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Hierarchical MIMO modulation in digital TV transmission

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ABSTRACT OF THE MASTER'S THESIS

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It is possible to use hierarchical modulation in broadcast systems so that there are two different levels of service with different coverage patterns. There is a basic reception quality, which should be available to almost all users in the system, and there is a higher reception quality which should be available for most users in the system. The higher quality is realized by combining the basic signal with an incremental signal. For this, the basic part of the signal should be more robustly encoded than the incremental part. The fundamental tradeoff in hierarchical modulation is between the coverage of the basic signal and the coverage of the incremental signal. Independently of the method used to multiplex the basic and incremental signals, the presence of the incremental signal takes resources from the basic signal or causes interference. Thus the larger the coverage of the incremental signal is, the smaller the coverage of the basic signal becomes. Most digital broadcast standards (DVB-T, DVB-H, LTE MBMS) are based on orthogonal frequency division multiplexing (OFDM) and single-frequency network (SFN) operation.

In this thesis, hierarchical modulation for single-antenna transmission is studied from technical point of view, based on a SFN environment, where time division multiplexing (TDM), superposition, hierarchical quadrature amplitude modulation (QAM) and hierarchical multiple-input and multiple-output (MIMO) scheme are illustrated. The alternatives for hierarchical multi-antenna modulation are investigated. The fundamental tradeoff of different hierarchical broadcasting methods are evaluated in MATLAB.

This thesis mainly focuses on the progress of hierarchical broadcasting methods and possible improvements that could be made. The aim of this thesis is to improve current digital broadcasting methods by introducing multiple antennas to both transmitter and receiver.

Keywords: digital TV, SFN, TDM, superposition, Hierarchical QAM, hierarchical MIMO modulation

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Gao Liang

In Espoo, Finland

September 25, 2009

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LIST OF ABBREVIATIONS

AWGN	Additive White Gaussian Noise
ATSC	Advanced Television Systems Committee for digital TV transmission
BS	Base station
COFDM	Coded orthogonal frequency-division multiplexing
CNR	Carrier-to-noise ratio
CSI	Channel state information
DFT	Discrete Fourier Transform
DMB-T/H	Digital Multimedia Broadcast-Terrestrial/Handheld
DTT	Digital Terrestrial Television
DVB	Digital Video Broadcasting
DVB-T/H	Digital Video Broadcasting – Terrestrial/Handheld
HDTV	High-definition television
HP	High priority
LP	Low priority
IFFT	Inverse Fast Fourier Transform
LOS	Line-of-sight
ISDB-T	Integrated Services Digital Broadcasting-Terrestrial
ISI	Inter-symbol interference
LTE	Long Term Evolution
MBMS	Multimedia broadcast multicast service
MFN	Multi-frequency network
MIMO	Multiple-input multiple-output

NLOS	Non-line-of-sight
OFDM	Orthogonal frequency-division multiplexing
QAM	Quadrature amplitude modulation
QPSK	Quadrature phase-shift keying
RMS	Root mean square
Rx	Receiver
SDTV	Standard-definition television
SFN	Single-frequency network
SNR	Signal-to-noise ratio
TDM	Time division multiplexing
Tx	Transmitter

LIST OF SYMBOLS

C	Shannon's capacity
d_1	half of the distance between the neighboring basic signal bits in hierarchical QAM scheme
d_2	half of the distance between the neighboring incremental signal bits in hierarchical QAM scheme
d_3	half of the distance between the neighboring quadrant constellation in hierarchical QAM scheme
E_s	Transmitted signal power
$E\{v\}$	The expected value of v
$\mathbf{H}$	MIMO channel matrix
$\mathbf{H'}$	Modified MIMO channel matrix
h	Channel gain
h_B	Rayleigh fading channel coefficient
h_G	Ricean fading channel coefficient
$h_{i,j}$	channel gain between i th antenna of the transmitter to j th antenna of the receiver
$I_0(\cdot)$	Modified Bessel function of the first kind and zero-order
K	Ricean factor
M	QAM constellation size parameter
N_T	Number of transmit antennas
N_R	Number of receive antennas
n	Channel noise
R_B	Achievable rate for bad user
R_G	Achievable rate for good user
R_b	Achievable rate for basic signal
R_i	Achievable rate for incremental signal
R_r	Transmit covariance matrix
R_t	Receive covariance matrix
$p_{Rayleigh}(\cdot)$	Rayleigh probability density function
$p_{Rice}(\cdot)$	Ricean probability density function

SNR_b	Receive SNR for basic signal
SNR_i	Receive SNR for incremental signal
SNR_i	Receive SNR for incremental signal
s	Transmitted signal
s_b	Transmitted basic signal
s_i	Transmitted incremental signal
y	Received signal
y_G	Received signal for good user
y_B	Received signal for bad user
α	hierarchical parameter in hierarchical QAM scheme
α_{MIMO}	fraction of transmit power used for basic signal in hierarchical MIMO scheme
α_{QAM}	fraction of transmit power used for basic signal in hierarchical QAM scheme
α_{SP}	fraction of transmit power used for basic signal in superposition scheme
α_{TDM}	time percent coefficient to transmit basic signal
ρ	Correlation coefficient
σ^2	Channel noise variance
M_b	Number of elements in basic signal set
M_i	Number of elements in incremental signal set
m	Power split parameter
N_T	Number of transmitters
N_R	Number of receivers
n	Noise
$p_{Rayleigh}(\cdot)$	Rayleigh probability density function
$p_{Rice}(\cdot)$	Ricean probability density function
R_G	Achievable rates for the good receiver
R_B	Achievable rates for the bad receiver
R_b	achievable rates for the basic stream
R_i	achievable rates for the incremental stream
s	Transmitted data symbol
y	Received data symbols

Z	Zero-mean AWGN
α_{TDM}	Fraction of time for transmitting the basic stream in TDM scheme
α_P	Fraction of power for transmitting the basic stream in superposition scheme
α_{QAM}	Fraction of power for transmitting the basic stream in hierarchical QAM scheme
α_{MIMO}	Fraction of power for transmitting the basic stream in hierarchical MIMO scheme
t_n	Propagation delay of the n th subchannel
σ^2	Thermal noise variance

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Digital TV transmits TV signals, including pictures and sound, as computerized information bits, which takes up much less space in the airwaves (bandwidth). As a result, there is room for more channels and features than basic channels available on analog TV [1]. The formats of digital TV can be generally divided into two categories: standard-definition television (SDTV) and high-definition television (HDTV). Due to limitations in the broadcasting system, currently, HDTV is mainly provided to nearby or fixed users, while normal digital TV programs are provided to distant or mobile users.

In order to provide a greater number of TV channels and/or better quality of pictures and sound using antenna broadcasts to a conventional antenna, Digital Terrestrial Television (DTT) is implemented, instead of a satellite dish or cable connection. An illustrative description of the worldwide situation is plotted in Figure 1.1. We can see from the figure that, North America and South Korea adopt Advanced Television Systems Committee for digital TV transmission (ATSC); Europe, Australia, New Zealand, Colombia, Uruguay and some African countries employ Digital Video Broadcasting-Terrestrial (DVB-T); China occupies Digital Multimedia Broadcast-Terrestrial/Handheld (DMB-T/H); while Japan, Brazil and Peru use Integrated Services Digital Broadcasting-Terrestrial (ISDB-T), which is very similar to DVB-T and can share front-end receiver and demodulator components. However, the rest of the world remains mostly undecided [2].

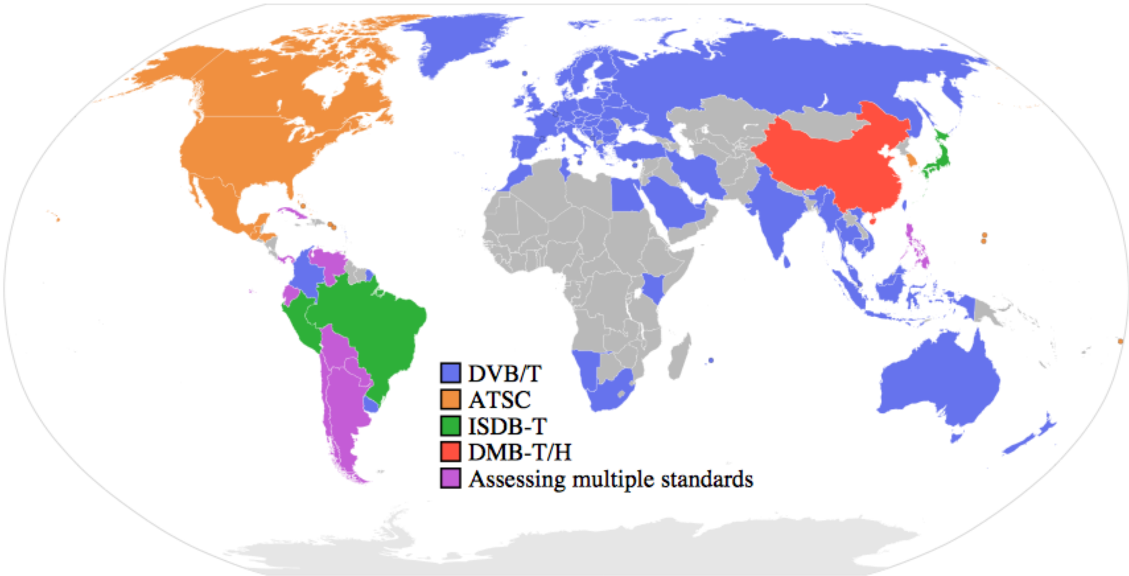

Figure 1.1 Distribution of Digital Terrestrial Television standards

1.2 STATEMENT OF OBJECTIVES

Nowadays, digital broadcast services, for example, DVB-T, DVB-H and LTE MBMS, are sharing a scarce spectrum. Due to the limited number of broadcast licenses, we need to optimize the broadcasting network in order to provide satisfying coverage and frequency economy. However, opportunities are always bringing new challenges. Especially, there exist potentials for improving the current transmit and receive efficiencies. With the fast development of antenna technology, their size is becoming smaller and their costs reduced. This motivates many research groups to commit to the digital broadcasting methodology.

This thesis mainly focuses on the progress of hierarchical broadcasting methods and possible improvements that could be made to those methods. The aim of this thesis is to improve current digital broadcasting methods by introducing multiple antennas to both the transmitter side and the receiver side. The objectives of this thesis can be concluded from the following aspects:

- Present an overview of digital broadcasting system

- Illustrate hierarchical modulation for single-antenna transmission, including a TDM scheme, a superposition scheme and a hierarchical QAM scheme, by focusing on the basic and incremental signal for different user experiences

- Investigate improvements when switching to hierarchical multi-antenna modulation

- Evaluate the fundamental tradeoff in different hierarchical broadcasting methods, including a TDM scheme, a superposition scheme, a hierarchical 64-QAM scheme and a hierarchical 2×2 MIMO scheme

1.3 METHODS AND APPROACHES

The methods of working through this thesis includes studying the available course books, papers, journals, and other relevant documents, where the most valuable source is the standardized technical specification.

The approaches used in this thesis are simulations which are built in MATLAB. The simulation result will present the improvement of spectral efficiency in a hierarchical multi-antenna scheme, compared with hierarchical single-antenna methods.

1.4 THESIS STRUCTURE

This thesis is composed of seven chapters. Chapter 2 is a brief introduction of broadcasting techniques involved, including SFN environment, OFDM modulation scheme, and MIMO transmission method. Chapter 3 is a literature review of hierarchical modulation for single-antenna transmission, as well as time multiplexing, superposition and hierarchical QAM scheme of basic and incremental signals. In Chapter 4, a SFN environment is set up, and the measurement of time multiplexing, superposition and QAM scheme is formulated for a single-antenna broadcasting system. Besides, alternatives for hierarchical multi-antenna modulation are investigated, an algorithm for a hierarchical MIMO transmission scheme is generated, as well as its corrections due to spatial correlation and the line-of-sight (LOS) phenomenon. Chapter 5 evaluates the fundamental tradeoff in hierarchical transmission involving time multiplexing, superposition, hierarchical QAM and hierarchical MIMO. Based on the simulation results, Chapter 6 contains conclusions drawn from comparing the spectral efficiencies of different broadcasting methods, and proposes some work which still remains to be done in the future.

CHAPTER 2

INTRODUCTION TO BROADCASTING SYSTEM

Currently, digital TV broadcasting by satellite, cable and terrestrial networks is a field of intensive development and standardization activities, especially in North America and Europe. Among all these applications, technically the most challenging one is terrestrial broadcasting, because of the presence of strong echoes which characterize the propagation medium. What makes the problem even more difficult is the objective in Europe of deploying SFN, in order to increase the number of TV channels in the allocated frequency bandwidth. The common approach for digital terrestrial TV broadcasting in Europe is based on OFDM, which has become extremely popular within the broadcasting community over the past decade. After reviewing an OFDM system model, we will study a MIMO structure based on SFN.

2.1 INTRODUCTION TO SFN

Considering that the fast-growing commercial deployment of popular digital broadcast services (DVB-T, DVB-H and LTE MBMS), broadcasters and network operators are facing the problem of spectrum scarcity. In addition, when taking the issue of broadcast license into consideration, operating a network where the spectrum is fully optimized becomes efficient and economical with regard to the business plan. A optimized spectrum is currently an ideal choice for deploying nationwide digital TV network, as it provides good coverage and frequency usage in wide area applications by letting all transmitters in a broadcasting network transmit on the same frequency, in other words, simulcast. Therefore, the SFN concept was introduced.

2.1.1 PRINCIPLES OF SFN

Compared with conventional analog broadcasting networks, there is an inherent gain yielding better coverage and frequency economy in SFN because of transmitter diversity. Thus, low outage probability can result from modest transmit power.

In contrast with a traditional multi-frequency network (MFN) as in Figure 2.1, all transmitters in a SFN are fed by an identical and synchronous signal, which is transmitted by occupying the same frequency block, as depicted in Figure 2.2.

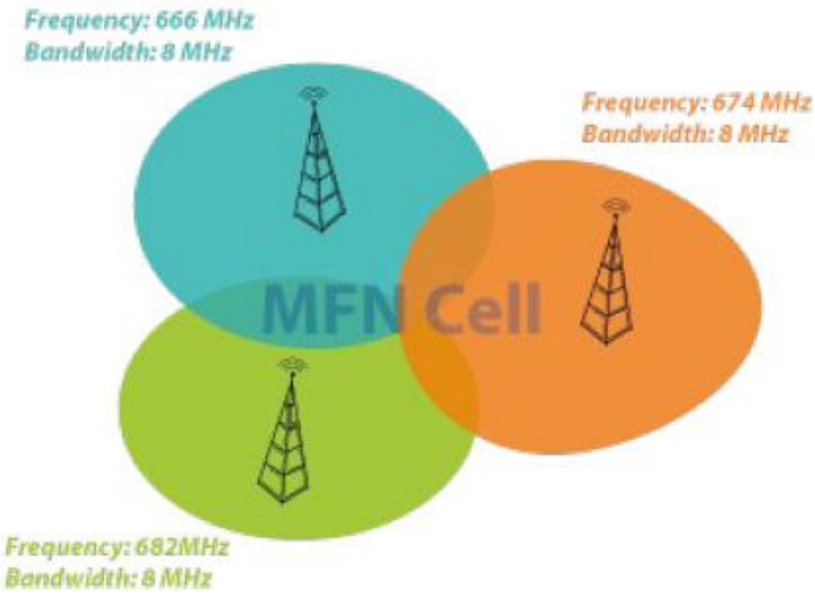

Figure 2.1 MFN topology

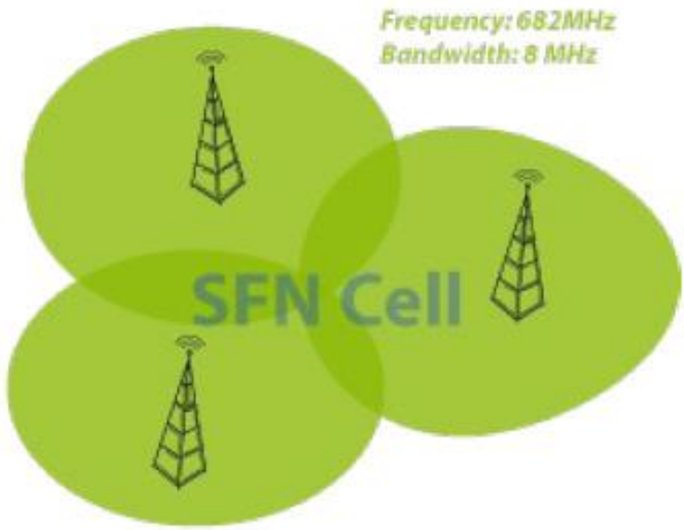

Figure 2.2 SFN topology

In the example MFN, three different broadcast frequencies are occupied, each having a spectral bandwidth of 8 MHz. Therefore, the MFN results in a total spectrum consumption of 24 MHz. Whereas in the example SFN, only one frequency is in use, resulting in tremendous bandwidth optimization, namely 8MHz [3], which is only 1/3 of that in the MFN. If there is a MFN with more transmitters, after switching to a SFN, the improvement will be even more obvious.

The aim of SFN transmission is to efficiently utilizing the radio spectrum, allowing a higher number of TV programs, in comparison to traditional MFN transmission. Besides, since the total received signal strength may increase to positions midway between the transmitters, a SFN can also increase the coverage area and reduce the outage probability, compared with a MFN.

2.1.2 LIMITATIONS OF SFN

In a SFN, most users experience an multipath environment, as illustrated in Figure 2.3. In this case, the transmitted signals will arrive at the receiving antenna by two or more paths. Causes of multipath include atmospheric ducting, ionospheric reflection and refraction, as well as reflection from water bodies and terrestrial objects such as mountains and buildings. During the simulcast transmission, signals are delayed according to different distances between the transmitter (Tx) and the receiver (Rx). At the receiver side, signals are added and appear to be the result of a transmission over a single time-dispersive channel [4].

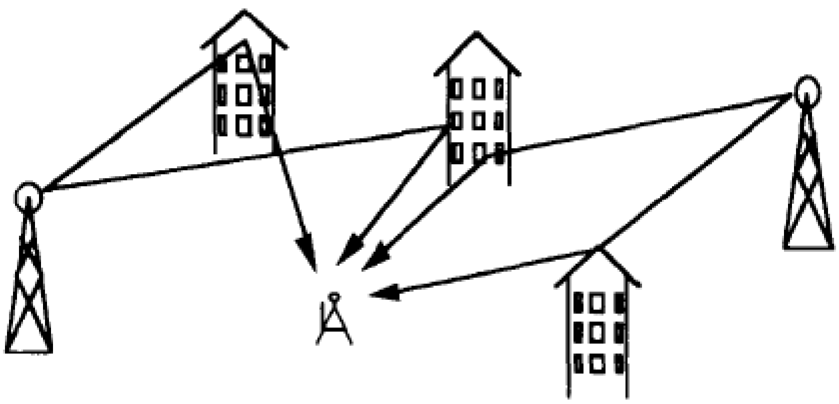

Figure 2.3 Multipath environment

A typical delay profile for the resulting communication channel is sketched in Figure 2.4. The time dispersion is mainly caused by two mechanisms: the natural dispersion and the artificial delay spread. The natural dispersion is caused by the wave component reflected in the vicinity of the receiver; the artificial delay spread is caused by the SFN structural multipath effect during the transmission, as different delays t_1, t_2, t_3, t_4,... marked below t axis.

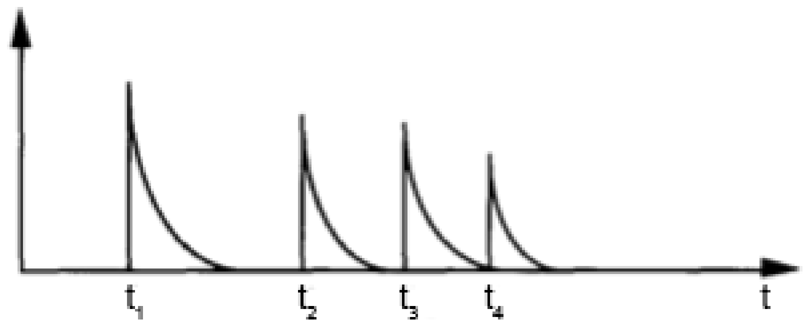

Figure 2.4 Typical delay profile for a radio communication channel

There are inherent defects associated with SFN when it is deployed. A SFN transmission can be considered as a severe form of multipath propagation, where the receiver receives multiple echoes of the same signal, as well as the constructive or destructive interference among these echoes, as known as self-interference, which may result in fading. Especially in wideband communication and high data rate digital broadcasting, the fading is more severe, in this case, it is frequency selective fading, and the time spreading of the echoes may result in inter-symbol interference (ISI). In practice, the effects of fading and ISI can be avoided by means of employing diversity schemes and equalization filters.

The traditional solution to counter the effect of a SFN structural multipath involves a equalizer, however, this method usually fails if some transmitters are located too far away from the receiver. In that case, some signals may arrive quite late and turn into interference instead of contributing to the output signal quality. Hence, the equalizer will fail to work because its observation interval is shorter than the length of delay spread due to SFN structural multipath.

2.2 INTRODUCTION TO OFDM

Under multipath propagation, the self-interference has two effects to the reception of signals in the receiver: frequency selective fading and ISI. Therefore, in wideband digital broadcasting, self-interference cancellation is facilitated by an OFDM modulation method. An OFDM modulation scheme is widely applied to provide digital TV broadcasting in Europe, as it allows for the use of simulcasting, and offers specific advantages for a SFN.

2.2.1 PRINCIPLES OF OFDM

OFDM is a transmission method in which a single channel is divided into multiple sub-carriers on adjacent frequencies. Besides, the sub-carriers in an OFDM system are overlapping in order to maximize spectral efficiency. In an ordinary way, overlapping adjacent channels will interfere with each other. However, by employing an OFDM system, sub-carriers are orthogonal to each other, because the maximum power of each sub-carrier corresponds directly with the minimum power of each adjacent channel. Thus, they are able to overlap without interfering. Therefore, OFDM systems are able to maximize spectral efficiency without introducing adjacent channel interference. The frequency domain of an OFDM scheme is represented in Figure 2.5 Frequency domain of an OFDM system [5].

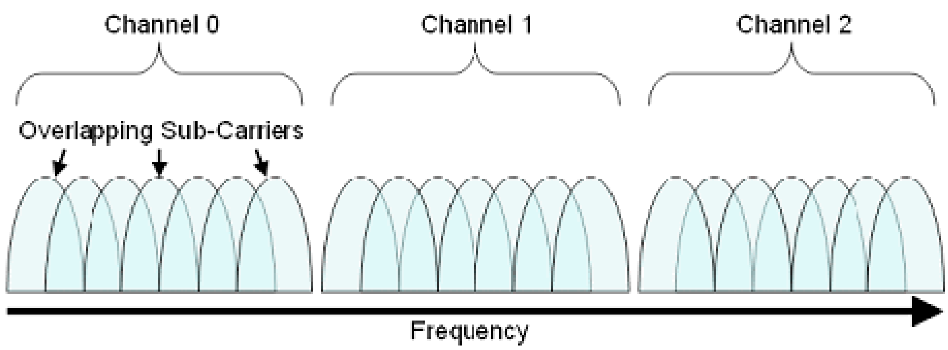

Figure 2.5 Frequency domain of an OFDM system

An OFDM scheme must perform several steps to utilize multiple sub-carriers, a typical OFDM system is described in Figure 2.6, where there are three key steps.

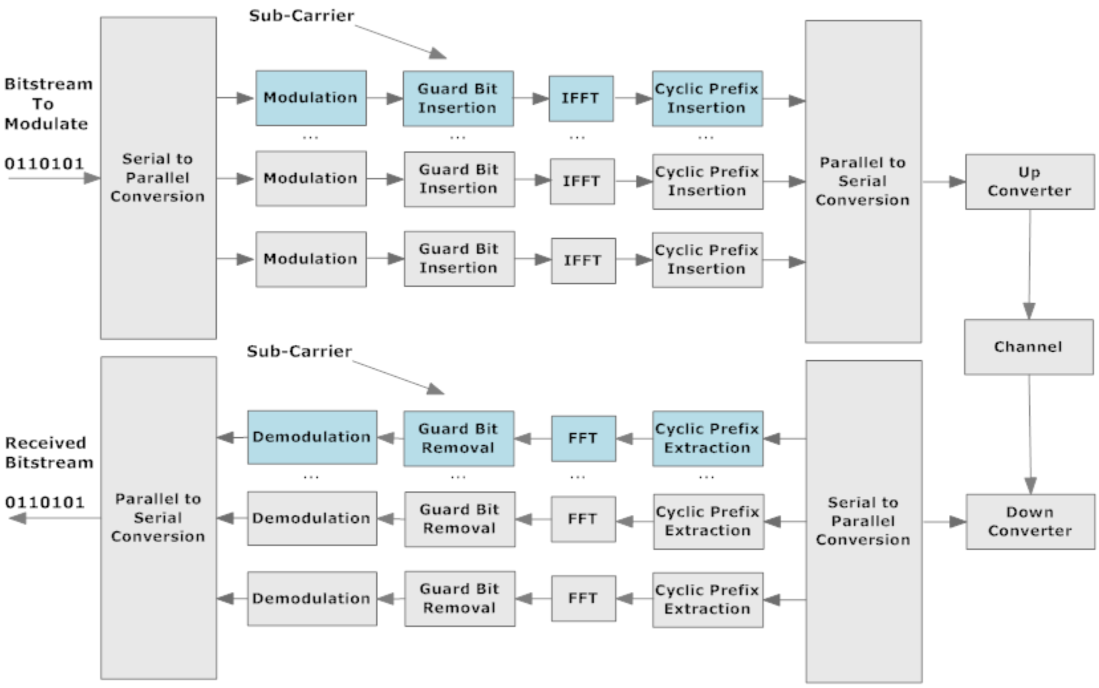

Figure 2.6 Block diagram of a typical OFDM system

The first important step is *Serial to Parallel and Parallel to Serial Conversion*. Each channel in an OFDM system can be divided into multiple sub-carriers, in order to optimize the usage of the frequency spectrum. Meanwhile, the use of sub-carriers requires additional processing in transmitter and receiver. In the transmitter side, a serial bit stream is converted into several parallel bit streams to be divided among sub-carriers. At this time, each sub-carrier is modulated as if it was an individual channel. During transmission in the channel, all sub-carriers are combined together and transmitted as a whole. In the receiver side, a reverse process is performed to divide the incoming signal into appropriate sub-carriers again. Then, the sub-carriers are demodulated individually, before reconstructed to the original bit stream. During the transmission, all sub carriers are generated simultaneously.

The second important step is *Modulation with IFFT*. At the Inverse Fast Fourier Transform (IFFT) stage of the transmitter, the modulation scheme of the specific channel being used can be chosen independently, based on the channel requirements. In other words, each individual sub-carrier can use a different modulation scheme.

The third important step is *Cyclic Prefix Insertion*. Since wireless communications systems suffer from multipath channel reflections which may result ISI, a cyclic prefix is added to mitigate this effect. A cyclic prefix is a repetition of the first section of a symbol, and appended to the end of the symbol, as shown in Figure 2.7. It is important to introduce cyclic prefix in an OFDM scheme, as it enables multipath representations of the original signal to fade. Thus, they do not interfere with the subsequent symbol.

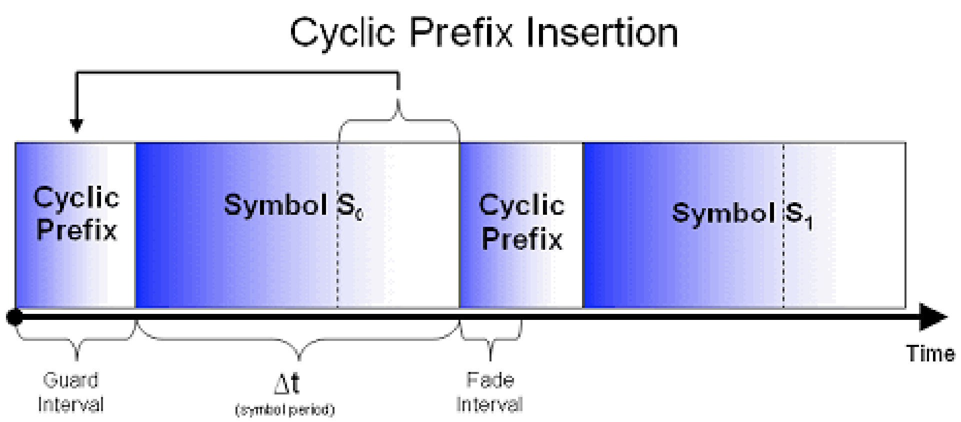

Figure 2.7 Insert cyclic prefix into an OFDM symbol

By employing an OFDM scheme, frequency selective fading may be successfully mitigated by means of coding and/or equalization. Besides, an OFDM scheme makes transmitted symbols slightly longer than the actual observation interval of the receiver, by introducing a guard interval. As long as the delay spread of the channel is smaller than the guard interval, no ISI will occur. Nevertheless, the guard interval may not be sufficient for very distant transmitters and may result in residual ISI.

2.2.2 LIMITATIONS OF OFDM

OFDM has two major inherent problems. One is nonlinear distortion, which is primarily due to the transmit power amplifier which must be driven as close to its saturation point as possible, in order to make the best possible use of the output power. The other is the problem of carrier synchronization. Resulting from the presence of carrier asynchronism, the orthogonality of the multiplexed signals is destroyed and interference is created between the data symbols in each sub-carrier, leading to a significant degradation of the carrier-to-noise ratio (CNR) [6].

In order to overcome transmission error due to the reasons mentioned above, the concept of coded orthogonal frequency-division multiplexing (COFDM) is introduced [7], involving forward error coding and interleaving at the transmitter side. Furthermore, the inclusion of channel-state information in the generation of soft-decisions is the key to the unique performance of COFDM in the presence of frequency-selective fading and interference.

2.3 INTRODUCTION TO MIMO CHANNELS

The district covered by the aforementioned SFN broadcasting environment will experience a heavy SFN structural multipath. If a single-carrier system is applied, the performance is even worse. In a multi-carrier scheme, there are many narrow subchannels transmitted in parallel. Each subchannel is modulated at a very low rate, to sufficiently expand the symbol period to be larger than the delay spread. Therefore the effect of frequency selective fading will be overcome. Furthermore, a guard interval is inserted between OFDM symbols, aiming to reduce the ISI. However, the guard interval may not be sufficient here. The reason is, due to the overlong delay and overlarge magnitude of different paths, the equalizer at the receiver side can not converge properly, and henceforth, residual ISI might still remains. Therefore, MIMO channels is introduced.

The concept of MIMO, which means multiple-input multiple-output signaling, was a vitally important innovation pioneered by Bell Laboratories in 1984 [8]. When there are multiple transmit and receive antennas being occupied, MIMO channels will arise.

2.3.1 PRINCIPLES OF MIMO CHANNELS

MIMO channels work best in a highly scattering transmission environment as shown in Figure 2.8, where a multipath environment exist between the transmitter and the receiver, due to obstacles in between.

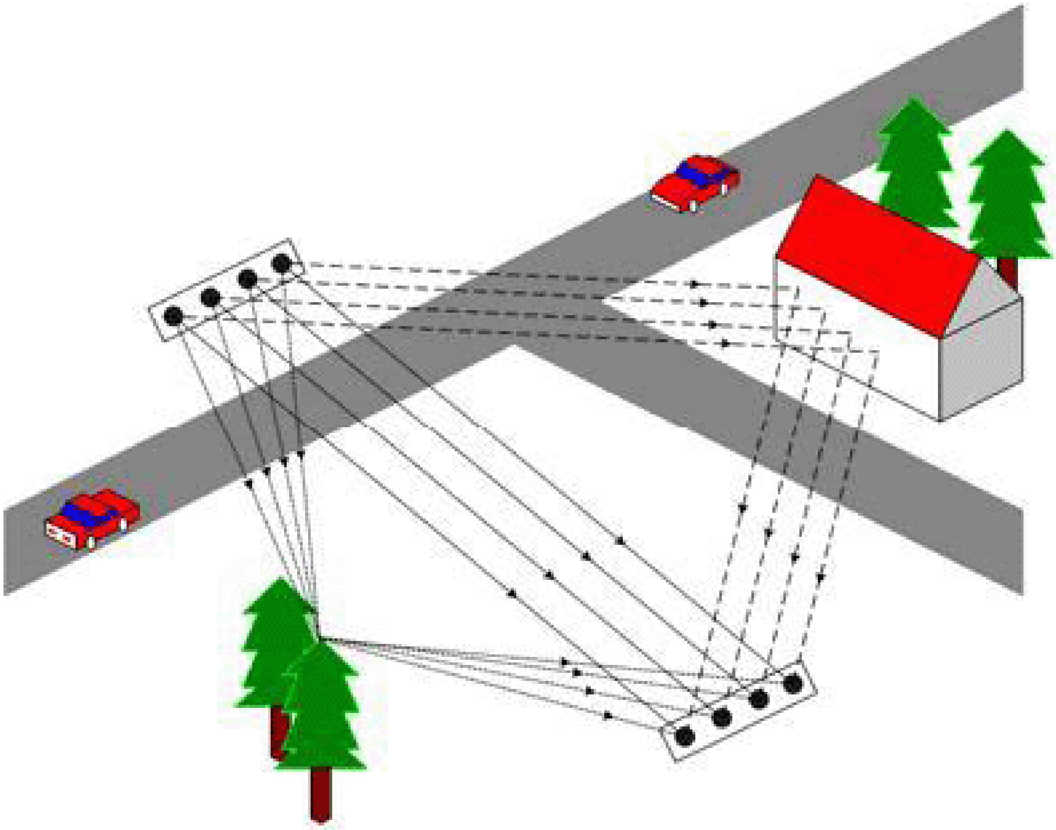

Figure 2.8 A case of MIMO channels

If we consider a single user Gaussian channel employing multiple transmit and receive antennas, and denote the number of transmit antennas by T and the number of receive antennas by R, we can use a block diagram as in Figure 2.9, for engineering purpose.

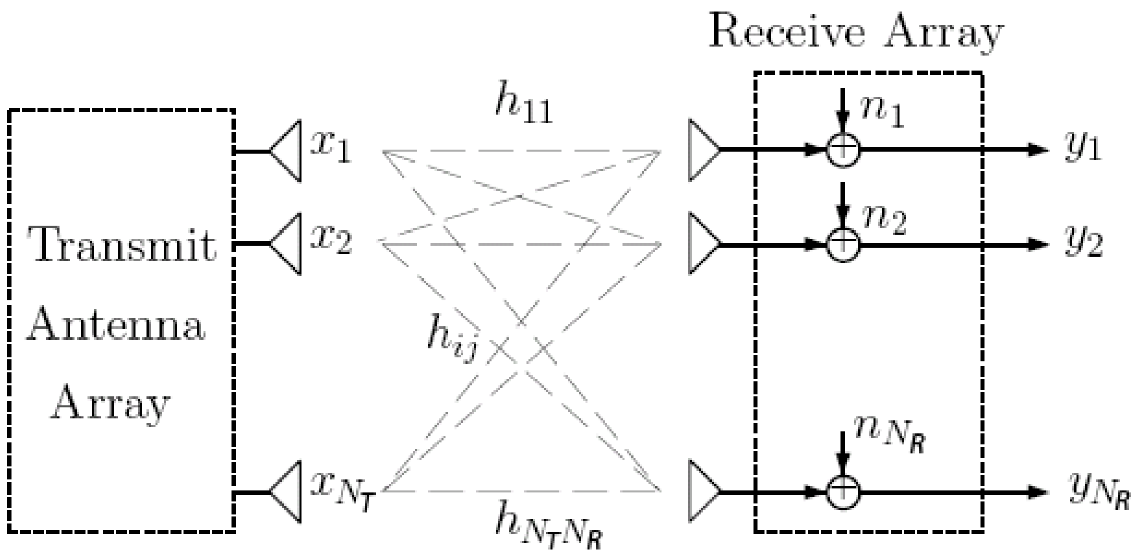

Figure 2.9 MIMO system model

At the transmitter side, $x_1, x_2 \dots x_{N_T}$ represent the transmitted signal by transmit antenna $1, 2 \dots N_T$ respectively, $h_{i,j}$ is the channel gain between ith transmit antenna and jth receive antenna, $n_1, n_2 \dots n_{N_R}$ are channel noise coefficients to be considered when the signal arrives at the receive antenna $1, 2 \dots N_R$ respectively. At the receiver side, the respective signals obtained by receive antenna $1, 2 \dots N_R$ are $y_1, y_2 \dots y_{N_R}$. The MIMO system model created by the scattering environment can be described by the matrix equation $\mathbf{y} = \mathbf{Hx} + \mathbf{n}$, under certain assumptions [9]. $\mathbf{y}$ and $\mathbf{x}$ are the received and transmitted signal vectors, respectively. Besides, $\mathbf{H}$ is the channel matrix. In addition, $\mathbf{n}$ is the noise vector. Specifically, there are two typical assumptions, one is that, the channel gains $h_{i,j}$ are independent complex gain coefficients modeled as Gaussian random variables assuming a scatter-rich or radio environment, and the other is that, the noise is complex additive Gaussian noise.

MIMO channels offer significant increases in data throughput and link range without additional bandwidth or transmit power, by providing higher spectral efficiency, link reliability and diversity which reduces fading.

2.3.2 DIVERSITY GAIN

Multipath fading is a significant problem in digital TV broadcasting. In practice, diversity methods are applied to combat fading. This involves providing replicas of the transmitted signal over time, frequency or space. Generally, there are three types of diversity schemes in wireless communications.

One diversity scheme is time diversity. In this case, replicas of the transmitted signal are provided across time by a combination of channel coding and time interleaving strategies. To make this diversity scheme effective, the channel must provide a sufficient variation in time. We can apply time diversity in cases where the coherence time of the channel is small compared with the desired interleaving symbol duration. As a result, the interleaved symbol is independent of the previous symbol, which makes it a completely new replica of the original symbol.

Another diversity scheme is frequency diversity, which provides replicas of the original signal in the frequency domain. We can apply it in cases where the coherence bandwidth of the channel is small compared with the bandwidth of the signal. Therefore, different parts of the relevant spectrum will suffer independent fades.

The third diversity scheme, named spatial diversity, is becoming more and more popular today. It is also called antenna diversity and is an effective method for combating multipath fading. In this scheme, replicas of the same transmitted signal are provided across different antennas of the receiver. We can apply it in cases where antenna spacing is larger than the coherent distance to ensure independent fades across different antennas. The traditional types of spatial diversity are selective combining, maximum ratio combining, and equal gain combining [10].

Spatial diversity can also be classified based on whether diversity is applied to the transmitter or to the receiver. With regard to receive diversity, it often employs maximum ratio combining to improve signal quality. But in a mobile receiver, such as cell phones, it becomes costly and cumbersome to deploy this scheme. This is one main reason that transmit diversity became popular, since it is easier to implement at the base station side. With transmit diversity, controlled redundancies are introduced at the transmitter, and then exploited by appropriate signal processing techniques at the receiver. Particularly, with space-time coding schemes like Alamouti's scheme [11], it became possible to implement transmit diversity without knowledge of the channel.

Furthermore, there are two more diversity types that we may need to consider, in the category of spatial diversity. One is polarization diversity, by which horizontal and vertical polarization signals are transmitted by two different polarized antennas and received correspondingly by two different polarized antennas at the receiver. Therefore, there is no correlation between the signals due to different polarizations. The other is angle diversity, which applies at carrier frequencies above 10 GHz. In this case, the transmitted signals are highly scattered in space, and henceforth the receiver can have two highly directional antennas facing in totally different directions. As a result, the receiver is able to collect two samples of the same signal, which are totally independent of each other.

2.3.3 MIMO MODEL IN SFN

The performance of a SFN is limited in both single carrier system and multi-carrier system. The inherent limitation in both transmission schemes come from the fact that they ignore the space information. In other words, the inherent diversity in a SFN is transferred into different delay after a multipath propagation, which means, only time diversity is considered in most previous methods. To figure out the problem from the SFN structural multipath, a MIMO structure is proposed [12].

Spatial diversity gain is achieved by employing multiple receive antennas. In this case, the SFN signals with different delay are treated as multiple signals through independent paths and can be separated successfully, rather than as a multipath propagation scheme. Therefore the interference from the SFN structural multipath can be properly removed. Moreover, the residual multipath delay spread is removed by a bank of parallel sub-filters, as sketched in Figure 2.10 MIMO structure of a SFN.

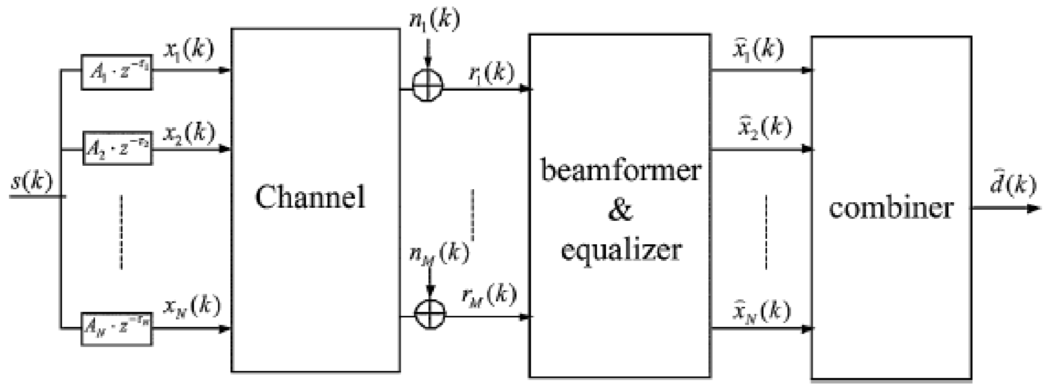

Figure 2.10 MIMO structure of a SFN

First of all, it is assumed there are N transmit antennas and M receiving antennas in the SFN scheme. The identical signal $s(k)$ is sent by N transmitters to the N input of the MIMO channels, and transmitted using different sub-channels. For the nth transmitter, A_n is the amplitude factor and τ_n is the propagation delay of the nth subchannel. At the output of the MIMO system, the signals arrive at the M respective receive antennas. At the N outputs of the beamformer, multiple transmitted signals are successfully separated using a beamformer, where their directions of arrival are taken into consideration. As a result, the problem of overlong delay and overlarge magnitude can be avoided. However, each residual single-channel ISI due to the SFN structural multipath remains at each output of the beamformer and can be removed by an equalizing filterbank with a short observation interval. Furthermore, the original signals are recovered at the output combiner with an ideal space diversity gain.

2.4 SUMMARY

In this chapter, the author reviewed basic technologies and concepts in a typical digital TV broadcasting system. Firstly, taking frequency economy into account, the SFN was introduced as a optimized medium of carrying digital TV services. However, there is both frequency selective fading and ISI as a result of the SFN structural multipath, therefore, the OFDM scheme was introduced. Also, the author studied its benefits and limitations. Furthermore, to take advantage of spatial diversity gain, as well as to provide higher spectrum efficiency without increasing transmit power or channel bandwidth, we can utilize MIMO channels. Then, we illustrate a proposal on how a MIMO model with beamformer and equalizer can be applied in a SFN environment, mainly from a study of relevant published literature on the subject.

CHAPTER 3

INTRODUCTION TO HIERARCHICAL MODULATION IN DIGITAL TV BROADCASTING

A digital broadcast system occupies regulated frequency bands with fixed bandwidth, and the capacity of a digital broadcast system is usually limited by the system transmission power and channel impairments. In a typical broadcast system, the same signal is transmitted to all users, therefore, there is a tradeoff between the transmitted data rates and the coverage areas. Provided with a fixed transmission power, a digital broadcast system is usually designed with a bit rate that can be reliably received by users in an intended coverage area. In order to suit different user requirements for the quality of digital TV program, a hierarchical modulation scheme is proposed to improve the traditional digital broadcast system [13], by adding more data in the transmission.

3.1 PRINCIPLES OF HIERARCHICAL MODULATION

Hierarchical modulation is one of the signal processing techniques for multiplexing and modulating multiple data streams into a single data stream, it is possible to use in broadcast systems so that there are two different levels of service with different coverage. One is a basic reception quality, for example, SDTV, which should be available to almost all users in the system, and the other is a higher reception quality which should only be available for some users in the system. The higher quality is realized by adding the basic signal with an incremental signal, which carries TV signal with a high data rate, such as HDTV.

Digital transmission methods often exhibit a hard “fall off the cliff” or “brick wall effect” when the reception abruptly halts because the limit of signal-to-noise ratio (SNR) has been exceeded. Naturally, this also applies to OFDM transmission methods. In some OFDM based digital terrestrial television system, for example, DVB-T, hierarchical modulation is used to counteract this effect, as an alternative to conventional modulation methods, for example, using quadrature phase-shift keying (QPSK), or QAM.

3.1.1 GOOD RECEIVER AND BAD RECEIVER

Considering a circular symmetric cell with a Transmitter in the center (see Figure 3.1), r is the distance between the transmitter and any possible receiver. The receivers within this cell can be classified into two groups. One group consists of receivers located in the vicinity $(r < R_G)$ of the Tx and has a non-zero direct path component. This class is characterized by a Ricean fading channel with a high receive SNR. The other group has no direct path component, and it is at a greater distance $(R_G < r < R_B)$ from the Tx. This class is, therefore, characterized by a Rayleigh fading channel with a moderate receive SNR.

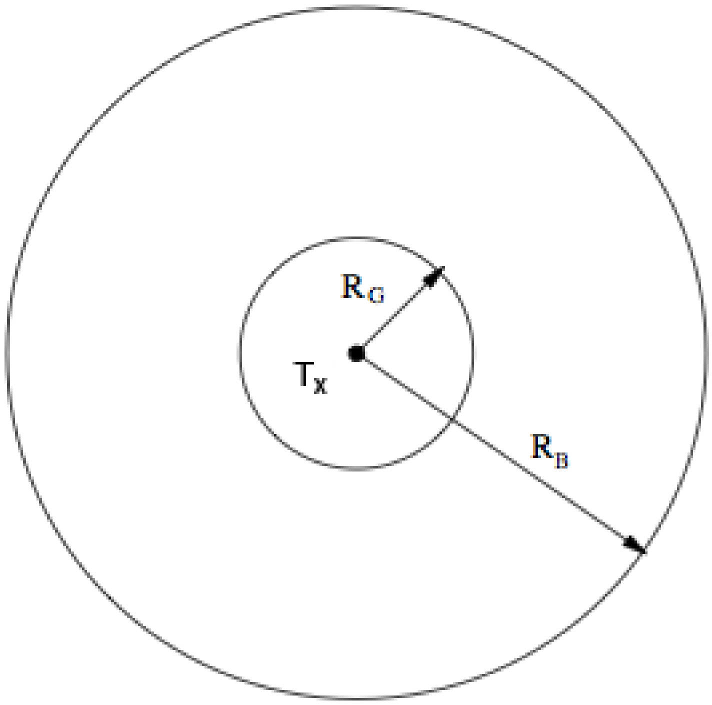

Figure 3.1 Simple cell model to illustrate good and bad receivers

3.1.2 BASIC SIGNAL AND INCREMENTAL SIGNAL

The aim of broadcasting digital TV to the two different groups of receivers described above naturally leads to a hierarchical transmission scheme. Therefore, the first requirement is a hierarchical source encoder/decoder which splits the digital TV data into two parts of different significance, called high priority (HP) signal and low priority (LP) signal, also known as basic signal and incremental signal respectively. In this thesis we will consider this as given and focus on the channel aspect.

The two transmission signals vary in their susceptibility to noise. The basic signal is more robust, in other words, heavily protected against noise and interference, but cannot support a high data rate, whereas the incremental signal is capable of handling a higher data rate with a compromise of much less robustness. As a result, the coverage of the service area differs in size. The basic signal can be used to supply a larger coverage area compared with non-hierarchical modulation, while the coverage area of the incremental signal is slightly smaller, or roughly as large as in the non-hierarchical case. In practice, the basic signal can be used for portable indoor and mobile reception, while the incremental signal can be chosen to deliver a HDTV program to a fixed receiver, such as a home TV set.

3.1.3 BENEFITS OF HIERARCHICAL MODULATION

Compared with traditional methods, hierarchical modulation is more flexible. For instance, with a two-layer transmission scheme, it is possible to transmit the same video signal with poorer and better signal quality in the same data stream. Moreover, it is possible to enlarge the coverage area of the basic signal by changing the modulation parameter, at the expense of losing robustness of the incremental signal, and thus the coverage of the incremental signal will be reduced.

Compared with non-hierarchical mode, hierarchical mode provides more rugged main services. The coverage of the basic signal service area is larger, with a penalty of a small loss of the coverage of incremental signal service area. In order to achieve a similar coverage, hierarchical mode requires more bit-rate than non-hierarchical mode, since the performance will be lost with a severe multipath. However, generally speaking, the benefits of from transferring to hierarchical mode outweighs the drawbacks.

Hierarchical modulation is backward compatible in practical construction, therefore, it is economical to deploy receivers in hierarchical broadcast network. Based on a non-hierarchical scheme, the original receivers can still receive the basic signal. Meanwhile, a new receiver is designed for the incremental signal, and is also possible to receive the basic signal at the same time.

3.2 HIERARCHICAL MODULATION FOR SINGLE-ANTENNA BROADCASTING

Hierarchical modulation is conventionally used for a single-antenna broadcasting system, which employs a single-antenna at both the transmitter and receiver sides. Meanwhile, there are three reception conditions for different receiver types. The first condition has structural differences from the receivers, for instance, various antenna gains. The second one is different locations of the receivers, for example, small or large distance from the transmitter, which may form a multipath structure. The last condition is mobility, such as fixed or mobile receivers.

3.2.1 PHYSICAL CHANNEL MODEL

Here is an illustrative model that shows the characteristics of the hierarchical single-antenna broadcasting system. For the simplest case, all receivers are classified into either a good receiver group or a bad receiver group, according to the respective receive SNR. Both receiver groups should be able to obtain the basic information data, for example, a lower resolution video. In addition, good receivers are able to acquire an enhanced resolution video, which is realized by combining the basic information with the incremental information. A simple scenario is depicted in Figure 3.2, where a base station (BS) is broadcasting to both receiver groups. The good receivers are located in the vicinity of the BS and each get a direct path component, i.e., line-of-sight (LOS) propagation, which is characterized by a Ricean fading channel. Compared to the good receivers, the bad receivers are further away from the BS and there is no direct path component available, i.e., non-line-of-sight (NLOS) propagation, which is characterized by a Rayleigh fading channel.

For both receivers, the fading channel is assumed to be non-frequency-selective, with ideal interleaving and perfect channel state information (CSI) at the receiver. Hence, the received signal y is $y = h \cdot s + n$, where h is the channel gain, s is the transmitted signal, and n is zero-mean additive white Gaussian noise (AWGN).

The hierarchical broadcasting system described above is depicted in Figure 3.2 Broadcast channel and two-stage transmitter structure, as a simplified broadcast channel. Regarding the output signal s, the whole energy per symbol is denoted by $E\left\{\left|s^2\right|\right\} = E_s$. The two groups of signal are statistically independent, the basic signal is denoted by s_b, and the incremental signal is denoted by s_i. Each type of signal is transmitted through a respective fading channel, where AWGN is added, before arriving at the receiver.

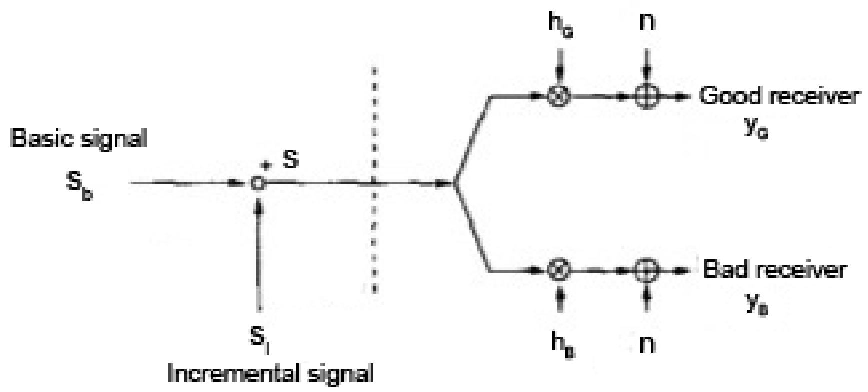

Figure 3.2 Broadcast channel and two-stage transmitter structure

At the receiver side, the decoding procedure has two steps. Firstly, the basic signal is detected by both good and bad receivers, during which the incremental signal can be treated as an additional distortion. Secondly, based on the decoding of basic signal, the good receiver will continue to decode the incremental signal. It is necessary that every information bit sent to a bad receiver can be decoded by a good receiver, when applying Rayleigh and Ricean fading channel models.

Hierarchical modulation in a single-antenna broadcasting system can be achieved by three strategies: a TDM scheme, a superposition scheme and a hierarchical QAM scheme. In the following sections, we will introduce them briefly.

3.2.2 TDM SCHEME

In the TDM scheme, the basic signal is sent during a certain fraction of the time, and the incremental signal is sent during the remainder of the time, as depicted in Figure 3.3 TDM scheme.

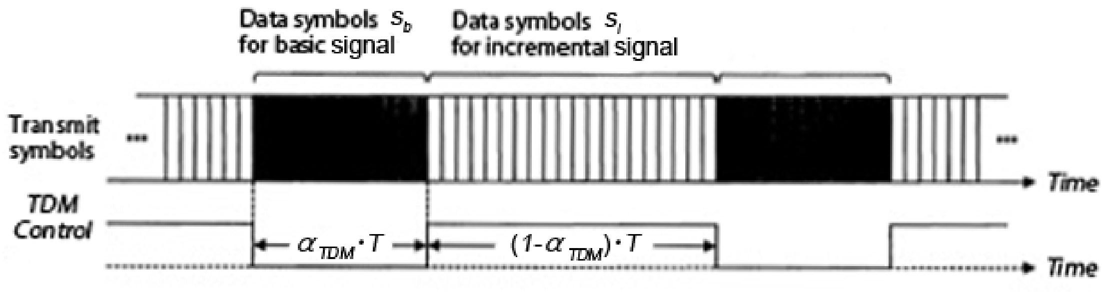

Figure 3.3 TDM scheme

In this case, for example, we can use α_{TDM} (percent) of the time to transmit the stream carrying the basic signal, which can be received by both good and bad users, meanwhile, the rest $1-\alpha_{TDM}$ (percent) of the time is used for carrying the incremental signal, which can be received only by a good user. By changing the percentage of time for each signal, a different data rate ratio between the basic signal and incremental signal can be achieved.

3.2.3 SUPERPOSITION SCHEME

It is theoretically possible to improve the TDM scheme, as shown by [14], therefore, the superposition scheme is introduced. The main idea of the superposition scheme is to send the basic signal and the incremental signal simultaneously, and to superimpose the incremental signal on the basic signal.

Figure 3.4 Superposition scheme is an illustrative model of the superposition scheme, where the transmit power is divided between the basic signal and incremental signal. Also, a different data rate ratio between the basic and incremental signal can be achieved, by assigning different share of the power to transmit each type of signal.

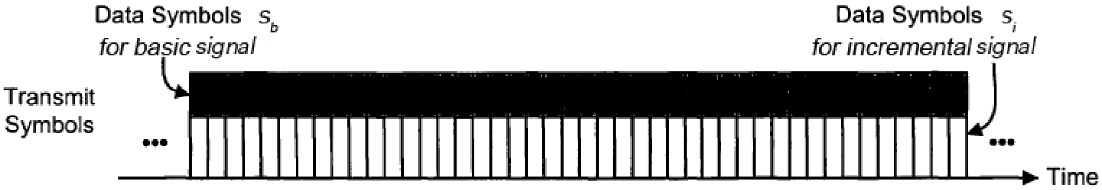

Figure 3.4 Superposition scheme

3.2.4 HIERARCHICAL QAM SCHEME

The hierarchical QAM scheme allows the transmission of different digital TV signals by embedding relative constellation points. Let the signal sets used to represent basic and incremental signal bits having M_b and M_i elements respectively. The transmitted signal set is formed by adding all elements in the incremental signal set to each element in the basic signal set, on the complex plane. Consequently, the hierarchical modulation signal sets can be divided into M_b groups of M_i elements, in all there are $M_b \cdot M_i$ signal constellation points. These definitions are illustrated by a 16-QAM constellation in Figure 3.5. In this fashion, the basic signal bit can be viewed as being transmitted by selecting one of the four fictitious symbols, whereas the incremental bits can be viewed as being transmitted via one of the four symbols surrounding the selected fictitious symbol.

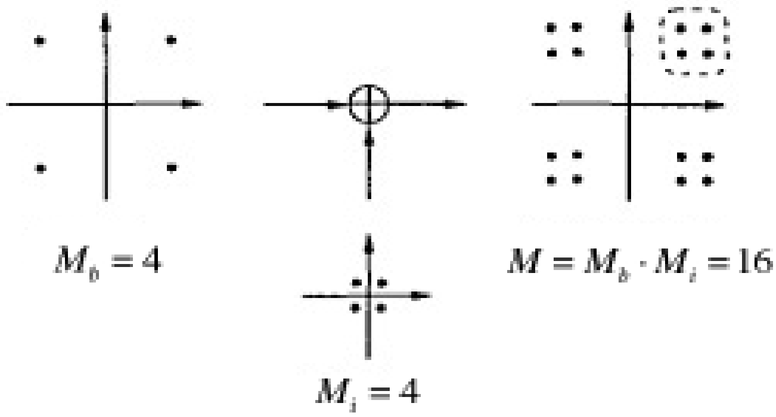

Figure 3.5 Hierarchical QAM scheme

3.3 HIERARCHICAL MODULATION FOR MULTI-ANTENNA BROADCASTING SYSTEM

A wireless communication system may employ multiple antennas at either transmitter side or receiver side, or both. The multiple antennas may be used to provide diversity against unwanted path effects and/or to improve transmission capacity, both of which are desirable. Therefore, there is a need for techniques to perform hierarchical modulation with multiple antennas in digital TV broadcasting.

3.4 SUMMARY

This chapter introduced the most essential concepts in a typical hierarchical modulation scheme, including good and bad receiver, as well as high-priority and low-priority signal. Then we studied the physical channel model of hierarchical modulation, and introduced three basic hierarchical schemes, namely, the TDM scheme, superposition scheme, and hierarchical QAM scheme, for single-antenna broadcasting. Furthermore, the concept of a hierarchical MIMO scheme will be explained with its measurement setup, in the next chapter.

CHAPTER 4

SIMULATION SETUP

In this chapter, we will build respective system models for TDM, superposition, hierarchical QAM and hierarchical MIMO schemes, based on a flat fading environment. Then, we will derive the algorithm for calculating achievable rates of basic and incremental signal in each hierarchical scheme, under certain assumptions.

4.1 HIERARCHICAL SINGLE-ANTENNA BROADCASTING SYSTEM

In general, a single-antenna broadcasting system includes one transmit antenna and one receive antenna on either good receiver or bad receiver, as depicted in Figure 4.1.

The communication channel for the transmitter and the good receiver has a complex channel gain of h_G and a noise variance of σ^2. Accordingly, for the transmitter and bad receiver, the respective complex channel gain is h_B, and the noise variance is also σ^2, since the noise considered here is assumed to be only related to environment temperature, which is a constant for a fixed broadcasting environment.

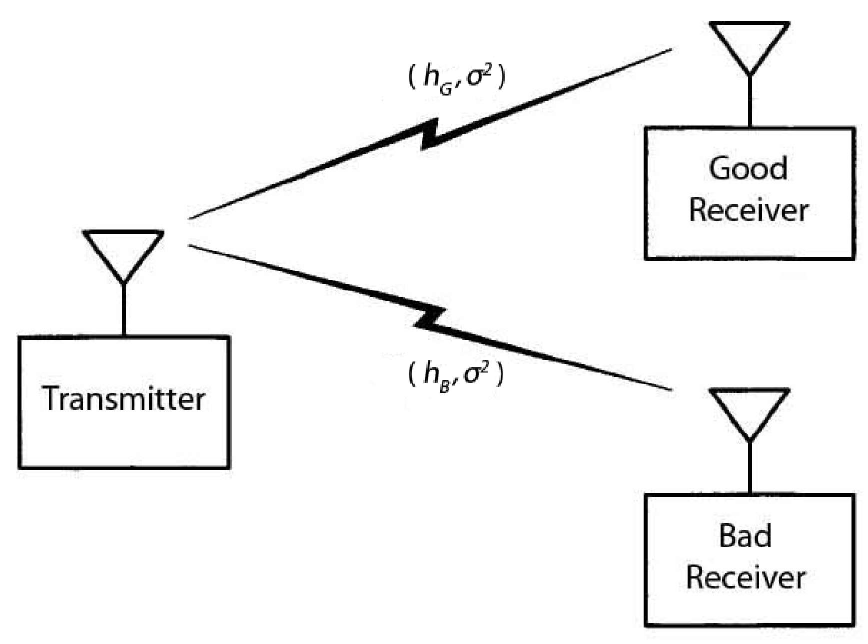

Figure 4.1 Typical structure of a single-antenna broadcasting system

A two-layered broadcast service may be implemented by dividing broadcast data into a basic signal and an incremental signal. The basic signal is sent at a rate that can be received by both receivers. The incremental signal is sent at a rate that can be only received by a good receiver with a better SNR. The two signals can be transmitted by using a TDM scheme, a superposition scheme, or a hierarchical QAM scheme.

4.1.1 TDM SCHEME

In a TDM scheme, the basic signal is sent during a fraction of the time, and the incremental signal is sent during the remainder of the time. Meanwhile, the channel between the transmitter and each receiver is assumed to be AWGN. The main characteristic of an AWGN channel is that it has a constant channel gain, denoted by h_G and h_B respectively for a good receiver and a bad receiver. Consequently, a system model of the TDM scheme for a good receiver and a bad receiver in a single-antenna broadcasting system can be expressed as [15]:

$$\begin{aligned} y_G &= h_G \cdot s + n \\ y_B &= h_B \cdot s + n \end{aligned} \tag{4.1}$$

where s is a transmitted data symbol that can be used for both the basic signal and the incremental signal. During the broadcasting, the transmitted signal is added with Gaussian noise n with variances σ^2. At the receiver side, y_G and y_B represent data symbols received by a good receiver and a bad receiver respectively.

Considering Shannon's capacity theory [16], the function gives the theoretical maximum data rate that can be reliably transmitted over a communication channel with a given noise variance and channel response. For simplicity, the unit of Shannon's capacity is normalized to bps/Hz in the following descriptions. Therefore, according to Shannon's capacity function, the maximum transmitted data rates for a good receiver and a bad receiver can be expressed as:

$$\begin{aligned} C_G &= log_2(1+SNR_i) \\ C_B &= log_2(1+SNR_b) \end{aligned} \quad \text{, bps/Hz} \tag{4.2}$$

where SNR_i is the receive SNR for the incremental signal, and SNR_b is the receive SNR for the basic signal. Besides, the communication channel can support an achievable rate of C_B for the bad receiver, which can also be received by the good receiver. Meanwhile, the communication channel can support an achievable rate of C_G for the good receiver which is greater than C_B, since $SNR_i > SNR_b$.

In the TDM scheme, the basic signal is sent during a fraction of the whole transmission time and needs to be received by both good and bad receiver, while the incremental signal is sent during the remainder of the time and can be only received by the good receiver, i.e., with no consideration of the bad receiver. The overall achievable rates for good and bad receiver are depicted by R_G and R_B respectively:

$$\begin{aligned} R_G &= R_b + R_i = \alpha_{TDM} C_B + (1-\alpha_{TDM}) C_G \\ R_B &= \alpha_{TDM} C_B \end{aligned} \tag{4.3}$$

where α_{TDM} is the fraction of time that the basic signal is transmitted, with $0 \le \alpha_{TDM} \le 1$, and $1-\alpha_{TDM}$ is the fraction of time that the incremental signal is transmitted. Besides, R_b and R_i are respective achievable rates for the basic and incremental signals.

The above description of a TDM scheme assumes an AWGN channel. For a flat fading channel based on a SFN, the channel gain from the transmitter to each receiver can be represented by the channel variable h and the noise variance σ^2. According to the actual geographical environment where the SFN is deployed, Rayleigh or Ricean distribution parameters can be chosen for realistic simulation.

The rates that can be achieved for the basic information and the incremental information for the TDM scheme in a flat fading channel can also be obtained as:

$$\begin{aligned} R_b &= \alpha_{TDM} C_B = \alpha_{TDM} E_{Rayleigh} \left\{ \log_2 \left(1 + SNR_b \right) \right\} \\ &= \alpha_{TDM} \int p_{Rayleigh}(h) \log_2 \left(1 + |h|^2 \, (E_s / \sigma^2)_b \right) dh \\ & \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad , \text{bps/Hz} \\ R_i &= (1-\alpha_{TDM}) C_G = (1-\alpha_{TDM}) E_{Rice} \left\{ \log_2 \left(1 + SNR_i \right) \right\} \\ &= (1-\alpha_{TDM}) \int p_{Rice}(h) \log_2 \left(1 + |h|^2 \, (E_s / \sigma^2)_i \right) dh \end{aligned} \tag{4.4}$$

where $E\{v\}$ denotes the expected value of v, and E_s is the transmitted energy per symbol. As described in the broadcasting channel model, the receive SNR for a incremental signal is higher, for example, 18 dB is a typical value for $(E_s / \sigma^2)_i$, while for a basic signal, the receive SNR is moderate, for example, 8 dB is a typical value for $(E_s / \sigma^2)_b$ [17]. Besides, $p_{Rayleigh}(h)$ is the Rayleigh probability density function given by

$$p_{Rayleigh}(h) = 2h\exp(-h^2) \tag{4.5}$$

and $p_{Rice}(h)$ is the Ricean probability density function given by

$$p_{Rice}(h) = 2h(1+K)\exp(-(h^2(1+K)+K))I_0\left(2h\sqrt{(1+K)K}\right) \tag{4.6}$$

where $I_0(\cdot)$ is the modified Bessel function of the first kind and zero-order, and K is the Ricean factor.

4.1.2 SUPERPOSITION SCHEME

In a superposition scheme, the basic signal and incremental data signal are combined and transmitted at the same time. The transmit power E_s is divided between the two signals. A signal model of the superposition scheme for a good receiver and a bad receiver in the single-antenna system can be formulated as:

$$\begin{aligned} y_G &= h_G(s_b\sqrt{\alpha_{SP}E_s} + s_i\sqrt{(1-\alpha_{SP})E_s}) + n \\ y_B &= h_B(s_b\sqrt{\alpha_{SP}E_s}) + n \end{aligned} \tag{4.7}$$

where s_b and s_i are data symbols for basic and the incremental signals respectively, α_{SP} is the fraction of the transmit power used for the basic signal, therefore, $1-\alpha_{SP}$ is the fraction of the transmit power used for the incremental signal.

At the receiver, the basic signal is recovered from a received signal by treating the incremental signal as an additive noise. Once the basic signal has been recovered, the interference due to the basic signal is estimated and removed from the received signal. The incremental signal is then recovered with the basic signal being removed. Based on the Shannon capacity function, in the hierarchical scheme with a flat fading channel, the achievable rates for the basic information and the incremental information can be expressed as:

$$\begin{aligned} R_b &= \int p_{Rayleigh}(h)\log_2\left(1+\frac{\alpha_{SP}E_s\left|h\right|^2}{(1-\alpha_{SP})E_s\left|h\right|^2+\sigma^2}\right)dh \\ &= \int p_{Rayleigh}(h)\log_2\left(1+\frac{\alpha_{SP}}{1-\alpha_{SP}+1/\left((E_s/\sigma^2)_b\left|h\right|^2\right)}\right)dh \end{aligned} \qquad (4.8)$$

$$R_i = \int p_{Rice}(h)\log_2\left(1+(1-\alpha_{SP})(E_s/\sigma^2)_i\left|h\right|^2\right)dh$$

Achievable rates for both receivers can be depicted as:

$$\begin{aligned} R_G &= R_b + R_i \\ R_B &= R_b \end{aligned} \qquad (4.9)$$

4.1.3 HIERARCHICAL QAM SCHEME

A typical hierarchical M-QAM scheme in DVB-T specification is shown in Figure 4.2. where M is defined as the constellation size parameter. In the hierarchical 64-QAM constellation there are 6 coded bits per symbol. The hierarchical system maps the data to 64-QAM by means of a QPSK signal embedded in the 64-QAM signal. This is referred to as “QPSK in 64-QAM”, which can be viewed as a combination of QPSK and 16-QAM modulation in each of the four quadrants. As shown beside an example constellation point, the QPSK can be treated as a basic signal, represented by the 2 most significant bits “11” of the 6 bits for a 64-QAM symbol, and would be used for more robust service, for example, SDTV. The reason why to select the first 2 most significant bits to transmit the basic signal is because the affiliation of 2-bit information to a quadrant is less likely to become disturbed due to noise [18]. The 16-QAM in each quadrant as the incremental signal, represented by the remaining 4 digits “0100”, could carry a less robust service, for example, HDTV. On the receiver side, in areas with good reception quality, receivers are able to determine the entire 64-QAM constellation states, including the basic signal and the incremental signal. Whereas in areas with poorer reception quality, receivers may only be able to resolve the black colored portions corresponding to QPSK (basic) signal. In addition, the spacing between constellation states can be increased to protect the QPSK (basic) signal, at the sacrifice of the robustness of 16-QAM (incremental) signal. Furthermore, standard signal constellations have limitations, where the increasing ratio of achievable rates will not pay for the significantly higher design complexity [19]. As a result of this, there are special and strict rules when deploying hierarchical modulation in practice.

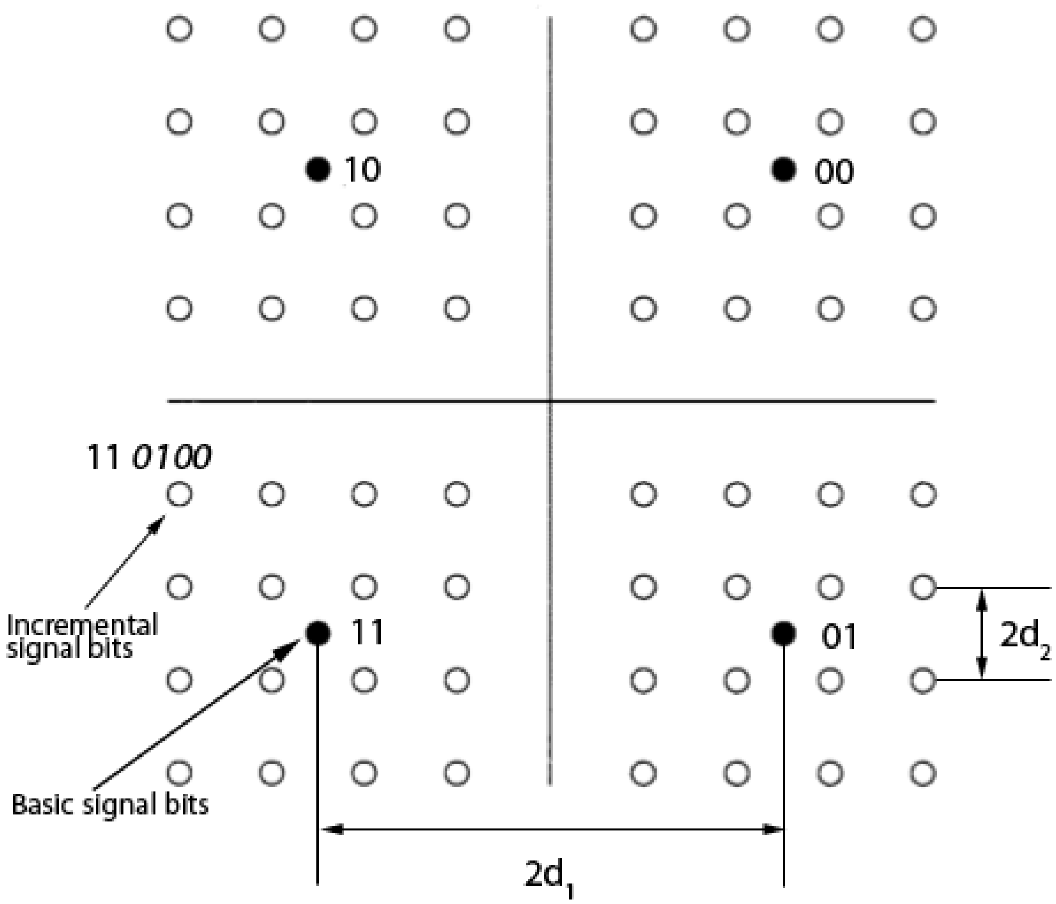

Figure 4.2 Hierarchical 64-QAM scheme

As shown in the figure, $2d_1$ represents the distances between two neighboring fictitious QPSK symbols, whereas $2d_2$ represents the distance between two neighboring 16-QAM symbols within one quadrant. The ratio of the energy in the fictitious QPSK constellation to the total average symbol energy is already derived in [20]:

$$\alpha_{QAM} = \frac{d_1^2}{d_1^2 + \frac{1}{3}\left(\frac{M}{4} - 1\right) d_2^2} \tag{4.10}$$

Based on α_{QAM}, the achievable rates for basic and incremental signals can be derived from an algorithm in the superposition scheme:

$$R_b = \int p_{Rayleigh}(h) \log_2 \left(1 + \frac{\alpha_{QAM}}{1 - \alpha_{QAM} + 1 / \left((E_s / \sigma^2)_b \, |h|^2 \right)} \right) dh \tag{4.11}$$

$$R_i = \int p_{Rice}(h) \log_2 \left(1 + (1 - \alpha_{QAM})(E_s / \sigma^2)_i \, |h|^2 \right) dh$$

4.2 HIERARCHICAL MULTI-ANTENNA BROADCASTING SYSTEM

When TV signals are broadcasted in an ideal environment as described in a typical MIMO scheme, for each transmitter, there are N_T and N_R antennas respectively for the good receiver and bad receiver, depicted in Figure 4.3. In the figure, it is assumed that $N_T = N_R = 2$.

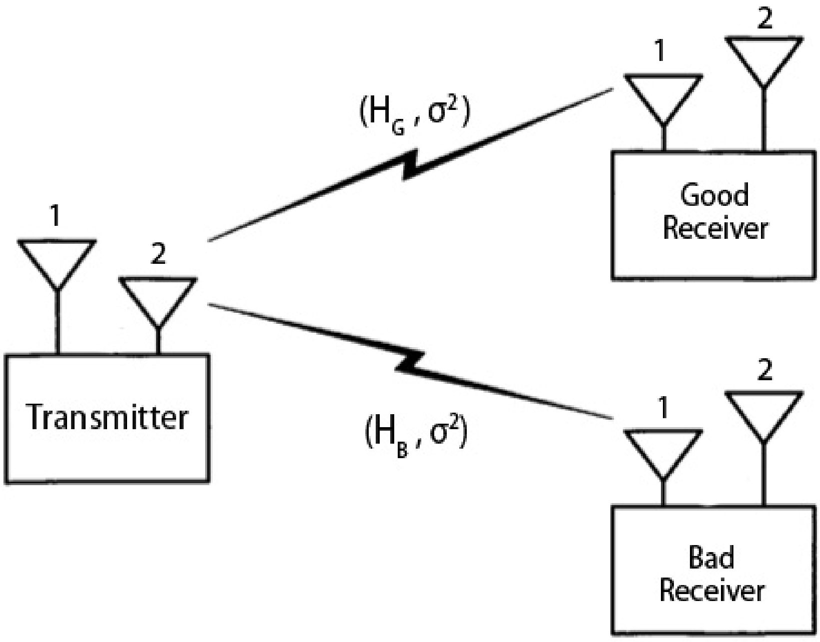

Figure 4.3 Typical structure of a multi-antenna broadcasting system

4.2.1 HIERARCHICAL MIMO TRANSMISSION IN SFN ENVIRONMENT

In an SFN environment considering Rayleigh fading between the transmitter and the bad receiver, and Ricean fading between the transmitter and the good receiver, similarly as in the superposition scheme, the achievable rates for the basic and incremental signal can be generated by

$$R_b = \int p_{Rayleigh}(\mathbf{H}) \log_2 \left(1 + \frac{\alpha_{MIMO}}{1 - \alpha_{MIMO} + \dfrac{1}{(E_s / \sigma^2)_b \left|\mathbf{H}\right|^2}} \right) d\mathbf{H} \tag{4.12}$$

, bps/Hz

$$R_i = \int p_{Rice}(\mathbf{H}) \log_2 \left(1 + (1 - \alpha_{MIMO})(E_s / \sigma^2)_i \left|\mathbf{H}\right|^2 \right) d\mathbf{H}$$

where α_{MIMO} is the fraction of power to transmit the basic signal in the hierarchical MIMO scheme. If we assign two transmitting antennas for the SFN base station, and two receiving antennas for the user equipment. Therefore, with open loop 2×2

diversity, $\mathbf{H}$ can be constructed by channel coefficients generated from one antenna of the transmitter to that of good or bad receiver, i.e., $h_{11}, h_{12}, \ldots h_{1N_R}, h_{21}, h_{22} \ldots, h_{N_T 1}$, $h_{N_T 2}, \ldots h_{N_T N_R}$, according to the number of antennas on the transmitter and receivers:

$$|\mathbf{H}|^2 = \frac{|h_{11}|^2 + \ldots + |h_{1N_R}|^2 + |h_{21}|^2 + \ldots + |h_{2N_R}|^2 + \ldots + |h_{N_T 1}|^2 + \ldots + |h_{N_T N_R}|^2}{N_T} \tag{4.13}$$

4.2.2 CORRECTION DUE TO SPATIAL FADING CORRELATION

Under realistic broadcasting conditions, the channel is not ideally Rayleigh independent and identically distributed (i.i.d). There are various factors that cause it to deviate from this, therefore the performance of MIMO systems deteriorates. One main reason is correlation, which arises because of the separation distance between antenna elements is in the order of a few centimeters in a base station. Therefore, the signals arriving at the base station from a distant receiver will be very close together, giving rise to correlation between them. Due to the geometry of this phenomenon, all the antenna elements will receive the same signal. The degree of "sameness" determines the correlation coefficient with 0 as no correlation and with 1 as maximum correlation. Here, we consider the influence due to inadequate antenna spacing or scattering leading to spatial correlation. In this case, we assume the channel is known perfectly to the receiver and is unknown to the transmitter.

From previous work [21], the effects of spatial fading correlation for a Rayleigh flat fading channel can be generated by modeling the MIMO channel $\mathbf{H}'$ as

$$\mathbf{H}' = \mathbf{R}_r^{1/2} \mathbf{H} \mathbf{R}_t^{1/2} \tag{4.14}$$

where $\mathbf{R}_r$ is the $N_R \times N_R$ transmit covariance matrix and $\mathbf{R}_t$ is the $N_T \times N_T$ receive covariance matrix. $\mathbf{R}_r$ and $\mathbf{R}_t$ specify the receive and transmit correlation respectively, and they are normalized so that $[\mathbf{R}_r]_{i,i} = 1$ ($i = 1, 2, \ldots N_R$) and $[\mathbf{R}_t]_{j,j} = 1$($j = 1, 2, \ldots N_T$), resulting in $E\left\{|h_{i,j}|^2\right\} = 1$.

In a hierarchical MIMO scheme where $N_T = N_R = 2$, if there is no transmitter or receiver correlation, we assume $\mathbf{R} = \mathbf{I}_2$. In a general case, the transmit or receive correlation matrix can be selected according to:

$$\mathbf{R} = \begin{bmatrix} 1 & \rho \\ \rho & 1 \end{bmatrix} \tag{4.15}$$

where ρ is correlation coefficient.

4.2.3 CORRECTION DUE TO LOS PHENOMENON

In the presence of a LOS component between the transmitter and receiver, the MIMO channel can be modeled as the sum of a fixed component and a variable of scattered component [22], as described by:

$$\mathbf{H}' = \sqrt{\frac{K}{1-K}}\overline{\mathbf{H}} + \sqrt{\frac{1}{1+K}}\mathbf{H} \tag{4.16}$$

where the first part of $\mathbf{H}'$ is the LOS component of the channel and the second part is the fading component that assumes uncorrelated fading. Besides, K is the Ricean K-factor. The elements of $\overline{\mathbf{H}}$ are assumed to have unit power, defined by $\overline{\mathbf{H}} = \begin{bmatrix} 1 & \rho \\ \rho & 1 \end{bmatrix}$.

4.3 SUMMARY

In this chapter the author calculated the spectral efficiencies of the basic and incremental signals, respective for the system model of a TDM, superposition, hierarchical QAM and a hierarchical MIMO scheme. Furthermore, we modified the ideal hierarchical MIMO algorithm by correlations due to spatial fading and the LOS phenomenon.

CHAPTER 5

SIMULATION RESULTS ANALYSIS

In the preceding chapter, we have generated algorithms to calculate achievable rates of basic signal and incremental signal in TDM, superposition, hierarchical QAM and hierarchical MIMO schemes. In this chapter numerical integration is employed to calculate respective achievable rates for good user and bad user, then present a clear view of how the variable of time fraction or power split coefficient will influence the basic and incremental signal individually. According to the DVB specification [17], we assume that the receive SNR is 8 dB for the bad user, and 18 dB for the good user. The transmission is determined so that the basic signal can be received by both users, and the incremental signal can be only received by the good user.

5.1 TDM SCHEME SIMULATION

In the TDM scheme, when the time fraction for transmitting basic signal changes, the distribution of ergodic capacities for the basic and incremental signal along with different receive SNR is plotted in Figure 5.1. For a fixed receive SNR, when the system uses more time to broadcast the basic signal, both users will obtain a higher basic signal rate, while the good user will suffer and get a lower incremental signal rate. When α_{TDM} becomes higher, the increasing speed for the achievable rate of the basic signal will be faster. Accordingly, when $1-\alpha_{TDM}$ rises, the increasing speed for the achievable rate of the incremental signal will also be faster. For a certain value of α_{TDM}, the achievable rates for both basic and incremental signal will increase with a higher receive SNR, also, the increasing speed is faster if provided higher receive SNR.

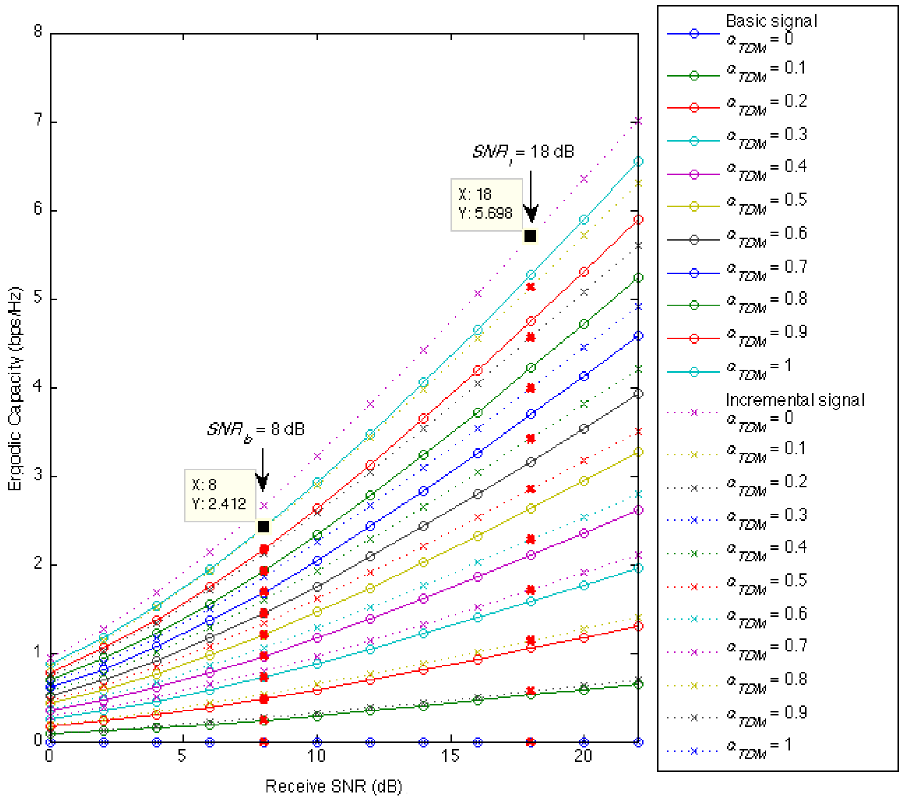

Figure 5.1 TDM ergodic capacities for basic and incremental signals

In the figure, the marked spot on the left column represents the achievable rate for the basic signal, which is as much as 2.4 bps/Hz, when the receive SNR is 8 dB for broadcasting the basic signal. Whereas the marked spot on the right column represents the achievable rate is as much as approximately 5.7 bps/Hz for the incremental signal, when the receive SNR is 18 dB for the good user.

Then we fix the maximum spectral efficiency for the basic signal as it can be achieved when the receive SNR is 8 dB, and fix the maximum spectral efficiency for the incremental signal as it can be achieved when the receive SNR is 18 dB. After that, we plot the distribution of spectral efficiencies for the good user and the bad user when the receive SNR is 18 dB for incremental signal, with different α_{TDM} values, as depicted in Figure 5.2. We can observe that, bad user spectral efficiency increases as α_{TDM} increases, however, the impact on the performance of the incremental signal makes a more negative impact on the good user than the basic signal does. Therefore, the good user spectral efficiency declines. In the SFN environment, if there is a bad user with a receive SNR larger than 8 dB, the TV signal can be as much as 2.4 bps/Hz, and if there is a good user with a receive SNR larger than 18 dB, the TV signal can be as much as 5.7 bps/Hz.

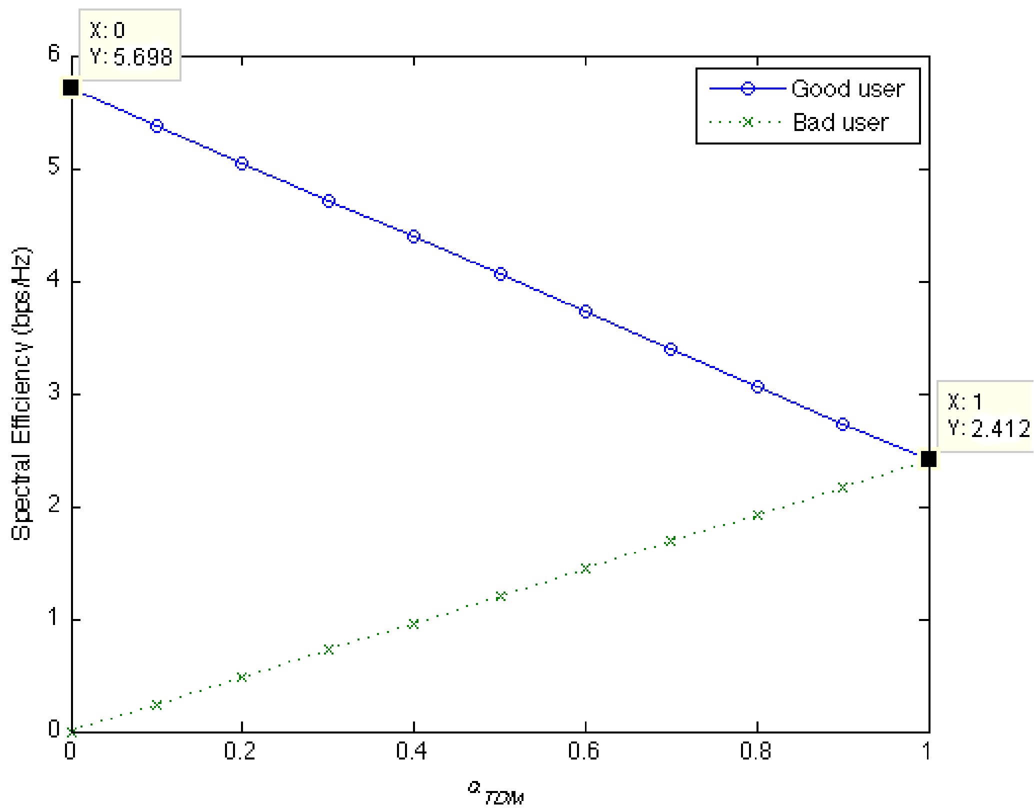

Figure 5.2 TDM spectral efficiency for good and bad users

When there is only the incremental signal transmitted, the overall achievable rate for the good user can be as much as 5.7 bps/Hz. As the fraction of time increases for transmitting the basic signal, the good user receives less overall achievable rate. On the contrary, the bad user receives an increasing amount of TV signals, until it achieves around 2.4 bps/Hz which is the same as that of good user, when there is only the basic signal transmitted.

5.2 SUPERPOSITION SCHEME SIMULATION

In the superposition scheme, when the basic signal transmit power changes, it is possible to plot the distribution of ergodic capacities of basic and incremental signal with different receive SNR, as depicted in Figure 5.3. As in the TDM scheme, it is clear that, there is a trade-off between data rates that can be achieved by the basic signal and incremental signal. For a fixed receive SNR, if the system uses more power to broadcast the basic signal, both users will be able to receive a higher basic signal rate, whereas the good user will also be compromised by a lower incremental signal rate. When α_{SP} becomes higher, the basic signal data rate will increase faster, but generally the increasing ratio is not obvious if $\alpha_{SP} < 0.6$. Meanwhile, the ergodic capacity for the incremental signal increases at a great speed. For a fixed α_{SP}, as the receive SNR increases, we can see that the increasing speed for the basic signal is generally slow, whereas that of incremental signal demonstrates a similarly remarkable speed.

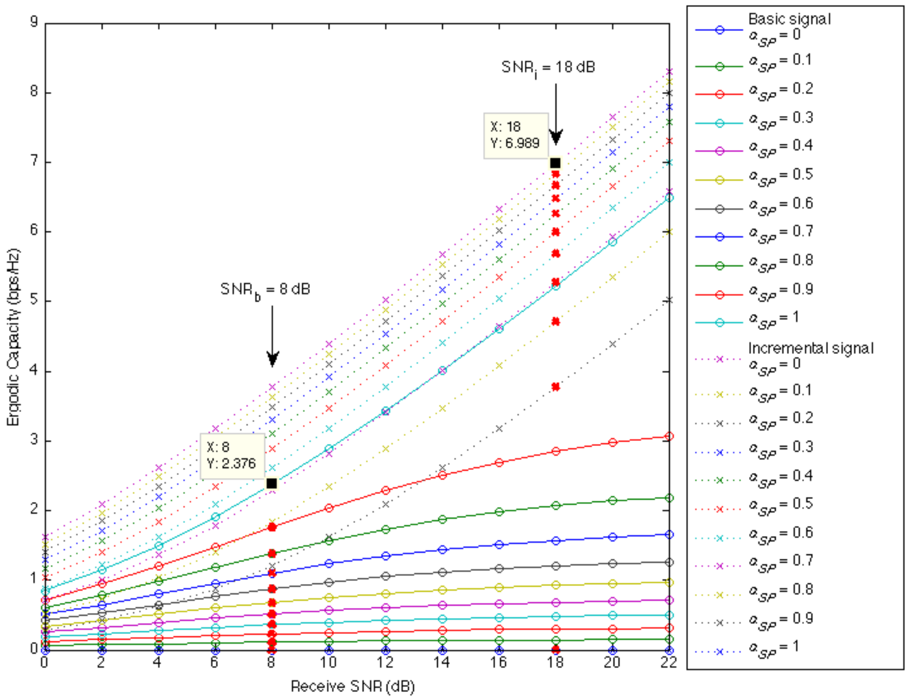

Figure 5.3 Superposition ergodic capacities for basic and incremental signals

In the figure, the marked spot on the left and right column demonstrates the achievable rate for the basic and incremental signal respectively, with the receive SNR becoming 8 dB and 18 dB accordingly. In this case, the achievable rate for the basic signal can be as much as 2.38 bps/Hz, giving a very similar performance as in the TDM scheme, but noticeably, the achievable rate for the incremental signal increases by as much as 1.3 bps/Hz.

Then the maximum spectral efficiencies for the basic signal and the incremental signal are fixed as was done for the TDM scheme. The distribution of spectral efficiency for the good user and the bad user with different α_{SP} values is plotted in Figure 5.4, when the basic signal receive SNR is 8 dB, and the incremental signal receive SNR is 18 dB. On the one hand, due to the contribution of the enhanced incremental signal, the overall achievable rate for the good user can be as much as nearly 7 bps/Hz, that is 1.3 bps/Hz compared with the TDM scheme. As the fraction of power for transmitting the basic signal increases, from 0 to 90%, the spectral efficiency for the good user declines at a moderate speed, noticeably, and from 90% to 100% power used for basic signal, the spectral efficiency drops dramatically, from 5.54 bps/Hz to 2.38 bps/Hz approximately. On the other hand, the spectral efficiency for the bad user increases steadily from 0 to 2.38 bps/Hz. Overall, the good user will keep receiving TV signal with a high data rate, which is between 6 and 7 bps/Hz, if the fraction of power used to transmit the basic signal ranges from 0 to 0.8. In the SFN environment, if there is a bad user with a receive SNR larger than 8 dB, its achievable rate can be as much as 2.38 bps/Hz, and if there is a good user with a receive SNR larger than 18 dB, its achievable rate can be as much as 7 bps/Hz.

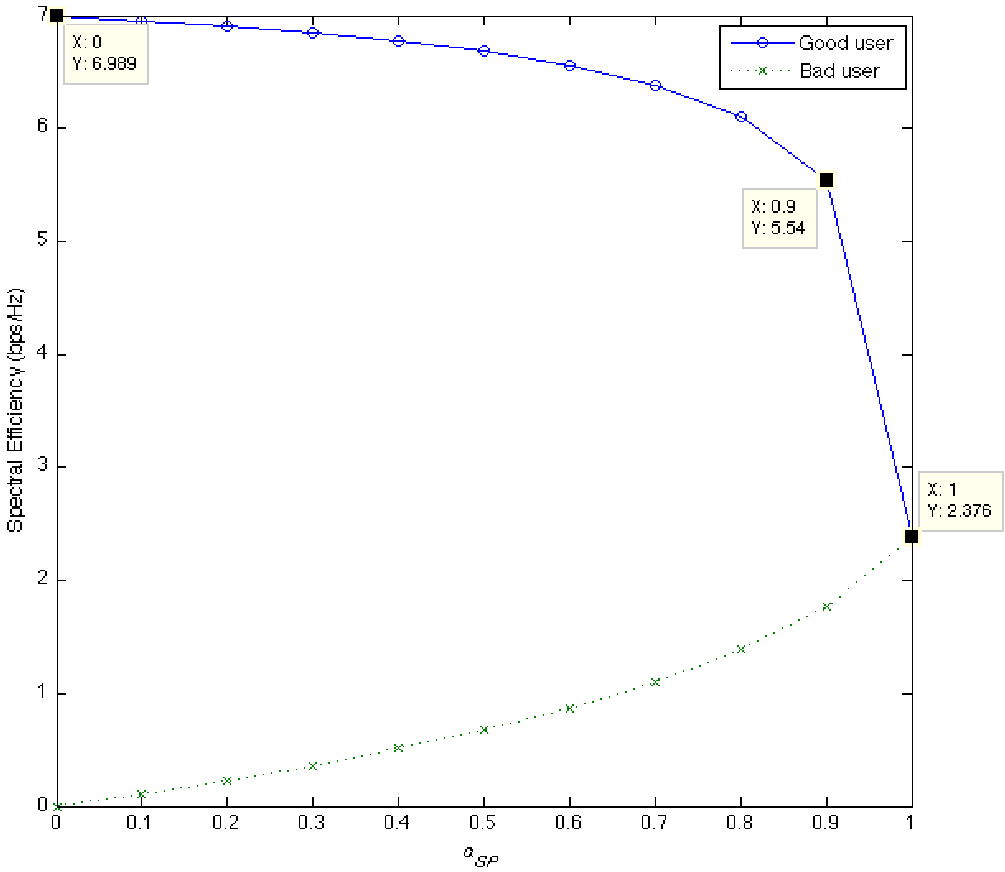

Figure 5.4 Superposition spectral efficiency for good and bad users

5.3 HIERARCHICAL QAM SCHEME SIMULATION

We have figured out the algorithm for calculating the basic and incremental signal rate, as well as the power allocation coefficient α_{QAM}, and we will simulate based on a hierarchical 64-QAM scheme, with the hierarchical parameter α taking three values 1, 2 or 4. The parameter α represents the minimum distance between the border of two neighboring quadrant, divided by the minimum distance separating the two neighboring incremental signal symbols in each quadrant. As an example, non-hierarchical broadcasting uses the same uniform constellation as the case in Figure 5.5, where $\alpha = d_3 / d_2 = 1$.

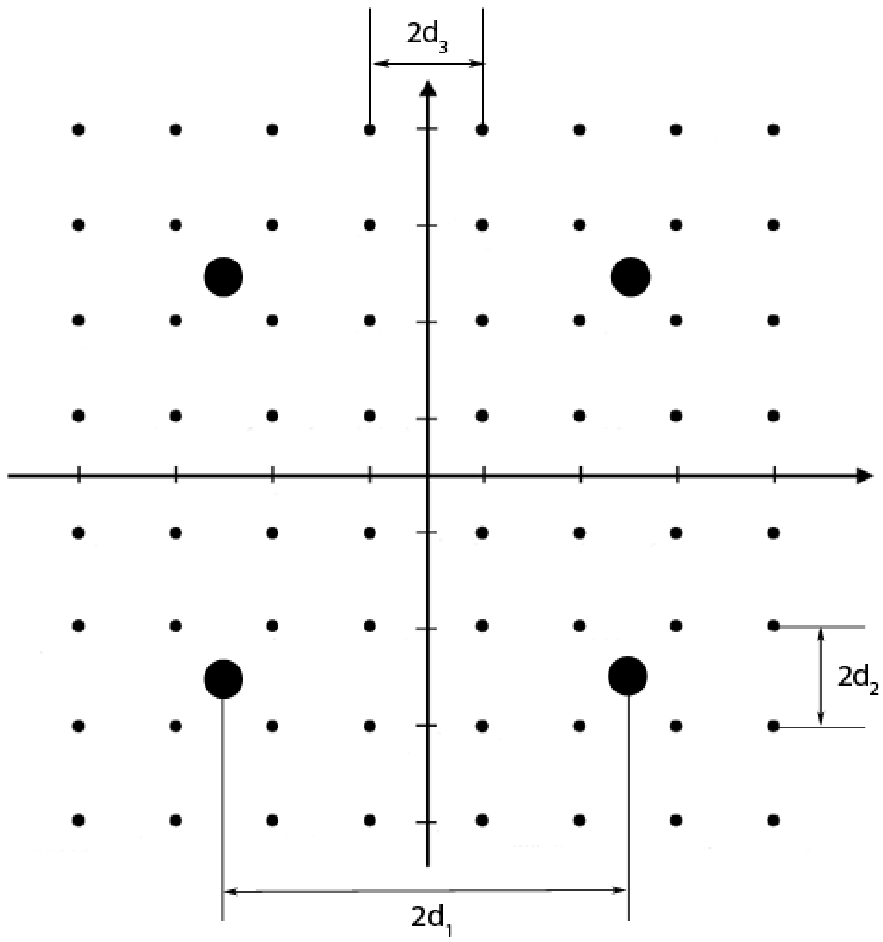

Figure 5.5 Hierarchical 64-QAM scheme to introduce hierarchical parameter α

Considering α_{QAM} and the algorithm of the hierarchical QAM, when a non-hierarchical QAM scheme is deployed, it is defined by $\alpha = d_3 / d_2 = 1$, therefore $d_1 = 4d_2$, thus $\alpha_{QAM} = 0.9412$. Similarly, $\alpha_{QAM} = 0.9615$ when $\alpha = 2$, and $\alpha_{QAM} = 0.98$ when $\alpha = 4$. As the hierarchical degree becomes even higher, α_{QAM} will approach 1.

Ergodic capacity for good and bad users with three α values is illustrated in Figure 5.6 Hierarchical 64-QAM ergodic capacities for basic and . Compared with the superposition scheme, the hierarchical QAM scheme retains an extremely high achievable rate for the basic signal, at the price of a relatively low incremental signal rate. When the receive SNR for the basic and incremental signal is set, as α becomes higher, the basic signal also gets a higher rate, whereas the incremental signal is compromised.

For all these hierarchical 64-QAM schemes, when the basic signal receive SNR is 8 dB, the basic signal will achieve around 2 bps/Hz. But the neighboring incremental signal shows about a 0.5 bps/Hz difference, ranging from 1.8 bps/Hz to 3.1 bps/Hz, when the incremental signal receive SNR is 18 dB.

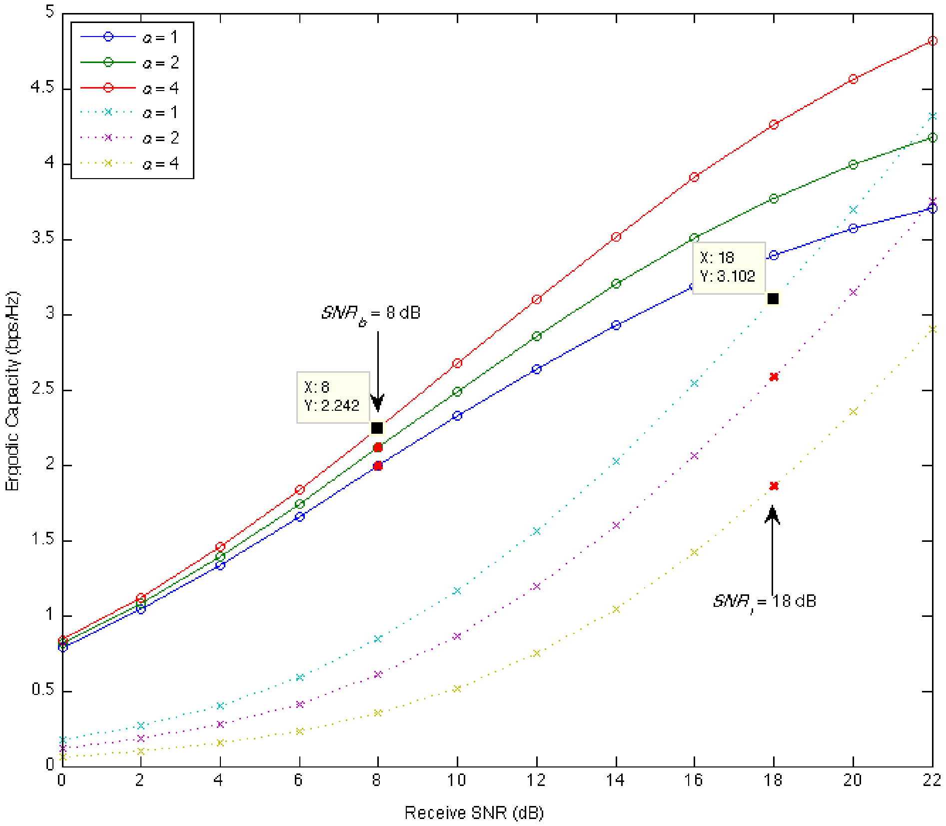

Figure 5.6 Hierarchical 64-QAM ergodic capacities for basic and incremental signals

When a non-hierarchical 64-QAM is used, the basic signal rate is lower than the incremental signal rate by around 1 bps/Hz. When the hierarchical 64-QAM with $\alpha = 1$ is used, the basic signal rate is still lower than the incremental signal rate, but the difference is less than 0.5 bps/Hz. Noticeably, when $\alpha = 4$, the basic signal rate is higher than the incremental signal rate, and if α becomes even larger, the basic signal rate can be multiple times that of the incremental signal rate.

As in the TDM and superposition schemes, the maximum spectral efficiencies are fixed for the basic signal and the incremental signal. The spectral efficiencies of the good user and the bad user in the hierarchical 64-QAM scheme with the same α values are taken from that of the superposition scheme, as in Figure 5.7 Hierarchical 64-QAM spectral efficiency for good and bad users. It can be observed that when α becomes larger, good user will be able to receive a lower TV signal rate, from over 5 bps/Hz down to nearly 4 bps/Hz, whereas the bad user can receive a higher TV signal rate, from 2 bps/Hz up to over 2.2 bps/Hz. In the SFN environment, if there is a bad user with a receive SNR larger than 8 dB, its achievable rate can be as much as 2.2 bps/Hz, and if there is a good user with a receive SNR larger than 18 dB, its achievable rate can be as much as 3.1 bps/Hz.

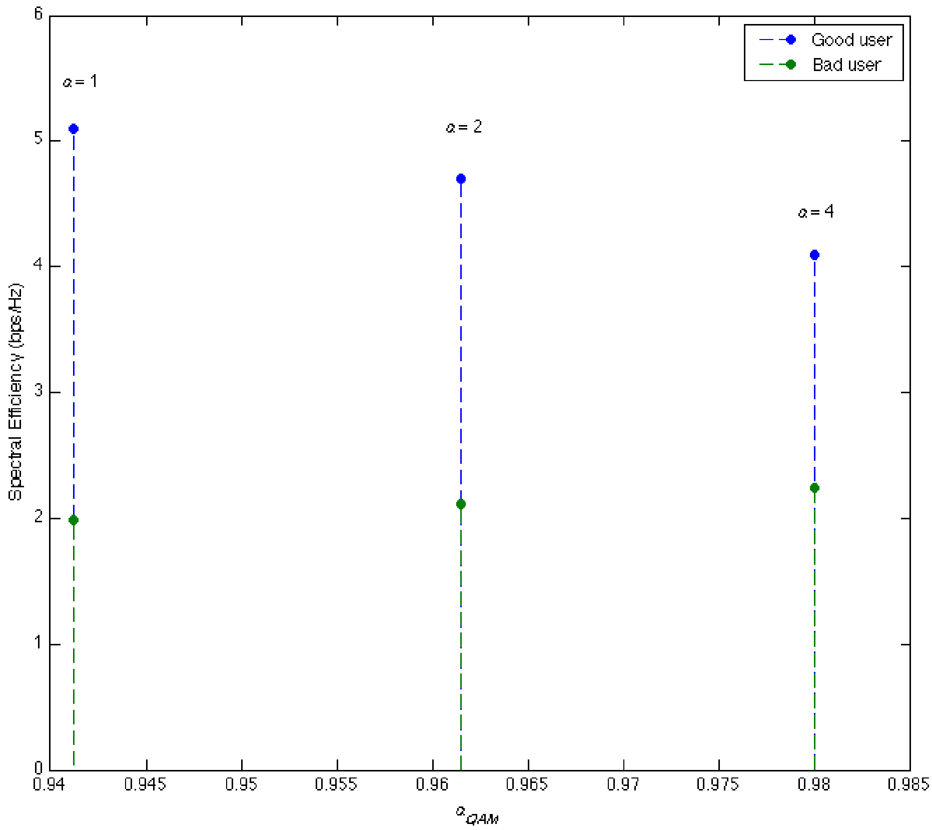

Figure 5.7 Hierarchical 64-QAM spectral efficiency for good and bad users

In practice, when a SFN is deployed based on a hierarchical QAM scheme, both users will be able to receive an acceptable rate of TV signal, which is more affordable for network operators, than employing a more costly superposition scheme.

5.4 HIERARCHICAL MIMO SCHEME SIMULATION

In this section we will first simulate a hierarchical 2×2 MIMO scheme without correlations in both transmit and receive antennas, then the modified model is simulated. The results for ergodic capacities for both the basic and incremental signals, as well as the spectral efficiencies for the good and bad user, are presented separately, for both the ideal model and the modified model.

5.4.1 RESULTS WITHOUT TRANMITTER AND RECEIVER CORRELATIONS

Our simulation is conducted from a hierarchical 2×2 MIMO scheme, where $N_T = N_R = 2$. Firstly, as an ideal case, it is assumed that there is no correlation in both the transmit and receive antennas, and the ergodic capacity is plotted for the good and bad users in Figure 5.8 Hierarchical 2×2 MIMO ergodic capacities for basic and incremental .

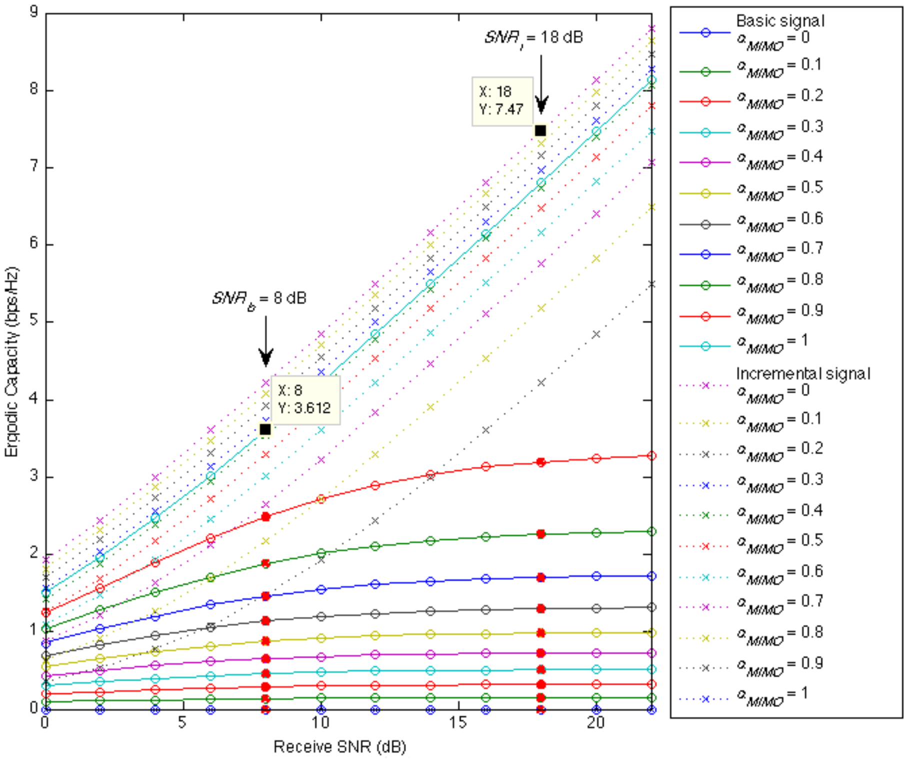

Figure 5.8 Hierarchical 2×2 MIMO ergodic capacities for basic and incremental signals (no correlation)

Compared with the superposition scheme, the hierarchical MIMO scheme greatly improve the achievable rates for both basic and incremental signals. In this simulation, the hierarchical 2×2 MIMO scheme noticeably increases the basic signal achievable rate by as much as 1.2 bps/Hz, when the basic signal receive SNR is 8 dB. Meanwhile, the increase in the achievable rate of the incremental signal can be as much as 0.4 bps/Hz, when the incremental signal receive SNR is 18 dB.

As in previous hierarchical schemes, the maximum spectral efficiencies are fixed for both signals. Then the spectral efficiencies for good and bad users are plotted in Figure 5.9. When there is only an incremental signal transmitted, the maximum achievable rates of the good user is around 7.5 bps/Hz, which is about 0.5 bps/Hz higher than that achieved in the superposition scheme. The good user spectral efficiency remains above 7 bps/Hz provided $\alpha_{MIMO} < 0.8$. Besides, when α_{MIMO} is between 0.83 and 1, the incremental signal spectral efficiency will be above 2 bps/Hz, which is also a remarkable improvement over the superposition scheme. Noticeably, the increasing speed of the bad user achievable rate is higher, compared with the superposition scheme. When there is only the basic signal transmitted, the achievable rates of the good user and bad user become to approximately 3.6 bps/Hz, which is about 1.2 bps/Hz significantly greater than the figure obtained through employing a superposition scheme. In the SFN environment, if there is a bad user with a receive SNR larger than 8 dB, the TV signal can be as much as 3.6 bps/Hz, and if there is a good user with a receive SNR larger than 18 dB, the TV signal can be as much as 7.5 bps/Hz.

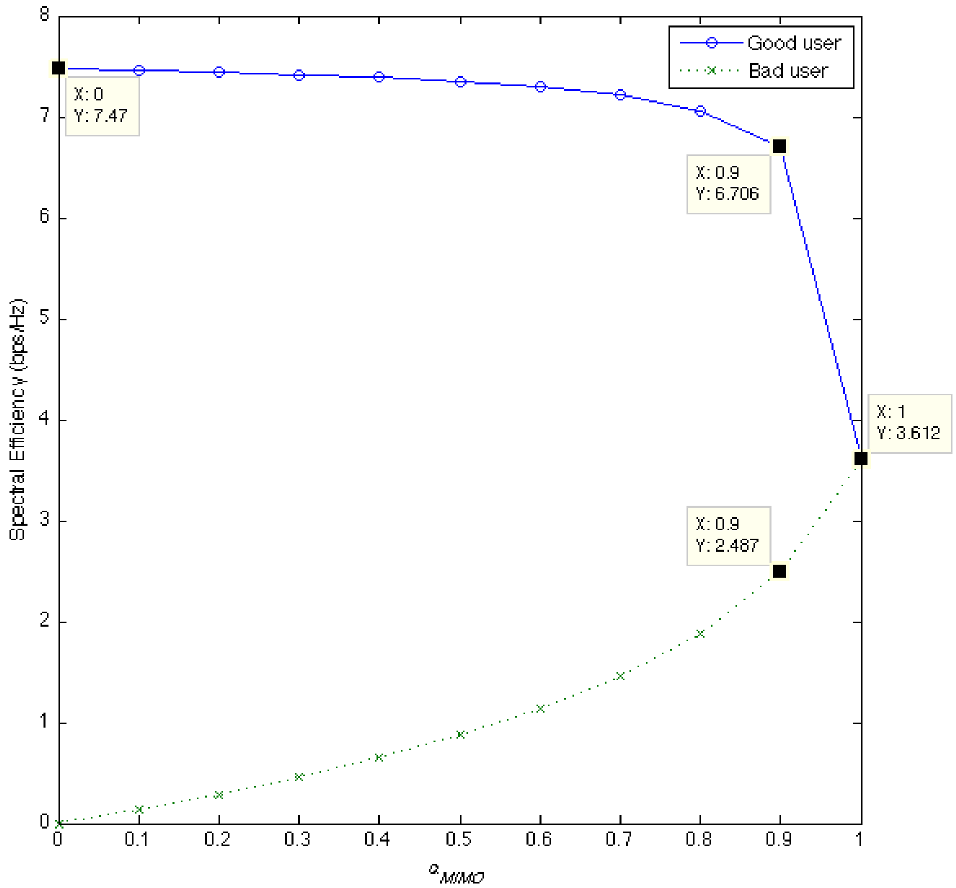

Figure 5.9 Hierarchical 2×2 MIMO spectral efficiency for good and bad users (no correlation)

5.4.2 CORRECTIONS DUE TO ANTENNA CORRELATIONS

In practice, the correlation usually exists only in the transmitter side. Assuming that $\rho = 0.9$, we will get the result of ergodic capacity for the good user and bad user in Figure 5.10 Hierarchical MIMO ergodic capacity for basic signal and incremental signals (with correlation).

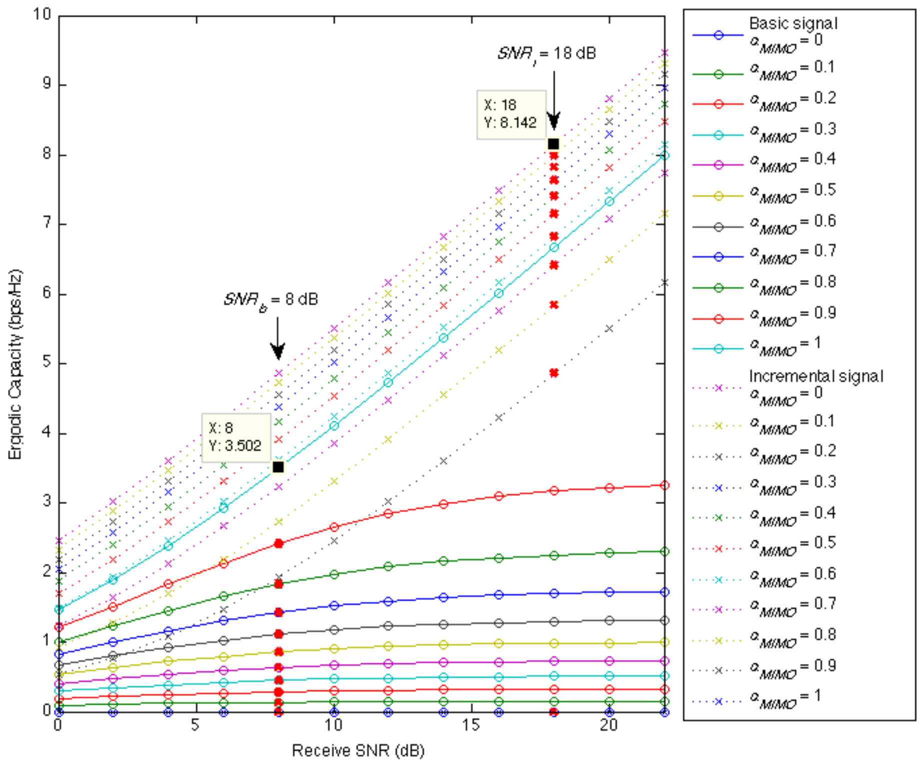

Figure 5.10 Hierarchical MIMO ergodic capacity for basic signal and incremental signals (with correlation)

Compared with the non-correlation hierarchical MIMO scheme, if there is a correlation in both sides of a broadcasting system, and when the receive SNR used for basic signal is 8 dB, the achievable rate downgrades by approximately 0.1 bps/Hz. Noticeably, when the receive SNR for the incremental signal is 18 dB, the achievable rate shows a significant gain of about 0.7 bps/Hz.

With the same fix to spectral efficiencies for both signal, the spectral efficiency with correlation is plotted in Figure 5.11 Hierarchical MIMO spectral efficiency for good and bad users. Compared with the non-hierarchical scheme, if there is only basic signal transmitted, the bad user will lose 0.1 bps/Hz achievable rate, and on the contrary, whereas the good user will receive approximately 0.7 bps/Hz more rate, if there is only an incremental signal transmitted. In the SFN environment, if there is a bad user with receive SNR larger than 8 dB, the TV signal can be as much as 3.5 bps/Hz, and if there is a good user with receive SNR larger than 18 dB, the TV signal can be as much as 8.14 bps/Hz.

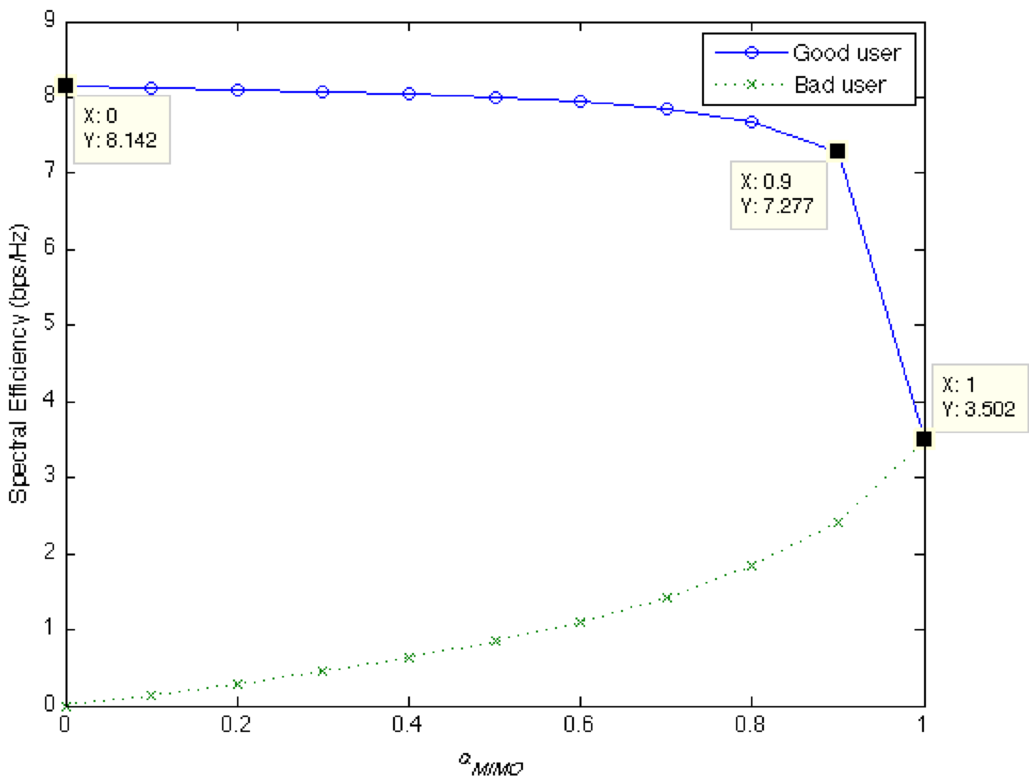

Figure 5.11 Hierarchical MIMO spectral efficiency for good and bad users (with correlation)

5.5 SUMMARY

In this chapter, the author simulated the achievable rates of the basic and incremental signals, when applying each hierarchical scheme discussed in the thesis. Furthermore, the simulation results of the spectral efficiencies for good and bad users were presented separately.

CHAPTER 6

SUMMARY AND CONCLUSIONS

In this chapter, we will analyze the results from the distribution of the spectral efficiencies by employing different hierarchical schemes. After this, comes an explanation of an improvement that can be theoretically achieved in a digital TV broadcasting system, when switching to a hierarchical MIMO scheme. Furthermore, possible future work is also presented.

6.1 CONCLUSIONS

If we have 100 samples for α_{TDM} , α_{SP} and α_{MIMO} between 0 and 1, and α in a hierarchical 64-QAM is 1, 2 or 4, then we can plot smooth curves for comparing the distribution of spectral efficiency for good and bad users in Figure 6.1, where the spectral efficiency is measured by bps/Hz.

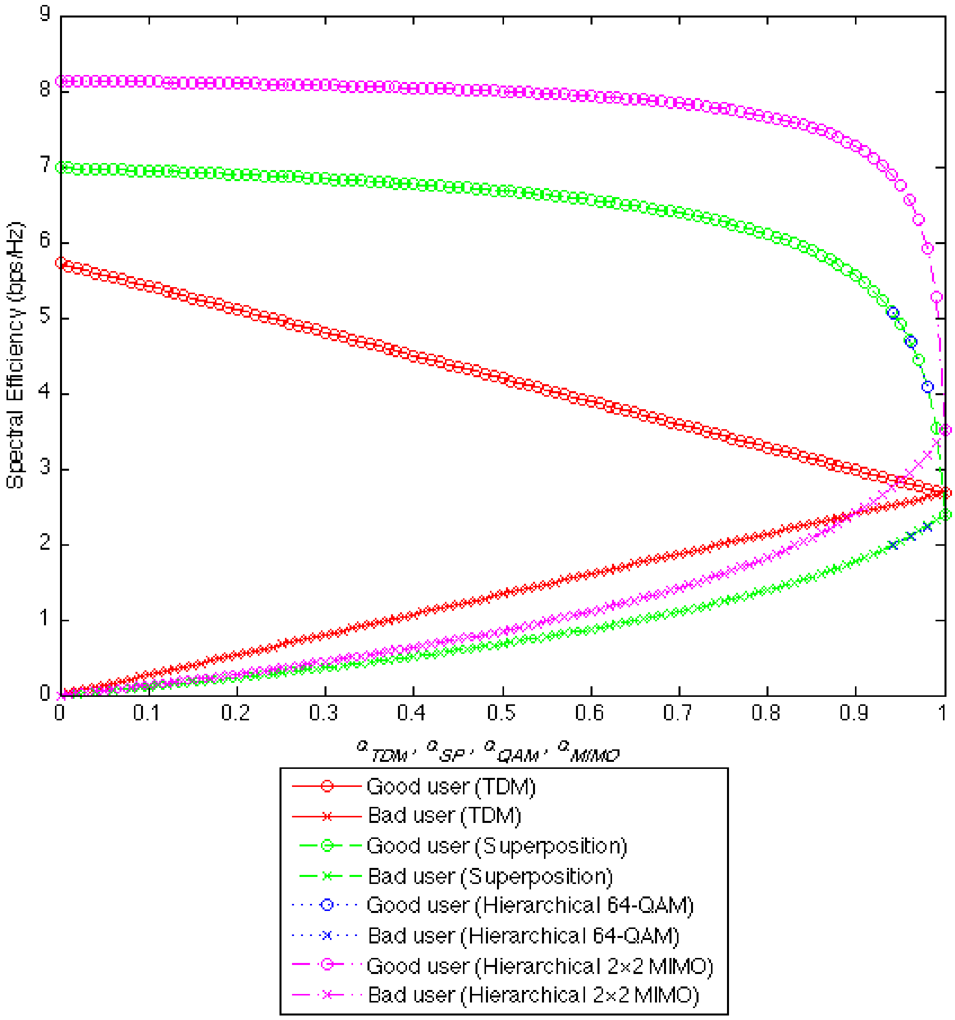

Figure 6.1 Comparison of spectral efficiencies for good user and bad user

On the one hand, for a bad user who can only receive the basic signal in TDM, superposition, hierarchical QAM and hierarchical MIMO schemes respectively, their spectral efficiencies start to increase along with α_{TDM} , α_{SP} , α_{QAM} and α_{MIMO} respectively. In the superposition scheme the spectral efficiency of the bad user was demonstrated to be the lowest, and in every respect it is lower than utilizing the TDM scheme. Whereas in a hierarchical MIMO scheme, the spectral efficiency is generally better, and rises faster, although it is still slower than in the TDM scheme until the value of α_{MIMO} is near to 0.9. After that, particularly when the transmit power is totally used for the basic signal, its spectral efficiency can be outperform that of the TDM scheme by as much as 0.9 bps/Hz. The difference in spectral efficiencies between the hierarchical superposition and the hierarchical MIMO scheme becomes more and more obvious when the transmit power for basic signal increases. Moreover, when a hierarchical 64-QAM is employed with $\alpha = 1, 2, 4$, the bad receiver gets a relatively high spectral efficiency for the basic signal. If we use a hierarchical 2×2 MIMO scheme, the difference of spectral efficiency can be as much as approximately 1 bps/Hz, compared with the hierarchical 64-QAM scheme with $\alpha = 4$, which provides the highest spectral efficiency among the considering hierarchical QAM schemes. In other words, by employing a hierarchical 2×2 MIMO scheme, the spectral efficiency of a bad user in a hierarchical 64-QAM scheme can be improved by as much as 45%.

On the other hand, for a good user who can receive both basic and incremental signals in the TDM, superposition, hierarchical QAM and hierarchical MIMO schemes respectively, their spectral efficiencies will decline with the increasing value of α_{TDM} , α_{SP} , α_{QAM} and α_{MIMO} respectively. The spectral efficiency for a bad user in the TDM scheme is the lowest among all hierarchical schemes. In the superposition scheme, the spectral efficiency being much higher when there is only the incremental signal transmitted. Here the peak spectral efficiency is approximately 7 bps/Hz, which is more than 1 bps/Hz higher than the peak value in the TDM scheme. However, when all the transmit power is used for the basic signal, its spectral efficiency is about 0.3 bps/Hz lower than in the TDM scheme. Besides, when the hierarchical 64-QAM is employed with $\alpha = 1, 2, 4$, the good user still gets an acceptable spectral efficiency between 4 and 5.2 bps/Hz. Furthermore, we will get very satisfying spectral efficiency performance, which outperforms that in the superposition scheme by overall more than 1 bps/Hz. Regarding the hierarchical 64-QAM scheme, when $\alpha = 1$, the spectral efficiency for the good user is the highest among the considering hierarchical QAM schemes, but it still can be improved by as much as 36%, by switching to a hierarchical 2×2 MIMO scheme.

As a conclusion of this thesis, we can find out that, when a hierarchical MIMO scheme is utilized for digital TV broadcasting, the coverage of both the basic signal and the incremental signal can be enlarged by switching the current hierarchical single-antenna broadcast system to a multi-antenna system. Meanwhile, the spectrum performance for both users improves, especially for the good user, as there is a remarkable improvement in the spectral efficiency of the received incremental signal.

6.2 FUTURE WORK

It is apparent that this thesis has shortcomings and problems. The algorithm and the according simulations are built in a flat fading environment, beside, only spatial correlation and LOS phenomenon are considered. The potential of the current hierarchical MIMO model can be further studied. Therefore, there are still some issues left for future studies and extensible research work.

Two things that could be investigated are: firstly, employing hierarchical M-QAM constellations with orthogonal space-time block coding; and secondly, considering transmit diversity and receive diversity, to achieve the SFN structural space diversity gain.

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