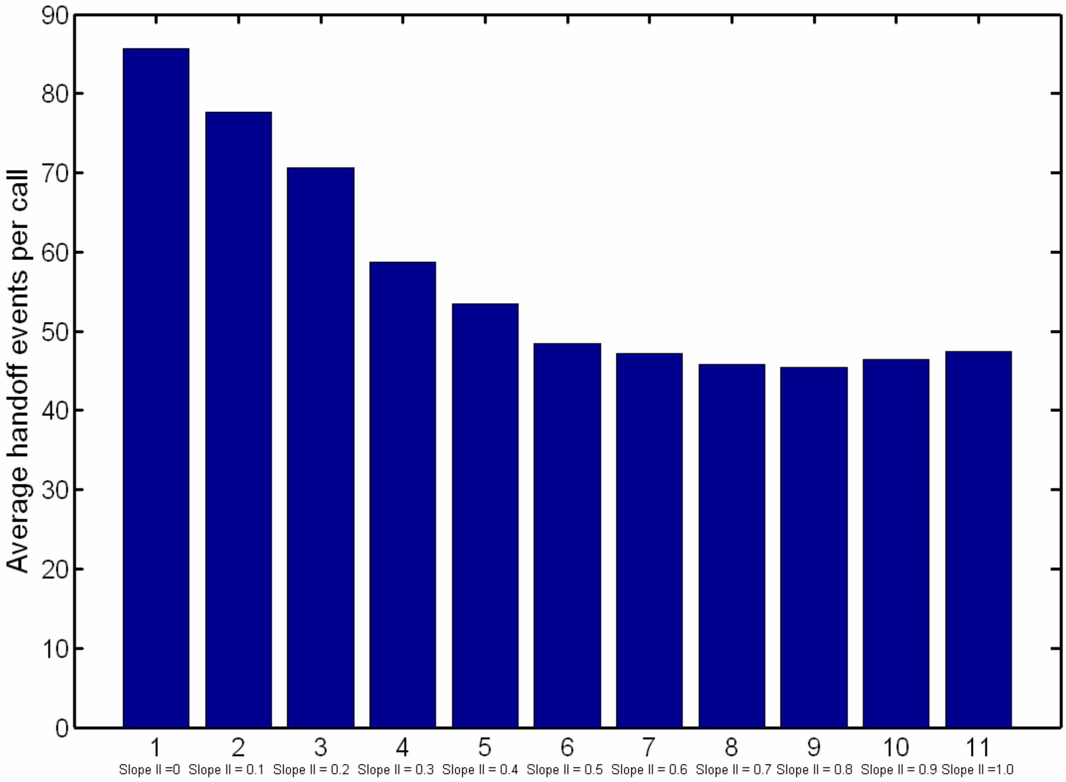

Figure 5.10, Handoff Events 5-minutes Call

5.6 Discussion

With comparable connection quality with cdmaOne and IS-95B/cdma2000, the Multi-Slope Quality Base Handoff algorithm can dynamically change its add/drop slopes and intercepts to gain the advantages of connection quality, and minimize the radio resource usage, such as the forward link power budget, channel element usage and handoff events. There exists a tradeoff between the slopeII values and the connection stability. However, with a minor impact in the connection stability, the MSHO can provide a flexibility of handoff control algorithm in wireless communication systems.

Chapter 6 Conclusions

In this thesis, the handoff simulation platform is developed for handoff control mechanisms studies in wireless communication systems, including IS-95A(cdmaOne), IS-95B/cdma2000, and proposed MSHO handoff control algorithms. In general, multi-slope quality-based handoff algorithms provide better resource management with comparable connection quality. The intention of having the conservative control in IS-95A(cdmaOne) to ensure the best connection quality does not stand. From our studies, with comparable connection quality, the multi-slope quality-based handoff control with the second slope minor up tiling, like 0.5, for slopeII provides the better saving and reduction in the required transmitted power, the channel element usage, and the number of the handoff triggers. Even the actual improvement depends on the traffic load and may vary from market-to-market and the multi-slope handoff control. Also, the design concepts provide the flexibility to meet different design criteria in future wireless systems.

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