COVERAGE EXTENSION USING POWER-CONTROLLED RELAYING IN CDMA

A Thesis by

Mahendra Karthik Vepuri

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The following faculty members have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science with a major in Electrical Engineering.

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Hyuck M. Kwon, Committee Chair

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Yanwu Ding, Committee Member

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Xiaomi Hu, Committee Member

DEDICATION

To my dad, Kishore, my mom, Madhavi, and my brother, Rohit

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ABSTRACT

In this thesis, the advantages of a power-control-based relay system for a code division multiple access (CDMA) network are explored. Relay nodes are placed in the form of a ring (not necessarily circular) based on system requirements, whereby a mobile user and base station can communicate directly or through relay nodes, depending on the received signal strength. Power control through the relays will provide an added advantage to the mobile stations, because they will use less power to transmit in reverse link. An optimal route is determined using the fundamental concept of the CDMA network, which is encouraging for implementing this system in practical circumstances. Through the proper allocation of relay nodes, coverage of the overall area (cell) can be extended. Area extension results for using relay nodes in the cell area are proven analytically. Finally, this thesis shows that power-controlled relaying in a CDMA network will increase the number of active users per given cell at a given time.

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CHAPTER 1

INTRODUCTION

1.1 Motivation and Objective

In a code division multiple access (CDMA) system, the near-far problem can affect system performance. To counter this problem, power control is used. A power-control system enables each user to transmit power that is required to maintain the minimum required bit energy-to-interference ratio (E_b/Io) [1]. The spectral efficiency of CDMA technology relies primarily on power control. The overall capacity of the CDMA system depends on intra-cell interference (interference due to users within the cell) and inter-cell interference (caused by adjacent cells that use the same frequency) [2]. Therefore, proper implementation of power control plays a very important role.

To achieve capacity, in other words to maximize the data rate of a CDMA network, Akl et al. developed an iterative algorithm [2]. In addition, they discussed the problem caused by different cell sizes [2]. Moreover, increasing the power in the forward link may increase interference to users in other cells. This will affect the overall capacity of the system [2]. Also, increasing the power in the reverse link will affect the overall capacity of the CDMA network due to increased interference within the cell.

In the literature, extensive studies about CDMA technologies and their coverage extension have been presented. Recently, Xiao et al. studied mobile relaying in a wireless infrastructure in order to extend base station coverage and enhance wireless connection throughput [3].

The goal of this thesis is to model a CDMA system to extend the coverage area and improve capacity. A new approach is presented based on the power-controlled relaying in CDMA systems.

In the literature, under relay communication networks, power allocation has been studied. However, power allocation and power control are fundamentally different. Power allocation is the distribution of power among the source and relay nodes, whereas power control is the control of the multiple access source transmitting power through several power control loops to minimize the effects of multiple-access interference. This is done to maintain the minimum required signal bit-to-noise ratio within which a certain frame error rate can be guaranteed [4]. In other words, the power used at the relays and the source has been studied in the literature. During power control, the base station does not know how much transmission power is used at the mobile station. Only a few papers have studied power control among the base station, mobiles, and relays.

Cell-size expansion directly contributes to a reduction in the number of base stations. Fewer larger cells covering a given geographical area provide the following benefits:

- Larger frequency-reuse distance (which decreases inter-cell interference).
- Cost reduction.
- Effective frequency planning.
- Effective capacity planning.

1.2 Thesis Outline

In Chapter 2, the system model is explained, and the relay selection method is presented. To simplify the relay selection, the principle of the handoff mechanism is used. In Chapter 3, coverage extension will be analyzed, whereby an out-of-coverage end user will need to communicate with the help of a relay. In this chapter, some of the important contributions of this thesis are provided by answering the following questions:

- What is the possible extension in coverage when power-controlled relays are employed?
- How is outage probability affected by power-controlled relaying?
- What is the possible increase in number of users per cell?

Finally, Chapter 4 concludes the thesis by providing observations.

1.3 Thesis Overview

Relays are positioned in a ring around a base station (B.S.) at distance "r," as shown in Figure 1.

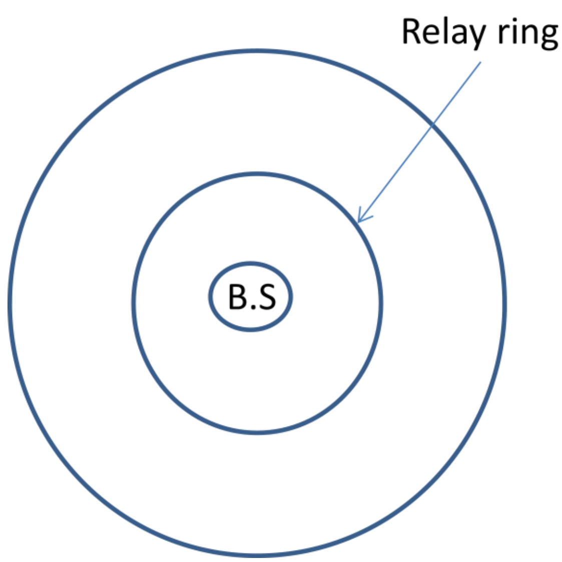

Figure 1. Relay Ring for Regular Cell.

This assumption is used only to explain the concept. In practice, the ring may not exist due to different path-loss exponents, even if the distance from the base station to the relays is the same. Within this ring, an end user is expected to connect directly with the base station. When the end user moves out of the ring, he/she will require assistance of relays to communicate with the base station. Perfect power control is assumed within the relay ring. Distances between the base station and the relay, between the relay and the end user, and between the base station and the end user are "r," "d," and "*l*," respectively. The angle between a direct path from the base station to the end user and the path from the base station to the relay is "θ." Figure 2 shows how the base station, the relay, and the end user are placed.

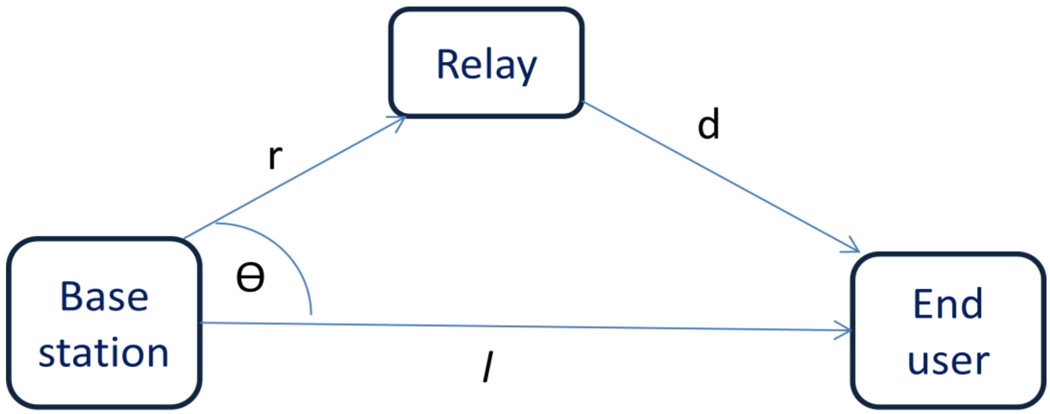

Figure 2. Simple Relay Network.

Equation (1) gives the relation between "θ" and distances (d, r, *l*), as considered by Xiao et al. [3]. Based on system requirements, the number of relays required for the system can be calculated using this equation. In order to have a larger "*l*," "θ" should be smaller (more relays in the system).

$$\theta = cos^{-1}((d^2 - r^2 - l^2)/2rl) \quad (1)$$

Relays are considered to be an integral part of a wireless infrastructure. At any given point of time, an end user (in the communication link) is connected to a single relay. When the link between the relay and the end user is established, the link between the base station and the end user is terminated, in order to save bandwidth and the number of active links connected to the base station. Relay handoff is also possible so that the link exists until the end of the call.

CHAPTER 2

SYSTEM MODEL

A single cell with a base station and an end user is considered in this model. The radius “r” of the cell is considered to be a unit, i.e., r = l for the no-relay case in Figure 2. Also, "l" is considered to be the distance between the base station and an end user. When a user is within the coverage area, then l < r, and when a user is out of the coverage area, then $l \geq$ r. A stationary relay is considered to be distance r from the base station, and the angle between the link of the base station-relay and the link of the base station-end user is “θ,” as shown in Figure 2.

The relation d < r is constrained since a relay is considered to be less powerful than the base station. It is assumed that two power-control loops, i.e., open-loop and closed-loop power control, according to Viterbi [1], are implemented independently to the end user from the relay, and to the relay from the base station. It is also assumed that the power-control links may be established among more than one base stations or relay-base station or relay-relay, but communication links are available only through one base station or relay.

How are relays selected?

In a conventional CDMA system, handoff takes place when a mobile station moves from one cell to another. During handoff, a mobile station is able to listen to both base stations at the same time. During this time, power-control commands sent by the two base stations can vary. One of the base stations can ask the mobile user to power up, and the other base station can ask the mobile user to power down. In this situation, the mobile user will listen to the base station that gives the power-down command. Therefore, in the situation when multiple commands are heard by the mobile unit, if any of the base stations asks a mobile user to power down, it listens to that command. In general, if a base station asks a mobile user to power down, this implies that the link between the base station and the mobile station is good. When the link between the base station and the mobile station is bad, then the command given to the mobile station will be to power up. This concept is illustrated in Figure 3.

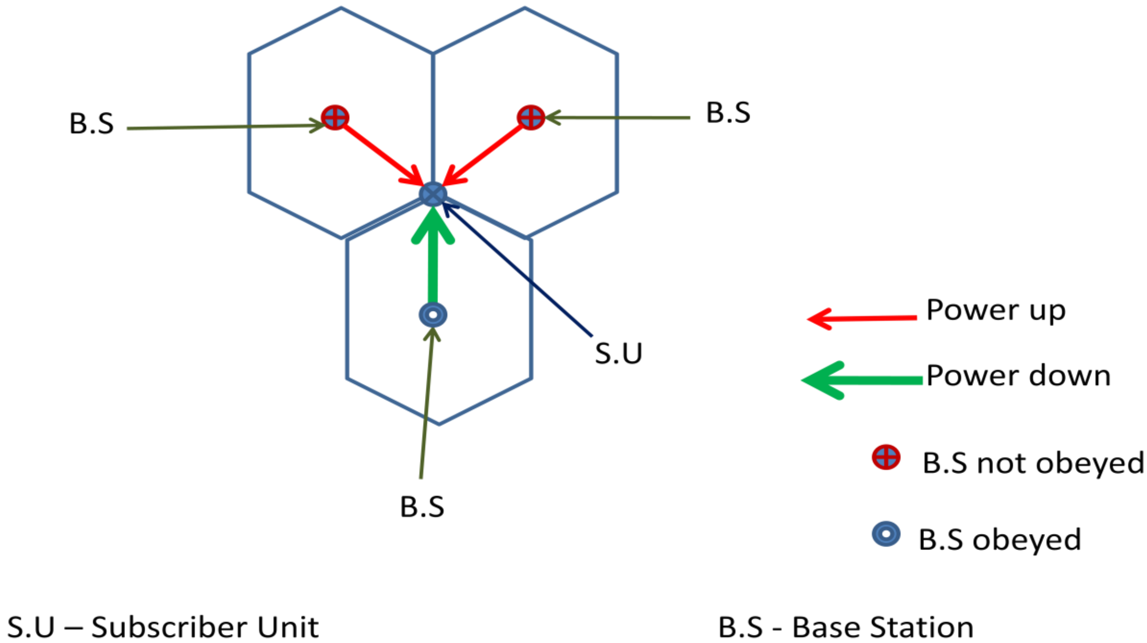

Figure 3. Handoff Mechanism in Regular CDMA Cell.

A similar concept can be applied to implement power control through relays in a CDMA system. In a relay-based CDMA system, if a base station requests the mobile user to power up and a relay request to power down, then the mobile user will try to communicate through the relay. Because of this, it is not necessary to be concerned about setting up the relay ring based on transmission time. Here, power control can be used as an advantage to the relay-based system. This technique will also help a mobile user to obtain an optimal route because a better link is chosen. Similarly, a relay-to-relay handoff can be implemented. When multiple power-control commands are received by a mobile station, the best link is selected based on those power-control commands. The relay that asks a mobile station to power down is preferred. This can be seen in Figure 4.

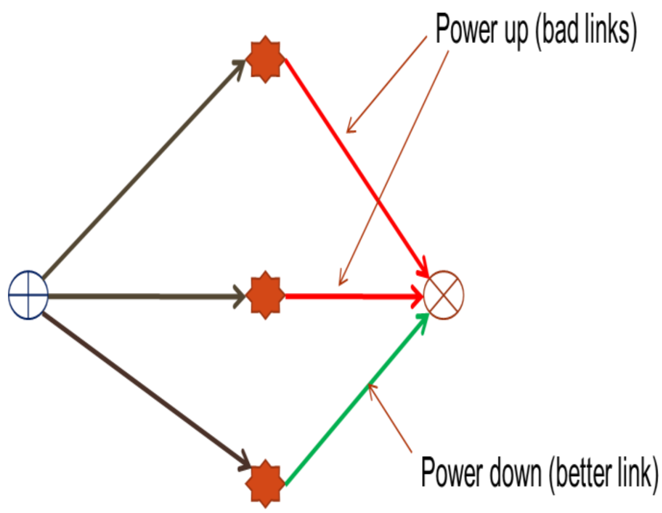

Figure 4. Relay Selection.

CHAPTER 3

COVERAGE EXTENSION

3.1 Analysis

For a regular CDMA system, a scenario where a mobile station moves into a poor-coverage zone is analyzed. For example the mobile-received power and the cell-received power drop by 10 dB. In this situation, power-control loops enable the cell-received power to rise to an acceptable level in approximately 10 ms, as observed in Figure 5.

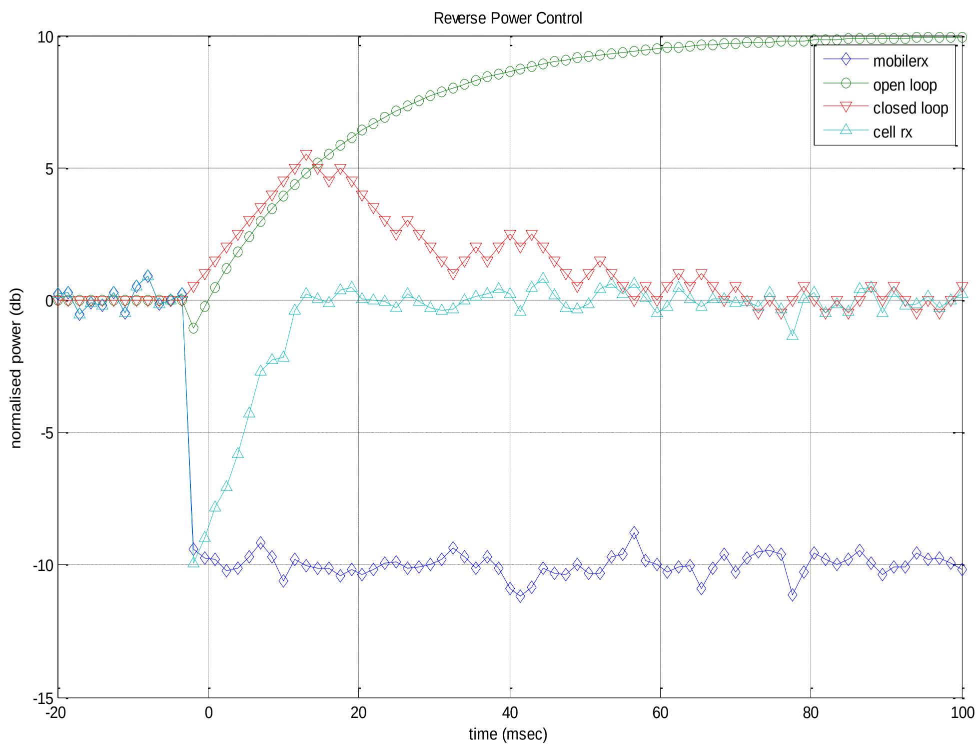

Figure 5. Reverse Power Control for Regular CDMA System.

A similar scenario can be analyzed for a relay-based system. When relays are implemented in the system, the relay gain is defined as

$$R_{gain}=P_{reg}-P_{w/rel} \quad (2)$$

where P_{reg} is the power required to transmit a signal to a unit distance in a regular CDMA system, and $P_{w/rel}$ is the power required to transmit a signal to a unit distance in a power-control-based relay system.

Following the numerical example, a similar model can be analyzed here. Because of this relay gain, an acceptable degradation can be extended to 13 dB, when the gain due to relay is considered to be 3 dB. When power-control loops are implemented, the relay gain helps the cell-received power to rise quickly. This additional degradation does not compromise quality because the time to rise to an acceptable quality in both a regular CDMA system and in a relay-based system is the same, i.e., 10 ms, as observed in Figure 6.

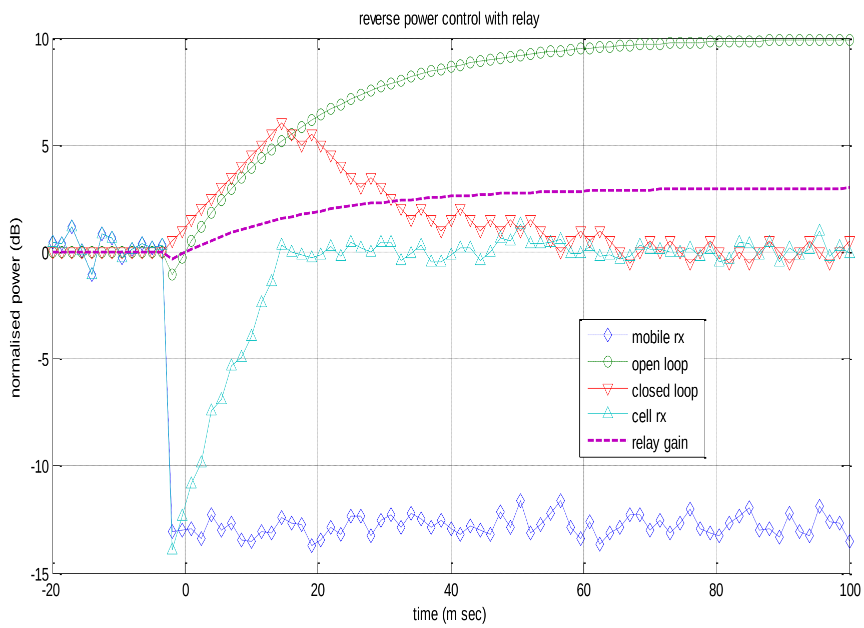

Figure 6. Reverse Power Control for Relay-Based CDMA System.

Thus, Figures 5 and 6 show the reverse power control in a regular and a relay-based CDMA system, respectively. Based on these results, it can be claimed that due to the use of relays, a mobile user can travel farther away from the base station, because the allowed degradation of the mobile received power is proportional to the distance. This will provide the required coverage extension in a CDMA system.

3.2 Outage Probability for Imperfect Power-Control Case

Imperfect power control is one of the most important issues in capacity analysis for a CDMA system. During an imperfect power-control scenario, the bit energy-to-interference power density ratio E_b/I_o fluctuates. This variation is log-normally distributed, with a standard deviation between 1.5 and 2.5 dB. Therefore, E_b is not considered a constant value, i.e., $E_{bi} \triangleq \in_i E_{bo}$, where $\in_i$ is the fluctuation parameter due to the imperfect power control. The following condition shows the relationship between the outage probability and the distribution of the sum of k_u users, as given by Akl et al. [2]:

$$P_{out} < Pr\,[Z^1 = \sum_{i=1}^{k_u} \in_i v_i > K_o^1]. \tag{3}$$

Here v_i is the binary random variable that indicates whether the *i*-th user is active at any instance or not. Let

$$x_i \triangleq 10log_{10}(\in_i E_{bo}/I_o) \tag{4}$$

where x_i is a random variable, which is normally distributed with mean m_c and standard deviation σ_c. The n-th moment of $\in_i$ is given by

$$E(\in_i^n) = \frac{(e^{\beta m_c})^n (e^{n^2(\beta\,\sigma_c)^2/2})}{(E_{bo}/I_o)^n} \tag{5}$$

Normal approximation for outage probability is given by Akl et al. [2] as

$$P_{out} \approx Q[\frac{K_o^1 - \rho(\lambda/\mu)(1+f)e^{(\beta\,\sigma_c)^2/2}}{\sqrt[2]{\rho(\lambda/\mu)(1+f)}e^{(\beta\,\sigma_c)^2}}] \tag{6}$$

where ρ is the activity factor, λ is the call arrival rate, $1/\mu$ is the call duration, and f is the frequency-reuse factor, which is equal to 0 for a single cell. The standard deviation σ_c ranges from 1.5 to 2.5 db. This fluctuation of E_b is caused by interference due to imperfect power control.

Relationship between σ_c and Distance d

The base station-received power is given by

$$P_{rx} = P_{tx}\left(\frac{1}{4\pi(d)^{\alpha}}\right)G_{tx}G_{rx} \quad (7)$$

where P_{tx} is the transmitted power from a mobile station; d is the distance between the mobile station and the base station; α is the path-loss exponent, where α = 2 for free space and α = 4 for urban areas; and G_{tx} and G_{rx} are transmitter gain and receiver gain, respectively. In equation 7, G_{tx}, G_{rx}, and α are constants, and P_{rx}, P_{tx}, and d are the only variables. Consider the same equation for different distances $d1$ and $d2$:

$$P_{rx1} = P_{tx1}(1/4\pi(d_1)^{\alpha})G_{tx}G_{rx} \quad (8)$$

$$P_{rx2} = P_{tx2}\left(\frac{1}{4\pi(d_2)^{\alpha}}\right)G_{tx}G_{rx} \quad (9)$$

Consider equations (8) and (9) for the imperfect power-control case, and this can be written by defining $P_{tx1} \triangleq \in_1 P_{tx1}$, and $P_{tx2} \triangleq \in_2 P_{tx2}$, respectively, by using these relationships and considering the cell-received power to be the same. Thus, for α = 2,

$$\in_1 (d_2)^2 \propto \in_2 (d_1)^2 \quad (10)$$

which implies that

$$\left(\frac{(d_2)^2}{(d_1)^2}\right) \propto (\in_1/\in_2) \quad (11)$$

because $\in_i$ depends on its standard deviation, i.e, $\in_i \propto \sigma_{ci}$

$$\left(\frac{(d_2)^2}{(d_1)^2}\right) \propto (\sigma_{c1}/\sigma_{c2}) \quad (12)$$

When the numerical values are substituted into the equation, taking $d_2 = 10$ and $d_1 = 5$, then

$$\sigma_{c1} \propto 4\sigma_{c2} \quad (13)$$

In other words, the greater the distance, the greater the variance. So with the help of equation (13), it can be clearly claimed that the standard deviation of fluctuation in the signal bit energy level σ_c mainly depends on distance (for free-space case). Therefore, $\sigma_c$is reduced if the path is shorter. For a power-control-based relay communication system, path loss can be reduced in an efficient manner, hence reducing σ_c. Figure 7 is plotted using equation (6) and shows how σ_c affects the number of users $\rho.\lambda/\mu$ in the system.

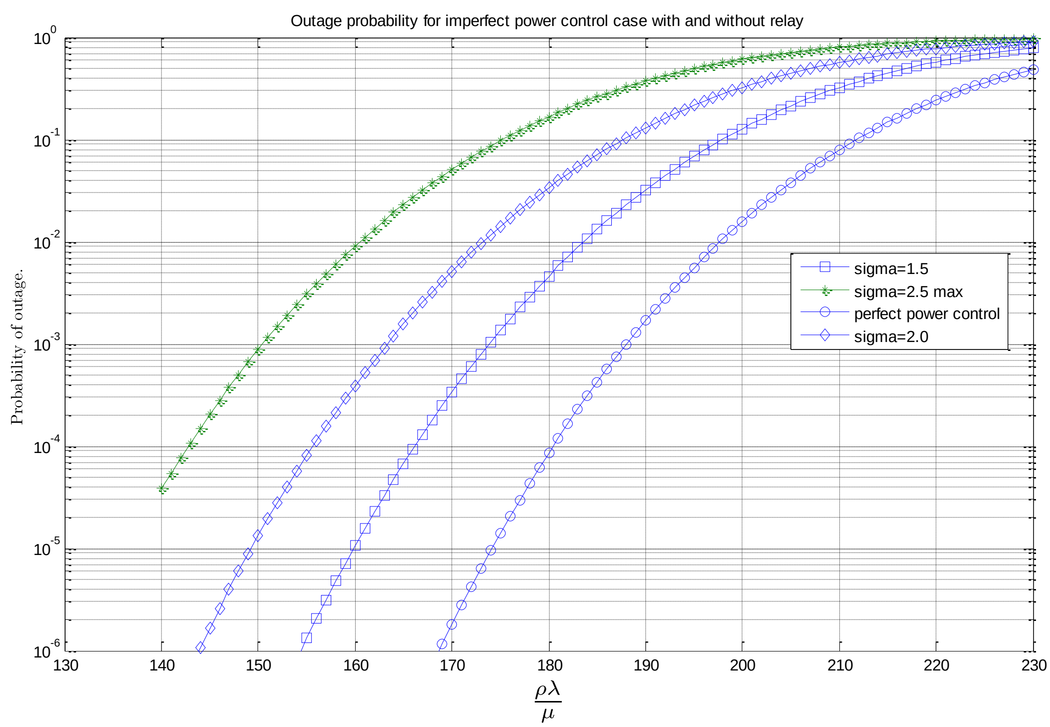

Figure 7. Outage Probability with Relaying.

In Figure 7, it can be seen that σ_c = 2.5 is for a regular CDMA system without relay, and σ_c = 1.5 and σ_c = 2.0 are for the power-control-based relay-system cases. When power-controlled relaying is employed, σ_c can be reduced, which means that the performance can be moved towards the perfect power-control case (which is desirable). In Figure 7, when all four graphs are compared, at outage probability equal to 10^{-3}, it can be observed that for the imperfect power-control case, the number of active users is about 150. This number increases to about 163, 173, and 188 for σ_c = 2.0, σ_c = 1.5, and σ_c = 0, respectively. This will allow the system to accommodate more users, which means that larger cells can be allowed, thus achieving coverage extension.

3.3 Propagation Loss Model

Variation in the standard deviation depends on interference. On the other hand, interference is directly proportional to the propagation loss, i.e.,

Interference (I) ∝ Propagation loss (L).

The propagation model of the Consultative Committee on International Radio (CCIR) for evaluating propagation loss as a function of distance is employed. According to this model, at 850 MHz, for a regular CDMA system, the following formula is available [1]:

$$L = 119.95 + (44.9 - 6.55 log_{10} h_{bs}) log_{10} d_{km} - 13.82 log_{10} h_{bs} - 2.52 h_{ms} + 25 log_{10}(\%) \quad (14)$$

where h_{bs} is the height of the base station, h_{ms} is the height of the mobile station, and d_{km} is the link distance in "kilometers."

A similar model can be used for the relay-based system. Here, the effective height of the relay "h_r" is introduced. The effective height is not equivalent to the true height of the relay. The effective height of the relay antenna depends on the relay gain; therefore, relay gain is added in the form of h_r as

$$L = 119.95 + (44.9 - 6.55 log_{10}(h_{bs} + h_r)) log_{10} d_{km} - 13.82 log_{10}(h_{bs} + h_r) - 2.52 h_{ms} + 25 log_{10}(\%) \quad (15)$$

Here, $h_r = \mu h_{relay}$, where h_{relay} is the true height of the relay, and μ is bounded as 0 ≤ μ ≤1. A constraint $h_{relay} \leq \left(\frac{1}{2}\right) h_{bs}$ is assumed, and μ mainly depends on σ_c, so that as σ_c is reduced, μ increases, i.e., $\mu \propto 1/\sigma_c$. This implies that the effective height will depend on σ_c.

Figure 8 is plotted based on equation (15) and illustrates the relationship between the coverage distance and the effective height of the relay (h_r) at percentages of 20 and 22. Here, percentage is the percent of land covered by buildings

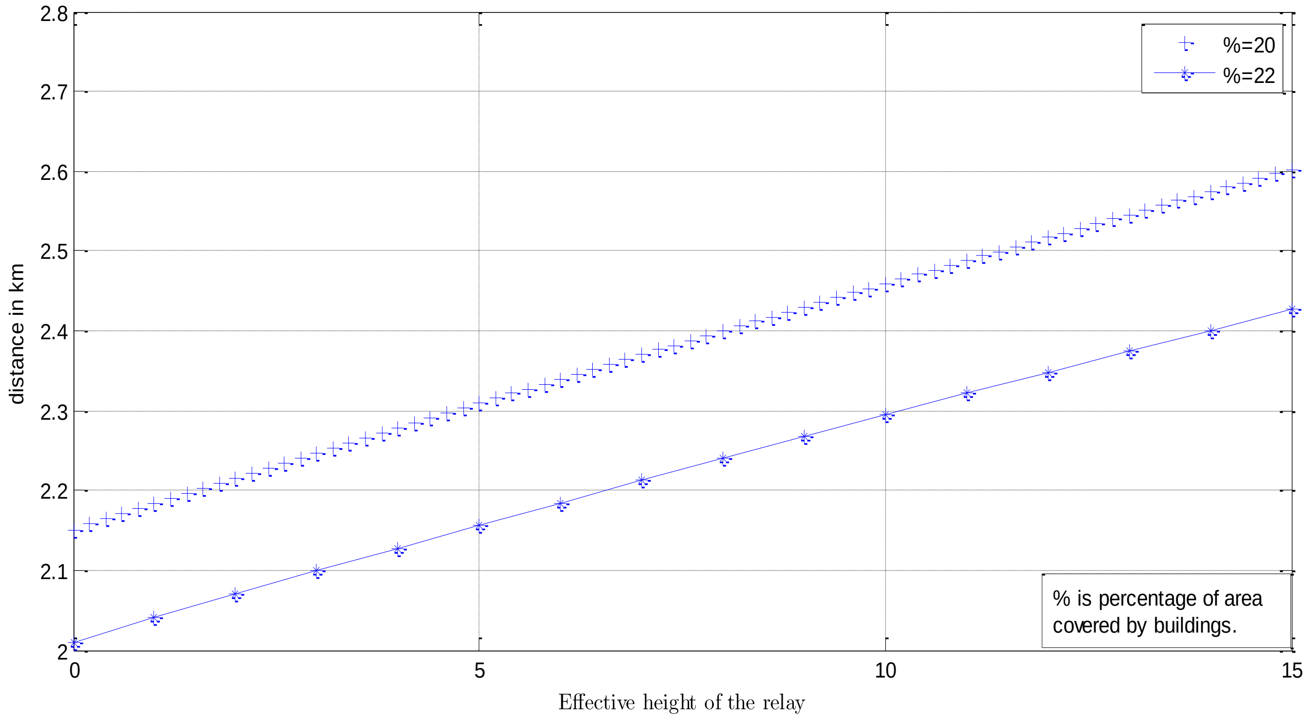

Figure 8. Distance in Kilometers Given Effective Height of Relay.

As shown, the effective height of the relay increases, and a significant increase in the link distance is achieved. At a height equal to zero (% = 20), the link distance is 2.15 km. And at h_r = 13 m, the link distance is almost 2.55 km. This is an improvement of about 0.4 km over the regular system, i.e., close to 20% improvement in the coverage area. With this, it can be claimed that the coverage extension is possible in a real-time CDMA system by implementing power-controlled relays.

CHAPTER 4

CONCLUSION

In this thesis, a new approach for relaying in cellular mobile systems is discussed. A possible way to implement the power-control-based relay system is provided. This approach is consistence with a regular CDMA system in the scope of real-time implementation. The important contributions of this work include simple, power-controlled ways to implement relays effectively, and the results are provided using a simple analytical approach. The effectiveness of power-controlled relaying is discussed by providing analytical results. A commonly accepted CCIR propagation loss model to provide proof of coverage extension is also discussed. It is observed that cell coverage can be extended up to 20% when the effective height of relay h_r is 13 m. With the analysis provided in the thesis, it can be claimed that the coverage extension can be obtained by applying power-controlled relaying in a CDMA system.

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APPENDIX

APPENDIX

MATLAB CODE

```
% Code For Figure 5 and 6
clc;
t=-20:1.5:100;% defining t-x axis
%t=linspace(-10,100,10);%
ol=10-10*exp(-50e-3*t);%open loop power
m=[1,length(t)];
m=0.5*randn(1,length(t))-13;%for mobile tx power
cl=zeros(1,length(t));
rl=3-3*exp(-50e-3*t);
for i=1:12
    m(i)=m(i)+13;
    ol(i)=0;
    cl(i)=0;
    rl(i)=0;
end
c=m;
for j=13:length(t)
    if ol(j)+cl(j-1)+m(j)+rl(j)<0
        cl(j)=cl(j-1)+0.5;
    else        cl(j)=cl(j-1)-0.5;
```

```
end
    c(j)=m(j)+ol(j)+cl(j)+rl(j);
end
plot(t,m,'d--');
hold all;
plot(t,ol,'o--');
hold all;
plot(t,cl,'v-');
hold all;
plot(t,c,'^-');
hold all;
plot(t,rl,'-')
grid on;
```

% Code for Figure 7

```
clc;
clear all;
ko1=230.4;
ko=230.4;
bet=log(10)/10;
ex=exp((bet*1.5)^2);
ex1=exp((bet*2.5)^2);
```

```
ex2=exp((bet*0)^2);

ex3=exp((bet*2.0)^2);


for y=140:230

    pout(y)=qfunc((ko-(y*sqrt(ex)))/(sqrt(y)*ex));

    pout1(y)=qfunc((ko1-y*sqrt(ex1))/(sqrt(y)*ex1));

     pout2(y)=qfunc((ko-(y*sqrt(ex2)))/(sqrt(y)*ex2));

     pout3(y)=qfunc((ko-(y*sqrt(ex3)))/(sqrt(y)*ex3));

end

semilogy(pout,'-s');

hold all;

semilogy(pout1,'-*');

hold on;

semilogy(pout2,'-o');

hold on;

semilogy(pout3,'-d');

grid on;

hold all;

legend('sgma=1.5','sgma=2.5 max','perfect p/c','sgma=2.0');


%Code for Figure 8

clc;
```

APPENDIX (continued)

```
clear all;
hb=30;
hm=1.5;
hr=0:.2:15;
%dmk=2.4;
l=140;
per=20;
%l=119.95+(44.9-6.55*log10(hb+ hr))*log10(dmk)-2.52*hm-
13.82*log10(hb+hr)+25*log10(20);
for i=1:length(hr)
dmk(i)=10^((l-119.95+2.52*hm+13.82*log10(hb+hr(i))-25*log10(per))/(44.9-6.55*log10(hb+
hr(i))));
end
plot(hr,dmk,'+');
grid on;
hold on;
clc;
clear all;
hb=30;
hm=1.5;
hr=0:15;
%dmk=2.4;
```

APPENDIX (continued)

```
l=140;

per=22;

%l=119.95+(44.9-6.55*log10(hb+ hr))*log10(dmk)-2.52*hm-
13.82*log10(hb+hr)+25*log10(20);

for i=1:length(hr)

dmk(i)=10^((l-119.95+2.52*hm+13.82*log10(hb+hr(i))-25*log10(per))/(44.9-6.55*log10(hb+
hr(i))));

end

plot(hr,dmk,'-*');

grid on;

hold all;

xlabel('hr');

ylabel('distance in km');

legend('%=20','%=22');
```