WIRELESS BROADCAST SERVICES

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A thesis submitted to the

Graduate School—New Brunswick

Rutgers, The State University of New Jersey

in partial fulfillment of the requirements

for the degree of

Master of Science

Graduate Program in Electrical and Computer Engineering

Written under the direction of

Professor Roy D. Yates

and approved by

New Brunswick, New Jersey

October, 2002

ABSTRACT OF THE THESIS

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In a mobile wireless communication network, broadcast signaling can be transmitted to multiple (two or more) receivers simultaneously. We define a coverage measure for broadcast transmission that counts both the data rate achievable by each user and the number of users receiving such data rate successfully under desired QoS requirements. We study a broadcast system with two QoS levels: common information received by all users, and additional information that can be decoded successfully by users with good channels. Broadcast power is allocated between these two subchannels. We examine the broadcast coverage from both an information theoretic perspective, as well as its implementation in a CDMA system. Depending on system constraints, we identify optimal power allocation policies. We show that for cellular CDMA systems, the moderate bit rate broadcast video may be practical.

Acknowledgements

My thesis advisor, Professor Roy D. Yates, has my sincerest gratitude, for both this thesis and my personal development. I have benefited greatly from his guidance and insight. I highly appreciate his continued support through my graduate studies, and interest in my research. His constructive criticism and detailed comments have greatly improved my technical writing and oral presentation.

I would like to express my thanks to Professor Narayan Mandayam, Professor Christopher Rose for accessing my work, participating my thesis committee, and for the invaluable comments and insights, without which it would not be complete. I would especially like to thank Professor Predrag Spasojevic, who took his time to listen to me and gave me very useful suggestions.

I am very thankful for the many friends and officemates I have known in WINLAB. A special word of thanks to Jianghong Luo, Lang Lin, Nan Feng and Dr. Siun-Chuon Mau for many useful discussions about my research problem.

Dedication

To my mom and dad

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Chapter 1

Introduction

Nowadays, wireless networks can provide many kinds of services to satisfy different customer demands [12, 41]. Voice services are delivered by a cellular phone. Short messages, such as stock market price quotations, can be downloaded to a Personal Digital Assistant (PDA). In the foreseeable future, surfing the Internet with a mobile computer will be widespread. Furthermore, higher date rate services are expected to be supported in future wireless networks.

An example of a future high data rate service is broadcast video transmission. While traveling, one could enjoy a favorite television channel, video program, or travel information, such as a road map. Such public information can be broadcast by a collection of base stations over a cellular system to a population of subscribers. Since these mobile wireless multimedia services will employ much greater radio bandwidth and higher transmission power, the efficient utilization of limited radio resources becomes increasingly important [4, 16, 17, 21, 22].

This thesis examines the cellular broadcast which can benefit a group of users within a given coverage area. Over time, a mobile user can experience great variation in the state of wireless channel. We may observe variations in the multipath fading, the path loss via distance attenuation, the shadowing by obstacles, and the interference from other users [32]. It is possible to serve a large number of subscribers by using high transmission power. If a broadcast strategy is used to transmit the same information to all users, a conventional approach will attempt to guarantee that every user within a given coverage area can receive the required QoS by limiting the transmission data rate to the channel capability of the worst user. However, a conventional broadcast strategy ignores the underutilization of better channels with higher channel capacity [27, 28].

In order to take advantage of the higher capacity of the better channels, we can provide a certain data rate to all users, while sending extra information to users with better channel conditions [6, 9, 10]. Each mobile terminal can determine how much information to decode according to its channel conditions. When the channel conditions are poor, a user will try to demodulate only a common information channel. When the user experiences a better channel state, she will decode extra bits, as well as the common information.

Some natural questions arise. What is a proper metric to evaluate broadcast throughput? What are the properties of a conventional single rate broadcast system under such a measure? What does information theory tell about the amount of information received successfully by a dual rate broadcast strategy with common and additional information? How can we implement such a strategy in a practical wireless system? What is the cost in radio resources to add a broadcast channel to a modern Code Division Multiple Access (CDMA) system? In answering these fundamental questions, we divide the thesis into four parts. The first develops the properties of single rate broadcast coverage and defines a coverage metric for broadcast throughput. The second addresses information theoretic aspects of a dual rate broadcast system. The third examines the practical spread spectrum CDMA implementation. The fourth elaborates on providing video broadcast service in a multi-cell CDMA system that already

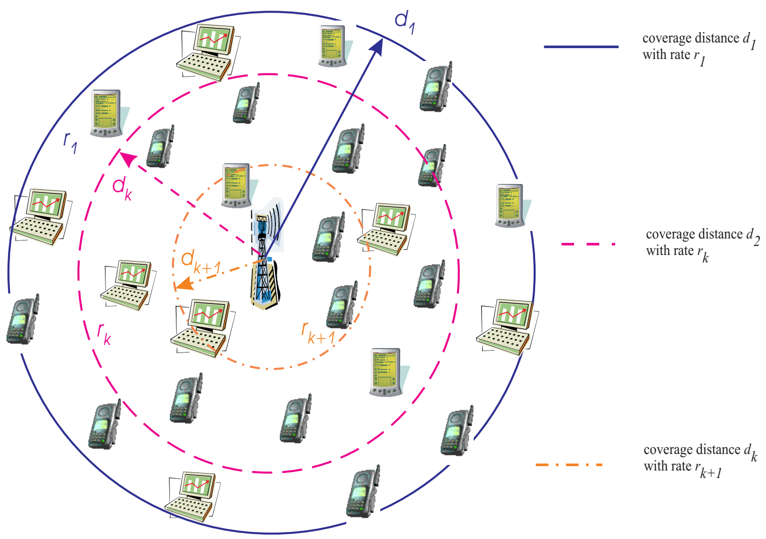


Figure 1.1: Illustration of multiple data rates r_k decoded successfully within corresponding coverage distances d_k $(k = 1, 2, 3, ..., K)$

supports voice service.

In the following sections, we give a short description of basic models and definitions addressed in this thesis. The outline of the thesis is given at the end of this chapter.

1.1 Channel Attenuation Model

In the downlink of a cellular system, public data or multimedia services can be multicast or broadcast from base station to mobile users within coverage area. In chapters 2, 3 and 4, we will restrict our attention to a single cell system with spatially uniform distributed users, as illustrated in Figure 1.1. In such a system, a broadcast session designed with multiple quality of service levels, for example, different data rates r_k $(k = 1, 2, ..)$, can reach users with varying quality of radio links.

We consider a signal propagation model that includes large scale geographic fading and deterministic path loss attenuation. In both analysis and numerical examples, we use such a path loss model, for example [20, 32], to define the average received power as a function of distance and transmission power. For an arbitrary transmitter and receiver separation distance d', the average large scale path gain $h(d')$ is

$$h(d') = H_g \left(\frac{\delta}{d'}\right)^{\beta}, \qquad d' \geq \delta. \tag{1.1}$$

In equation (1.1), δ is close-in reference distance, beyond which users should always be in the far field of the antenna so that near-field effects do not alter the reference path loss [32]. For example, in cellular systems with large coverage areas, reference distance of $\delta = 1$ km are commonly used, while in microcell systems, much smaller distances, for example, 100 m or 1 m, are used [32]. The path loss attenuation exponent β indicates the rate at which the path loss increases with distance δ. The value of β depends on the specific propagation environment. For instance, in a free space $\beta = 2$, while in cellular systems, values of β between $3 \ll \beta \ll 4$ are typical. The gain factor H_g is determined by the height of transmitter and receiver antennas and other fixed elements.

If the transmission power is P_t, the received power at distance δ will be

$$P_r(\delta) = h(\delta)P_t = H_g P_t. \tag{1.2}$$

The received power at distance d' becomes:

$$P_r(d') = h(d')P_t = \frac{H_g P_t}{(d'/\delta)^{\beta}} = \frac{P_r(\delta)}{(d'/\delta)^{\beta}}. \tag{1.3}$$

We will let

$$P_b = P_r(\delta)/N_0 W \tag{1.4}$$

denote the received SNR at the reference distance δ. And N_0 is the noise power density, W is the signal bandwidth. In addition, let $d = d'/\delta$ denote the normalized distance from a mobile to the base station. From equation (1.3), the average received SNR P' is

$$P' = \frac{P_b}{d^\beta}. \tag{1.5}$$

We note that in equation (1.5) that both P_b and d are unitless quantities. For convenient, we will often refer to P_b and P' as normalized transmit power and received power respectively.

1.2 Coverage Distance and Number of Users

We assume that the distribution of users in a cellular system is given by a spatially uniform Poisson process with ρ users per unit area. We assume that distances are measured in units of the reference distance δ.

For a given data rate r_k, we define the *coverage distance* d_k as the largest distance from a base station, where data at rate r_k can still be received successfully. A *coverage area* includes all the users who can successfully receive that data rate. In a cellular system with a path loss model, users located at the same distance to the base station experience the same attenuation. In this case, within the coverage area of radius d_k, the expected number of users is

$$N(d_k) = \rho\pi d_k^2. \tag{1.6}$$

For users who are even closer to base station, a higher data rate r_{k+i} $(i > 0)$, may be able to be successfully decoded. The expected number of users who can merely successfully receive data at rate r_k is

$$N_k = \rho\pi(d_k^2 - d_{k+1}^2), \qquad d_{k+1} \leq d_k. \tag{1.7}$$

Figure 1.1 illustrates a single cell system with multiple circular coverage areas associated with broadcast service at different data rates.

In the presence of shadow fading, not all users within a nominal coverage area can receive the signals at the desired data rate. A more general definition for *coverage area* is the region where at least certain percentage (for example, 90%) of users within that region can receive signals with required data rate. With this definition, our results would become more complicated but with little additional insight. Thus, we consider the path loss attenuation model in chapters 2, 3 and 4 to characterize the fundamental properties of multiple rate broadcast transmission. We do consider shadowing when we examine the behavior of wireless broadcast services in a multi-cell CDMA system in chapter 5.

1.3 Cellular Broadcast Transmission and its Measure

The radio resource management (RRM) problem is to make use of limited system resources, such as power and bandwidth, to support higher data rates. The downlink of a cellular system can support both individual user services and broadcast services. The network resources can be allocated among individual users, by using power control and rate adaptation, as in the proposed WCDMA system [1, 2, 25]. For an individual user, the user's objective is to receive a desired data rate reliably. For a collection of individuals, the system tries to satisfy all users' requirements. Usually, for given desired rates, the base station tries to minimize the transmission powers to achieve those rates. This differs from the RRM problem for a broadcast service because the same information is intended for all users, while users still experience different channel states.

In this work, we will develop measures to describe the throughput and performance of such a cellular broadcast system. It is common sense that the value of a broadcast service should be proportional to the number of subscribers. If the total investment for a broadcast service is fixed, increasing the number of subscribers will reduce the cost per user. Therefore, a performance measure for broadcast transmission should include the achievable data rate of each user with required QoS, and the number of users receiving such data rate [35]. For a single cell scenario, we measure performance by the *coverage*:

Definition 1 *The* **coverage** *is the expected total number of information bits received per second by all users within the broadcast coverage areas.*

The system supports K levels of data rates $\{r_1, r_2, ..., r_K\}$, where $r_k \leq r_{k+1}$. That is, r_1 is the lowest data rate providing a basic broadcast service, and r_K is the highest data rate, corresponding to the best possible QoS. We can express the coverage in the form

$$U = \sum_{k=1}^{K} N_k r_k. \tag{1.8}$$

where, N_k is the expected number of users receiving data rate r_k.

The definition of coverage captures the tradeoffs between achievable data rates of the users and the number of users receiving those rates. It can be expected that coverage as one of the RRM functions will impact the overall system efficiency and the operator infrastructure cost.

In a single cell system with path loss model, the expected number of users N_k is given by equation (1.7). Let $r_k - r_{k-1} = R_k$ for $k = 2, 3, ...K$, $r_1 = R_1$, and $r_0 = 0$. By applying equation (1.7) in equation (1.8), we obtain:

$$\begin{aligned} U &= \rho\pi \sum_{k=1}^{K-1} (d_k^2 - d_{k+1}^2) r_k + \rho\pi d_K^2 r_K, & (1.9) \\ &= \rho\pi \sum_{k=1}^{K} d_k^2 (r_k - r_{k-1}), & (1.10) \\ &= \rho\pi \sum_{k=1}^{K} d_k^2 R_k. & (1.11) \end{aligned}$$

Therefore, for a path loss model, in a single cell broadcast system with K data rate levels, the coverage is a function of coverage distance d_k and R_k for $k = 1, 2, ...K$.

Users beyond coverage distance d_1 cannot decode any data rate reliably. Users between coverage distance d_1 and d_2 can only successfully decode data at the lowest rate r_1. Users between coverage distance d_2 and d_3 have better channel conditions and can successfully receive the higher data rate r_2, by decoding data rate r_1 first. Users between coverage distance d_k and d_{k+1} can decode at rate r_k by decoding r_1, ... $r_{k_j} - r_{k_j - 1}$, $r_k - r_{k-1}$ step by step. Therefore, if broadcast can send out data with differential QoS levels, users closer to the base station can exploit their better channel capabilities by decoding more information within the same broadcast transmission.

Note that adding the higher data rates to the broadcast system brings additional interference to the lower rate users, as the additional information cannot be utilized by the worse case users. Since the dual rate strategy captures the key characteristics of the multiple rate broadcast system, we compare the dual rate system to single rate broadcast in chapters 2, 3, and 4 of the thesis. The outline of the thesis is as follows.

1.4 Outline of the Thesis

In this work, we examine the performance of multiple QoS broadcast. In chapter 2, we first investigate the properties of single rate broadcast coverage. In chapter 3, information theoretic results characterizing broadcast capacity are reviewed first. We then propose dual rate broadcast strategies with corresponding coverage areas. Analytical results to optimize broadcast coverage are derived from an information theoretic perspective. In chapter 4, the implementation of the dual rate cellular broadcast with different data rates and SIR requirements is dicussed for a CDMA system. Broadcast coverage is maximized by optimal choice of power allocation policy and associated coverage areas. In chapter 5, we consider the video broadcast with transmit diversity in the presence of voice service in a multi-cell CDMA system. We examine the cost of adding one video broadcast channel to the system. Finally, we summarize results and give conclusions in chapter 6.

Chapter 2

Single Rate Coverage for Cellular Broadcast

In a conventional cellular broadcast system, path loss dictates that the broadcast data rate should be received reliably by the most distant user within a coverage area. Users closer to base station with better channel conditions still obtain the same information as the worst case user.

In this chapter, we examine the broadcast coverage metric defined in chapter 1 for single rate broadcast. According to equation (1.11), for $K = 1$, the single rate broadcast coverage U_1 is

$$U_1 = \rho\pi d_0^2 R_0, \tag{2.1}$$

where d_0 is the normalized broadcast coverage distance for users receiving the common data rate R_0. We also investigate the coverage in terms of the normalized transmission power P_b.

2.1 Objective Function for Single Rate Coverage

For a single cell path loss model, the broadcast capacity is the maximum data rate received reliably by the most distant user within the coverage area. The achievable information theoretic broadcast data rate is:

$$R_0 = \frac{1}{2}\log\left(1 + \frac{P_b}{d_0^\beta}\right). \tag{2.2}$$

Let $q = P_b/d_0^\beta$ represent the boundary SNR at coverage distance d_0. Then, the data rate becomes a function of the boundary SNR q:

$$R_0(q, \beta) = \frac{1}{2}\log\left(1 + q\right). \tag{2.3}$$

Given transmission power P_b and path loss exponent β, the coverage distance d_0 as a function of the boundary SNR q is

$$d_0 = \left(\frac{P_b}{q}\right)^{1/\beta}. \tag{2.4}$$

Replacing R_0 and d_0 in equation (2.1) by (2.3) and (2.4), we obtain the coverage as a function of boundary SNR q:

$$\begin{aligned} U_1(q, \beta) &= \rho\pi(P_b/q)^{2/\beta} R_0(q, \beta), && (2.5) \\ &= \rho\pi\frac{(P_b/q)^{2/\beta}}{2}\log(1+q). && (2.6) \end{aligned}$$

Our objective is to maximize single rate coverage U_1 over q.

2.2 Analysis of Single Rate Coverage

By investigating the objective function of $U_1(q, \beta)$, we see that when the boundary SNR q approaches infinity, the coverage approaches zero; when the boundary SNR q

tends to zero, the single rate coverage also goes to zero. That is for very high q, too few users are covered and the single rate coverage will approach zero, even though the information rate received by a very close user would be very high. For very low q, the coverage region tends to infinity, but a very low information rate would be transmitted to every user in order to match the channel capability of the most distant user. Both cases will result in inefficient coverage and therefore should be avoided. We can expect that there exists optimal coverage and corresponding coverage area.

By using standard optimization methods, the objective function (2.6) of single rate coverage can be maximized with respect to q. The first derivative of $U_1(q,\beta)$ is:

$$\frac{\partial U_1(q,\beta)}{\partial q} = \rho\pi \frac{P_b^{2/\beta}}{2} q^{-\frac{2}{\beta}} \left(\frac{1}{1+q} - \frac{2}{\beta} \frac{\ln(1+q)}{q} \right) \tag{2.7}$$

In order to obtain the optimum point q^*, let the first derivative of the objective function be zero at $q = q^*$, yielding:

$$\frac{2(1+q^*)}{q^*} \ln(1+q^*) = \beta \tag{2.8}$$

Let

$$f(q) = \frac{2(1+q)}{q} \ln(1+q). \tag{2.9}$$

We observe that for $q > 0$, $f(q)$ is a continuous monotonic increasing function, such

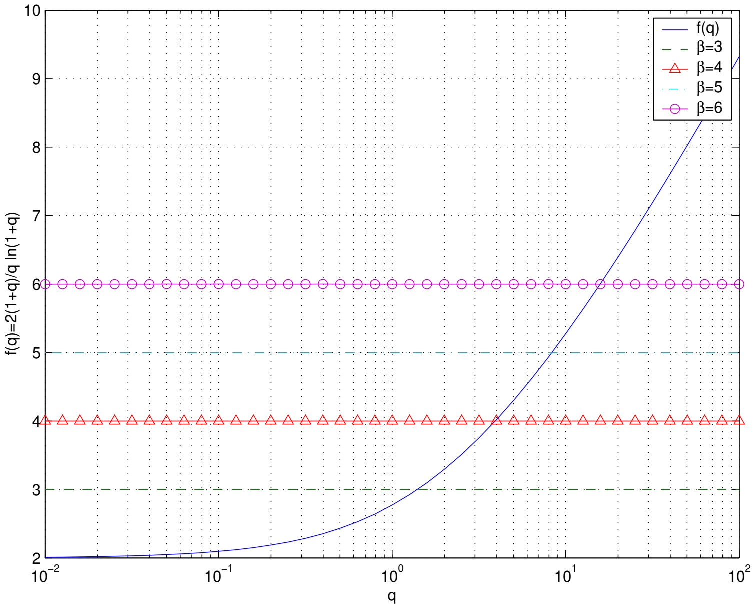


Figure 2.1: Solutions of function $f(q) = (2(1+q)/q)\log(1+q) = \beta$ for $\beta = 3, 4, 5, 6$

Table 2.1: Typical optimum received SNR q^* for $\beta = 2.5, 3, 4, 5, 6$ for single rate coverage

β	2.5	3	3.5	4	4.5	5	5.5	6
q^* (dB)	-2.29	1.15	3.94	5.93	7.65	9.21	10.62	12.00

that

$$\lim_{q\to 0} f(q) = 2, \tag{2.10}$$

$$\lim_{q\to\infty} f(q) = \infty. \tag{2.11}$$

Thus, for any $\beta > 2$, $f(q) = \beta$ has a unique solution at $q = q^* > 0$ as shown in Figure 2.1. The solution of equation (2.8) grows monotonically with β, as shown in Figure 2.3. Physically, q^* is the boundary SNR at the coverage distance d_0^* that maximizes the single rate coverage for given transmission power P_b. We give the typical

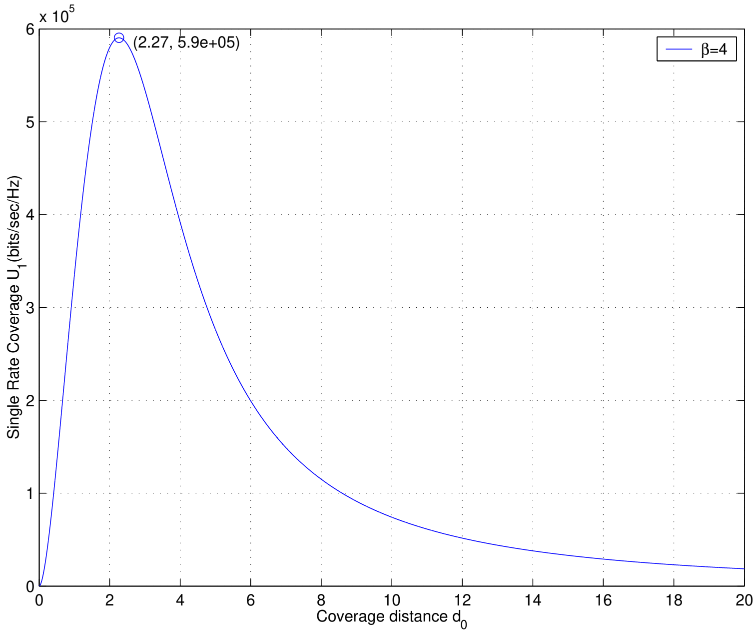


Figure 2.2: Coverage for single rate cellular broadcast: U_1 optimized over coverage distance d_0. Numerical parameters are listed in Table 2.2.

boundary SNR q^* at optimal coverage distance for $\beta = 2.5, 3, \ldots, 6$ in Table 2.1. As $\beta \to 2$, $q^* \to 0$ ($-\infty$ dB). At $\beta = 2$, our model breaks down. In this case, it is straightforward to show the expected total received power over all users infinity as $\beta = 2$, which is impossible since transmit power is finite. In the following, we restrict our analysis to the case $\beta > 2$, which includes typical values of β in the range of 3 to 4.

In Appendix A.1, we show that the second derivative of $U_1(q, \beta)$ with respect to q is less than zero at q^*. Thus, $U_1(q, \beta)$ has maximum value at q^*. Since q^* is the unique solution, the local maximum is also the global maximum for $q \geq 0$. From equation (2.8), we can see that the optimum boundary SNR q^* depends on the path loss parameter β, but is independent of the transmission power P_b. From $f(q^*) = \beta$, we can view

$$q^* = q^*(\beta), \tag{2.12}$$

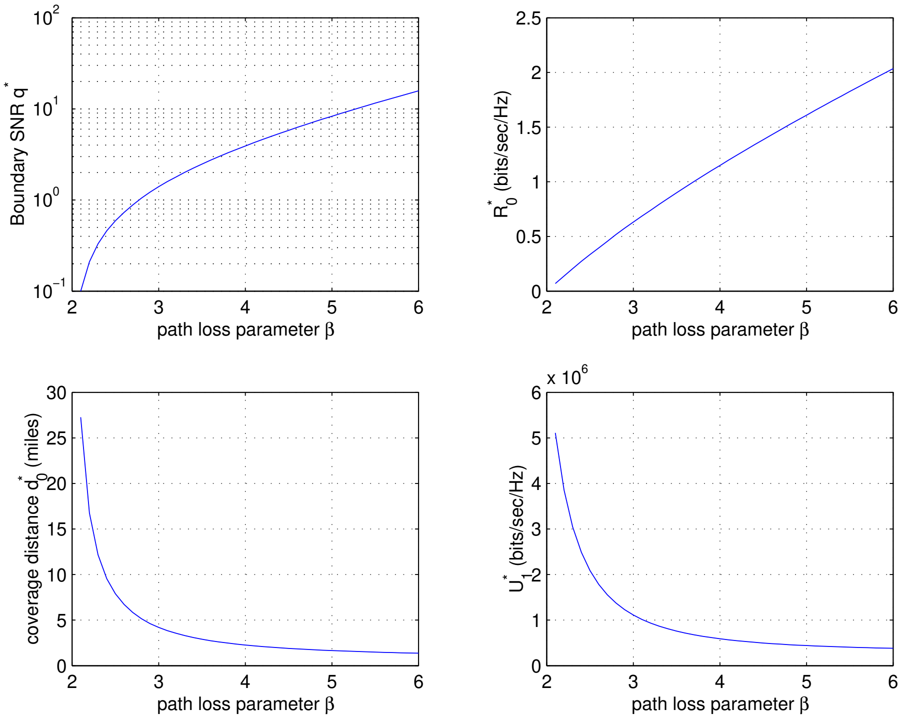


Figure 2.3: Properties of single rate cellular broadcast with different path loss attenuation. Numerical parameters are listed in Table 2.2.

the optimum boundary SNR q^* is a function of path loss attenuation β. Thus, for $\beta > 2$, the optimum single rate coverage defined by $q^*(\beta)$ at the coverage boundary is:

$$U_1(q^*, \beta) = U_1^*(\beta) = \rho\pi P_b^{2/\beta} \frac{\log(1 + q^*(\beta))}{2(q^*(\beta))^{2/\beta}}, \tag{2.13}$$

with corresponding coverage distance d_0^*:

$$d_0^* = (P_b/q^*)^{1/\beta}. \tag{2.14}$$

We point out one property of d_0^β for $\beta > 2$. Given d_0, when $d_0 > 1$, d_0^β is an increasing function of β; when $d_0 < 1$, d_0^β is a decreasing function of β. It is reasonable for the received signal strength to be a decreasing function of the proper path loss exponent β. Thus, we assume that the distance d_0 between the base station and the

Table 2.2: Parameters for a single rate broadcast with Lee's model

β	path loss exponent	4
P_t	Transmitted power	1W
h_1	BS antenna height	100 feet
h_2	MS antenna height	5 feet
W	Bandwidth	3.84MHz
N_0	Noise spectral density	-165dBm
ρ	User density per mile square	3.2×10^4

mobile terminal is greater than one. That is, d_0^β increases with β.

With the increase of transmission power, the coverage distance will increase in order to maintain the same associated boundary SNR q^*. That means the coverage distance is proportional to the transmission power by satisfying $q^* = P_b/d_0^{*\beta}$. Therefore, given β, $U_1(q^*, \beta)$ in equation (2.13) and d_0^* in (2.14) will increase with P_b. The larger the transmission power is, the larger the coverage distance is, therefore, the larger the single rate coverage is.

For a numerical example, the parameters are listed in Table 2.2. When $G_t = G_m =$ 0dB, $\beta = 4$, $\delta = 1$ mi, we apply Lee's model [20] for calculating the received power:

$$P_r(\delta) = P_t - 156 - 40 \log \delta + 20 \log h_1 + 10 \log h_2 + G_t + G_m. \tag{2.15}$$

Thus, for $P_b = P_r(\delta)/N_0W$, we obtain $P_b = 20$ dB. The optimum coverage distance according to equation (2.14) is 2.27 miles. The corresponding boundary SNR q^* is 5.93dB, shown in Figure 2.2.

We now examine coverage as a function of path loss exponent β. First, we assume that the normalized transmission power P_b referenced to distance δ is the same for varying path loss attenuation β.

Theorem 1 *$U_1^*(\beta)$ is a decreasing function of β.*

Proof: Assume that $\beta_1 < \beta_2$. Let the d_{0i}^* be the coverage distance for $U^*(\beta_i)$ ($i = 1, 2$). Equation (2.13) implies that

$$U_1^*(\beta_1) = U_1(d_{01}^*, \beta_1) \geq U_1(\hat{d}_{01}, \beta_1). \tag{2.16}$$

for all $\hat{d}_{01}$. Choose $\hat{d}_{01}$ such that

$$\frac{P_b}{\hat{d}_{01}^{\beta_1}} = \frac{P_b}{(d_{02}^*)^{\beta_2}}. \tag{2.17}$$

Since $\beta_1 < \beta_2$ and coverage distances are greater than 1, we obtain that $\hat{d}_{01} > d_{02}^*$.

Thus

$$\begin{aligned} U_1(\hat{d}_{01}, \beta_1) &= \rho\pi\frac{\hat{d}_{01}^2}{2}\log\left(1 + \frac{P_b}{(\hat{d}_{01})^{\beta_1}}\right) \\ &= \rho\pi\frac{\hat{d}_{01}^2}{2}\log\left(1 + \frac{P_b}{(d_{02}^*)^{\beta_2}}\right) \\ &\geq \rho\pi\frac{{d_{02}^*}^2}{2}\log\left(1 + \frac{P_b}{(d_{02}^*)^{\beta_2}}\right) \\ &= U_1(d_{02}^*, \beta_2) \\ &= U_1^*(\beta_2) \end{aligned} \tag{2.18}$$

According to inequalities (2.16) and (2.18), we can conclude that $U_1^*(\beta_1) \geq U_1^*(\beta_2)$.

In short, as the path loss factor β increases, the optimum coverage area diminishes faster than the increase of the associated optimum data rate as shown in Figure 2.3. That is, when the environment experiences larger path loss attenuation, we shrink the coverage area and increase the data rate in order to obtain the optimum single rate coverage.

2.3 Summary

As a measure of broadcast service, coverage accounts for the tradeoff between achievable data rate per user and the number of users receiving that rate successfully. Suppose the transmission power is fixed. Both too large coverage radius or too small coverage radius yields poor coverage.

In this chapter, we derived the optimization problem for a single rate cellular broadcast system. We found that the coverage is optimized by a unique coverage distance at which the optimal boundary SNR is achieved, independent of transmission power. A consequence is that single rate broadcast coverage is monotonically increasing with transmission power. Lastly, for given transmission power, the optimum single rate coverage is a decreasing function of the path loss attenuation β.

Chapter 3

Dual Rate Broadcast: An Information Theoretic Perspective

In this chapter, we first review the application of Shannon network information theory [10, 13] to a broadcast system with one sender and many receivers. We are interested in whether adding additional information can benefit the service provider by sacrificing some part of users' capability to obtain common information. In particular, we examine the performance of a broadcast system with two QoS levels from an information theoretic point of view.

In such a dual rate broadcast system, power is allocated between common and additional information. The coverage depends on both achievable data rates and the corresponding number of users receiving those rates. Our objective is to find the optimal power allocation and the associated coverage area to maximize the broadcast coverage. The properties of such a system will be shown through analysis and numerical examples.

In section 3.2, we describe the structure of a dual rate broadcast system. In section 3.3, we develop a coverage objective function to characterize the cellular broadcast. In section 3.4, the properties of optimal coverage are analyzed with numerical results for basic and enhanced coverage distances. Conclusions for this chapter are summarized in section 3.5.

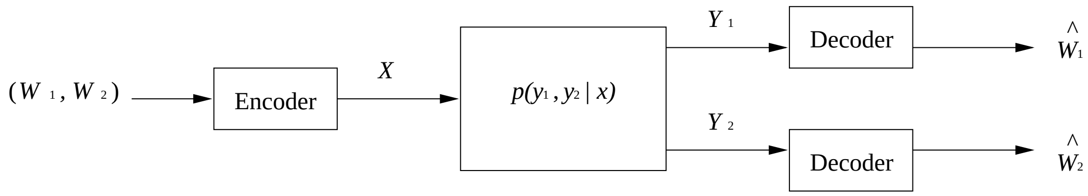


Figure 3.1: Broadcast channel

3.1 Broadcast Channels: an Information Theoretic Review

The broadcast channel [9, 10] is a communication channel in which there is one sender and two or more receivers, as illustrated in Figure 3.1. Note that, X is the transmitted signal, Y_i is the received signal, and $\hat{W}_i$ is the decoded signal from Y_i for user i.

Definition 2 A broadcast channel *consists of an input alphabet* $\mathbf{X}$ *and two output alphabets* $\mathbf{Y_1}$ *and* $\mathbf{Y_2}$ *and a probability transition function* $p(y_1, y_2|x)$*. The broadcast channel will be said to be memoryless if for sequences of* n *inputs* $y_k^n = y_{k1}, y_{k2} \ldots y_{kn}$, $p(y_1^n, y_2^n|x^n) = \prod_{i=1}^{n} p(y_{1i}, y_{2i}|x_i)$.

The basic problem is to find the set of rates simultaneously achievable for reliable communication. The problem we consider in this thesis is a specific case. For instance, a video broadcast is normally intended for a group of users, and the same information is sent to everybody. The maximum achievable common information rate is

$$C = \max_{P(x)} \min_{i} I(X; Y_i) \tag{3.1}$$

Since C may be less than the capacity of the better channels, we may wish to transmit in such a way that the receivers with better channels can decode extra information in order to produce a better picture or sound. At the same time, all receivers should continue to receive a basic information rate. The methods to accomplish this will be explained in the discussion of the broadcast channel.

First we will present some background information about Gaussian broadcast channels.

3.1.1 Degraded Broadcast Channel (DBC)

Definition 3 *A broadcast channel is said to be* physically degraded *if* $p(y_1, y_2|x) = p(y_2|x)p(y_1|y_2)$.

Since we can always write $p(y_1, y_2|x) = p(y_2|x)p(y_1|y_2, x)$, we observe that a broadcast channel is physically degraded if $p(y_1|y_2, x) = p(y_1|y_2)$. That is, given Y_2, random variables Y_1 and X are independent. Therefore, for a degraded broadcast channel, random variables X, Y_1 and Y_2 can be represented by a Markov chain $X \to Y_2 \to Y_1$. Such Markov chain with the degraded broadcast channel has the transition probabilities $p(y_2|x)$ from X to Y_2 and $p(y_1|y_2)$ from Y_2 to Y_1.

Note that the capacity region of a degraded broadcast channel depends only on the conditional marginal distributions. In the following discussion, we will assume that the channel is physically degraded. Suppose that independent information is sent over a degraded broadcast channel at rate R_1 to Y_1 and rate R_2 to Y_2. We have the following theorems [10].

Theorem 2 *The capacity region of the degraded broadcast channel* $X \to Y_2 \to Y_1$ *is the convex hull of the closure of all* (R_1, R_2) *satisfying*

$$R_1 \leq I(V; Y_1) \tag{3.2}$$

$$R_2 \leq I(X; Y_2|V) \tag{3.3}$$

for some joint distribution $p(v)p(x|v)p(y_1, y_2|x)$, where the auxiliary random variable V has its cardinality bounded as follows $|V| \leq \{|X|, |Y_1|, |Y_2|\}$.

Assume that superposition coding is used for the broadcast channel. The auxiliary random variable V will serve as a cloud center that can be distinguished by both receiver Y_1 and Y_2. Each cloud consists of 2^{nR_2} codewords X^n distinguishable by the receiver Y_2. The worst receiver can only see the clouds, while the better receiver can see the individual codewords within the clouds. Interested readers can refer to the Cover and Thomas text [10] to see the proof.

In the case of a degraded broadcast channel, the better receiver can always decode all the information that is sent to the worst channel. Thus common information with rate R_0 designed for worst receiver can be decoded by better receivers. Hence we have the following theorem:

Theorem 3 *If the rate pair (R_1, R_2) is achievable for a degraded broadcast channel, the rate triple $(R_0, R_1 - R_0, R_2)$ is achievable for the channel with common information rate R_0, provided that $R_0 < R_1$.*

The data rate $R_1 - R_0$ is the individual rate achieved by the worse channel, in addition to common information with rate R_0. For a degraded channel, information with rate R_0 can also be decoded by the better receiver, as well as the information with rate R_2. In fact, when $R_1 = R_0$, the worse user can only decode common information R_1, while better receiver can decode additional information with rate R_2, as well as R_1.

We will give an example of how to make use of the common and additional information for a broadcast strategy over a Gaussian channel.

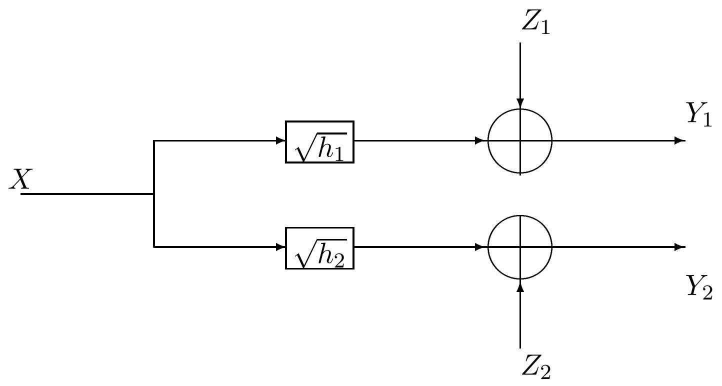


Figure 3.2: An example of a degraded Gaussian broadcast channel with two receivers

3.1.2 An Example

For a broadcast system, the transmitter regards the Gaussian channels of the receivers as degraded broadcast channels (DBC) where each noise variance level is associated with a receiver in the DBC. Let us consider an example of a Gaussian broadcast channel with two receivers depicted in Figure 3.2. Suppose there are two receivers for the same broadcast information transmission over Gaussian channel. The received signal at receivers 1 and 2 are

$$Y_1 = \sqrt{h_1}X + Z_1, \tag{3.4}$$

$$Y_2 = \sqrt{h_2}X + Z_2. \tag{3.5}$$

We assume the Gaussian noise variables Z_1 and Z_2 have the same noise variance N_0. When $h_1 < h_2$, channel 1 is worse than channel 2.

The channel gains h_1, h_2 may describe path loss, Rayleigh fading, or shadow fading. In our subsequent analysis, we focus on a path loss model, where channel gains are inversely proportional to d_i^β where d_i is the distance from the transmitter i. That

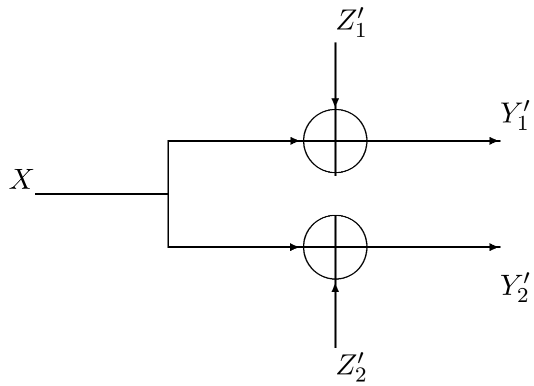


Figure 3.3: An equivalent degraded Gaussian broadcast channel with two receivers

means, users closer to the base station have higher channel gains and therefore better channels.

For a slowly time-varying broadcast channel, we can obtain an equivalent channel model with the same channel gain but different noise variance, which is shown in Figure 3.3.

Dividing by $\sqrt{h_1}$ and $\sqrt{h_2}$ respectively of the equations (3.4), (3.5), we have

$$Y_1' = X + Z_1', \tag{3.6}$$

$$Y_2' = X + Z_2'. \tag{3.7}$$

The variance of Z_i' is $N_i = N_0/h_i$.

In our example, the poor channel 1 can be considered as the degraded channel of the good channel 2. Since $h_1 < h_2$ implies $N_1 > N_2$, we can represent the system by:

$$Y_2' = X + Z_2', \tag{3.8}$$

$$Y_1' = Y_2' + Z_1'', \tag{3.9}$$

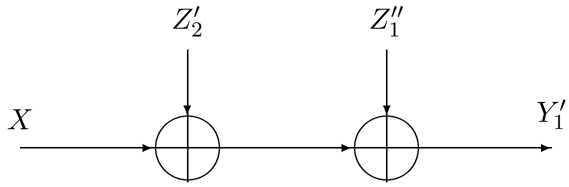


Figure 3.4: The degraded Gaussian broadcast channel

as shown in Figure 3.4. Note that in equations (3.8) and (3.9), $Z_2' \sim N(0, N_2)$ and $Z_1'' \sim N(0, N_1 - N_2)$.

We use P to denote the power of the broadcast transmitter X. The received SNR for user i ($i = 1, 2$) is:

$$Q_i = \frac{P}{N_i}. \tag{3.10}$$

For an arbitrary constant $\alpha \in [0, 1]$, the received SIR for common information is

$$\gamma_1 = \frac{(1-\alpha)P}{\alpha P + N_1} = \frac{(1-\alpha)Q_1}{\alpha Q_1 + 1}. \tag{3.11}$$

After decoding and subtracting common information, the received SIR for additional information is:

$$\gamma_2 = \frac{\alpha P}{N_2} = \alpha Q_2. \tag{3.12}$$

Then, the capacity region of this channel is given [9] by

$$R_2 < C(\gamma_2), \tag{3.13}$$

$$R_1 < C(\gamma_1). \tag{3.14}$$

where, $N_1 > N_2$ and $C(\gamma_i) = 1/2 \log(1 + \gamma_i)$ denotes the Shannon capacity.

To encode the messages, the transmitter generates two code books, one with power $(1-\alpha)P_b$ at rate R_1, and another with power αP_b at rate R_2. The transmitter sends the combined index of $i \in \{1, 2, 3, ..., 2^{nR_1}\}$ and $j \in \{1, 2, 3, ..., 2^{nR_2}\}$ from two code books to Y_1 and Y_2.

Receiver 1 can decode data stream at rate R_1 reliably by treating data with rate R_2 as interference. The effective signal to noise ratio is $\bar{\alpha}P_b/(\alpha P_b + N_1)$.

The good receiver Y_2 can decode data stream at rate R_1 reliably because of its lower noise variance N_2. By subtracting the decoded signal $\hat{X}_1$ from Y_2, it can decode data with rate R_2 reliably. The effective signal to noise after the clearance of data rate R_1 is $\alpha P_b/N_2$. We emphasize that data stream of rate R_2 can be decoded reliably by receiver 2, but not by receiver 1. The total data rate received reliably by receiver 1 is R_1, while the total data rate received reliably by receiver 2 is $R_1 + R_2$.

Comparison

Broadcast transmission power is allocated between common and additional information. Power allocation policy α is the proportion of total transmission power assigned to additional information data stream with rate R_2. In Figure 3.5, points a, b are two achievable data rate pairs on the boundary of the capacity region. Compared to point a, the power allocation policy at point b will result in a higher additional information rate but a lower common information rate. On the other hand, the power allocation policy at point a will allow higher common information rate. A natural question is which power allocation policy is preferred.

We first describe the structure of a dual rate broadcast system. We, then, formulate

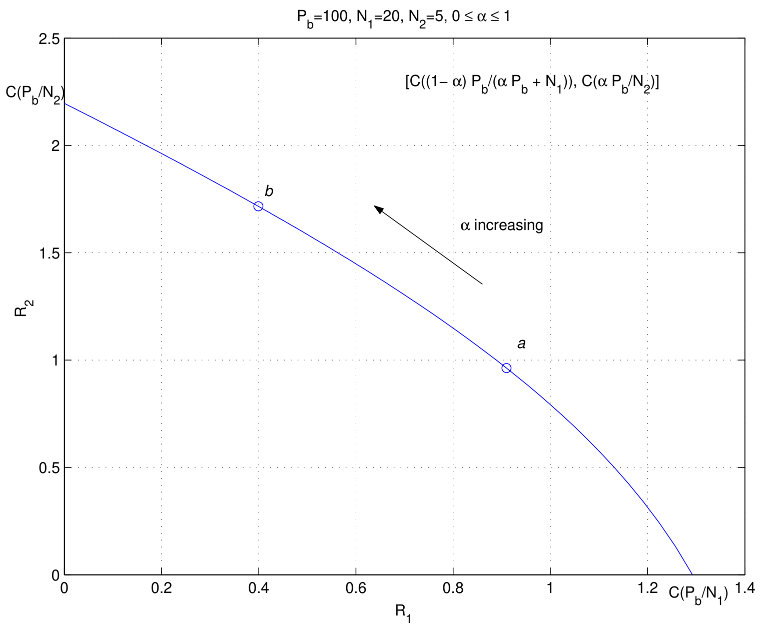


Figure 3.5: Capacity region for degraded Gaussian broadcast channel

a coverage objective to address this problem.

3.2 Proposed Broadcast System Structure

In order to make use of heterogeneous link capabilities, it may be desirable to provide two or more quality of service levels within one broadcast transmission. Our challenge is to determine the benefit of multiple levels in a broadcast system.

3.2.1 System Structure for Dual Rate Broadcast

In a two QoS level broadcast system, the transmitter generates common and additional information at rates pair (R_1, R_2) with powers $P_2 = \alpha P_b$ and $P_1 = (1-\alpha)P_b$, respectively. Then common and additional information data are encoded, multiplexed, and then transmitted over the channel, as illustrated in Figure 3.6.

With a path loss model, users closer to the base station, such as user B in Figure 3.7, have smaller channel attenuation, thus, they have good channel conditions. Users

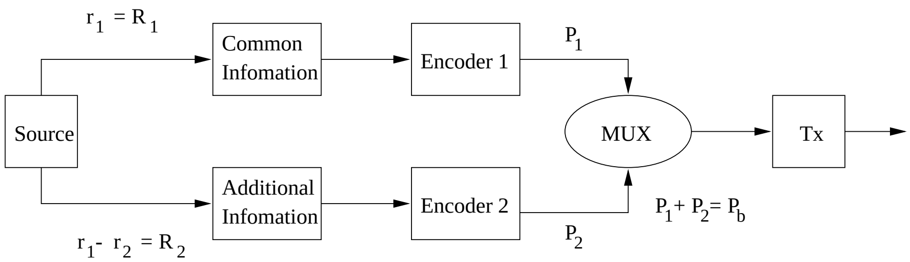


Figure 3.6: Proposed broadcast system structure

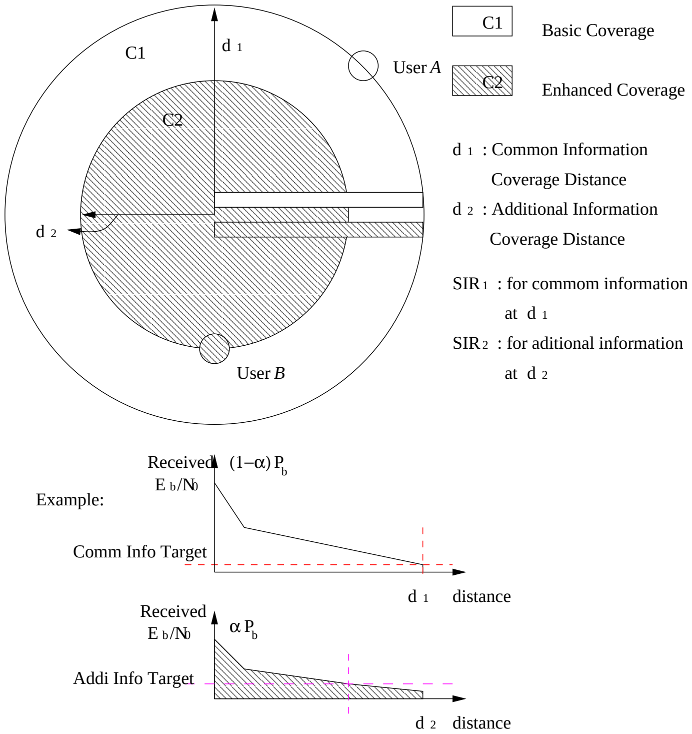


Figure 3.7: Channel attenuation with different distance from base station to mobile users

farther from base station, such as user A, have much larger channel attenuation, thus, they are users with worse channel conditions. The worst case user A can merely satisfy the SIR requirement for common information, since her received SIR for additional information is less then its associated SIR requirement. So user A only decodes common information. The additional information can only act as interference to user A.

The good user B first decodes common information, which can be accomplished because of its relatively lower noise variance. She subtracts this common information

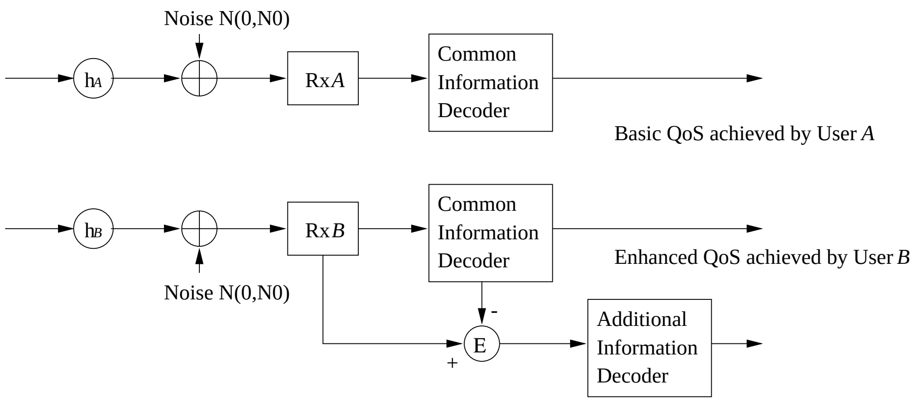


Figure 3.8: Decoding structure for users with good or bad channel conditions: $h_A < h_B$

from the received signal and feeds this signal to the additional information decoder as shown in Figure 3.8. Since she can satisfy the target SIR requirement for additional information, she can decode the additional information successfully. Therefore, user B can achieve enhanced quality of broadcast service.

3.3 Objective Functions for Cellular Broadcast

According to the broadcast transmission strategy proposed in Section 3.2, power P_b is partitioned between common and additional information streams as $(1-\alpha)P_b$ and αP_b, where, $\alpha \in [0,1]$ defines the power allocation policy. We examine the performance of such a dual rate broadcast system with superposition coding and successive decoding [10]. We also compare it to single rate broadcast. First, the objective function for broadcast with successive decoding is formulated.

3.3.1 Coverage Function for Dual Rate Broadcast Channel

For the degraded broadcast channel described in Section 3.1, additional information is treated as interference to common information. We assume coverage distances $d_1 > d_2$. According to equation (3.10), the received SNR Q_i $(i = 1, 2)$ at the associated coverage distances d_i with path loss attenuation is

$$Q_i = \frac{P}{N_i} = \frac{Ph_i}{N_0} = P_b d_i^{-\beta}. \tag{3.15}$$

Assume that user 1 is at the boundary of basic coverage, and user 2 at distance $d_2 < d_1$ is at the edge of the enhanced coverage. Then, the respective coverage distances d_1 and d_2 can be written as functions of Q_1 and Q_2 as

$$d_1 = (P_b/Q_1)^{1/\beta}, \tag{3.16}$$

$$d_2 = (P_b/Q_2)^{1/\beta}. \tag{3.17}$$

Analogous to equation (3.11), the received SIR for common information at the basic coverage distance d_1 is:

$$\gamma_1 = \frac{(1-\alpha)P_b/d_1^{\beta}}{1+\alpha P_b/d_1^{\beta}} = \frac{(1-\alpha)Q_1}{1+\alpha Q_1}. \tag{3.18}$$

Similarly, as in equation (3.12), the SIR for the additional information is at the enhanced coverage distance d_2 is:

$$\gamma_2 = \frac{\alpha P_b}{d_2^{\beta}} = \alpha Q_2. \tag{3.19}$$

We can see that γ_1 and γ_2 are functions of α, Q_1 and Q_2.

Then, the data rate R_1 for users within d_1, and additional information with rate R_2

achievable by users within d_2 are:

$$R_1 = \frac{1}{2}\log\left(1+\gamma_1\right) \tag{3.20}$$

$$R_2 = \frac{1}{2}\log\left(1+\gamma_2\right), \tag{3.21}$$

which can also be considered as functions of α, Q_1 and Q_2.

From equation (1.11), for $K = 2$, the dual rate broadcast coverage is:

$$U_2 = \rho\pi(d_1^2 R_1 + d_2^2 R_2). \tag{3.22}$$

From equations (3.20), (3.21) and (3.18), (3.19), we can express R_1 and R_2 as functions of α, Q_1 and Q_2,

$$R_1(\alpha, Q_1) = \frac{1}{2}\log\left(1+\frac{(1-\alpha)Q_1}{1+\alpha Q_1}\right), \tag{3.23}$$

$$R_2(\alpha, Q_2) = \frac{1}{2}\log(1+\alpha Q_2). \tag{3.24}$$

By applying d_1, d_2, R_1 and R_2 in equations (3.16), (3.17), (3.20) and (3.21), the dual rate coverage can be expressed as the function of α, Q_1 and Q_2:

$$U_2(\alpha, Q_1, Q_2) = \rho\pi P_b^{2/\beta}\left[Q_1^{-2/\beta}R_1(\alpha, Q_1) + Q_2^{-2/\beta}R_2(\alpha, Q_2)\right]. \tag{3.25}$$

3.3.2 Optimization Problems

From the objective function U_2 of equation (3.25), we observe that the transmission power P_b, power allocation policy α, basic and enhanced rate boundary SNR Q_1 and Q_2 at coverage distances d_1 and d_2, and path loss parameter β define the broadcast coverage. Given transmission power P_b and path loss exponent β, the optimization problem is to maximize the broadcast system coverage:

$$U_2^*(\beta) = \max_{\alpha, Q_1, Q_2} U_2(\alpha, Q_1, Q_2), \tag{3.26}$$

From function (3.25), we note that the optimization of the broadcast coverage over α, Q_1, Q_2 is independent of the transmission power P_b. That is, the optimum α^*, Q_1^*, Q_2^* remain the same for different P_b, given β. Thus the expression of objective functions in terms of Q_1, Q_2 reveal the characteristics of optimum coverage, which is achieved at the coverage distance where the received SNRs are Q_1^* and Q_2^*. The actual value of optimal broadcast coverage is proportional to $P_b^{2/\beta}$.

We will use the variables Q_1 and Q_2, instead of d_1 and d_2, to analyze the properties of coverage with numerical results in the following sections. When necessary, we will go back to coverage distance d_1 and d_2 to understand the properties of corresponding coverage areas.

3.4 Quality of Cellular Broadcast Services: Analysis and Results

From equation (3.25), we observe that the cellular broadcast coverage $U_2(\alpha, Q_1, Q_2)$ is composed of basic coverage $U_{21}(\alpha, Q_1)$ and enhanced coverage $U_{22}(\alpha, Q_2)$:

$$U_2(\alpha, Q_1, Q_2) = U_{21}(\alpha, Q_1) + U_{22}(\alpha, Q_2), \tag{3.27}$$

where

$$U_{21}(\alpha, Q_1) = \rho\pi \frac{P_b^{2/\beta}}{2} Q_1^{-2/\beta} \log\left(1 + \frac{(1-\alpha)Q_1}{1+\alpha Q_1}\right), \tag{3.28}$$

$$U_{22}(\alpha, Q_2) = \rho\pi \frac{P_b^{2/\beta}}{2} Q_2^{-2/\beta} \log\left(1 + \alpha Q_1\right). \tag{3.29}$$

Given a power allocation policy α, the two components can be optimized independently, since

$$\frac{\partial U_2(\alpha, Q_1, Q_2)}{\partial Q_1} = \frac{\partial U_{21}(\alpha, Q_1)}{\partial Q_1}, \tag{3.30}$$

$$\frac{\partial U_2(\alpha, Q_1, Q_2)}{\partial Q_2} = \frac{\partial U_{22}(\alpha, Q_2)}{\partial Q_2}. \tag{3.31}$$

We take the first derivative of function (3.25) or (3.28) with respect to Q_1:

$$\frac{\partial U_2(\alpha, Q_1, Q_2)}{\partial Q_1} = \rho\pi \frac{P_b^{2/\beta} Q_1^{-2/\beta-1}}{2} \left[\frac{(1-\alpha)Q_1}{(1+Q_1)(1+\alpha Q_1)} - \frac{2}{\beta}\log\left(\frac{1+Q_1}{1+\alpha Q_1}\right)\right]. \tag{3.32}$$

In order to get optimum point, we set the derivative at $Q_1 = Q_1^*$ to zero, yielding,

$$\frac{2(1+Q_1^*)(1+\alpha Q_1^*)}{(1-\alpha)Q_1^*} \log\left(\frac{1+Q_1^*}{1+\alpha Q_1^*}\right) = \beta. \tag{3.33}$$

Let

$$g(Q_1^*) = \frac{2(1+Q_1^*)(1+\alpha Q_1^*)}{(1-\alpha)Q_1^*} \log\left(\frac{1+Q_1^*}{1+\alpha Q_1^*}\right). \tag{3.34}$$

For fixed α, we verify in Appendix A.2 that $g(Q_1^*)$ is monotonically increasing with Q_1^*. Thus we can obtain a unique solution $Q_1^*(\alpha, \beta)$ for equation (3.33). For fixed β, we

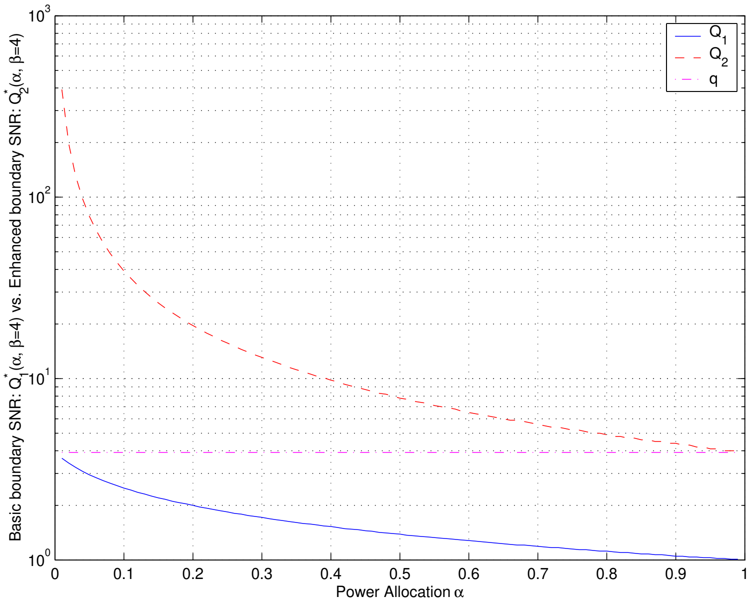


Figure 3.9: Optimal boundary SNR with respect to power allocation policy α, with superposition coding and interference cancelation, $P_b = 20$ dB at 1 mile

show in Appendix A.3 that $Q_1^*(\alpha, \beta)$ is a decreasing function of α.

The first derivative of $U_2(\alpha, Q_1, Q_2)$ in equation (3.25) in terms of Q_2 is:

$$\frac{\partial U_2(\alpha, Q_1, Q_2)}{\partial Q_2} = \rho\pi \frac{P_b^{2/\beta}}{2} Q_2^{-2/\beta-1}\left(\frac{\alpha Q_2}{1+\alpha Q_2} - \log(1+\alpha Q_2)\right). \tag{3.35}$$

Setting equation (3.35) to zero, yields the solution:

$$Q_2^*(\alpha, \beta) = q^*(\beta)/\alpha, \tag{3.36}$$

where $q^*(\beta)$ is defined in equation (2.12) in the context of single rate broadcast coverage. Effectively, once the common information is decoded and subtracted, the additional information is transmitted through a clear channel with SNR αQ_2, just as in a single rate broadcast system. Thus, given β, it is easy to see that $Q_2^*(\alpha, \beta)$ is a decreasing function of α.

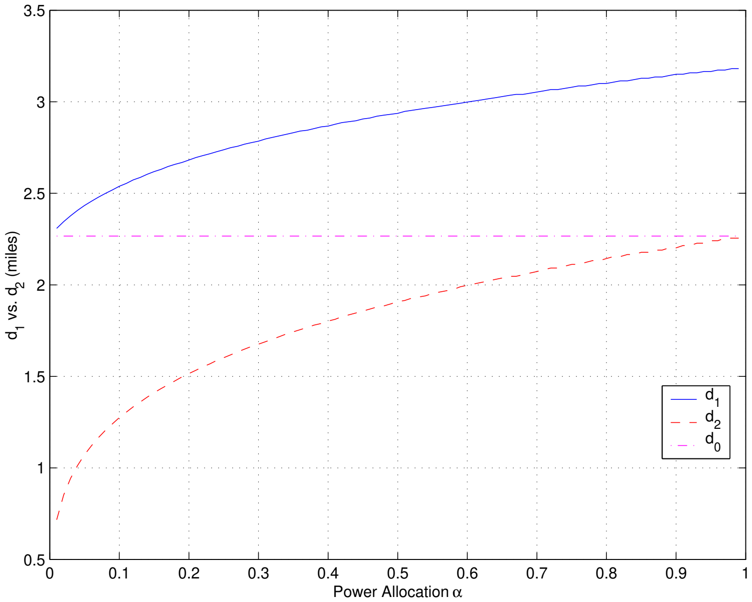


Figure 3.10: Coverage distance for broadcast with common and additional information, with superposition coding and interference cancelation, $P_b = 20$ dB at 1 mile

Given a power allocation policy α, the optimum basic and enhanced coverage $U_{21}^*(\alpha,\beta)$, $U_{22}^*(\alpha,\beta)$ are the functions of $Q_1^*(\alpha,\beta)$ and $Q_2^*(\alpha,\beta)$:

$$U_{21}^*(\alpha,\beta) = \rho\pi\frac{P_b^{2/\beta}}{2}Q_1^{-\frac{2}{\beta}}\log\left(\frac{1+Q_1^*(\alpha,\beta)}{1+\alpha Q_1^*(\alpha,\beta)}\right), \tag{3.37}$$

$$U_{22}^*(\alpha,\beta) = \rho\pi\frac{P_b^{2/\beta}}{2}\left(\frac{q^*(\beta)}{\alpha}\right)^{-2/\beta}\log\left(1+q^*(\beta)\right). \tag{3.38}$$

By summing equations (3.37) and (3.38), we obtain the overall coverage $U_2^*(\alpha,\beta)$:

$$U_2^*(\alpha,\beta) = U_{21}^*(\alpha,\beta) + U_{22}^*(\alpha,\beta). \tag{3.39}$$

which is a function of $Q_1^*(\alpha,\beta)$ and $Q_2^*(\alpha,\beta)$.

Finally, by optimizing $U_2^*(\alpha,\beta)$ over α, we obtain an optimal policy,

$$U_2^*(\alpha^*) = \max_{\alpha} U_2^*(\alpha,\beta). \tag{3.40}$$

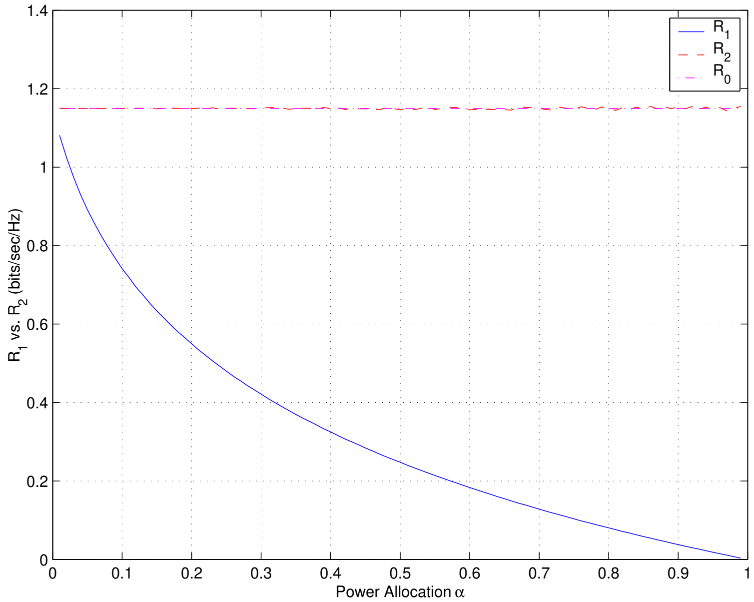


Figure 3.11: Optimal common and additional data rate with respect to power allocation policy α, with superposition coding and interference cancelation, $P_b = 20$ dB at 1 mile

This optimal policy has the following properties:

- **Optimum boundary SNRs** As shown in Figure 3.9, the boundary SNR, Q_1^* at the optimum basic coverage distance is a decreasing function of α. The boundary SNR, Q_2^* at the optimum enhanced coverage distance is also a decreasing function of α. We also find in Appendix A.3 that $Q_2^* > q^* > Q_1^*$, for $0 < \alpha < 1$.

- **Basic and enhanced coverage areas** The basic coverage distance d_1^* and enhanced coverage distance d_2^* will increase with α as shown in Figure 3.10. In addition, $Q_1^* < q^* < Q_2^*$ implies $d_1^* > d_0^* > d_2^*$.

- **Common and additional rates** In Figure 3.11, the additional information rate is a constant for $0 < \alpha < 1$. The common information rate will decrease as less power is assigned to it and there is more interference from additional information; see Appendix A.3.

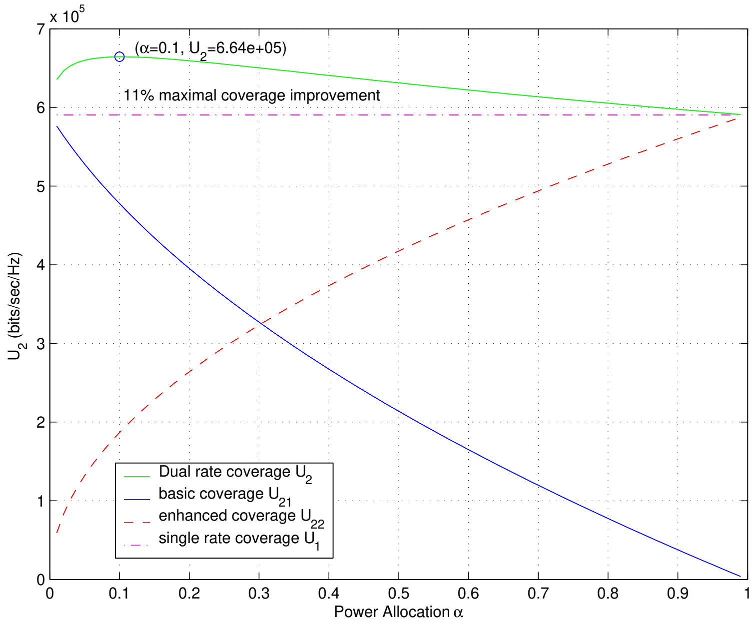


Figure 3.12: Dual rate cellular broadcast coverage with superposition coding and interference cancelation, $P_b = 20$ dB at 1 mile

- **Basic and enhanced rate coverage** The larger the proportion of power allocated to common information, the greater the associated optimum basic coverage in terms of α is, as shown in Figure 3.12. Proof can be found in Appendix A.3. The reason is that the decrease of achievable common information rate overwhelms the increase of corresponding coverage area, as α grows. The enhanced coverage distance will decrease with α in order to maintain the same optimum additional data rate for different α: $q^* = \alpha Q_1^*$. Thus, the optimum enhanced coverage will decrease with α.

- **Optimum coverage with respect to** α, d_1 (or Q_1) **and** d_2 (or Q_2) There exist α, d_1 and d_2, to maximize the broadcast coverage U_d as shown in Figure 3.12. From the same parameters shown in Table 2.2, the optimum coverage is: 6.64×10^5 bits/sec/Hz, which has 11% coverage enhancement compared to a single rate cellular broadcast system shown in Figure 2.2. The optimum power allocation policy α^* is 0.10. The corresponding basic and enhanced coverage distances are 2.54 miles and 1.27 miles, respectively. Thus, within whole coverage area, 25% of the supported users can receive enhanced quality of service.

3.5 Summary

In this chapter, we derived the optimization problem for a dual rate cellular broadcast system. The concepts of the basic and enhanced quality of broadcast service with corresponding coverage areas are introduced. The SNR at the optimal basic and enhanced coverage distances are independent of transmission power. There exists an optimal power allocation α with the corresponding basic and enhanced coverage areas to maximize broadcast coverage. We also derived the gain of dual rate coverage over single rate coverage to give the additional insight to the tradeoff of resources.

We sacrifice some part of the basic coverage by letting users closer to base station to get some additional information. For example, by diminishing the basic coverage area, we can provide additional information to a smaller coverage area closer to base station, where users can receive extra information, in addition to common information. Our motivation to consider this possibility is that if the network revenue is proportional to the total received data rates, then revenue might be increased when additional information is added by sacrificing the coverage area with a lower common information rate. Thus, we have observed that the overall coverage could be increased by proper power allocation between common and additional information with associated coverage areas. However, as we see in Figure 3.12, the improvement in coverage is small in the neighborhood of 10%.

Chapter 4

Dual Rate Broadcast in a Single-cell CDMA System

The previous chapters discuss an information theoretic model of a cellular broadcast channel. Coverage is optimized over the choice of basic and enhanced coverage areas. In this chapter, we explore the cellular broadcast strategies providing two QoS levels in a practical CDMA system.

In an information theoretic model, error free communication is assumed when the data rate is less than the channel capacity [10]. In a practical system, channel errors cannot be completely avoided. In this case, we define the achievable data rate as the transmission data rate that can be successfully decoded with a desired BER. As in earlier chapters, the coverage is the sum of products of the achievable data rates and the expected number of users in the corresponding coverage areas.

The objective of this chapter is to find the coverage of different power allocation policies. We compare the optimum power allocation policies and corresponding coverage to other schemes in terms of SIR requirements and data rate ratio in a CDMA system.

This chapter is organized as follows. In Section 4.1, we propose to implement the two QoS level broadcast in a CDMA system. In Section 4.2, a physical model describing CDMA signals is defined. In Section 4.3, coverage optimization is analyzed. Numerical results for dual rate broadcast coverage are shown and discussed in Section 4.4. In Section 4.5, the results are summarized and conclusions are given.

4.1 Introduction

With the introduction of the IS-95 CDMA standard [5], commercial wireless systems with spread spectrum technology have become common. The third generation (3G) wireless systems [1, 2] are designed to support high rate multimedia services, as well as conventional low rate voice service. A CDMA system with code multiplexing provides a natural way to encode different parts of an information stream with different spreading sequences.

In this chapter, we consider the efficient use of the downlink radio resources by exploiting wireless broadcast services. In particular, we elaborate on the coverage for the downlink transmission of wireless real-time streams in a Direct Sequence CDMA (DS-CDMA) system. The value of the service will depend on the number of users receiving quality-based streams in addition to the data rates of those streams. The main focus herein is to offer a multiple rate [23, 30, 33] data stream with maximum overall coverage.

To simplify the analysis and develop an understanding of basic properties, we consider a dual rate CDMA system [14, 31, 34, 36] with two data rates. In such a system, transmit power is allocated between common and additional information subchannels.

The objective of this chapter is to find the coverage of different power allocation policies. The same coverage distance scheme must allocate proper power to two subchannels such that the coverage distances are the same for both subchannels of a stream. The rate ratio scheme is to assign power proportional to the rates between two subchannels. We compare the optimum coverage to the coverages for the same coverage distance scheme and rate ratio scheme in terms of target SIR ratio and data rate ratio.

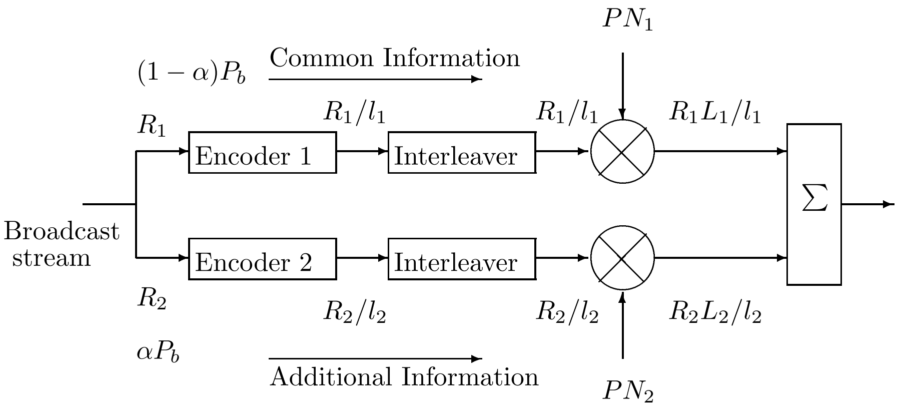


Figure 4.1: A proposed dual rate CDMA system

4.2 System Model

We study the broadcast coverage of a dual rate CDMA system as shown in Figure 4.1. Common information is transmitted on subchannel 1 and additional information is transmitted on subchannel 2. Let R_j denote the information data rate, l_j the channel coding rate, and L_j the spreading factor of subchannel j. Since the subchannels occupy the same bandwidth W, they satisfy:

$$W = \frac{R_1 L_1}{l_1} = \frac{R_2 L_2}{l_2}. \tag{4.1}$$

We also assume that the CDMA chip rate is equal to the system bandwidth W [7].

If the transmitted signals remain orthogonal at the receivers, there is no interference from the other subchannels, and matched filtering is optimal in this case. If there is interference from other broadcast subchannels, we can use the ordinary matched filter decoder, although it will be suboptimal.

4.2.1 A CDMA signal model

We consider only the behavior of one broadcast channel in a single cell wireless system. Other broadcast channels and non-broadcast channels are approximated by a white Gaussian interference process. We assume each user's channel is only characterized by its distance-based path loss. We also assume a spatially uniform density of users on the plane. We consider a baseband DS-CDMA system model supporting a two data rate broadcast with a coherent BPSK modulation format.

In a data frame of interest, let K_j be the number of data symbols per frame and T_j the symbol duration corresponding to subchannel j $(j = 1, 2)$. Thus, for the same frame length, $K_1T_1 = K_2T_2$. Without loss of generality, we assume that $T_1 \leq T_2$. The received amplitude of subchannel j for users at coverage distance d_i is $\sqrt{\alpha_j P_b h_i T_j}$ where α_j is the power ratio to subchannel j. The channel gain h_i is proportional to distance attenuation $d_i^{-\beta}$. We assume that the broadcast power P_b is normalized by the actual receiver noise variance. Thus, the normalized one sided power spectral density of white Gaussian noise $n_i(t)$ is 1.

We consider the received signal over one symbol interval T_j of subchannel j. The symbol stream of subchannel j is spread using the signature $s_j(t)$. We assume $s_j(t)$ is a random sequence:

$$s_j(t) = \frac{1}{\sqrt{L_j}} \sum_{k=0}^{L_j-1} c_{jk} p_c(t - kT_c), \tag{4.2}$$

where c_{jk} is a binary sequence element taking on values ± 1 equiprobably and T_c is the chip interval satisfying $T_c = 1/W = T_j/L_j$. The direct waveform $p_c(t)$ satisfies [38]:

$$R_p(nT_c) = \int_{-\infty}^{\infty} p_c(t)p_c(t - nT_c)dt = \begin{cases} 1 & n = 0, \\ 0 & n = \pm 1, \pm 2, ... \end{cases} \tag{4.3}$$

where $R_p(nT_c)$ is the autocorrelation of $p_c(t)$.

Then, the random sequence $s_j(t)$ has unit power

$$\int_0^{T_j} s_j^2(t)dt = 1. \tag{4.4}$$

We use a chip synchronous model for analytic simplicity. First, we consider the demodulation of the signal on subchannel 1, shown in Figure 4.2. Because we intend to demodulate the signal on subchannel 1, we only focus on the spread signature $s_2(t)$ that is transmitted during time interval $[0, T_1)$. Without loss of generality, we assume that over $[0, T_1)$, stream 2 sends a single bit b_2 with signature $s_2(t)$. Over one symbol interval $[0, T_1)$, the broadcast waveform received by a given user at coverage distance d_i is

$$r_i(t) = \sqrt{\alpha_1 P_b h_i T_1} b_1 s_1(t) + \sqrt{\alpha_2 P_b h_i T_2} b_2 s_2(t) + n_i(t). \tag{4.5}$$

It is possible with undesirable time offsets for subchannel 2 to have multiple symbols transmitted within time interval $[0, T_1)$. However, the overlap of symbols of subchannel 2 within $[0, T_1)$ will not destroy the properties of the average interference power, as we will see later.

When the received waveform is passed through a filter, matched to the signature

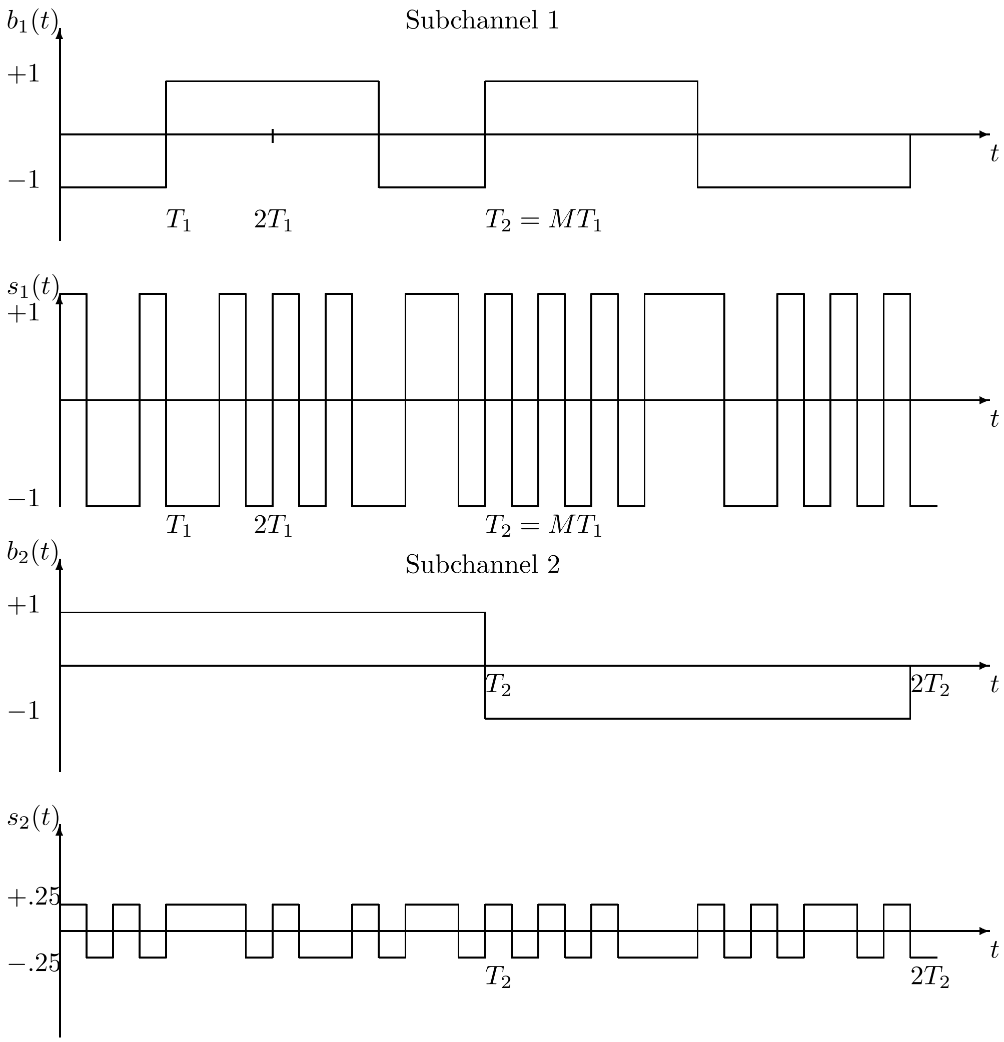


Figure 4.2: Data stream during time interval T_1 and T_2

waveform $s_1(t)$ of subchannel 1, the filter output is

$$
\begin{aligned}
y_{i_1}(t) &= \int_0^{T_1} r_i(t)s_1(t)dt && (4.6)\\
&= \sqrt{\alpha_1 P_b h_i T_1}b_1 \int_0^{T_1} s_1(t)s_1(t)dt, \\
&\qquad + \sqrt{\alpha_2 P_b h_i T_2}b_2 \int_0^{T_1} s_2(t)s_1(t)dt + \int_0^{T_1} n_i(t)s_1(t)dt. && (4.7)\\
&= \sqrt{\alpha_1 P_b h_i T_1}b_1 + \sqrt{\alpha_2 P_b h_i T_2}\rho_{12} b_2 + n_{i_1}. && (4.8)
\end{aligned}
$$

where

$$\begin{aligned}
\rho_{12} &= \int_0^{T_1} s_1(t)s_2(t)dt && (4.9)\\
&= \frac{1}{\sqrt{L_1L_2}}\int_0^{T_1}\left[\sum_{k=0}^{L_1-1} c_{1k}p_c(t-kT_c)\right]\left[\sum_{l=0}^{L_1-1} c_{2l}p_c(t-lT_c)\right]dt && (4.10)\\
&= \frac{1}{\sqrt{L_1L_2}}\sum_{k=0}^{L_1-1}\sum_{l=0}^{L_1-1} c_{1k}c_{2l}R_p((l-k)T_c) && (4.11)\\
&= \frac{1}{\sqrt{L_1L_2}}\sum_{k=0}^{L_1-1} c_{1k}c_{2k} && (4.12)
\end{aligned}$$

denotes the crosscorrelation. Note that the number of chips of subchannel 2 within T_1 is also L_1. Because c_{1k} and c_{2l} are independent binary variables taking on ± 1 equiprobably, the mean of the crosscorrelation is

$$E[\rho_{12}] = 0 \qquad (4.13)$$

and the variance of the crosscorrelation ρ_{12} is

$$\mathrm{Var}[\rho_{12}] = \frac{1}{L_1L_2}\sum_{k=0}^{L_1-1}\mathrm{Var}[c_{1k}c_{2k}] = \frac{1}{L_2}. \qquad (4.14)$$

In addition, the noise term $n_{i_1} = \int_0^{T_1} n_i(t)s_1(t)dt$ has zero mean and variance 1.

The symbol energy of the expected useful signal from subchannel 1 is $\alpha_1 P_b h_i T_1$. The variance of interference from subchannel 2 is

$$\begin{aligned}
I_{12} &= \mathrm{Var}[(\sqrt{\alpha_2 P_b h_i T_2}\rho_{12})] && (4.15)\\
&= \alpha_2 P_b h_i T_2\{\mathrm{Var}[\rho_{12}]\} && (4.16)\\
&= \alpha_2 P_b h_i T_2/L_2 = \alpha_2 P_b h_i/W && (4.17)
\end{aligned}$$

The effective interference and noise variance at the output of matched filter is:

$$Z_{12} = 1 + I_{12} \tag{4.18}$$

Note that, the second term is the interference from other subchannels, which does not exist when two subchannels are still orthogonal at the receiver.

Combining (4.8) and (4.14), the signal to interference and noise ratio γ_{s_1}, of subchannel 1 for users with channel gains $h_i = d_i^{-\beta}$ is

$$\gamma_{s_1} = \frac{\alpha_1 P_b d_i^{-\beta} T_1}{1 + \alpha_2 P_b d_i^{-\beta}/W}. \tag{4.19}$$

Now, we consider the demodulation of signals on subchannel 2. Assume $T_2 = MT_1$, where M is a positive integer. We observe the time duration T_2, within which the interference from subchannel 1 includes several symbols b_{1m}, $(m = 1, 2, ..., M)$, as shown in Figure 4.2. For convenience, we rewrite the received signal as,

$$r_i(t) = \sqrt{\alpha_2 P_b h_i T_2} b_2 s_2(t) + \sqrt{\alpha_1 P_b h_i T_1} \sum_{m=1}^{M} b_{1m} s_1(t - mT_1) + n_i(t). \tag{4.20}$$

From equation (4.20), we can intuitively think of the received signals $r_i(t)$ as the sum of multiple channels with signals $\sqrt{\alpha_1 P_b h_i T_1} b_{1m} s_1(t - mT_1)$. The output of the matched filter with the signature waveform $s_2(t)$ is:

$$y_{i_2}(t) = \sqrt{\alpha_2 P_b h_i T_2} b_2 + \sqrt{\alpha_1 P_b h_i T_1} \sum_{m=1}^{M} b_{1m} \rho_{12}^{(m)} + n_{i_2} \tag{4.21}$$

where, the noise component n_{i_2} has zero mean and variance 1. Parallel to the analysis of ρ_{12}, the crosscorrelation $\rho_{12}^{(m)}$ has the analogous properties as ρ_{12} in equations (4.13) and (4.14). In particular,

$$E\left[\rho_{12}^{(m)}\right] = 0, \tag{4.22}$$

$$\mathrm{Var}\left[\rho_{12}^{(m)}\right] = \frac{1}{L_2} \qquad m = 1, 2, ...M. \tag{4.23}$$

The symbol energy of the expected useful signal from subchannel 2 is $\alpha_2 P_b h_i T_2$. By applying $T_2 = MT_1$ and $L_2/L_1 = M$, and noting that b_{1m} and $\rho_{12}^{(m)}$ are independent identically distributed sequence in m, the variance of interference from subchannel 1 at the output of matched filter $s_2(t)$ is

$$\begin{aligned} I_{21} &= \mathrm{Var}\left[\sqrt{\alpha_1 P_b h_i T_1} \sum_{m=1}^{M} b_{1m}(\rho_{12}^{(m)})\right] && (4.24) \\ &= \alpha_1 P_b h_i T_1 \sum_{m=1}^{M} \left\{\mathrm{Var}[b_{1m}\rho_{12}^{(k)}]\right\} && (4.25) \\ &= \alpha_1 P_b h_i T_1 \frac{M}{L_2} = \alpha_1 P_b h_i / W && (4.26) \end{aligned}$$

The analysis of interference energy I_{21} implies that the overlap of symbols of subchannel 2 within T_1 does not change the variance of interference from subchannel 2. The underlying assumption is the independent symbols b_k and chips c_k taking on ± 1 equiprobably with chip synchronous demodulation. We can safely conclude that *for a dual rate CDMA system, with random spreading sequence, the interference power from subchannel j is $\alpha_j P_b h_i T_j / L_j = \alpha_j P_b h_i / W$.*

Assuming that the interference is white and is treated as noise, the effective interference and noise variance from subchannel 1 is:

$$Z_{21} = 1 + I_{21}. \tag{4.27}$$

Thus, from equation (4.20), the symbol energy to interference and noise ratio of subchannel 2 γ_{s_2} for users with channel gains $h_i = d_i^{-\beta}$ is:

$$\gamma_{s_2} = \frac{\alpha_2 P_b d_i^{-\beta} L_2/W}{1 + \alpha_1 P_b d_i^{-\beta}/W}. \tag{4.28}$$

We are interested in the bit energy to noise ratio at the output of Viterbi decoder for the desired bit error rate (BER). The relation of bit energy to noise ratio γ_{b_j} and symbol energy to noise ratio γ_{s_j} is $\gamma_{s_j}/l_j = \gamma_{b_j}$. Since the power of a broadcast stream is allocated between two subchannels, that is $\alpha_1 + \alpha_2 = 1$, we can assume that the power allocated to subchannel 2 is $\alpha = \alpha_2$ and to subchannel 1 is $(1 - \alpha) = \alpha_1$. In order to satisfy desired BER, the bit energy to noise ratio should be greater than target SIRs, γ_j^t at coverage distances d_1 and d_2:

$$\gamma_{b_1} = \frac{(1-\alpha) P_b d_1^{-\beta} L_1/(l_1 W)}{1 + \alpha P_b d_1^{-\beta}/W} \geq \gamma_1^t, \tag{4.29}$$

$$\gamma_{b_2} = \frac{\alpha P_b d_2^{-\beta} L_2/(l_2 W)}{1 + (1-\alpha) P_b d_2^{-\beta}/W} \geq \gamma_2^t. \tag{4.30}$$

At the maximum coverage distance d_i, we have $\gamma_{b_j} = \gamma_j^t$. By applying $R_j = l_j W/L_j$, we obtain:

$$d_1^*(\alpha) = \left(\frac{(1-\alpha)P_b}{\gamma_1^t R_1} - \frac{\alpha P_b}{W}\right)^{1/\beta}, \tag{4.31}$$

$$d_2^*(\alpha) = \left(\frac{\alpha P_b}{\gamma_2^t R_2} - \frac{(1-\alpha)P_b}{W}\right)^{1/\beta}. \tag{4.32}$$

In equation (4.31), the second term $\alpha P_b/W$ is the result of interference from subchannel 2 and reduces the range $d_1^*(\alpha)$ of subchannel 2. Similarly, in equation(4.32), $(1-\alpha)P_b/W$ is the result of interference from subchannel 1 on subchannel 2. Thus, the second term P_b/W in each of the above equations are the interference from the other broadcast subchannel when it applies. When the two channels are orthogonal to each other, the coverage distance are enlarged to

$$d_1^*(\alpha) = \left(\frac{(1-\alpha)P_b}{\gamma_1^t R_1}\right)^{1/\beta}, \tag{4.33}$$

$$d_2^*(\alpha) = \left(\frac{\alpha P_b}{\gamma_2^t R_2}\right)^{1/\beta}. \tag{4.34}$$

Let

$$\omega_j = W/\gamma_j^t R_j, \qquad j = 1, 2 \tag{4.35}$$

$$A_0 = P_b/W. \tag{4.36}$$

where, ω_j can be interpreted as the gain of overall processing factor over the target SIR; A_0 is the normalized transmitted chip energy. Then, the coverage distances in equations (4.31) (4.32) become:

$$d_1^*(\alpha) = A_0^{1/\beta}[(1-\alpha)\omega_1 - \alpha]^{1/\beta}, \tag{4.37}$$

$$d_2^*(\alpha) = A_0^{1/\beta}[\alpha\omega_2 - (1-\alpha)]^{1/\beta}. \tag{4.38}$$

It can be seen that the region of power allocation policies α resulting in feasible coverage areas for subchannels 1 and 2 are:

$$\alpha \leq \frac{\omega_1}{(\omega_1+1)} = \alpha', \tag{4.39}$$

$$\alpha \geq \frac{1}{(\omega_2+1)} = \alpha''. \tag{4.40}$$

When $\alpha \geq \alpha'$, subchannel 1 becomes infeasible. When $\alpha \leq \alpha''$, subchannel 2 becomes infeasible. We note that $\alpha'' \leq \alpha'$ if and only if

$$\omega_1\omega_2 \geq 1, \tag{4.41}$$

or equivalently,

$$\gamma_1^t\gamma_2^t \geq \frac{W^2}{R_1R_2}. \tag{4.42}$$

In this case, subchannel 1 and subchannel 2 will both have the feasible coverage areas simultaneously for $\alpha'' \leq \alpha \leq \alpha'$. In fact, simultaneous coverage areas can often be achieved, since the inequality (4.41) can be satisfied in most of the cases for moderately large spreading bandwidth W.

4.3 Maximum Coverage Problem in a Single-cell CDMA System

4.3.1 Power Allocation for Orthogonal Channels

With different power allocation policy, the coverage distances, as well as the overall coverage, vary. The coverage function is

$$
\begin{aligned}
U_2(\alpha) &= \rho\pi \left[d_1^2(\alpha) R_1 + d_2^2(\alpha) R_2 \right] && (4.43)\\
&= \rho\pi \left[\left(\frac{(1-\alpha)P_b}{\gamma_1^t R_1} \right)^{2/\beta} R_1 + \left(\frac{\alpha P_b}{\gamma_2^t R_2} \right)^{2/\beta} R_2 \right] && (4.44)\\
&= \rho\pi P_b^{2/\beta} \left[(1-\alpha)^{2/\beta} (\gamma_1^t)^{-2/\beta} R_1^{(1-2/\beta)} + \alpha^{2/\beta} (\gamma_2^t)^{-2/\beta} R_2^{(1-2/\beta)} \right]. && (4.45)
\end{aligned}
$$

The coverage in equation (4.45) is specified in terms of power allocation policies over the service requirements γ_1^t, γ_2^t and data rates R_1, R_2. One possible power allocation strategy is to assign power in proportion to the channel data rates. That is, $\alpha/(1-\alpha) \propto R_2/R_1$. Another way would be to allocate more power to the channel with the lower SIR requirement because more users can be covered by the same power. In terms of maximizing $U_2(\alpha)$, the optimal solution satisfies

$$
\begin{aligned}
\frac{\alpha^*}{1-\alpha^*} &= \left(\frac{\gamma_1^t}{\gamma_2^t} \right)^{2/(\beta-2)} \left(\frac{R_2}{R_1} \right). && (4.46)\\
&= \left(\frac{\omega_2}{\omega_1} \right)^{2/(\beta-2)} \left(\frac{R_2}{R_1} \right)^{\beta/(\beta-2)} && (4.47)
\end{aligned}
$$

The optimal allocation policy is proportional to R_2/R_1 and $(\gamma_1^t/\gamma_2^t)^{2/(\beta-2)}$. When $\beta = 2$, the objective function in equation (4.45) becomes

$$
U_2(\alpha) = \rho\pi P_b^{2/\beta} \left[\frac{1}{\gamma_1^t} + \left(\frac{1}{\gamma_2^t} - \frac{1}{\gamma_1^t} \right) \alpha \right]. \quad (4.48)
$$

The result of $U_2(\alpha)$ in equation (4.48) is impacted only by target SIR and is independent of the data rates R_1 and R_2. It is easy to see that for $\beta = 2$, when $\gamma_1^t < \gamma_2^t$, $U_2(\alpha)$ is a decreasing function with α. Thus, $\alpha = 0$ yields the best coverage. Similarly, if $\gamma_1^t > \gamma_2^t$, $\alpha = 1$ yields the best coverage. That is, for $\beta = 2$, power should be only allocated to the subchannel with the lower SIR requirement in order to achieve the maximum coverage.

When both subchannels have a feasible solution, substituting α in equation (4.45) by solution in equation (4.47), the optimal coverage is

$$\begin{aligned} U_2(\alpha^*) &= \rho\pi P_b^{2/\beta}\left[R_1(\gamma_1^t)^{2/(2-\beta)} + R_2(\gamma_2^t)^{2/(2-\beta)}\right]^{(\beta-2)/\beta} && (4.49) \\ &= \rho\pi A_0^{2/\beta}\left[\omega_1^{2/(\beta-2)}R_1^{\beta/(\beta-2)} + \omega_2^{2/(\beta-2)}R_2^{\beta/(\beta-2)}\right]^{(\beta-2)/\beta} && (4.50) \end{aligned}$$

It is later shown in numerical results that for $1/(1+\omega_2) < \alpha < 1 - 1/(1+\omega_1)$, and $\omega_1, \omega_2 \gg 1$, the optimal point for orthogonal channels is similar to that for the correlated channels.

4.3.2 Power Allocation for Correlated Channels

Consider the problem of finding the power allocation policy that maximize the overall broadcast coverage for the correlated channels in a CDMA system:

$$\max_{\alpha} U_2(\alpha) = \max_{\alpha} \rho\pi A_0^{2/\beta}[[(1-\alpha)\omega_1 - \alpha]^{2/\beta}R_1 + [\alpha\omega_2 - (1-\alpha)]^{2/\beta}R_2]. \quad (4.51)$$

In order to obtain the optimal solution of equation (4.51), we set the first derivative of coverage $U_2(\alpha)$ over α to zero:

$$\frac{\partial U_2(\alpha)}{\partial \alpha} = \rho\pi A_0^{2/\beta}\Big[-\frac{2}{\beta}(\omega_1+1)(\omega_1-(\omega_1+1)\alpha)^{2/\beta-1}R_1 \\ +\frac{2}{\beta}(\omega_2+1)((\omega_2+1)\alpha-1)^{2/\beta-1}R_2\Big]=0. \tag{4.52}$$

The solution α^* to the above equation must satisfy

$$\frac{\omega_1-(\omega_1+1)\alpha^*}{(\omega_2+1)\alpha^*-1} = \left(\frac{(\omega_2+1)R_2}{(\omega_1+1)R_1}\right)^{\beta/(2-\beta)}. \tag{4.53}$$

This implies

$$\alpha^* = \frac{\frac{\omega_1}{(\omega_1+1)}(\omega_2+1)^{2/(\beta-2)}R_2^{\beta/(\beta-2)}+\frac{1}{\omega_2+1}(\omega_1+1)^{2/(\beta-2)}R_1^{\beta/(\beta-2)}}{(\omega_1+1)^{2/(\beta-2)}R_1^{\beta/(\beta-2)}+(\omega_2+1)^{2/(\beta-2)}R_2^{\beta/(\beta-2)}}. \tag{4.54}$$

The important observation from the above optimal solution is that the optimal power policy α^* depends on dual data rates and ω_1, ω_2, which are the ratio of processing gains to target SIR. Combining (4.51) and (4.54), the corresponding optimum dual rate broadcast coverage of a CDMA system is

$$\begin{aligned} U_2^* &= \left[\frac{\omega_1\omega_2-1}{(\omega_1+1)(\omega_2+1)}\right]^{2/\beta} \\ &\times \rho\pi A_0^{2/\beta}\Big[(\omega_1+1)^{2/(\beta-2)}R_1^{\beta/(\beta-2)}+(\omega_2+1)^{2/(\beta-2)}R_2^{\beta/(\beta-2)}\Big]^{(\beta-2)/\beta} \end{aligned} \tag{4.55}$$

Note that the optimum solution is symmetric and is obtained when the two subchannels are both feasible. Compared to the optimum coverage for orthogonal subchannels in equation (4.50), the primary reduction in coverage is due to the first term in equation (4.55). Since for $\omega_j \gg 1$, $\omega_j+1 \simeq \omega_j$, the second term in equation (4.55) are similar to that in equation (4.50) ($j = 1, 2$). If for some power allocation policy, one of the subchannels is not feasible, the whole power can be allocated to the other. In that case, the conventional single rate broadcast will be employed.

4.4 Numerical Results

The numerical examples of the dual rate broadcast coverage are presented for a single cell CDMA system in this section. For the numerical examples, bandwidth $W = 3.84$ MHz with BPSK modulation on both subchannels are assumed.

We compare the optimal coverage strategy to the coverage of two other power allocation schemes for orthogonal subchannels first:

(A) Rate ratio scheme: power allocation between two subchannels are proportional to data rate ratio. That is, $\alpha_A/(1-\alpha_A) = R_2/R_1$. The corresponding coverage is

$$\begin{aligned} U_2(\alpha = \alpha_A) &= \rho\pi P_b^{2/\beta}\gamma_1^{-2/\beta}R_1^{1-2/\beta} \\ &\times \left(1+\frac{R_2}{R_1}\right)^{-2/\beta}\left[1+\left(\frac{R_2}{R_1}\right)\left(\frac{\gamma_2^t}{\gamma_1^t}\right)^{-2/\beta}\right]. \end{aligned} \tag{4.56}$$

(B) Dual rate same coverage distance scheme: same coverage distances for both base and enhanced QoS subchannels. That is, $d_1(\alpha_B) = d_2(\alpha_B)$. This implies, $\alpha_B/(1-\alpha_B) = (\gamma_2^t/\gamma_1^t)(R_2/R_1)$. The corresponding coverage is

$$\begin{aligned} U_2(\alpha = \alpha_B) &= \rho\pi P_b^{2/\beta}\gamma_1^{-2/\beta}R_1^{1-2/\beta} \\ &\times \left[1+\left(\frac{R_2}{R_1}\right)\left(\frac{\gamma_2^t}{\gamma_1^t}\right)\right]^{-2/\beta}\left[1+\frac{R_2}{R_1}\right]. \end{aligned} \tag{4.57}$$

According to the optimal coverage power allocation $\alpha^*/(1-\alpha^*) = (\gamma_1^t/\gamma_2^t)^{2/(\beta-2)}R_2/R_1$,

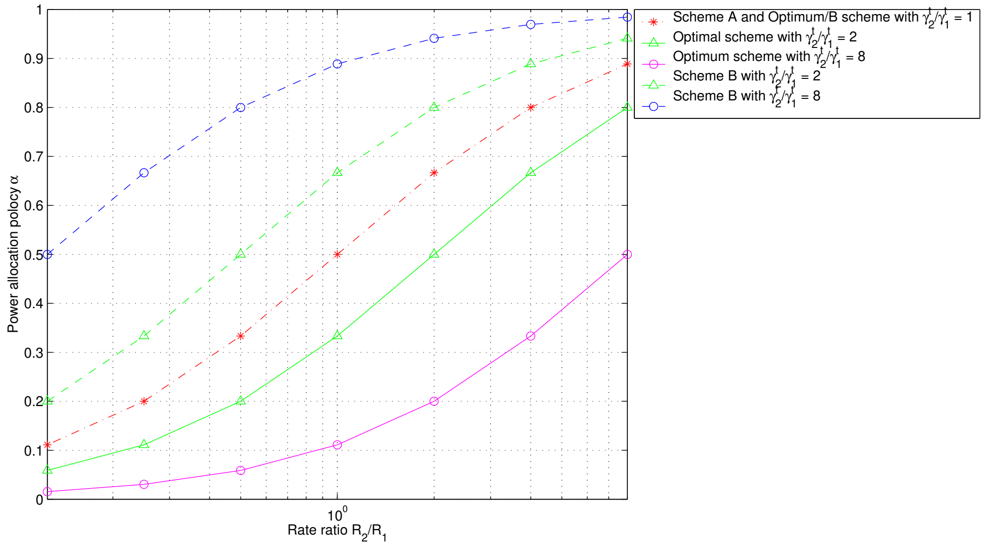


Figure 4.3: Power allocation in terms of dual rate ratio and the required SIR ratio. $\beta = 4$

the optimal coverage can be rewritten from equation (4.50) as

$$\begin{aligned} U_2(\alpha = \alpha^*) &= \rho\pi P_b^{2/\beta}\gamma_1^{-2/\beta}R_1^{1-2/\beta} \\ &\times \left[1 + \frac{R_2}{R_1}\left(\frac{\gamma_2^t}{\gamma_1^t}\right)^{2/(2-\beta)}\right]^{1-2/\beta}. \end{aligned} \tag{4.58}$$

The first term $\rho\pi P_b^{2/\beta}\gamma_1^{-2/\beta}R_1^{1-2/\beta}$ of the above coverages in equations (4.56), (4.57) and (4.58) is also the coverage when all power allocated to the first subchannel. In the numerical examples, the coverage is normalized by the first term, then, the relative coverage is the second term and is shown in terms of rate ratio and SIR requirement ratio in Figure 4.4.

The numerical example parameters are

- Required SIR ratio (γ_2^t/γ_1^t) is 1, 2, or 8;
- Dual rate ratio (R_2/R_1) is 1/8, 1/4, 1/2, 1, 2, 4, 8;

In Figure 4.3, the power allocation policies are shown for different SIR ratio γ_2^t/γ_1^t

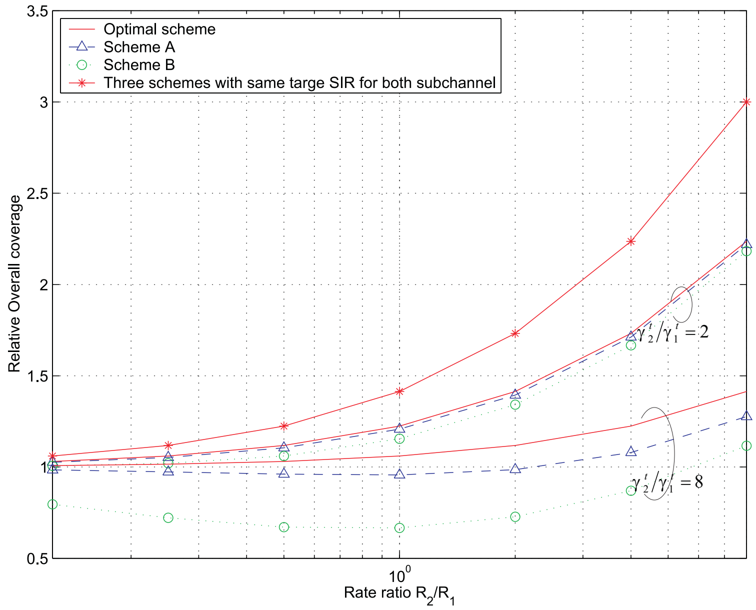


Figure 4.4: Coverage in terms of dual rate ratio and the required SIR ratio. $\beta = 4$

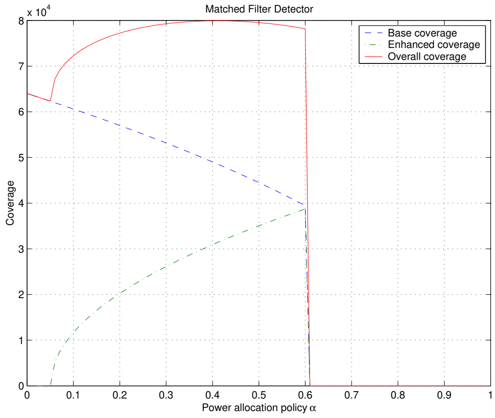
in terms of moderate data rate ratio R_2/R_1 with $\beta = 4$. From Figure 4.4, we find

1. With the increase of the difference between the SIR requirements, such as $\gamma_2^t/\gamma_1^t = 8$, the optimal coverage has an obvious advantage over the same coverage distance scheme.

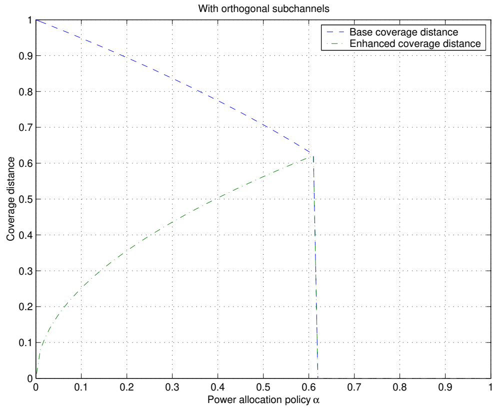
2. The optimum coverage scheme is to allocate more power to the subchannel with the lower SIR requirement and higher data rate according to equation (4.46).

3. When the SIR requirements are the same for two subchannels, the rate ratio scheme can be used for optimum coverage scheduling.

When R_2/R_1 is large (or small) enough, the coverage with schemes A and B will approach the optimum coverage. Given γ_2^t/γ_1^t, the relative optimum coverage will increase with the increase of R_2/R_1. We also note that the schemes A and B have minimum coverage with certain R_2/R_1. We need to choose α carefully for moderate R_2/R_1 in order to achieve better coverage when the difference between SIR requirements



(a) Coverage vs. power allocation



(b) Coverage distance vs. power allocation

Figure 4.5: Dual rate broadcast in a single cell CDMA system – correlated subchannels with matched filter detector

is large.

We discuss the power allocation with coverage for correlated subchannels with matched filter detection next. In Figure 4.5, the broadcast coverage and coverage distances are shown as a function of α with matched filter detectors. The coverage distance for only transmitting common information is normalized to 1. The product of users density ρ and π is also normalized as 1. We consider the QoS requirements for broadcast sources as:

- 64Kbps base QoS subchannel with the required E_b/I_0 of 3dB;
- 64Kbps, 128Kbps or 32Kbps enhanced QoS subchannel with the required E_b/I_0 of 5dB.

In Figure 4.5, we observe that, when $\alpha = 0$, power is only allocated to the base subchannel, the coverage distance is 1 and the overall coverage is 6.4×10^4. If power is distributed according to the rate ratio between two subchannels (here, $\alpha =$ 64kbps/64kbps $=$

0.5), the actual base and enhanced coverage distances are 0.70 and 0.54 respectively. The overall coverage is 7.95×10^4.

In Figure 4.5(a), the optimum coverage is 8.0×10^4 with base and enhanced coverage distances as 0.76 and 0.49 respectively. The corresponding optimum power allocated to base information is 59%. That is, by choosing the optimum power allocation policy, the overall coverage can be improved by approximately 25% compared to only providing base channel to mobile subscribers.

We note that in Figure 4.5(a), when too little power is allocated to the enhanced subchannel, no feasible enhanced coverage distance exists, as a result of the combination of high interference from base subchannel and low power on the enhanced QoS subchannel.

In Table 4.2, the overall coverage for data rate ratio power allocation (scheme A), same coverage distances scheme (Scheme B) and the optimum power policy are close to each other. This is due to the fact that the coverage for opitum coverage and sub-optimal coverage with schemes A and B are close to each other when the required SIR on two subchannels are not so different as long as $\omega_1, \omega_2 \gg 1$. It is illustrated clearly in Figure 4.5(a), that the overall coverage changes slowly when the power allocation policies are around the optimum point. That is, the optimum coverage is not very sensitive to α in this example.

It can be expected that if the received signal can still maintain orthogonal, the overall coverage is better than the case of the correlated subchannels. The optimum power allocation policies with respect to these two cases are listed in Table 4.2. They are so close to each other, due to the large ω_1, ω_2. The features of power allocation policies discussed for the orthogonal subchannels can also be applied to the correlated

Table 4.1: Optimal coverage for correlated channels and orthogonal channels

Received Signals	$(1-\alpha,\alpha)$	$(d_1,\, d_2)$	$U^* \times 10^4$
Correlated	(0.59, 0.41)	(0.76, 0.49)	8.00
Orthogonal	(0.61, 0.39)	(0.78, 0.50)	8.18

Table 4.2: Coverage for correlated channels and orthogonal channels. When $\alpha = 0$, power is only allocated to the base QoS subchannel. The corresponding coverage is 6.40×10^4. $P_b = 1.28 \times 10^5$.

System Parameter	Received signals	Coverage $\times 10^4$		
		Schemes		
		A	B	Optimum
$\gamma_2^t = 5$ dB $R_2/R_1 = 1$	Correlated	7.95	7.82	8.00
	Orthogonal	8.13	7.97	8.18

subchannels as long as $\omega_1, \omega_2 \gg 1$.

4.5 Summary

In this chapter, we proposed practical schemes to transmit common and additional information with code multiplexing in a CDMA system to achieve two QoS level broadcast. Users with better channels can decode signals from both common and additional information subchannels by satisfying associated SIR requirements. Users with worse channel can only decode common information from one broadcast subchannel to achieve basic QoS.

At the mobile receiver, the signals from the dual rate broadcast subchannels transmitted orthogonally, can remain or lose the orthogonal properties due to the different radio link situations. Matched filter detection can be used at the receiver. We found the optimal power allocation policy and the associated coverage areas to maximize broadcast coverage for given SIR requirements and data rates. The corresponding coverage strikes a balance between data rate achievable by each user and the number of users who can receive that rate with the required SIR. The optimal power allocation policy merits for large difference between SIR requirements.

Chapter 5

Video Broadcast in a Multi-cell CDMA System

In chapter 4, we discussed the broadcast coverage with respect to power allocation ratio in a single cell scenario. The underlying assumption is that all signals come only from an isolated base station. In a seamless network infrastructure, multiple cells are neighbors and interference from neighboring base stations is unavoidable.

In this chapter, we consider a multi-cell CDMA system with video broadcast service in addition to voice service. We define voice capacity as the maximum Erlangs of voice traffic that can be supported in a power controlled integrated voice and video CDMA system [8]. The video stream is broadcast from multiple base stations. Therefore, transmit signals from multiple base stations can be utilized to improve performance. By examining the tradeoff of forward link capacity between voice and video services, we analyze the cost of adding the video channel into a cellular system.

This chapter is organized as follows. The system model and interference model for voice and video traffic are described in Section 5.2. Forward link outage probability, Erlang capacity and video power allocation are derived in Section 5.3. Our derivation for voice outage follows the approach of [39] by considering the video and pilot signaling as constant interference. Numerical results are presented in Section 5.4. The cost of video broadcast is discussed in Section 5.5. In section 5.6, a brief summary is given.

5.1 Introduction

Multiple antennas are an important means to improve the performance of wireless systems. It is widely understood that a system with multiple transmit and receive antennas (MIMO) can achieve much higher spectral efficiency than that of a conventional single antenna system [24]. Recent research on multiple antenna channels, including the study of the channel capacity [11], the fundamental tradeoff of diversity and multiplexing to achieve multiple antenna channel capacity [43], and the design of communication schemes [3, 18, 19], demonstrates a great improvement of performance. In this chapter, we consider a cellular system supporting video broadcast in addition to voice services. In particular, we evaluate the system performance by utilizing transmit diversity in a forward link wideband CDMA system.

For a broadcast video service, the same video streams are broadcast from multiple base stations. Since the antennas from different base stations are subject to uncorrelated fading, transmit diversity can be achieved. Therefore, video broadcast can utilize the natural transmit diversity provided by adjacent base stations to improve the performance or increase system capacity. This kind of diversity is also called macrodiverisity [37]. For example, when the best signal from one of the base stations is chosen to decode, selective macrodiversity is utilized to significantly improve the performance for users at the boundary of the cell [37]. Under Maximal Ratio Combining (MRC) of two or more signals from adjacent base stations, as shown in Figure 5.1, even better performance can be expected under severe shadowing.

For traditional voice service, soft handoff, which is a form of macrodiversity, is used to extend CDMA capacity [15, 40]. By introducing video service into a cellular CDMA

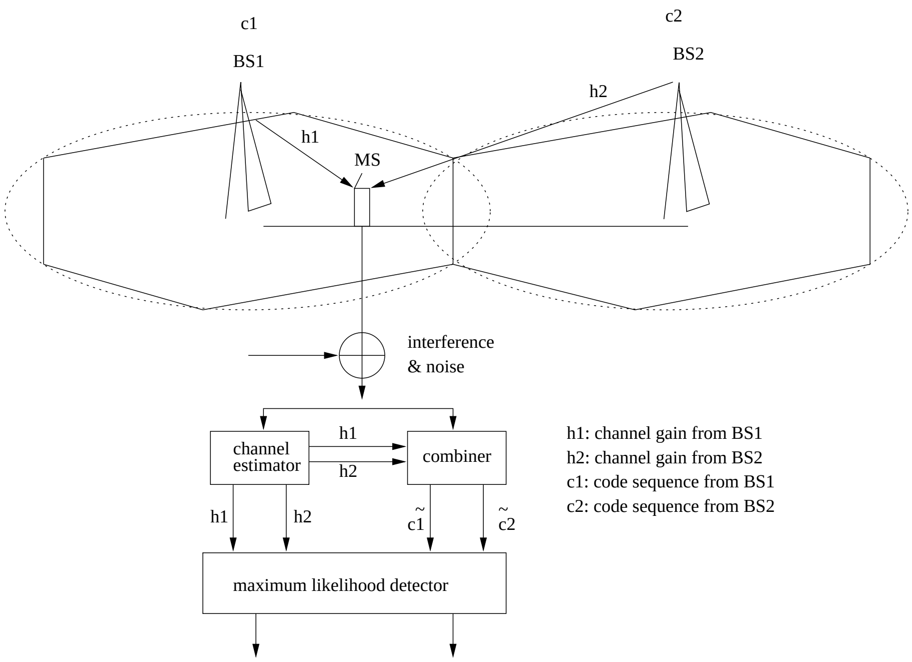


Figure 5.1: The illustration of transmit diversity scheme with Maximal Ratio Combiner (MRC) between two base stations

system, service providers are concerned about how much voice capacity decreases and how much it will cost. We evaluate the reduction in Erlang capacity for providing a video channel with respect to different video service outage requirements. With these statistics, we characterize the economic feasibility of video broadcast.

5.2 System Model

In a wideband CDMA cellular system, two classes of services are supported. Power control is applied to voice users in order to properly convey information with just enough energy. Therefore, the interference to other users is no more than necessary. When voice users are approaching the cell boundary, soft handoff is initialized to reduce the required margin or increase the cell capacity. For video service, the streams are broadcast from multiple base stations. For the reception of video channels, multiple base station signals can be combined to improve performance. Therefore, transmit

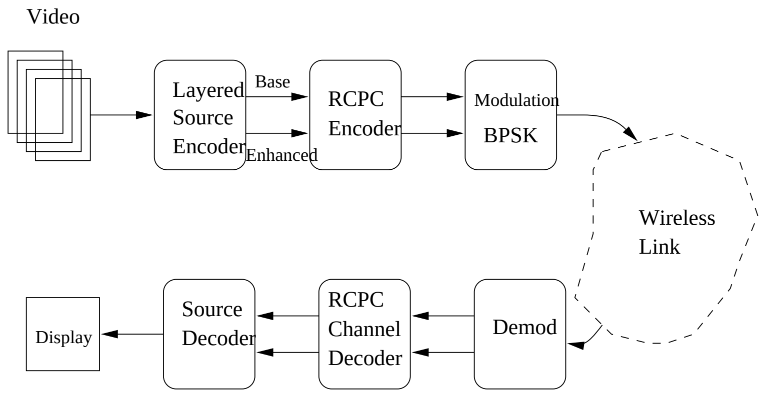


Figure 5.2: An example of the video traffic model

diversity can be utilized by the video service.

5.2.1 Video Traffic Model

In our scenario, raw video data is compressed to a much lower data rate using a video encoding standard, such as H.263 [29]. Since video broadcast cannot track all users' channel states, the source has fixed or less frequently changed coders for broadcast service. With the help of channel coding, it is reported [26] that low channel coding rates (such as 8/16) with the E_b/I_0 requirement as 3 to 4 dB can achieve relatively good quality. An example of the video traffic model is shown in Figure 5.2.

We also assume that both the transmitter and the receiver have enough buffer space to store the variable rate video data. In this case, we can approximately assume that constant rate traffic is transmitted across the radio channels. This implies that the video traffic interference to the voice service is just like the interference from pilot channels to voice users despite the much higher rate.

We need to find the transmitted power ratio for one video channel. The consequent reduction in Erlang capacity for voice service by adding a video channel into a CDMA system is evaluated by Monte Carlo simulation in the following sections.

5.2.2 Signal Model

Voice service and video broadcast service can be simultaneously supported by a Wideband CDMA system. Assume there are K_j^a voice users in the cell j, where K_j^a are Poisson distributed random variable. Note that we use the subscript "a" as in "audio" for the variables characterizing the voice service. And there are K_j^v video channels supported by base station j. Mobile subscribers are uniformly spread over all cells.

We assume that the total transmit power P_b from each base station is the same. The portion $\psi_j^a P_b$ of transmit power is allocated to voice service in base station j. The portion $\psi_j^a \phi_{ji}^a P_b$ of transmit power is allocated from base station j to mobile user i according to the voice user position and its current fading state. The portion $\psi_j^v P_b$ of transmit power is assigned to video service in base station j. Video channel k is transmitted with $\psi_j^v \phi_{jk}^v P_b$ of total power to cover the service area with certain outage e.g. $0.1\%, 1\%, 10\%, \dots$ or 90%. The power ratio allocated to the pilot channel from base station j is ψ_j^{pilot} and satisfies:

$$\psi_j^{\text{pilot}} = 1 - \psi_j^a - \psi_j^v. \tag{5.1}$$

Then, the transmit signal from the base station j is:

$$x_j(t) = \sum_{i=1}^{K_j^a} V_{ji}^a \sqrt{\psi_j^a \phi_{ji}^a P_b} s_{ji}^a(t) + \sum_{k=1}^{K_k^v} \sqrt{\psi_j^v \phi_{jk}^v P_b} s_{jk}^v(t) + \sqrt{\psi_j^{\text{pilot}} P_b} s_j^{\text{pilot}}(t), \tag{5.2}$$

where $s_{ji}^a(t)$, $s_{jk}^v(t)$ and $s_j^{\text{pilot}}(t)$ are the unit power signals for voice, video services and pilot respectively.

The activity of voice users is modelled as independent binary random variables with probability distribution:

$$\rho = P_r(V_{ji}^a = 1) = 1 - P_r(V_{ji}^a = 0), \qquad \forall i, j. \tag{5.3}$$

Here, ρ denotes the activity factor for voice service. When $V_{ji}^a = 1$, voice user i is in the active state and transmits at rate R^a, while for $V_{ji}^a = 0$, voice user i does not transmit.

We consider a baseband DS-CDMA system model supporting such two QoS level services and using a coherent BPSK modulation format. Each user's channel is only characterized by large scale shadow fading along with its distance-based path loss. In cell j, the resulting received baseband signals for voice user i is

$$\begin{aligned} r_i^{(j)}(t) \;=\;& V_{ji}^a \sqrt{\psi_j^a \phi_{ji}^a S_{R_{ji}}}\, s_{ji}^a(t) \\ &+ \left[\sum_{q \neq i}^{K_j^a} V_{jq}^a \sqrt{\psi_j^a \phi_{jq}^a S_{R_{ji}}}\, s_{jq}^a(t) + \sum_{k=1}^{K_j^v} \sqrt{\psi_j^v \phi_{jk}^v S_{R_{ji}}}\, s_{jk}^v(t) \right] \\ &+ \sum_{l \neq j}^{J} \left[\sum_{q=1}^{K_l^a} V_{lq}^a \sqrt{\psi_l^a \phi_{lq}^a S_{R_{li}}}\, s_{lq}^a(t) + \sum_{k=1}^{K_l^v} \sqrt{\psi_l^v \phi_{lk}^v S_{R_{li}}}\, s_{lk}^v(t) \right] \\ &+ \sum_{l=1}^{J} \sqrt{\psi_j^{\text{pilot}} S_{R_{li}}}\, s_j^{\text{pilot}}(t) + n_{ji}(t). \end{aligned} \tag{5.4}$$

Here, the normalized total received power $S_{R_{ji}}$ from base station j to mobile user i is given by

$$S_{R_{ji}} = P_b r_{ji}^{-m} 10^{\zeta_{ji}}/10, \tag{5.5}$$

where r_{ji} is the distance between base station j mobile station i; m is the path loss attenuation exponent; and ζ_{ji} is Gaussian random variable with variance in the range of 2dB to 14dB.

In equation (5.4), the first term is the desired voice signal for user i in base station j. The second term is the interference from voice and video channels other than voice channel i in the local cell. The third term is voice and video interference from other cells. The fourth term is the interference from pilot channels and the last is the thermal noise modeled as white Gaussian process with the normalized one sided power spectral density N_0. The number of base stations in the system is J.

5.2.3 Interference Model

Due to the multipath transmission, orthogonal transmit signals become interference at the receiver. Without loss of generality, we only need to consider the interference characteristics for user i at base station 1. Thus, for simplicity, we drop subscript 1 from the notations, such that the power allocated to voice and video services are $\psi^a = \psi_1^a$ and $\psi^v = \psi_1^v$ respectively. We use V_i^a to represent V_{ji}^a. And we use ϕ_i^a to represent ϕ_{1i}^a and ϕ_k^v for ϕ_{1k}^v; K^a and K^v represent K_1^a and K_1^v respectively.

For voice user i and video user decoding video channel k, the same-cell interference in cell 1 is given by

$$I_{sc}^a = (1 - \psi^a \phi_i^a) S_{R_{1i}}, \tag{5.6}$$

$$I_{sc}^v = (1 - \psi^v \phi_k^v) S_{R_{1i}}. \tag{5.7}$$

respectively. The other-cell interference from the adjacent base stations is

$$I_{oc} = \sum_{j=2}^{J} S_{R_{ji}}. \tag{5.8}$$

5.3 Forward Link Capacity

5.3.1 Voice Service

In this section, we derive the forward-link outage probability and evaluate the capacity [39]. The received E_b/I_0 at the MS for the decoding of voice service, when the voice activity is on, is given by

$$\gamma_i^a = \frac{W}{R^a}\frac{\psi^a\phi_i^a S_{R_{1i}}}{(\sum_{j=2}^{J} S_{R_{ji}} + (1-\psi^a\phi_i^a)S_{R_{1i}} + N_0 W)}, \tag{5.9}$$

where R^a is the voice data rate, W is the spreading bandwidth.

It is reasonable to assume that $\psi^a\phi_i^a$ is much less than 1. We also assume that the background noise will be negligible compared to the total signal power received from all base stations. Thus, we can drop N_0W in equation (5.9). In this case, the received E_b/I_0 can be approximated as

$$\gamma_i{}^a = \frac{W}{R^a}\frac{\psi^a\phi_i^a S_{R_{1i}}}{\sum_{j=1}^{J} S_{R_{ji}}}. \tag{5.10}$$

Now suppose all voice users in the cell are allocated the same E_b/I_0. Then with $\gamma_i^a = (E_b/I_0)^a$ for all i, we can obtain the relative power allocation for the ith user,

$$\phi_i^a = \frac{(E_b/I_0)^a}{\psi^a(W/R^a)}\left(1 + \sum_{j=2}^{J} S_{R_{ji}}/S_{R1i}\right). \tag{5.11}$$

We note that the ϕ_i^a have the constraint that

$$\sum_{i=1}^{K^a} V_i^a\phi_i^a < 1. \tag{5.12}$$

When (5.12) is not satisfied, an outage occurs. The outage probability is

$$\begin{aligned} P_{\text{out}} &= P_r\left(\sum_{i=1}^{K^a} V_i^a \phi_i^a > 1\right) && (5.13) \\ &= P_r\left[\sum_{i=1}^{K^a} V_i^a \left(1 + \sum_{j=2}^{J} S_{R_{ji}}/S_{R_{1i}}\right) > \frac{\psi^a (W/R^a)}{(E_b/I_0)^a}\right]. && (5.14) \end{aligned}$$

Defining

$$Y_i = \sum_{j=2}^{J} S_{R_{ji}}/S_{R_{1i}}, \tag{5.15}$$

the Y_i is a random variable as the ratio of total interference from other base stations to the signal strength from local base station. The Y_i vary with path loss and shadowing.

We define

$$M_0^a = \frac{W/R^a}{(E_b/I_0)^a}. \tag{5.16}$$

Then,

$$P_{\text{out}} = P_r\left[\sum_{i=1}^{K^a} V_i^a (1 + Y_i) - \psi^a M_0^a > 0\right]. \tag{5.17}$$

From the Chernoff bound [42], we have such that for any $s > 0$,

$$P_{\text{out}} \leq e^{-s\psi^a M_0^a} \mathbb{E}\left\{\exp\left[\sum_{i=1}^{K_a} s V_i^a (1 + Y_i)\right]\right\}. \tag{5.18}$$

Taking the expectations with respect to K^a, V_i^a and Y_i (mutually independent), we

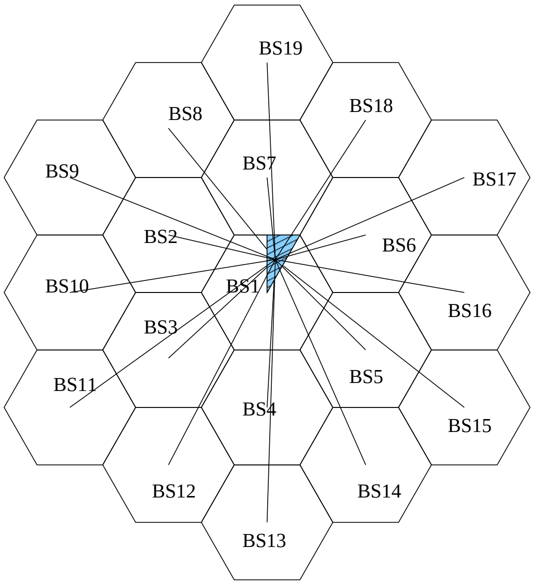


Figure 5.3: Cell configuration

have

$$
\begin{aligned}
P_{\text{out}} &\leq \min_{s\geq 0} e^{-s\psi^a M_0^a} \mathbb{E}_{K^a} \Pi_{i=1}^{K^a} \mathbb{E}_{V_i^a} \mathbb{E}_{Y_i} e^{sv_i(1+Y_i)} && (5.19)\\
&= \min_{s\geq 0} e^{-s\psi^a M_0^a} \mathbb{E}_{K^a} \left[\rho \mathbb{E}_Y \left[e^{s(1+Y)}\right] + (1-\rho)\right]^{K^a} && (5.20)\\
&= \min_{s\geq 0} e^{-s\psi^a M_0^a} \sum_{K^a=0}^{\infty} \frac{[\lambda/\mu(1+g)]^{K^a} e^{-\lambda/\mu(1+g)}}{K^a!} \left[\rho e^s \mathbb{E}_Y[e^{sY}] + (1-\rho)\right]^{K^a} && (5.21)\\
&= \min_{s\geq 0} \exp\left\{\rho(\lambda/\mu)(1+g)\left[e^s \mathbb{E}_Y[e^{sY}] - 1\right] - s\psi^a M_0^a\right\} && (5.22)
\end{aligned}
$$

where $\mathbb{E}_y[\cdot]$ denotes expectation on random variable Y and $\lambda/\mu = \mathbb{E}[K^a]$ is the average number of voice users.

When MSs are at the boundary of the cell, they will communicate with multiple adjacent base stations to implement soft handoff. By utilizing macrodiversity, the total transmit power for a mobile voice user decreases [37]. On the other hand, soft handoff utilize more resources, such as code sequences, available channels, than users who only connect to its local base station [18]. We assume that the fraction $g < 1$ of all the MSs are in soft handoff, and both BSs involved in soft handoff allocate essentially the same fraction of power to that MS. If the supported average Erlangs in one cell is λ/μ, the effective Erlangs supported by each cell becomes $(\lambda/\mu)(1+g)$ [39].

The Chernoff bound on the outage probability in equation (5.22) can be obtained by evaluating the distribution of Y by Monte Carlo simulation. We will assume only interference from base stations within the two rings of a given cell, (thus, $J = 19$ including the given base station) as shown in Figure 5.3. The variable Y_i will depend on the position of the ith user, which is uniformly distributed in space. Thus, the distribution is averaged over all positions in the cell. However, by symmetry, it is only necessary to perform simulations over 30^o right shaded triangle as shown in Figure 5.3. About 1550 equally spaced points on the shaded triangle are simulated and for each point we perform 100 trials. The Monte Carlo estimate of $\mathbb{E}_Y[e^{sY}]$ is substituted into equation (5.22).

5.3.2 Video Channel

Assuming total power ratio allocated to video channels are the same, the received E_b/I_0 at the ith MS to decode the video channel k is given by

$$\gamma_i^v = \frac{W}{R_k^v} \frac{\psi^v \phi_{1k}^v S_{R_{1i}}}{\sum_{j=2}^{J} S_{R_{ji}} + (1-\psi^v\phi_{1k}^v) S_{R_{1i}} + N_0 W} \tag{5.23}$$

where R_k^v is video data rate for channel k. Defining

$$M_k^v = \frac{W/R_k^v}{(E_b/I_0)_k^v} \tag{5.24}$$

where $(E_b/I_0)_k^v$ is the required SIR for the successful decoding of video channel k. Thus, the received SIR should satisfy $\gamma_i^v \geq (E_b/I_0)_k^v$. When $\gamma_i^v < (E_b/I_0)_k^v$, outage will occur.

Therefore, the power ratio allocated to a video channel should satisfy the following inequality with the required outage $\overline{P_o}$,

$$\begin{aligned} P_{\text{out}} &= P_r(\gamma_i^v < (E_b/I_0)_k^v) && (5.25) \\ &= P_r\left[\sum_{j=2}^{J} \frac{S_{R_{ji}}}{S_{R_{1i}}} > \psi^v \phi_{1k}^v M_k^v - 1\right] < \overline{P_o} && (5.26) \end{aligned}$$

where

$$S_{R_{1i}} = \max_j S_{R_{ji}} \tag{5.27}$$

if the selection diversity is used.

If transmit diversity with MRC is applied, we can evaluate the performance by utilizing the energy from the two most favorite base stations. If perfect MRC is assumed, γ_i^v can be represented in terms of the sum of SIR of the same signal from adjacent base stations,

$$\gamma_i^v = \frac{W}{R_k^v}\left[\frac{\psi^v \phi_{1k}^v}{Y_{1i} + 1 + N_0 W / S_{R_{1i}}} + \frac{\psi^v \phi_{2k}^v}{Y_{2i} + 1 + N_0 W / S_{R_{2i}}}\right], \tag{5.28}$$

where,

$$Y_{1i} = \sum_{j=2}^{J} S_{R_{ji}} / S_{R_{1i}}, \tag{5.29}$$

$$Y_{2i} = \sum_{\substack{j=1 \\ j \neq 2}}^{J} S_{R_{ji}} / S_{R_{2i}}. \tag{5.30}$$

Here, $S_{R_{ji}}$ $(j = 1, 2)$ represent the two best base station signals.

Thus, the power ratio ϕ_{1k}^v and ϕ_{2k}^v to the video channel k should satisfy the following inequality with the required outage:

$$P_{\text{out}} = P_r \left[\frac{\psi^v \phi_{1k}^v}{Y_{1i} + 1 + N_0 W / S_{R_{1i}}} + \frac{\psi^v \phi_{2k}^v}{Y_{2i} + 1 + N_0 W / S_{R_{2i}}} < 1/M_k^v \right] < \overline{P_o}. \quad (5.31)$$

Assume the same portion of power is allocated to the same video broadcast channel from different base stations, then $\phi_{1k}^v = \phi_{2k}^v$. The fraction of power $\psi^v \phi_{1k}^v$ allocated to one video channel is evaluated by Monte Carlo simulation. We also assume that only interference from base stations within the two rings of a given cell $(J = 19)$ are counted. The variables Y_{1i} and Y_{2i} depend on the position of the ith user, which are uniformly distributed. We collect the statistics of 1550 equally spaced users on the shaded triangle with 100 trials each point. The Monte Carlo estimate of $\psi^v \phi_{1k}^v$ is shown in Figure 5.6.

The system can also support a two-layered video stream, which is transmitted on code multiplexing CDMA subchannels as discussed in chapter 4. The power portion for either subchannel can be derived and evaluated from (5.31) with different M_k^v in equation (5.24), which includes system parameters, such as the required SIR and the data rates.

5.4 Numerical Results

The numerical examples of the reduction in Erlang capacity by adding one video channel into the system are presented in this section. Particularly, we show the forward link Erlang capacity of the third generation CDMA system. The system can support any Erlang set that keeps the outage probability at a target level.

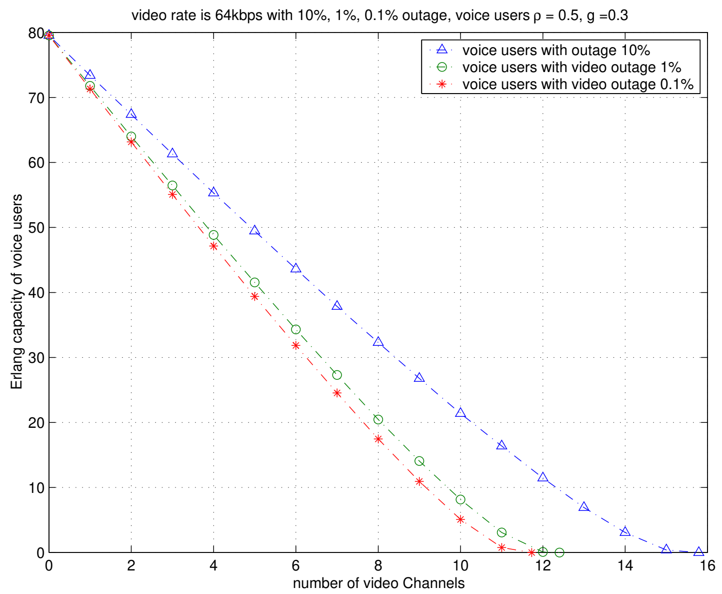
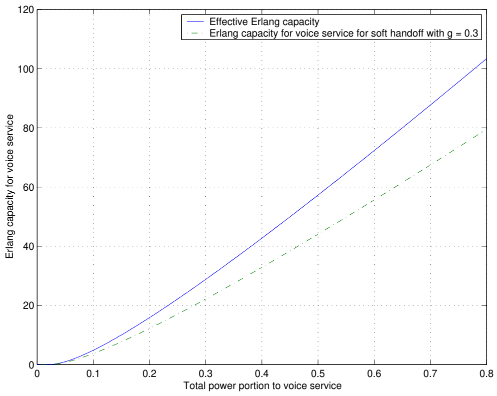


Figure 5.4: Forward link voice user Erlang capacity with number of video channels

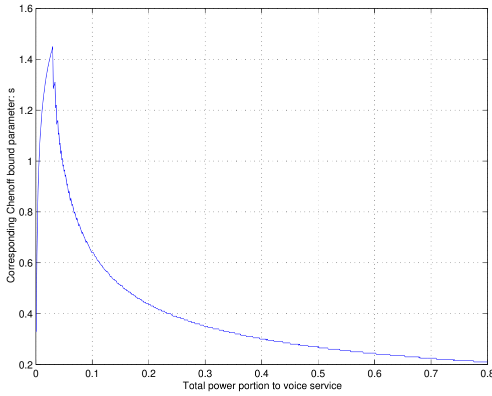
For the numerical examples, path loss exponent $m = 4$, target outage is 0.01 for voice users, soft handoff fraction $g = 0.3$, and a fraction of power for pilot signaling 0.2 are assumed. In Figure 5.4, a forward link Erlang capacity of a WCDMA (chip rate = 3.84 Mc/s) system is shown for the standard deviation of lognormal shadow fading 8 dB with perfect power control. We consider two classes of traffic sources:

- 8kb/s voice service with the required E_b/I_0 of 5dB and voice activity factor $\rho =$ 0.5;
- 64kb/s video channel with the required E_b/I_0 of 3dB and the outage of video service within a hexogan cell is 0.1%, 1% or 10%.

Typically, the required E_b/I_0 depends on the system operating conditions, including vehicular speed and link level parameters. The system can support any Erlang capacity and number of video channels below the line shown in Figure 5.4. For example, without video channels, the supported voice Erlangs are approximately 80. By adding one video broadcast channel into the system, 6.2 Erlangs are sacrificed for video outage



(a) Erlang capacity



(b) Corresponding Chernoff bound parameter: s

Figure 5.5: Erlang capacity with the power allocated to voice users. Pilot signaling occupies 20% base station power

10% and 7.8 Erlangs for 1% video outage. We see that the system can support more calls with higher video service outage 10% than that of low outage 1%. This can be easily explained by Figure 5.6, which illustrates the power portion per video channel needed regarding different video service outage. With higher outage rate 10%, the power portion per video channel is less than that with small outage 1%. Thus, more power can be utilized by voice users, therefore, supporting more voice traffic.

In Figure 5.5(a), a forward link Erlang capacity is shown with different portion of power allocated to such voice service. It is approximately that 15.7 effective Erlangs are supported by 10% total power. The total average voice rates supported by 10% power is about $8 \times 15.7 = 125$Kbps. The Erlang with soft handoff is suppressed by $1/(1+g)$ to 12 Erlang, therefore the total average voice rates supported is 96Kbps. The corresponding Chenoff bound parameter s which minimize the outage for different power allocation is shown in Figure 5.5(b).

In Figure 5.6, power portion per video channel and total number of video channels supported by the system are shown with respect to video service outage. The outage can

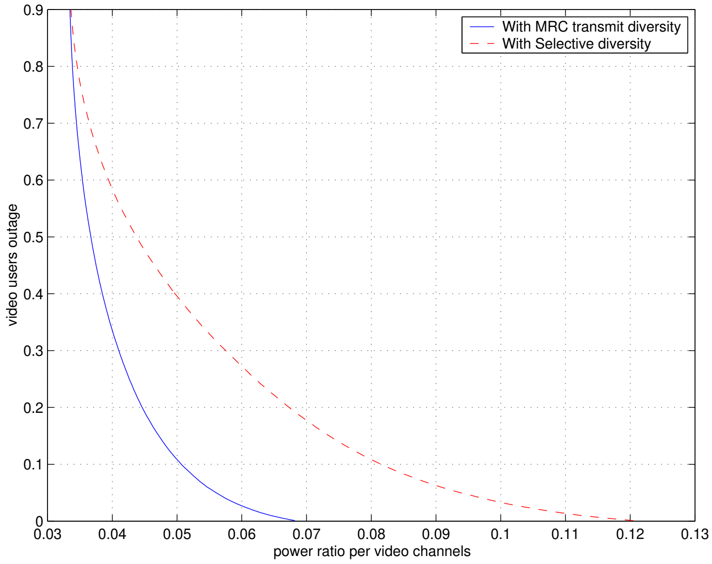


Figure 5.6: Power allocation ratio per video channel with MRC and selection diversity

be understood as the actual percentage of service area not covered by video broadcast. For video service with 1% outage, the power allocation per video channel with 64 Kbps rate is around 6.5% total power with MRC transmit diveristy, which instead can support 7.8 Erlang or 62 Kpbs voice data rate. With selection diversity, the power portion per video channel is 11.2% which can support 13.5 Erlang or 108 Kbps.

We also note that for voice users, power is allocated to maintain the received SIR as small as possible but above the target SIR wherever the voice user locates. On the other hand, power assigned to video channels is to maintain the whole coverage area with certain outage by letting closer users achieve higher SIR than necessary.

It is obvious from Figure 5.7, that the utilization of transmit diversity to cover the users close to the boundary of the cell is critical for the achievement of much better performance. Without any diversity, user close to the boundary would not be able to receive satisfied service, outage would occur. In other words, without transmit diversity, the actual coverage area will shrink. With selection diversity, in order to cover almost

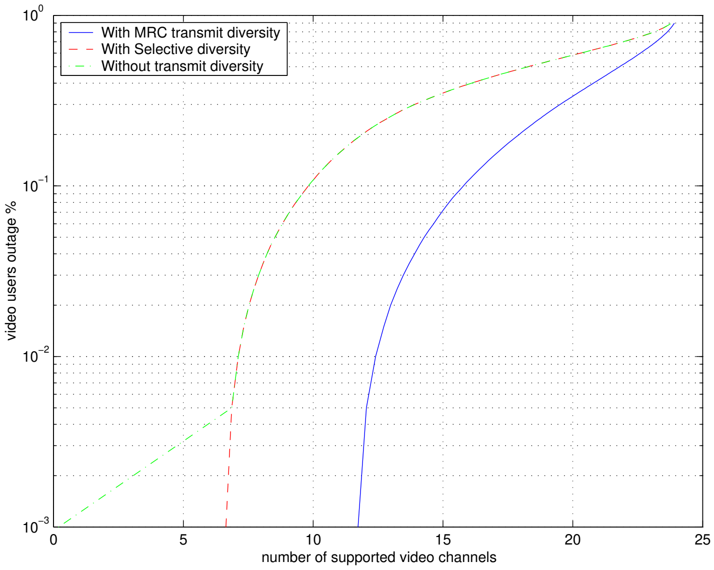


Figure 5.7: The maximum number of video channels that can be supported with and without transmit diversity

the whole coverage area (i.e. 0.1% outage), approximately 12.1% of total power is needed. With MRC receiver, the needed power reduces to 6.8%. When larger outage is allowed, the gain for transmit diversity over without any diversity becomes negligible. In Figure 5.7, when outage is greater than 0.5%, the required power without diversity is similar to that with selection diversity. We note that the gain of MRC transmit diversity over selection diversity will decrease as the video outage increases.

In Figures 5.8, the relation between the voice Erlang capacity and the video outage with selection diversity and MRC diversity are presented. It clearly demonstrates that the Erlang capacity increases with the video service outage probability.

In Figure 5.9, power allocation of a two layered video channel is shown with respect to different service outage for lognormal shadow fading with standard deviation 8dB. The system is considered with the following parameters:

- 8kb/s voice service with the required E_b/I_0 of 5dB and voice activity factor $\rho = 0.5$;

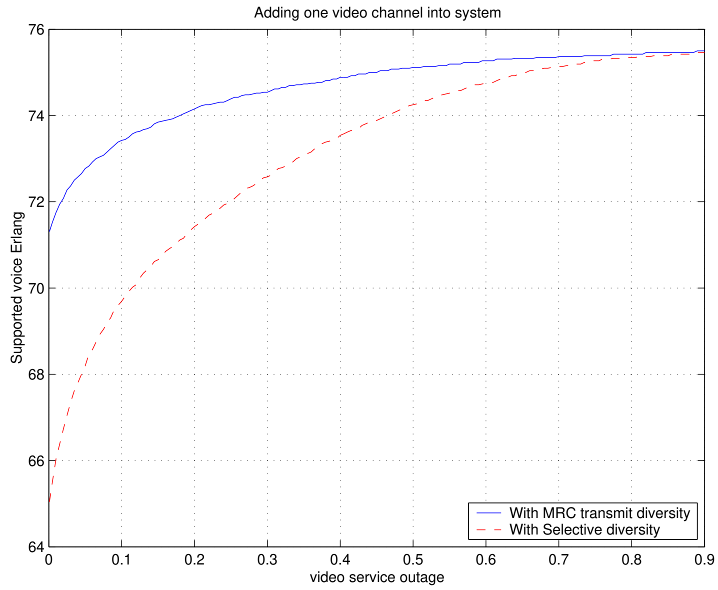


Figure 5.8: Relation of video outage and Erlang for voice service

- 64kb/s base video subchannel with the required E_b/I_0 of 3dB and the outage $P^b_{\text{out}} \in (0.01\%, 90\%)$;
- 64kb/s enchanced video subchannel with the required E_b/I_0 of 5dB and the video service outage $P^e_{\text{out}} \in (0.01\%, 90\%)$. Users who receive the enhanced subchannel should already decode the base subchannel successfully.

For a successful two-layered video stream transmission, the outage P^b_{out} of base layer video should be no more than the outage P^e_{out} of enhanced layer video subchannel as shown in Figure 5.10. Given the same outage, the power portion required for the enhanced subchannel is more than that for the base subchannel. That is, due to the higher requirement SIR for the enhanced layer, only users closer to base station can receive it successfully.

In Figure 5.10, the system can support any Erlang sets below the three-dimensional surface. It is apparent that the Erlang capacity for voice users increases as the outage for base and enhanced layer video substreams goes up. Note that the feasible part of

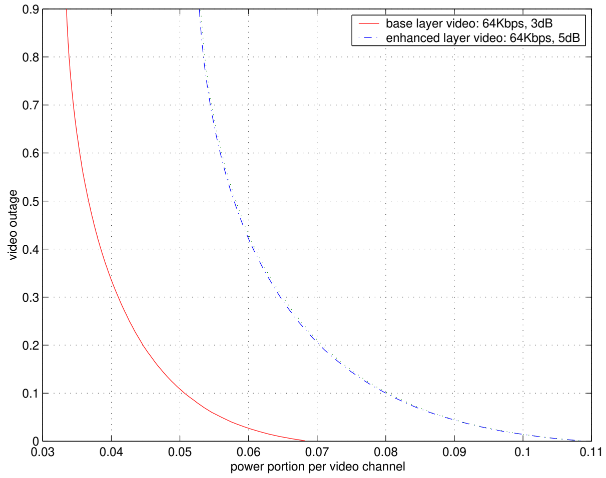


Figure 5.9: Power portion for base and enhanced video channel with MRC transmit diversity

the graph is the region when $P_{\text{out}}^b < P_{\text{out}}^e$.

5.5 Video Broadcast: A Cost Estimate

5.5.1 Bandwidth Cost

For 3G network operators, the cost of providing video broadcast service by sacrificing the voice capacity is an important issue. Globally, cellular operators seem to need to generate at least 5 cents per minute (c_a) over all subscribers and call minutes in order to sustain their operations. With the data rate of cellular voice calls averaging about 5kbps with voice activity, it is apparent that the retail price for one kilobit bandwidth per minute is one cent.

Video broadcast, like voice, is a "real-time" service that is intolerant of delay. For example, consider a video channel with a gross rate of 64kbps. At one cent per kbps, the video channel would retail for \$0.64 per minute.

This calculation shows what an operator must charge simply to maintain its operating profit margin. It assumes that 3G infrastructure capacity costs the same on a

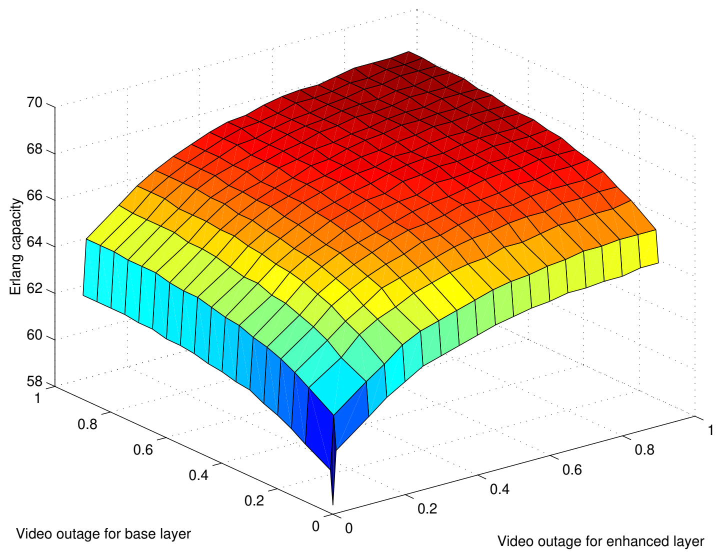


Figure 5.10: Video broadcast with two layered video stream: Erlang capacity vs. base and enhanced layer video outage

per-kbps basis as existing infrasture, which seems rather optimistic.

On the other hand, from the Figure 5.11, with 10% overall video service outage, adding one video channel will eliminate roughly 6.1 Erlangs. Then, 30.5 cents per minute of video service per channel should be charged. With higher video service outage, the cost per video channel is proportionally lower. The associated cost is also shown in Figure 5.11.

5.5.2 Number of Video Users Needed

From the subscriber point of view, a customer may want to subscribe to video service when the cost for a video channel is 1 cent/minute or c_v = \$0.60/hour. The overall system profit margin for a reduction of 6.1 Erlangs is calculated as \$18.3 per hour (from $0.05 \times 6.1 \times 60$) for 10% video outage. That means about 31 users (this is calculated from $18.3/0.6 = 31$) are needed to turn on video channel in order to maintain the profit. This is not impossible and actually may be quite reasonable in a dense urban areas such

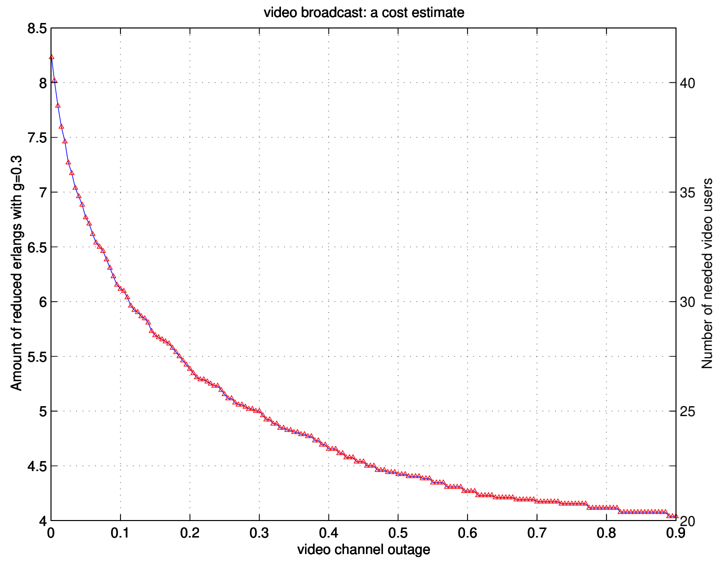


Figure 5.11: Video broadcast: A cost estimate example (I). Amount of reduced Erlangs vs. outage and the number of video users needed within coverage area vs. outage. Parameters: voice cost per Erlang: $c_a = \$3.00$/hour, and video cost per channel $c_v = \$0.60$/hour for a video receiver

as New York City or Tokyo.

Moreover, if the advertisement on public TV channels are also introduced to cellular video service, the customer cost can be further reduced. Therefore more users will be attracted to use video service by even lower cost.

If Δ is the reduction in voice Erlangs when introducing a video broadcast channel with outage P_{out} to the system, the number of video users needed N_v must satify $c_v N_v = c_a \Delta$ to sustain the same revenue. That is,

$$N_v = \frac{c_a \Delta(\lambda/\mu)}{c_v}. \tag{5.32}$$

It is apparent that the number of video users increases with the decreasing of video outage as shown in Figure 5.11.

In Figure 5.12, the video broadcast cost of the two layered video streams is shown with two charge plans:

- *Plan 1:* Users who receive both base rate and enhanced rate video service pay the same as those who only receive base rate videos. The underlying assumption is that video users are randomly located and everyone has the same probability to receive either both substreams or only the base rate substream. We assume that subscribers who only receive base rate service pay c_v^b per hour and subscribers who receive both substreams pay c_v^e for the cost of the service. For numerical results, we consider $c_v^b = c_v^e = \$0.60$.

- *Plan 2:* Users who can receive enhanced layer service pay double as those only receive base video service. In this charge plan, users who locate within enhanced QoS coverage region can still choose whether to turn on the high quality video mode, and therefore to pay more. For a numerical example, we consider $c_v^e = \$1.20$ and $c_v^b = \$0.60$.

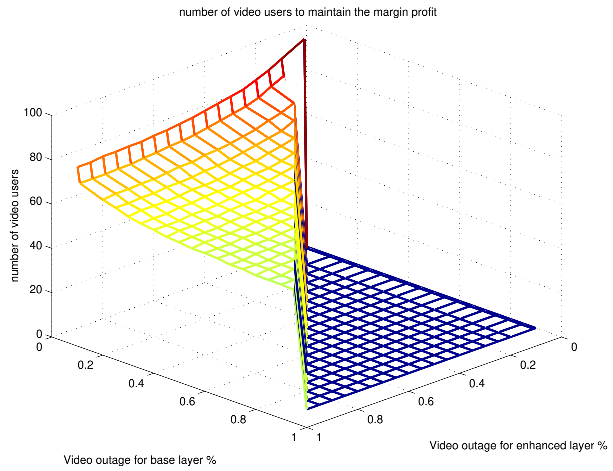
We assume that the video outage for base and enhanced QoS substream are P_{out}^b and P_{out}^e respectively. If Δ is the reduction in voice Erlangs when a two layered video channel is addede to the system, the numbers of video users needed must satisfty $N_c[c_v^b u_v^b + c_v^e u_v^e] = c_a \Delta$. Here, $u_v^b = [(1 - P_{\text{out}}^b) - (1 - P_{\text{out}}^e)]/(1 - P_{\text{out}}^b)$ is the portion of video users only receiving base rate substrea, and $u_v^e = (1 - P_{\text{out}}^e)/(1 - P_{\text{out}}^b)$ is the portion of video users receiving both base and enhanced QoS substreams. The number of video users N_v, then, are calculated for the above charge plans by:

$$N_v = \frac{c_a \Delta(\lambda/\mu)}{c_v^b[(1 - P_{\text{out}}^b) - (1 - P_{\text{out}}^e)]/(1 - P_{\text{out}}^b) + c_v^e(1 - P_{\text{out}}^e)/(1 - P_{\text{out}}^b)}, \tag{5.33}$$

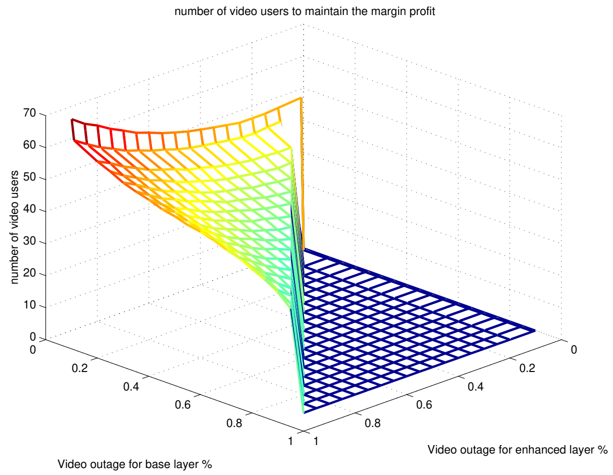
and shown in Figure 5.12.

5.6 Conclusion

In this chapter, we derived the reduction in Erlang capacity in the forward link CDMA system by adding one video broadcast channel. By using Monte Carlo simulation, the Erlang capacity of voice service and power ratio per video channel with different video outage are shown with numerical examples. The cost of introducing one video broadcast channel was analyzed in terms of bandwidth cost and the number of video users needed in the system to sustain the same revenue. We showed that by requiring acceptable cost of one video channel, the number of video users needed within video service area will decrease as the outage increases. The needed potential video users are less than 45 users/cell, which may be reasonable for cellular systems around shopping malls, transport stations and cities. Therefore, for a reasonable required number of video users in the cellular system, the service provider can benefit by providing video broadcast service to their end users.



(a) Plan 1: users pay the same



(b) Plan 2: users receive enhanced QoS video service pay double

Figure 5.12: Video broadcast: A cost estimate for a two layer video system

Chapter 6

Summary and Conclusion

In this thesis, we first developed measures to describe the cost of the wireless broadcast services. We started with the consideration that broadcast data rate is limited by the worst case user within coverage area and the value of a broadcast service should be proportional to the number of subscribers. Therefore, we defined a coverage measure for broadcast transmission by counting both the data rate achievable by each user and the number of users who can receive such data rate successfully. We then analyzed the dual rate broadcast coverage from an information theoretic aspect in Chapter 3. We have proposed and discussed the implementation of dual rate broadcast in a WCDMA system in Chapter 4. Our objective is to maximize the coverage with respect to power allocation and coverage areas in a single cell cellular system. A more realistic model of adding wireless broadcast service in multi-cell systems is discussed in Chapter 5. We address how many Erlangs of voice capacity will be sacrificed by adding a video broadcast channel into system. The cost is computed to decide the reasonable strategy to the successful service expansion.

In Chapter 2, we discuss the single rate broadcast coverage. Neither too large nor too small coverage area is favorable for single rate coverage. A large coverage area results in low transmission data rate, while the higher rate leads to small number of users to be covered. Our objective is to find a balance between achievable broadcast data rate and the number of users within coverage area with desired QoS requirements. We observed that the single rate coverage depends only on the boundary SNR. We found that coverage is optimized with the unique coverage distance at which the boundary SNR is achieved independently of transmission power.

In Chapter 3, we considered a dual rate broadcast system, in which common information is received by all users, while additional information can be decoded successfully by users with good channels. We found that the optimal boundary SNRs to achieve maximal dual rate coverage are independent of transmission power. By diminishing the basic coverage area, we can provide additional information to a smaller coverage area closer to the base station, to achieve better coverage. Our motivation to consider this possibility is that if the network revenue is proportional to the total received data rates, then revenue might be increased when additional information is added by sacrificing the coverage area with a lower common information rate.

In Chapter 4, by investigating a practical system, we proposed to multiplex common and additional information in a WCDMA system. We found that the optimum power allocation policy is to allocate more power to the subchannel with higher data rate and lower SIR requirement. For a practical system, we also considered the feasible coverage areas with different power allocation policies. When only one of the coverage areas is feasible for broadcast transmission, we can either switch back to single rate broadcast, or just waste a little power for infeasible subchannel to simplify resource control.

In Chapter 5, we derived the voice Erlang capacity in a CDMA system. We identified the reduction in Erlang when a video broadcast channel with certain outage is introduced into the system with and without transmit diversity. By assuming the acceptable cost for receiving a video channel, we obtained the reasonable required number of video users in order to maintain the service provider's margin profit. We concluded that, by using transmit diversity for video broadcast channel and the consideration of video user market, the wireless services can be profitable by including video broadcast into 3G wireless systems.

6.1 Future Work

This thesis introduces a broadcast coverage measure to analyze wireless broadcast services both from an information theoretic view and also for implementation in a WCDMA system. We established the characteristics of single and dual rate broadcast transmission under the coverage measure, which captures the efficiency of the wireless broadcast. The scope of the system was however restricted to the cellular system with fixed positions of base stations. Future work can evaluate MAC and network layer algorithms for efficient broadcast in a wireless multi-hop ad hoc network. This would lead to efficient broadcast strategies in low energy wireless systems. For example, automatic repeat request (ARQ) protocols may offer some benefits for unreliable wireless links. The efficient retransmission schemes in a multi-hop ad hoc network may also be of interest.

Appendix A

Proofs for the Functions of Single and Dual Rate Coverage

A.1 Second Derivative of Single Coverage Function

The second derivative of the single rate coverage $U_1(q,\beta)$ in equation (2.6) is

$$\begin{aligned}\frac{\partial U_1^2(q,\beta)}{\partial q^2} &= \rho\pi\frac{P_b^{2/\beta}}{2}(-\frac{2}{\beta}-1)q^{(-2/\beta-2)}\left(\frac{q}{1+q}-\frac{2}{\beta}\log(1+q)\right) \\ &\quad +\rho\pi\frac{P_b^{2/\beta}}{2}\frac{q^{(-2/\beta-1)}}{1+q}\left(\frac{1}{1+q}-\frac{2}{\beta}\right) \qquad (A.1)\end{aligned}$$

The first term at the right hand side of equation (A.1) is equal to zero at $q = q^*$, where q^* is the solution to let the first derivative of $U_1(q,\beta)$ in equation (2.7) be zero. Since at $q = q^*$, we have

$$\frac{1}{1+q} = \frac{2}{\beta}\frac{\log(1+q)}{q}. \qquad (A.2)$$

Let the second term of equation (A.1) be represented by w(q). Replace $q/(1+q)$ by equation (A.2), $w(q)$ can be written as

$$w(q) = \rho\pi\frac{P_b^{2/\beta}}{2}\frac{q^{(-2/\beta-1)}}{1+q}\frac{2}{\beta}\left(\frac{\log(1+q)}{q}-1\right). \qquad (A.3)$$

It is easy to show that $ln(1+q)/q$ is a decreasing function for $q > 0$. Since $\lim_{q\to 0} ln(1+q)/q = 1$, for $q > 0$

$$\frac{\log(1+q)}{q} < 1. \tag{A.4}$$

Thus, the second term of equation $w(q)$ is less than zero. Therefore, the second derivative of $U_1(q,\beta)$ is

$$\left.\frac{\partial U_1^2(q,\beta)}{\partial q^2}\right|_{q=q^*} < 0. \tag{A.5}$$

The single rate coverage can be maximized at $q = q^*$.

A.2 Properties of $g(Q_1)$

Given $0 < \alpha < 1$,

$$g(Q_1) = \frac{2(1+Q_1)(1+\alpha Q_1)}{(1-\alpha)Q_1} \log\left(1 + \frac{(1-\alpha)Q_1}{1+\alpha Q_1}\right), \tag{A.6}$$

is monotonically increasing in terms of $Q_1 > 0$, and

$$\lim_{Q_1\to 0} g(Q_1) = 2, \tag{A.7}$$

$$\lim_{Q_1\to +\infty} g(Q_1) = +\infty. \tag{A.8}$$

Proof:

Let

$$A(Q_1) = 2(1+Q_1)(1+\alpha Q_1)\log\left(\frac{1+Q_1}{1+\alpha Q_1}\right), \tag{A.9}$$

$$B(Q_1) = (1-\alpha)Q_1. \tag{A.10}$$

We have the first derivative of $A(Q_1)$ and $B(Q_1)$ as:

$$A'(Q_1) = 2(1+\alpha Q_1+\alpha+\alpha Q_1)\log\left(\frac{1+Q_1}{1+\alpha Q_1}\right)+2(1-\alpha), \tag{A.11}$$

$$B'(Q_1) = 1-\alpha. \tag{A.12}$$

The limitation of $A'(Q_1)$ when Q_1 approaches zero is:

$$\lim_{Q_1\to 0} A'(Q_1) = 2(1-\alpha). \tag{A.13}$$

Then,

$$\lim_{Q_1\to 0} g(Q_1) = \lim_{Q_1\to 0}\frac{A(Q_1)}{B(Q_1)} = \lim_{Q_1\to 0}\frac{A'(Q_1)}{B'(Q_1)} = \lim_{Q_1\to 0}\frac{2(1-\alpha)}{1-\alpha} = 2. \tag{A.14}$$

Similarly,

$$\lim_{Q_1\to\infty} A'(Q_1) = +\infty. \tag{A.15}$$

We obtain

$$\lim_{Q_1\to+\infty} g(Q_1) = +\infty. \tag{A.16}$$

The first derivative of $g(Q_1)$:

$$\frac{\partial g(Q_1)}{\partial Q_1} = \frac{A'(Q_1)B(Q_1) - A(Q_1)B'(Q_1)}{B^2(Q_1)}. \tag{A.17}$$

Then,

$$\frac{\partial g(Q_1)}{\partial Q_1} = \frac{2[(\alpha Q_1^2 - 1)\log\left(\frac{1+Q_1}{1+\alpha Q_1}\right) + (1-\alpha)Q_1]}{(1-\alpha)Q_1^2}. \tag{A.18}$$

Assume that,

$$h(Q_1) = (\alpha Q_1^2 - 1)\log\left(\frac{1+Q_1}{1+\alpha Q_1}\right) + (1-\alpha)Q_1. \tag{A.19}$$

Since

$$h'(Q_1) = 2\alpha Q_1 \log\left(\frac{1+Q_1}{1+\alpha Q_1}\right) + \frac{2\alpha Q_1^2 + Q_1 + \alpha Q_1}{(1+Q_1)(1+\alpha Q_1)} > 0, \tag{A.20}$$

then $h(Q_1)$ is an increasing function. Since

$$\lim_{Q_1 \to 0} h(Q_1) = 0, \tag{A.21}$$

$$\lim_{Q_1 \to \infty} h(Q_1) = +\infty, \tag{A.22}$$

then $h(Q_1) > 0$ for $Q_1 > 0$. Thus, the first derivative of $g(Q_1)$ is greater than 0. Therefore, $g(Q_1)$ is monotonically increasing for $Q_1 > 0$.

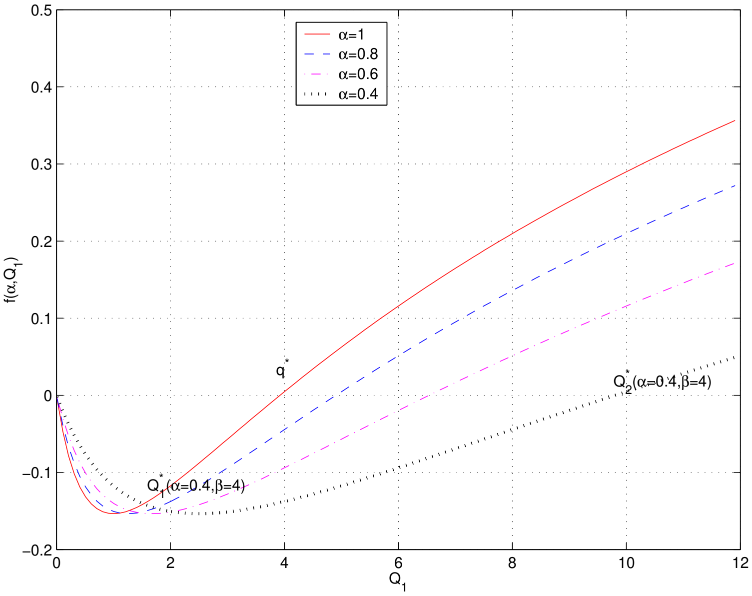


Figure A.1: Optimum solution of $Q_1^*(\alpha, \beta)$ for two rate broadcast. $\beta = 4$

A.3 Properties of Dual Rate Broadcast Coverage

Let

$$f_1(\alpha, Q_1) = \frac{2}{\beta} \log(1 + \alpha Q_1) - \frac{\alpha Q_1}{1 + \alpha Q_1}, \tag{A.23}$$

the second term at the right hand side of equation (3.32) can be rewritten as:

$$f_1(\alpha, Q_1) - f_1(1, Q_1) = \left[\frac{2}{\beta} \log(1 + \alpha Q_1) - \frac{\alpha Q_1}{1 + \alpha Q_1}\right] - \left[\frac{2}{\beta} \log(1 + Q_1) - \frac{Q_1}{1 + Q_1}\right]. \tag{A.24}$$

In order to get the optimum point for given α, the above equation should be set to zero, we have

$$f_1(\alpha, Q_1) = f_1(1, Q_1). \tag{A.25}$$

Figure A.1 illustrates the function $f(1, Q_1)$ and $f(\alpha, Q_1)$ in terms of Q_1 with different α. The solution of equation (A.25) is $Q_1 = Q_1^*(\alpha)$, which is at the intersection of function $f(1, Q_1)$ and $f(\alpha, Q_1)$. It can be observed from Figure A.1 that the less the α, the larger the received SNR $Q_1^*(\alpha, \beta)$ is.

The value $Q_1 > 0$ of intersection of $f_1(1, Q_1) = 0$ is the received optimum SNR q^* for single rate broadcast. The value $Q_1 > 0$ at the intersection of $f_1(1, \beta = 4) = f_1(\alpha, Q_1)$ is the optimum SNR $Q_1^*(\alpha, \beta)$ at the basic coverage distance. And the value $Q_1 > 0$ at the intersection of $f_1(\alpha, Q_1) = 0$ is the optimum SNR $Q_2^*(\alpha, \beta)$ at the enhanced coverage distance. It can also be observed from Figure A.1 that $Q_2^*(\alpha, \beta) > q^* > Q_1^*(\alpha, \beta)$.

Given path loss attenuation β, it is easy to prove that $f_1(1, \alpha Q_1^*) = f_1(Q_1^*, \alpha)$. And the greater the α, the greater αQ_1^* is. Combined with the fact that the greater the α, the less the Q_1^*, the common information rate:

$$R_1^* = \frac{1}{2} \log \left(\frac{1 + Q_1^*}{1 + \alpha Q_1^*} \right), \tag{A.26}$$

will decrease with increasing α.

The basic coverage can be written in terms of Q_1^* as:

$$U_{21}(\alpha) = \rho \pi \frac{P_b^{2/\beta}}{2} \log \left(\frac{1 + Q_1^*}{1 + \alpha Q_1^*} \right)^{{Q_1^*}^{-\frac{2}{\beta}}} \tag{A.27}$$

Let

$$J(\alpha, Q_1) = \left(\frac{1 + Q_1(\alpha)}{1 + \alpha Q_1(\alpha)} \right)^{Q_1(\alpha)^{-\frac{2}{\beta}}}. \tag{A.28}$$

Assume that $Q_1^*(\alpha_1)$ and $Q_1^*(\alpha_2)$ are optimum received SNR for α_1 and α_2 respectively, and $\alpha_1 < \alpha_2$. Let $Q_1(\alpha_1) = Q_1^*(\alpha_2)$, we have,

$$\begin{aligned}
J(\alpha_1, Q_1^*(\alpha_1)) &= \left(\frac{1+Q_1^*(\alpha_1)}{1+\alpha_1 Q_1^*(\alpha_1)}\right)^{Q_1^*(\alpha_1)^{-\frac{2}{\beta}}} && \text{(A.29)}\\
&\geq \left(\frac{1+Q_1(\alpha_1)}{1+\alpha_1 Q_1(\alpha_1)}\right)^{Q_1(\alpha_1)^{-\frac{2}{\beta}}} && \text{(A.30)}\\
&= \left(\frac{1+Q_1^*(\alpha_2)}{1+\alpha_1 Q_1^*(\alpha_2)}\right)^{Q_1^*(\alpha_2)^{-\frac{2}{\beta}}} && \text{(A.31)}\\
&\geq \left(\frac{1+Q_1^*(\alpha_2)}{1+\alpha_2 Q_1^*(\alpha_2)}\right)^{Q_1^*(\alpha_2)^{-\frac{2}{\beta}}} && \text{(A.32)}\\
&= J(\alpha_2, Q_1^*(\alpha_2)). && \text{(A.33)}
\end{aligned}$$

Since log function is an increasing fuction, we conclude that

$$\rho\pi\frac{P_b^{2/\beta}}{2}\log(J(\alpha_1, Q_1^*(\alpha_1))) \geq \rho\pi\frac{P_b^{2/\beta}}{2}\log(J(\alpha_2, Q_2^*(\alpha_2))). \tag{A.34}$$

That means $U_{21}(\alpha_1) \geq U_{21}(\alpha_2)$. That is, $U_{21}(\alpha)$ is an decreasing function with α.

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