國 立 交 通 大 學

電機學院　電信學程

碩 士 論 文

多輸入多輸出正交分頻多工行動網路宏觀天線分集合併機制之研究

Macro-Diversity Antenna Combining for MIMO OFDM Cellular Mobile Networks

研究生：周哲樺

指導教授：王蒞君 教授

中 華 民 國 九十九 年 七 月

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摘　　要

在未來正交分頻多工(Orthogonal Frequency Division Multiplexing)行動網路中，基地台將會採用多輸入多輸出(Multi-input Multi-output)天線技術來改善對使用者的傳輸容量(Throughput)和鏈結可靠度(Link Reliability)。當基地台使用天線之空間多工技術，在下行連結的情況下，鄰近目前服務基地台的使用者的傳輸容量會被大量的增加，但是基地台全部的傳輸功率被分散到各個傳送天線，訊號干擾加雜訊比率(Signal to Interference-and-Noise Ratio)會隨著傳送天線個數增加而一直降低，特別是在細胞邊界的地方，會造成傳輸容量會嚴重下降，導致細胞服務範圍的縮減，為了涵蓋原先的服務範圍，電信業者需要佈建更多的基地台，這樣會增加業者基地台佈建的成本和增加使用者切換到不同基地台的次數。在實際的環境中，由於天線之間沒有足夠的距離和缺乏通道的散射效應(Scatter Effect)，天線相關性會存在於基地台或使用者，若傳送天線端存在天線相關性，多輸入多輸出天線之空間多工效能會大大的受到影響，如此，要解決多輸入多輸出天線之空間多工的涵蓋問題會變成一個更困難的工作。

我們在論文中提出兩種宏觀天線分集結合機制，增加使用多輸入多輸出天線之空間多工正交分頻多工行動網路基地台邊界的傳輸容量和進一步改善進行換手(Handover)的傳輸容量，一個是空頻編碼宏觀分集結合空間多工機制(Space-Frequency Block Code Macro-Diversity Combining Spatial Multiplexing)，另一個是循環延遲宏觀分集結合空間多工機制(Cyclic Delay Macro-Diversity Combining Spatial Multiplexing)，在相鄰的基地台之間增加傳送分集並結合基地台本身使用的天線之空間多工技術，在不增加傳送天線或基地台的個數下，我們可以同時得到多輸入多輸出之空間多工和空間分集的優勢，當使用者往基地台邊界移動，相同資料經由空頻編碼或循環延遲調製在相鄰的基地台以相同的頻率傳送，使用者的接收端可以執行天線分集結合的機制獲得分集增益，提供更高的傳輸容量並改善宏觀分集交遞(Macro-Diversity Handover)的效能。

模擬結果顯示，基於降低系統複雜性以及對現存無線通訊系統的兼容性，我們可以選擇採用循環延遲宏觀天線分集結合空間多工機制來改善使用者在基地台邊界面臨傳輸容量不佳的問題。兩種宏觀天線分集結合機制在傳送端天線相關性較低的條件下，能大量改善使用者在基地台邊界的傳輸容量。當傳送天線相關性為0.1時，空頻編碼宏觀天線分集結合空間多工機制可以提供比原先天線之空

間多工機制多2 bit/s/Hs的傳輸容量，當傳送天線相關性為0.9時，也還增加0.5 bit/s/Hs的傳輸容量。而循環延遲宏觀天線分集結合空間多工機制當傳送天線相關性為0.1時，可以提供比原先天線之空間多工機制多1 bit/s/Hs的傳輸容量，當傳送天線相關性為0.9時，也還增加0.5 bit/s/Hs的傳輸容量。隨著在基地台傳送天線相關性的增加，仍然可以提供比原本使用天線之空間多工的機制更高的傳輸容量，而且空頻編碼宏觀天線分集結合空間多工機制和循環延遲宏觀天線分集結合空間多工機制之間對傳輸容量改善的差異越來越小。

Macro-Diversity Antenna Combining for MIMO OFDM Cellular Mobile Networks

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ABSTRACT

In the future orthogonal frequency division multiplexing (OFDM) cellular network, base station will adopt multi-input multi-output (MIMO) techniques to improve throughput and link reliability for mobile stations. When the base station using spatial multiplexing (SM) in the downlink case, the throughput of mobile station can be hugely increased nearby the serving base station. However, the total transmit power is split uniformly across the transmit antennas, the signal to interference-and-noise ratio (SINR) degreases with the increasing number of transmit antennas. Additionally, the capacity will seriously decrease at the cell boundary. Thus, SM will reduce the cell coverage in this kind of MIMO OFDM system, the telecommunications operators need to set up more base stations for covering the service areas. This will raise the base station equipment cost of the operators and increase the handover frequency. In a real environment, spatial correlation exists at base station or mobile station due to insufficient antenna separation and the lack of scatter effect. The performance of SM degreases seriously with non-trivial spatial correlation among the transmit antennas, therefore, it becomes a more difficult task to overcome the problem of cell coverage reduced by SM.

In this thesis, we introduce two kinds of macro-diversity combining techniques for spatial multiplexing based MIMO OFDM cellular networks to increase cell boundary throughput and improve soft handover performance. The one is space-frequency block code macro-diversity combining spatial multiplexing scheme. The other is cyclic delay macro-diversity combining spatial multiplexing scheme. Applying transmit diversity at adjacent base station sides and using SM of each base station, we can take both advantages of spatial multiplexing and spatial diversity without increasing the number of transmit antennas or base stations. When a mobile station moves near the cell boundary, the adjacent base stations transmit the same data encoded by SFBC or CDD at the same frequency. At the receiver of the mobile station can perform diversity combining to get the macro-diversity gain, thereby improving throughput and the handover performance.

Because of lower complexity and compatibility to existing wireless communication systems, we conclude that adopting the CDD macro-diversity

combining with SM scheme is a preferable scheme to improve the poor throughput of mobile stations near the cell boundary. These two macro-diversity combining schemes can provide a high throughput improvement of mobile station at the cell area in low spatially-correlated channels. As transmit antenna spatial correlation is equal to 0.1, SFBC macro-diversity combining with SM scheme can improve 2 bit/s/Hz more than the conventional SM scheme. As transmit spatial correlation is equal to 0.9, it can still improve 0.5 bit/s/Hz higher than the conventional SM scheme. As transmit antenna spatial correlation is equal to 0.1, CDD macro-diversity combining with SM scheme can improve 1 bit/s/Hz higher than the conventional SM scheme. As transmit spatial correlation is equal to 0.9, it can also improve 0.5 bit/s/Hz more than the conventional SM scheme. With spatial correlation increased at each transmitters of each base station, they also can provide higher throughput than the conventional SM scheme. The variations of throughputs between CDD macro-diversity combining with SM scheme and SFBC macro-diversity combining with SM scheme are getting small at the cell boundary.

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CHAPTER 1

Introduction

It is well-known that multi-input multi-output (MIMO) antenna transmission systems can provide spatial multiplexing gain and diversity gain to increase spectral efficiency and link reliability [1] [2] [3] [4]. For future broadband wireless systems, in order to meet the data rate and quality-of-service (QoS) requirements of mobile stations, spectral efficiency and link reliability should be improved. Spatial multiplexing techniques in MIMO systems can provide huge capacity gains by creating a number of spatial pipes, through which several independent information streams can be transmitted at the same frequency. MIMO systems also provide independent fading channels between the transmit antennas and receiver antennas. The replicas of the same signal yield the transmit and receive diversity techniques.

Orthogonal frequency division multiplexing (OFDM) is a very popular modulation technique for transmitting broadband signals in multi-path fading environments, which converts a frequency selective fading channel into a parallel collection of frequency flat fading sub-channels. OFDM can overcome inter-symbol interference (ISI) by applying a cyclic symbol extension. Besides, orthogonal sub-carriers with overlapped spectra can achieve high spectral efficiency. However, OFDM based transmission schemes has no built-in spatial diversity, therefore combining MIMO with OFDM (MIMO OFDM) has been chosen as an attractive air-interface solution for the next generation high speed wireless systems [5], including the IEEE 802.16e/WiMAX and the 3GPP long-term evolution (LTE).

1.1 Problem and Solution

MIMO technology exploits the spatial components of the wireless channel to improve throughput and bit error rate (BER) performance of communications systems, through multiplexing or diversity transmission techniques. In future cellular mobile networks, supporting spatial multiplexing [6], the mobile station can receive sub-streams from multiple transmit antennas on one or more base stations. When the base station uses spatial multiplexing in MIMO OFDM system, the total transmit power of the base station is split uniformly across transmit antennas. Increasing the number of transmit antennas leads to lower signal to interference-and-noise ratio (SINR) per degree of freedom. Additionally, the capacity decreases seriously at the cell boundary. Thus, SM technique will decrease the cell coverage in this kind of MIMO OFDM systems [7]. In order to provide radio services to mobile station, the telecommunications operators need to set up more base stations for covering the service areas. This leads to raise the base station equipment cost of the operators and increases the handover frequency. In the hard handover case, it increases the probability of service disruption and ping-pong effect [8]. Soft handover can improve this drawback of hard handover.

Besides, the increase in throughput using spatial multiplexing relies on the independence of the channels from a transmitter to a receiver. If we consider the spatially correlated channel, the impacts of spatial correlation on spatial multiplexing can be dramatic [9]. Spatial correlation at the transmitter increases the linear dependence of the input streams response, which makes stream separation and decoding processes more difficult.

Through spatial multiplexing, the MIMO OFDM cellular mobile network can provide a huge increase in throughput for the mobile station close to the serving base station, but it is quite difficult to improve or maintain the throughput of mobile station at the cell boundary, especially in spatially-correlated channels. The performance of spatial multiplexing degrades seriously. In order to overcome the drawbacks of spatial multiplexing, we provide a simple and effective method to increase the SINR by applying transmit diversity techniques at the adjacent base station sides instead of the transmitters of each base station. When the mobile station moves near the serving base station, the huge throughput is provided by the serving base station using SM. When the mobile station moves near the cell boundary, the throughput is improved by applying transmit diversity techniques with the cooperation of the adjacent base stations.

1.2 Challenges

In order to provide required data throughput of mobile station around the cell edge, the serving base station performs spatial multiplexing to offer more capacity for the nearby mobile station. Due to path loss and spatial correlation, the SINR decreases seriously as the distance from the serving base station. Around the cell edge, the throughput performance of spatial multiplexing is even worse than spatial diversity, because SM needs high SINR for reliable detection. Both [10] [11] have shown that space-time block code achieves higher capacity and throughput than spatial multiplexing at low SINR, especially when there is non-trivial spatial correlation among the transmit antennas. The capacity of spatial multiplexing decreases significantly at low SINR. Because the total transmit power is limited for each base station in a cellular network to avoid interference to other cells and system constrains, increasing the transmit power is not a reasonable and efficient method to overcome this difficulty. We need to find another method suitable for a cellular system to increase the SINR of mobile station around cell edge. To increase spatial diversity and maintain the number of transmit antennas of a base station, we can apply transmit diversity scheme at the adjacent base station sides. When a mobile station moves to cell boundary, the adjacent base station cooperates with the serving base station to transmit the same signals, and the mobile station combines the received signals to get the spatial diversity for increasing SINR. The required data throughput of the mobile station can be achieved and the problem of cell coverage reduced due to SM is solved.

In this thesis, we introduce two kinds of macro-diversity combining schemes for spatial multiplexing based MIMO OFDM cellular mobile networks to increase throughput at the cell boundary. One is the space-frequency block code macro-diversity combining with spatial multiplexing scheme and the other is cyclic delay macro-diversity combining with spatial multiplexing scheme, these two schemes are investigated under a more realistic channel model in which spatial correlation due to insufficient antenna separation at the transmitters of each base station and the lack of scatter effects of the channel. Through a system performance analysis approach, we compare the performances of the two different macro-diversity combining schemes and their improvements, which are evaluated in terms of the distance from the desired base station versus throughput.

1.3 Thesis Outline

The rest of this thesis is organized as follows. Chapter 2 introduces the backgrounds of macro-diversity applications in CDMA and OFDM systems and transmit macro-diversity techniques for MIMO OFDM cellular mobile networks. Chapter 3 shows the system model of macro-diversity scheme for MIMO OFDM cellular network. The effects of spatial correlation are considered by applying spatially-correlated Rayleigh MIMO channel. The Exponential Effective SNR Mapping (EESM) method is introduced for system level evaluation to simplify simulation complexity. In Chapter 4, we analyze the SFBC macro-diversity combining with SM scheme and discuss the simulation results. In Chapter 5, we analyze CDD macro-diversity combining with SM scheme and discuss the simulation results compared with SFBC macro-diversity combining with SM scheme. Conclusions are given in Chapter 6.

CHAPTER 2

Background

In this chapter, we discuss the macro-diversity applications in code division multiple access (CDMA) [12] and OFDM [13] systems and the differences between them. Then, we introduce the transmit diversity techniques in OFDM-based systems. The transmit diversity techniques are applied at the adjacent base station sides and the receiver of mobile station performs macro-diversity combining in MIMO OFDM cellular mobile network.

2.1 Macro-Diversity Applications in CDMA and OFDM Systems

In CDMA systems, macro-diversity is provided for the downlink in a soft handover case. Diversity gain is achieved by using Rake receiver with maximal-ratio combining (MRC) at mobile station. Rake receiver can combine the multi-path signals, which is the time-delayed versions of the original signal. When the one of Rake receiver fingers in the user is receiving signal from one base station, and another might be receiving signal from another base station, the Rake receiver performs maximal-ratio combining to get the diversity gain [14] .

For OFDM systems, there are two types of soft handover defined in IEEE 802.16e [15]: Fast Base Station Switching (FBSS) and Macro Diversity Handover (MDHO). Their initiation criteria are assumed by the IEEE 802.16 management messages. one is channel quality indicators, such as CINR (Carrier to Interference Noise Ratio) or the signal strength. Another is QoS characterized by service level prediction, or other criteria such as the bit error rate(BER) [13]. Mobile station and base stations maintain the list of base stations involved in the handover (HO) procedure, which is called diversity set. There are two threshold defined: Add Threshold (ADD_T) and Delete Threshold (Delete_T) as Fig. 2.1. While the Add Threshold is used to decide the absolute CINR level for adding base station into the diversity set, and the Delete Threshold is used to decide the absolute CINR level for removing base station into the diversity set. When one of these threshold is met by the adjacent base station, the HO procedure is started. For downlink, in case of FBSS, the mobile station communicates only with so called anchor base station from the diversity set, which the mobile station is currently synchronized and registered. mobile station performs ranging with anchor base station and monitors the downlink channel for control information. The anchor base station can be switched among all base stations in the Diversity set on frame by frame basis. It reduces the HO procedure for switching of anchor base stations, In case of MDHO, the mobile station communicates with all base stations in the diversity set, and all base stations transmit the same data to the mobile station such that the mobile station can perform the diversity combining. Because FBSS mobiles does not perform diversity combining, we focus on MDHO case which can provide diversity gain to improve the performance at the cell boundary.

2.2 Transmit Macro-Diversity Techniques for MIMO OFDM Cellular Mobile Networks

Open loop transmit diversity techniques are used to realize the reliability benefits of multi-antenna systems in flat fading environment without channel state information (CSI) available at the transmitter side. They transmit multiple signals conveying the same information

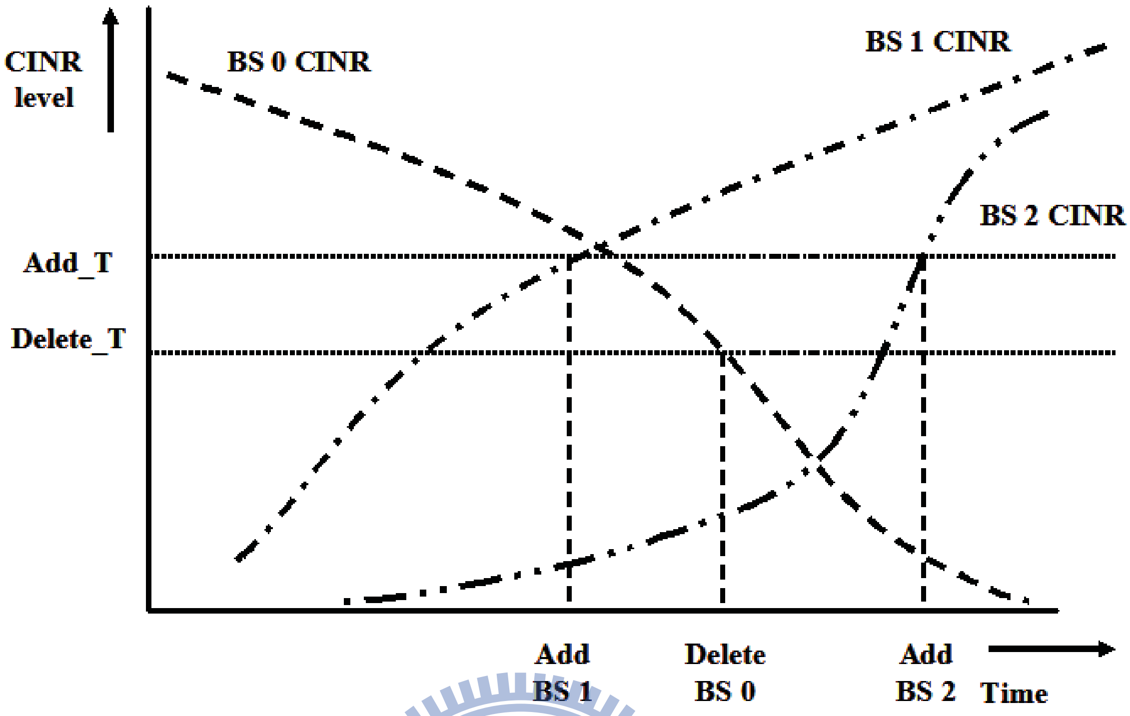

Figure 2.1: Principle of HO initialization in MDHO and FBSS. Black arrows present the time instance of initialization of HO.

over different spatial channels. Alamouti space-frequency block code (SFBC) [16] and cyclic delay diversity (CDD) [17] are widely used for 2-transmit antenna diversity systems. Here we apply the two transmit diversity techniques at the adjacent base stations side instead of multiple antennas for one base station to perform transmit macro-diversity in OFDM-based system, and the receiver of the mobile station can get the spatial diversity gain to improve SINR for better performance.

2.2.1 Space-Frequency Block Code

The signals of SFBC are encoded into multiple sets of orthogonal signals in the frequency domain for the transmit antennas, and superimposed in the receiving antennas. After receiver decodes signals from channels with different frequencies, they are combined to reconstruct the original signals. Because OFDM can convert the frequency selective channel to a set of flat sub-channels, SFBC schemes can be extended to frequency selective channel in OFDM systems.

In Alamouti SFBC scheme, two consecutive signals are encoded for two transmit antennas. Let the two consecutive signals in frequency domain be $X_1(m)$ and $X_2(m)$. They are coded as Table 2.1.

Table 2.1: Alamouti Scheme Table

OFDM sub-carrier index	Transmit antenna 1	Transmit antenna 2
i^{th} sub-carrier	$X_1(m)$	$X_2(m)$
$(i+1)^{th}$ sub-carrier	$-X_2(m)^*$	$X_1(m)^*$

2.2.2 Cyclic Delay Diversity

CDD is a simple approach to introduce spatial diversity in an OFDM based transmission that itself has no built-in diversity and can be applied at the transmitter or receiver [18]. The signal is not truly delayed, but cyclic shifted between the respective antennas. It actually provides virtual echos and thus increases the frequency selectivity of the channel seen by the receiver. When CDD inserts the delays in time domain, it appears as different phase angles in different sub-carriers in frequency domain after FFT. For M_t transmit antennas the transmitted signal is given by

$$x(t)^{CDD} = \frac{1}{\sqrt{M_t}} \sum_{i=1}^{M_t} x\left(t - \tau_i\right), \tag{2.1}$$

where $x(t)$ is the original signal, τ_i is the cyclic delay at the i^{th} transmit antenna, and N_{FFT} is the FFT size. The frequency domain representation of the signal with cyclically shifted is given by,

$$Y^{CDD}(f) = \frac{1}{\sqrt{M_t}} \sum_{i=1}^{M_t} H_i(f) X(f) e^{\frac{-j2\pi f \tau_i}{N_{FFT}}} + N_0 \, . \tag{2.2}$$

where $H_i(f)$ is channel response and N_0 is AWGN. The composie channel response $H^{CDD}(f)$ can be modified as

$$H^{CDD}(f) = \frac{1}{\sqrt{M_t}} \sum_{i=1}^{M_t} H_i(f) e^{\frac{-j2\pi f \tau_i}{N_{FFT}}} \, , \tag{2.3}$$

and (2.2) becomes

$$Y^{CDD}(f) = H^{CDD}(f) X(f) + N_0 \, . \tag{2.4}$$

2.2.3 Comparsion

SFBC is easy to encode at the transmitter side and decode at the receiver side while still achieving the optimal diversity gain in 2x1 Rayleigh fading channels. Hence, SFBC is very suitable to increase spatial diversity at the adjacent base stations performing cooperation. In most cases, SFBC outperforms CDD. But the main advantage of CDD remains in its structural simplicity and much lower complexity compared to SFBC. When the number of transmit antennas is large than two, no orthogonal schemes of SFBC have been found achieving the full rate [4]. CDD can be designed for arbitrary number of transmit antennas. However, block-error rate (BLER) performance of CDD is worse than SFBC. Besides, CDD has some drawbacks such as frequency-selective nulls [19] in spatially-correlated channels. It means CDD can not achieve the same diversity gain as obtained in antenna-uncorrelated channels [20]. Fortunately, the distance between the adjacent base stations is far enough, we can apply CDD at the adjacent base stations free from spatial correlation effects and get the diversity gain.

2.3 Literature Survey

In the literature, the bit error rate (BER) performance and throughput of the mobile station nearby the cell boundary are studied in some depth. The work in [21] only investigated the BER improvement of a CDMA cell system. That applied space-time block code (STBC) between the base stations and considers the inter-cell-interference (ICI) in each cell. In [22], the BER performance of OFDM cellular network was investigated, CDD was applied between the adjacent base stations to improve BER of mobile station at the cell boundary. Both [21] and [22] consider the case that each base station is equipped a single antenna without the implementation of MIMO techniques. Hence, the throughput of mobile stations can not be improved greatly. In [23], the throughput improvement for the distributed MIMO OFDM system was investigated. Each cell is divided to two parts: an inner cell area and an outer cell area. Depending on whether the mobile station is in the inner cell or outer cell, the system selects either a localized or distributed antenna configuration based on SNR measurement. It assumed that each base station is equipped two antennas and uses STBC in the serving base station or between the adjacent base stations according the location of mobile station. Different from [21]- [23], this paper developed the macro-diversity combining for MIMO OFDM cellular mobile networks with SM. The serving base station applying SM can offer huge throughput for the nearby mobile station. We adopt transmit macro-diversity techniques at the adjacent base stations side to increasing SINR of mobile station around cell edge and overcome the drawback of SM. In addition, the impacts of spatial correlation were investigated. The related literature survey is summarized in Table 2.2. It is shown that none of existing work has considered the OFDM-based SFBC or CDD macro-diversity in SM MIMO systems.

Table 2.2: Comparison of Recent Research Works

	CDMA / OFDM system	Macro-Diversity method	MIMO in single base station	The impact of spatial correlation
[Fujii, 05] [21]	CDMA	STBC	X	X
[Dammann ,07] [22]	OFDM	CDD	X	X
[Zhou, 06] [23]	OFDM	STBC	STBC	X
Our work	OFDM	SFBC and CDD	SM	O

CHAPTER 3

System Model and Problem Formulation

In this chapter, we consider the MIMO OFDM cellular system in the downlink case. In the distributed macro-diversity scheme, cooperation among base stations is very important. Hence, the system must have a base station controller, which implements functions such as power control, system synchronization and radio resource allocation, etc.

When a mobile station moves nearby the cell boundary of the serving base station, the adjacent base stations transmit the same signals at the same time and over the same frequency to the mobile station due to the MDHO procedure started. It can be regard as a Dynamic Single Frequency Networks (DSFN) [24]. Consider a mobile station in the target Cell 0. Each base station and mobile station are equipped with multi antennas as depicted in Fig. 3.1. There are M_t transmit antennas at each base station and M_r receive antennas at a mobile station. The mobile station in the cell receives the desired signals form its serving base station and the adjacent base station. Here we consider the impacts of path-loss, multi-path fading channel and spatially-correlated Rayleigh Channel as follows.

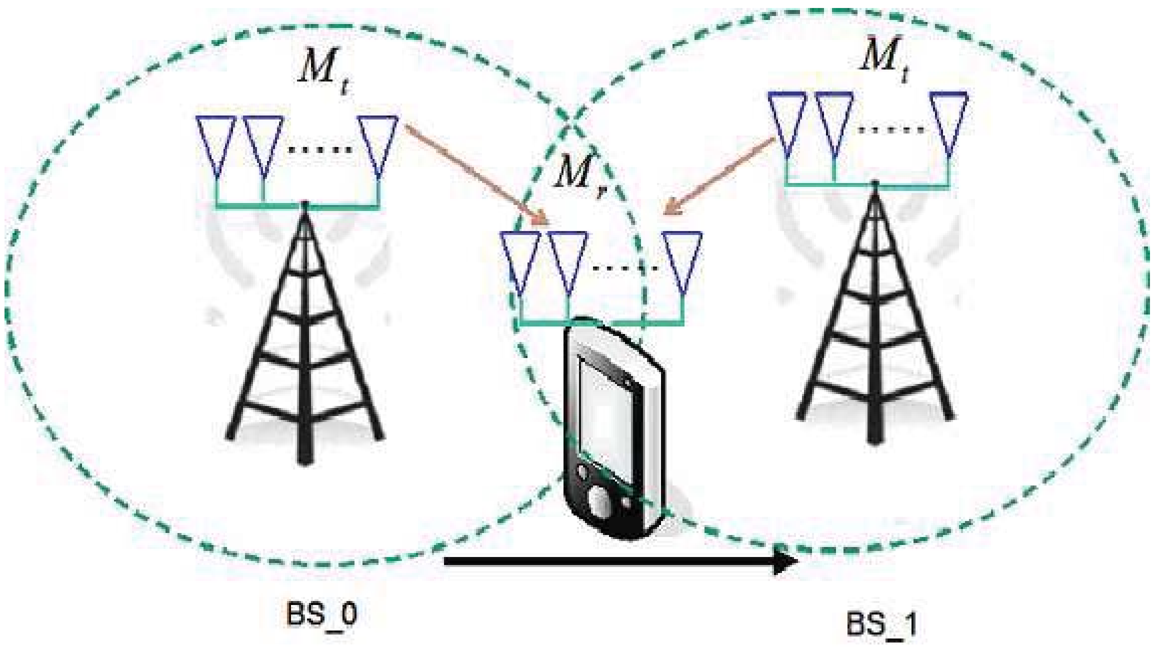

Figure 3.1: The System Model of Macro-Diversity Combining for MIMO OFDM Cellular Mobile Network in The Downlink Case.

3.1 Propagation Model

3.1.1 Path Loss

To begin with, let P_T is the total transmit power of each base station. Then the received signal after path loss becomes

$$P_b = \frac{P_T/M_t}{L(d_b)} \quad , \tag{3.1}$$

where $L(d_b)$ is the path loss and d_b is the distance from the b-th base station to the receiver of mobile station. In the following simulations, we will adopt the path loss model defined in [25] as

$$L(d_b) = 130.62 + 37.6 \log(d_b) \ . \tag{3.2}$$

3.1.2 Multi-Path Fading Channel Model

Table 3.1 shows that multi-path fading channel model described as ITU Pedestrian-B channel [25], which defines six multi-path delays and power profiles with a velocity of 3 km/hr of the mobile station.

Table 3.1: Multi-Path Delay and Power Profile of The ITU PEDESTRIAN B Channel Model

Number of Paths	Power of the each path (dB)	Path Delay (ns)
1	0	0
2	-0.9	200
3	-4.9	800
4	-8	1200
5	-7.8	2300
6	-23.9	3700

3.1.3 Spatially-Correlated Rayleigh MIMO Channel

In the real-world wireless channel, spatial correlation can occur at a base station or a mobile station due to insufficient antenna separation and scattering environment. Correlation results in diversity loss and performance degradation. In this paper, a downlink case in the MIMO OFDM system is considered. Spatially-correlated Rayleigh MIMO channel is constructed by using the Jakes fading model [26] widely adopted [20] [27]. The simple model can illustrate clearly the impacts of spatial correlation in relative performance. In the following N_t and N_r are denoted as the number of transmit and receive antennas, and H is the N_r x N_t transfer function of the MIMO channel. Thus, we have

$$H_c = R^{1/2} H S^{1/2} \,, \tag{3.3}$$

where $H \in C^{N_r x N_t}$ contains independent entries and distribution is $CN(0,1)$, and S and R denote the transmit and receive spatial correlation matrices. We use the exponential correlation model at the transmitter and receiver: $R_{i.j} = \rho_{rx}^{|i-j|}$, $S_{i.j} = \rho_{tx}^{|i-j|}$. ρ_{rx} and ρ_{tx} are the receive and transmit spatial correlation coefficients between adjacent antennas.

3.2 OFDM Signal Model

OFDM is a multiplexing technique that subdivides the bandwidth into multiple frequency sub-carriers as Fig. 3.2. The input stream is divided into several sub-streams to reduce data rates and each sub-stream is modulated and transmitted on a separate orthogonal sub-carrier. The symbol duration is increased by reducing data rates. OFDM is more robust to the delay spread, and the introduction of cyclic prefix (CP) can preserves the orthogonality of the sub-carriers and completely avoid the Inter-Symbol Interference (ISI) when the CP duration is longer than the channel delay spread, the equalization at the receiver is low-complexity. In this system model, there are the propagation delays for those signals. A simple FFT window is utilized such that the first signal received from the serving base station (BS 0) is used as the reference signal. All signals from the adjacent base stations will arrive later, and the signals from the adjacent base stations will align to the first received signal.

For k^{th} sub-carrier, the received signal $R(k)$ at the location between the serving base station and the adjacent base stations is

$$\begin{aligned} R(k) &= \sum_{b=0}^{N_{BS}} \sqrt{P_b} \begin{bmatrix} H_{1,1}^b(k) & \cdots & H_{1,M_t}^b(k) \\ \vdots & \cdots & \vdots \\ H_{M_r,1}^b(k) & \cdots & H_{M_r,M_t}^b(k) \end{bmatrix} \begin{bmatrix} S_1^b(k) \\ S_2^b(k) \\ \vdots \\ S_{M_t}^b(k) \end{bmatrix} + \begin{bmatrix} N_1^b(k) \\ N_2^b(k) \\ \vdots \\ N_{M_t}^b(k) \end{bmatrix} \\ &= H^e(k) S^b(k) + N_0(k) \, , \end{aligned} \tag{3.4}$$

where $N_{BS} + 1$ is the number of effective base stations, $R(k)$ is a received vector, $H_{j,i}^b$ is the channel frequency response from the i^{th} transmit antenna of the b-th base station to the

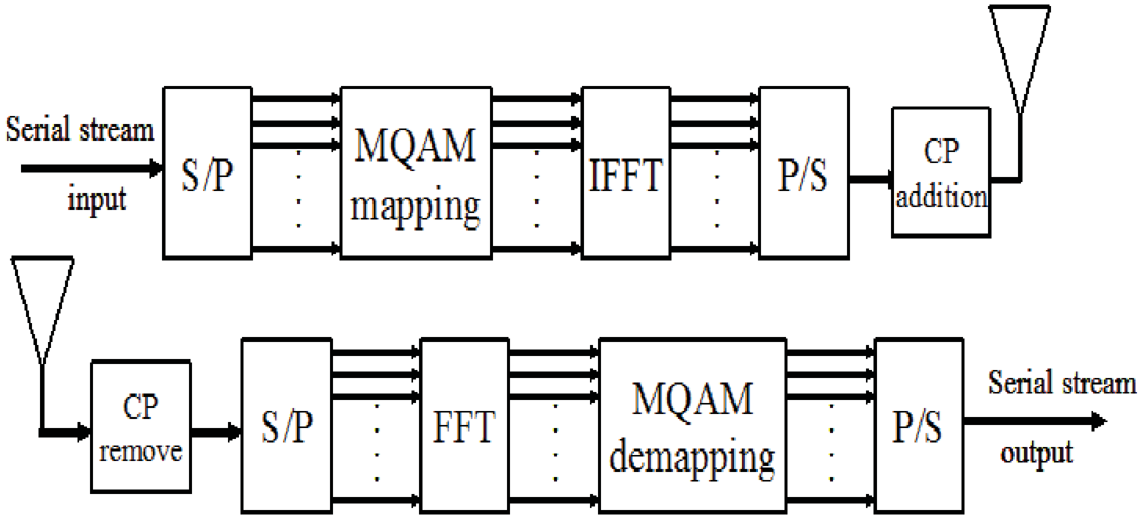

Figure 3.2: Block Diagram of a Conventional OFDM System Model.

j^{th} receiver of mobile station and BS 0 is the serving base station, S^b is the signal vector of the b^{th} base station, N_0 is AWGN of variance, and P_b is the received power from the b^{th} base station represented as (3.1).

3.2.1 Signal to Interference-and-Noise Ratio

The composite channel frequency response $H^e(k)$ can also be represented as the Fourier transform of composite channel impulse response

$$h^e(t) = \sum_{p=0}^{P-1} \sum_{j}^{M_r} \sum_{i}^{M_t} h_{j,i}^p \delta(t - \tau_p) \ , \tag{3.5}$$

where P is total number of paths from different base station, $h_{j,i}^p$ and τ_p are the complex path-gain and non-negative path-delay associated with the p^{th} path, respectively. Those paths with τ_p lying beyond guard interval will cause ISI. Let $w(t)$ be a tapered window defined as

$$w(t) = \begin{cases} 1 & 0 \leq t < T_g \\ \frac{T_s-(t-T_g)}{T_s} & T_g \leq t < T_s + T_g \\ 0 & t \geq T_s + T_g \end{cases} \tag{3.6}$$

where T_s and T_g is the symbol duration and guard interval in OFDM systems, respectively.

Then the expression for SINR at k^{th}sub-carrier can be expressed as

$$\gamma(k) = \frac{|H^e(k)|^2}{P_i + \frac{N_0}{E_s}}, \tag{3.7}$$

where

$$H^e(k) = \Im\left(w(t)h^e(t)\right) \tag{3.8}$$

and

$$P_i = \sum_{p=1}^{P}\sum_{j}^{M_r}\sum_{i}^{M_t}\left(1 - w^2(\tau_p)\right)\left|h^p_{j,i}\right|^2 \tag{3.9}$$

is the ISI caused by paths arriving late and E_s is the transmit energy per QAM symbol. The ISI impact is avoided by CP design of the OFDM system if it can be assured that all multi-path signals of the target mobile station arrive within the guard interval. For simplicity, P_i is ignored in the following calculation of the distributed macro-diversity schemes.

3.2.2 Exponential Effective SINR Mapping (EESM)

EESM is an effective method in predicting link-level performance in a system level simulations [28] [29], and can be generalized to the multi-state channel with different SINR values at each sub-carrier or each symbol transmission time interval (TTI). EESM maps power level and modulation coding schemes (MCS) level to SINR values in AWGN channel domain, which allows using this mapping along with AWGN assumptions in order to predict the effects of MCS. When only the influence of channel frequency selectivity is considered, the equation of EESM is given by [30]

$$r_{eff} = EESM(r, \beta) = -\beta \ln \left(\frac{1}{N} \sum_{i=1}^{N} e^{-\frac{r_i}{\beta}} \right) \quad , \tag{3.10}$$

where γ is vector $[r_1, r_2, ...r_N]$ of the per-tone SINR values, r_{eff} is the effective SINR mapping, while β is a parameter dependent on the adopted MCS.

When doing system level simulations, we no longer worry the perfect channel condition at the link level. It is only necessary to know AWGN performance of different modulation and coding rates and their corresponding factors β. For our simulations, a set of β calibrated for link-level interface in the IEEE 802.16e (WiMAX) is adopted and listed in Table 3.2 [25]. Therefore, interface from link level to system level simulation will be greatly simplified. Once the SINR at a given location is calculated as described above, spectral efficiency (SE) can be obtained for a dedicated MCS and throughput is directly related to the corresponding spectral efficiency (SE). Then the system performance can be measured by using the EESM method.

3.3 Problem Formulation

In future cellular networks, base stations will be equipped with multi-antenna and adopt MIMO techniques to provide higher data throughput and link reliability for better services or new applications. By using spatial multiplexing (SM), base stations can offer huge throughput for mobile station at neighboring area. The total transmit power of the base station is split uniformly across transmit antennas, and it leads to lower SINR. Since SM needs high SINR for reliable detection, the throughput of mobile stations around cell edge decreases seriously, it is even worse than using spatial diversity (SD). Hence, the cell coverage of the serving base station is reduced. To cover the service area, the telecommunications operators need to set up more base stations, this causes higher equipment cost and increases the handover frequency of mobile station due to smaller cell size. In reality,

Table 3.2: Reference EESM β Values for ITU Pedestrian B Channel

Modulation	Code Rate (Repetition: default=1)	Spectrum Efficiency σ (bit/s/Hz)	Minimum SINR	EESM factor β
QPSK	1/2(4)	0.25	-2.5 dB	2.18
QPSK	1/2(2)	0.5	0.5 dB	2.28
QPSK	1/2	1	3.5 dB	2.46
QPSK	3/4	1.5	6.5 dB	2.56
16-QAM	1/2	2	9 dB	7.45
16-QAM	3/4	3	12.5 dB	8.93
64-QAM	1/2	3	14.5 dB	11.31
64-QAM	2/3	4	16.5 dB	13.8
64-QAM	3/4	4.5	18.5 dB	14.71

spatial correlation can occur at a base station or mobile stations due to insufficient separation and scattering environment, and the correlation causes diversity loss and performance degradation. For SM especially, the increased throughput depends upon the fact that the channels from a transmitter to a receiver follow independent paths. Increasing the linear dependence of the input streams response make it more difficult to separate streams and decode signals. The impacts of spatial correlation in SM MIMO systems is more dramatic than that in SD MIMO systems.

In this thesis, we want to get the multiplexing gain of SM and improve the performance around the cell edge. Due to the limitation of transmit power for avoiding interference and system constrains, increasing transmit power or transmit antennas is not a feasible way to overcome this problem. Therefore, we purpose to apply transmit diversity at the base stations sides for increasing SINR of mobile station at the cell area. With MDHO, when the mobile station moves around the cell edge, the adjacent base stations in diversity set are synchronized to transmit the same signals at the same time over the same frequency to mobile station, seen as a DSFN. SFBC and CDD techniques are adopted for transmit macro-diversity at the base station sides. Each base station performs SM and the impacts of spatial correlation are considered. The performances of the transmit macro-diversity combining with SM are investigated and discussed with simulation results.

CHAPTER 4

Space-Frequency Block Code Macro-Diversity Combining for MIMO OFDM Cellular Mobile Networks

Spatial multiplexing (SM) can be applied as a promising and powerful method to dramatically increase the system capacity. In a rich scattering environment, the independent spatial channels can be exploited to transmit multiple signals at the same time and frequency resulting in higher spectral efficiency. Due to path loss and spatial correlation, the SINR of mobile station degrades when it moves away from the serving base station, and thus decreasing throughput seriously. Spatial Diversity (SD) methods can be used to improve signal quality, which is more robust than SM for the spatially correlated channel. Alamouti transmission structure [16] can be applied in the space-time and space-frequency domain in OFDM systems. By using STBC and SFBC in OFDM cellular networks, the SINR can be increased at the receiver and cell coverage is extended. In contrast to this, using SM in the OFDM cellular networks reduces the cell coverage and needs high receive SINR for reliable detection. Thus it is required to combine the SM and SD MIMO techniques in the cellular network. Both spatial diversity and spatial multiplexing gains can be achieved at farther locations from the serving base station. Because the encoding of SFBC is done across the sub-carriers inside the OFDM symbol and STBC applies encoding across the OFDM symbol, there is an inherent processing delay unavoidable in STBC system. Delay spreads in frequency selective fading channels destroy the orthogonality of the receive signals [31]. Thus in OFDM systems the sub-carrier spacing is usually small and symbol time is long. Thus it is more reasonable to use SFBC instead of STBC in the OFDM cellular networks with moving mobiles. In this chapter, we introduce the space-frequency block code macro-diversity combining with spatial multiplexing scheme.

4.1 SFBC Macro-Diversity Scheme

In this section, we introduce the space-frequency block code macro-diversity combining to improve the throughput of the mobile station around cell edge with the cooperation of the adjacent suitable base stations. When the mobile station moves from the serving base station (BS 0) to the target base station (BS 1) as depicted in Fig. 3.1. When reaching the cell boundary, the mobile station receives the signals from two groups of antennas located at adjacent base stations by MDHO. The adjacent base stations transmit the same data encoded by SFBC at the same frequency as depicted in Fig. 4.1. The receiver of the mobile station can performs diversity combining to get the diversity gain. Hence we can increase the SINR of the mobile station around cell edge to provide higher throughput. At the receiver, each antenna receives the MIMO OFDM signals. The guard interval is removed and fast Fourier transform on each receive antenna is performed to get the output signals of OFDM demodulation.

4.2 SINR Performance

When applying SFBC among the adjacent base stations, each base station uses two transmit antennas to perform spatial multiplexing as depicted Fig. 4.2. For N used sub-carriers in the OFDM system, we denote those modulated symbols as s_m. Then, the sequences of s_m encoded by SFBC can be separated into two groups for each base station as vectors S^0 and

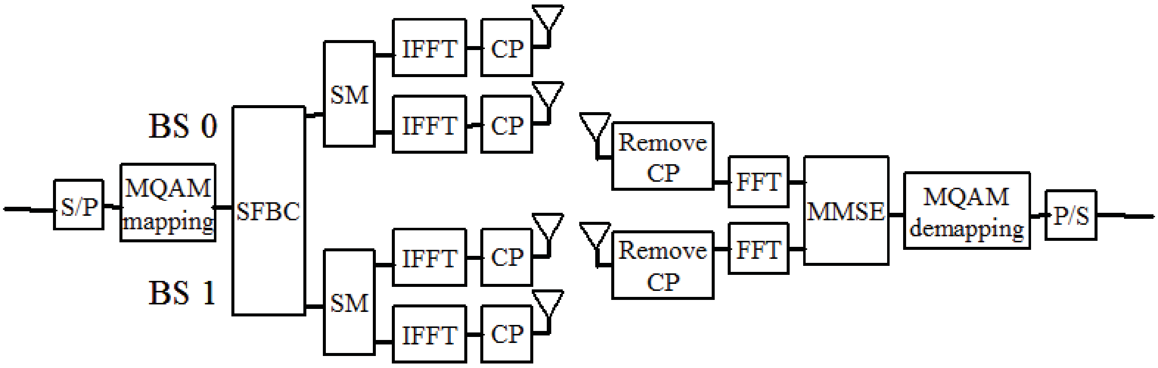

Figure 4.1: The Block Diagram of Space-Frequency Block Code Macro-Diversity Combining with Spatial Multiplexing Scheme.

S^1:

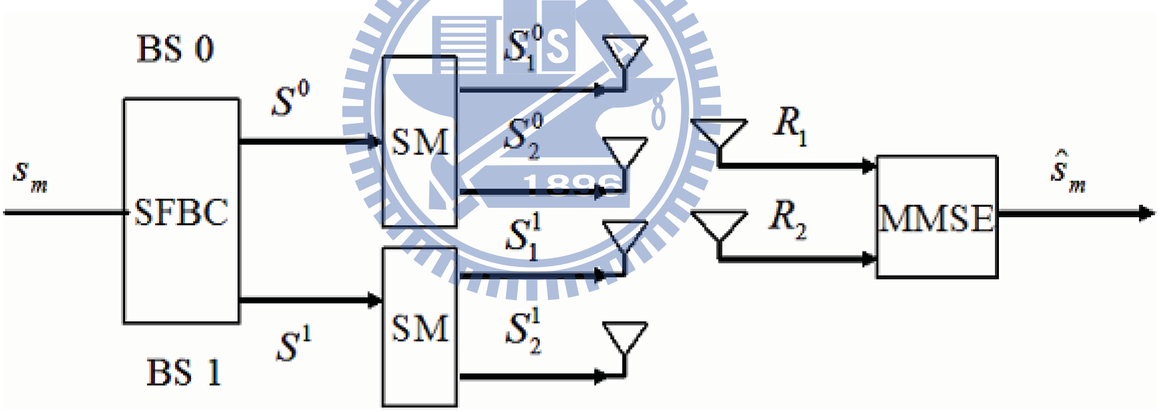

Figure 4.2: DSFBC-SM Simplified System Model

$$S^0 = \begin{bmatrix} s_1 & s_2 & -s_3^* & -s_4^* & s_5 & s_6 & -s_7^* & -s_8^* \ldots & s_{2N-3} & s_{2N-2} & -s_{2N-1}^* & -s_{2N}^* \end{bmatrix} ;$$
$$S^1 = \begin{bmatrix} s_3 & s_4 & s_1^* & s_2^* & s_7 & s_8 & s_5^* & s_6^* \ldots & s_{2N-1} & s_{2N} & s_{2N-3}^* & s_{2N-2}^* \end{bmatrix} .$$

For the next SM branches, S^0 is split into two vectors S_1^0 and S_2^0. Also, S^1 is split into two vectors S_1^1 and S_2^1 for the transmit antennas of each base station. Thus, the output signals of the SM modules become

$$S_1^0 = \left[s_1 \; - s_3^* \; s_5 \; - s_7^* ... \; s_{2N-3} \; - s_{2N-1}^*\right]$$
$$S_2^0 = \left[s_2 \; - s_4^* \; s_6 \; - s_8^* ... \; s_{2N-2} \; - s_{2N}^*\right]$$
$$S_1^1 = \left[s_3 \;\; s_1^* \; s_7 \;\; s_5^* ... \; s_{2N-1} \; s_{2N-3}^*\right]$$
$$S_2^1 = \left[s_4 \;\; s_2^* \; s_8 \;\; s_6^* ... \; s_{2N} \;\; s_{2N-2}^*\right] .$$

$$\begin{bmatrix} \mathrm{R}_1(2\mathrm{m}-1) \\ \mathrm{R}_1(2\mathrm{m})^* \\ \mathrm{R}_2(2\mathrm{m}-1) \\ \mathrm{R}_2(2\mathrm{m})^* \end{bmatrix} = \begin{bmatrix} \mathrm{H}_{11}^0(2\mathrm{m}-1) & \mathrm{H}_{12}^0(2\mathrm{m}-1) & \mathrm{H}_{11}^1(2\mathrm{m}-1) & \mathrm{H}_{12}^1(2\mathrm{m}-1) \\ \mathrm{H}_{11}^1(2\mathrm{m})^* & \mathrm{H}_{12}^1(2\mathrm{m})^* & -\mathrm{H}_{11}^0(2\mathrm{m})^* & -\mathrm{H}_{12}^0(2\mathrm{m})^* \\ \mathrm{H}_{21}^0(2\mathrm{m}-1) & \mathrm{H}_{22}^0(2\mathrm{m}-1) & \mathrm{H}_{21}^1(2\mathrm{m}-1) & \mathrm{H}_{22}^1(2\mathrm{m}-1) \\ \mathrm{H}_{21}^1(2\mathrm{m})^* & \mathrm{H}_{22}^1(2\mathrm{m})^* & -\mathrm{H}_{21}^0(2\mathrm{m})^* & -\mathrm{H}_{22}^0(2\mathrm{m})^* \end{bmatrix} \times$$

$$\begin{bmatrix} \mathrm{S}(4(\mathrm{m}-1)+1) \\ \mathrm{S}(4(\mathrm{m}-1)+2) \\ \mathrm{S}(4(\mathrm{m}-1)+3) \\ \mathrm{S}(4(\mathrm{m}-1)+4) \end{bmatrix} + \begin{bmatrix} \mathrm{n}_1(2\mathrm{m}-1) \\ \mathrm{n}_1(2\mathrm{m})^* \\ \mathrm{n}_2(2\mathrm{m}-1) \\ \mathrm{n}_2(2\mathrm{m})^* \end{bmatrix} . \tag{4.1}$$

In short, we can represent (4.1) as

$$R_{dsfbcsm}(m) = H_{dsfbcsm}(m) S_{dsfbcsm}(m) + N_{dsfbcsm}(m) \; , \tag{4.2}$$

$$R_{dsfbcsm}(m) = \begin{bmatrix} R_1(2m-1) \\ R_1(2m)^* \\ R_2(2m-1) \\ R_2(2m)^* \end{bmatrix} ,$$

$$H_{dsfbcsm}(m) = \begin{bmatrix} \mathrm{H}_{11}^0(2\mathrm{m}-1) & \mathrm{H}_{12}^0(2\mathrm{m}-1) & \mathrm{H}_{11}^1(2\mathrm{m}-1) & \mathrm{H}_{12}^1(2\mathrm{m}-1) \\ \mathrm{H}_{11}^1(2\mathrm{m})^* & \mathrm{H}_{12}^1(2\mathrm{m})^* & -\mathrm{H}_{11}^0(2\mathrm{m})^* & -\mathrm{H}_{12}^0(2\mathrm{m})^* \\ \mathrm{H}_{21}^0(2\mathrm{m}-1) & \mathrm{H}_{22}^0(2\mathrm{m}-1) & \mathrm{H}_{21}^1(2\mathrm{m}-1) & \mathrm{H}_{22}^1(2\mathrm{m}-1) \\ \mathrm{H}_{21}^1(2\mathrm{m})^* & \mathrm{H}_{22}^1(2\mathrm{m})^* & -\mathrm{H}_{21}^0(2\mathrm{m})^* & -\mathrm{H}_{22}^0(2\mathrm{m})^* \end{bmatrix} ,$$

and

$$S_{dsfbcsm}(m) = \begin{bmatrix} S(4(m-1)+1) \\ S(4(m-1)+2) \\ S(4(m-1)+3) \\ S(4(m-1)+4) \end{bmatrix}, \; N_{dsfbcsm}(m) = \begin{bmatrix} n_1(2m-1) \\ n_1(2m)^* \\ n_2(2m-1) \\ n_2(2m)^* \end{bmatrix}.$$

where $m = 1, 2, 3, ..., \frac{N}{2}$. In a linear MMSE receiver, the receive signal vector $\mathrm{R}_{dsfbcsm}(m)$ is multiplied with $G^{MMSE}(m)$. The MMSE detector minimizes the mean square error between the actually transmitted symbols and the output of the receiver, i.e.,

$$\hat{S}_{dsfbcsm}(m) = G^{MMSE}(m)\mathrm{R}_{dsfbcsm}(m) \tag{4.3}$$

and

$$G_e^{MMSE}(m) = (H^*_{dsfbcsm}(m)H_{dsfbcsm}(m) + (M_t\frac{N_0}{E_s})I_{2M_t})^{-1}H^*_{dsfbcsm}(m) \tag{4.4}$$

where H^* is the Hermitian transpose of H. The total power transmitted on M_t antennas at one symbol time is E_s at each base station. We extend SINR calculations in the narrow-band MIMO systems [32] to the SFBC combining with SM in OFDM system. Given the equivalent MIMO channel $H_{dsfbcsm}(m)$ the per-tone SINR calculation at the s^{th} sub-carrier is given by

$$SINR_s^{MMSE} = \frac{E_s}{M_tN_0\left[(H^*_{dsfbcsm}(m)H_{dsfbcsm}(m) + (M_t\frac{N_0}{E_s})I_{2M_t})^{-1}\right]_{s,s}} - 1\,. \tag{4.5}$$

After the SINR evaluation of MMSE detector, we can apply the EESM approximation method to get the effective SINR r_{eff} from (4.5) and then decide the MCS to the same block error rate (BLER) by a lookup table through an AWGN curves as Table 3.1. We can find the throughputs with the decided MCS of the SFBC macro-diversity combining with SM scheme.

4.3 Simulation Results

The system level performance of the SFBC macro-diversity combining with SM is investigated in this section. The parameter used in the simulation are listed in Table 4.1 [25]. When the mobile station moves from the serving base station (BS 0) to the adjacent base station (BS 1) as shown in Fig. 3.1, we calculate the throughputs under different spatial correlation at the transmitter of each base station and compare with the single base station using SM or SFBC. The separation of each base station is far enough to ignore the spatial correlation between the transmit antennas of BS 0 and BS 1.

This simulation is investigated to show the throughput gain by adopting SFBC macro-diversity combining with SM around cell edge compared with that of the conventional centralized MIMO-OFDM scheme and then reform the performance of MDHO. Perfect channel state information at receivers is assumed during the simulations.

Table 4.1: Simulation Parameters

Parameter	Value	Remark
Center frequency	2.5 GHz	
Channel bandwidth	10 MHz	
FFT size	1024	
Cyclic prefix ratio	1/8	
Guard sub-carriers (N_g)	159	Right : 80 , Left : 79
Used sub-carriers (N_u)	865	
Site-to-site distance	1.5 km	
Transmit power	37 dBm (5W)	
Path loss	130.62+37.6log(d)	d:km
Thermal noise density	-174 dBm	
Channel model	ITU Pedestrian B	

From Fig. 4.3, with spatial correlation at the transmitter $\rho_{tx} = 0.1$, it is observed that mobile station can get huge throughput close to the serving base station using SM, but the throughput decreases seriously with the distance from the serving base station. The throughput performance of SM reaches 1 bit/s/Hz around cell edge which is similar

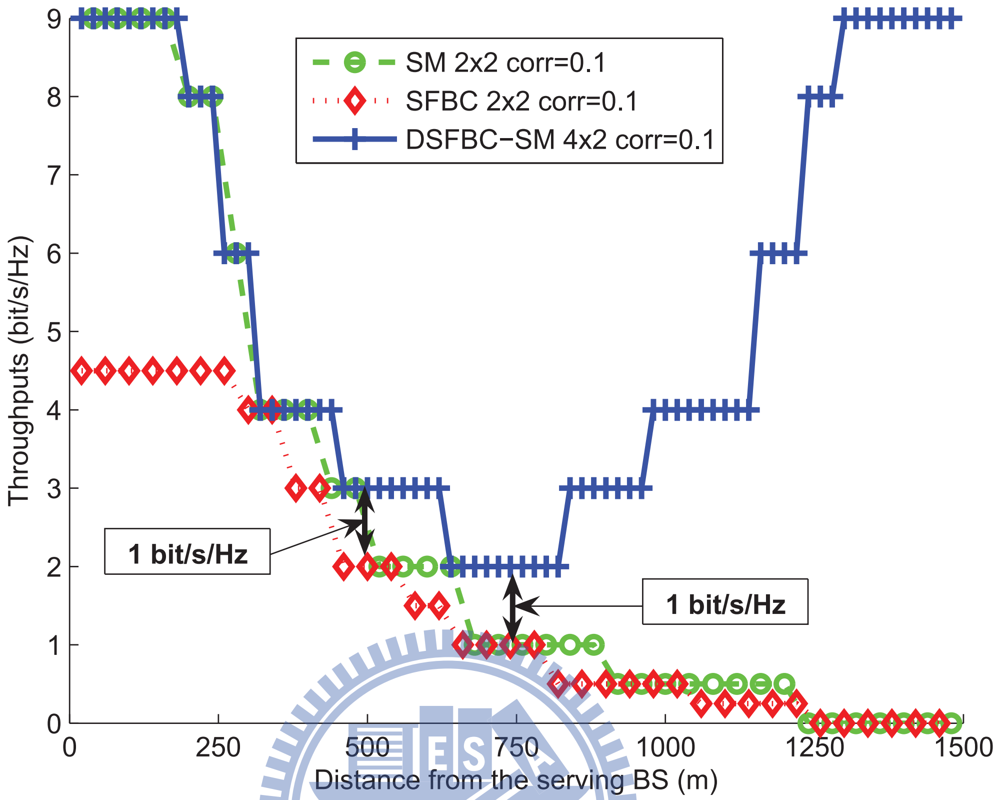

Figure 4.3: Throughputs of SM 2x2 , SFBC 2x2 and DSFBC-SM 4x2 with $\rho_{tx} = 0.1$ at each BS.

to SFBC. The poor throughput around the cell edge is improved obviously by applying distributed SFBC technique at the base station sides. Because of the equal receive signal strength from each base station, using transmit diversity at the base station sides increases SINR quite effectively around the cell edge, thereby allowing for choosing higher order MCS in Table II for higher spectrum efficiency. Therefore, the SFBC macro-diversity combining with SM scheme can overcome the drawbacks of the single base station using SM and maintain the large throughput for mobile station around cell edge. Even if the offered throughput satisfies the requirement of a mobile station, call-dropped frequency can be reduced at the cell boundary and the ping-pong effect [12] can be relieved. Here the ping-pong effect means that the mobile station handovers back and forth several times between the adjacent base stations. Hence, the handover performance in OFDM cellular network is also enhanced greatly.

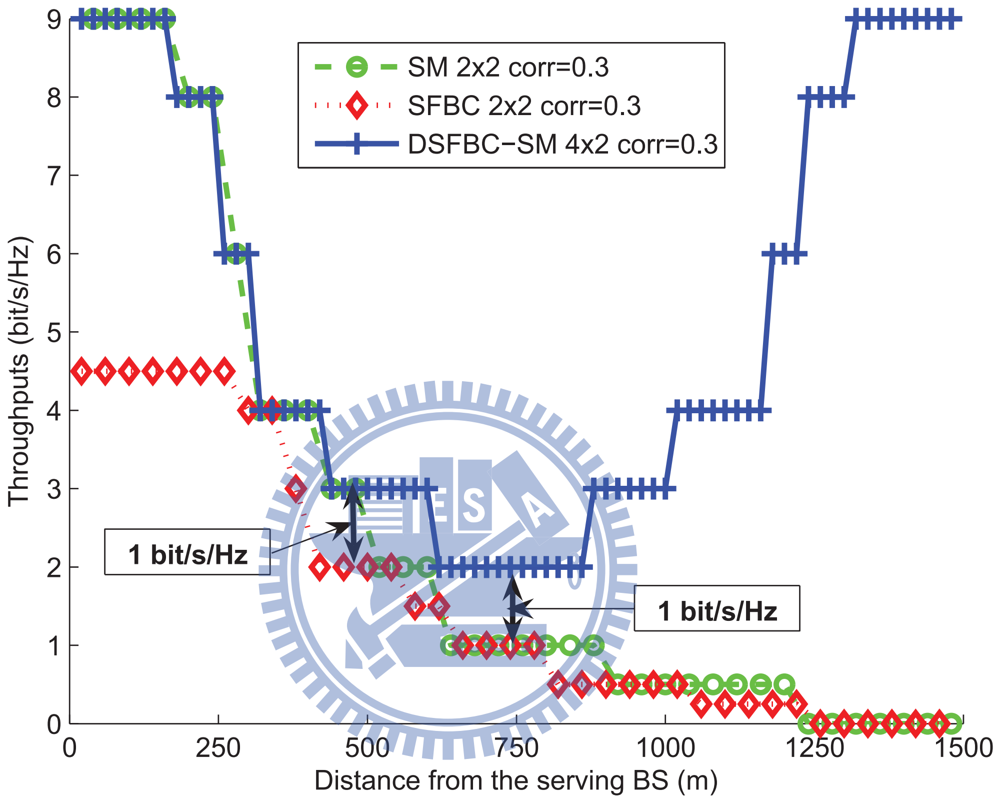

Figure 4.4: Throughputs of SM 2x2 , SFBC 2x2 and DSFBC-SM 4x2 with ρ_{tx} = 0.3 at each BS.

The effects of increasing the spatial correlation of each transmitters at each base station are showed in Figs. 4.4, 4.5, 4.6 and 4.7. In a rich spatially-correlated channel, the throughput of the single base station using SM is worse as [11] [33] [34] and is even lower than that using SFBC around the cell edge. The SFBC macro-diversity combining with SM

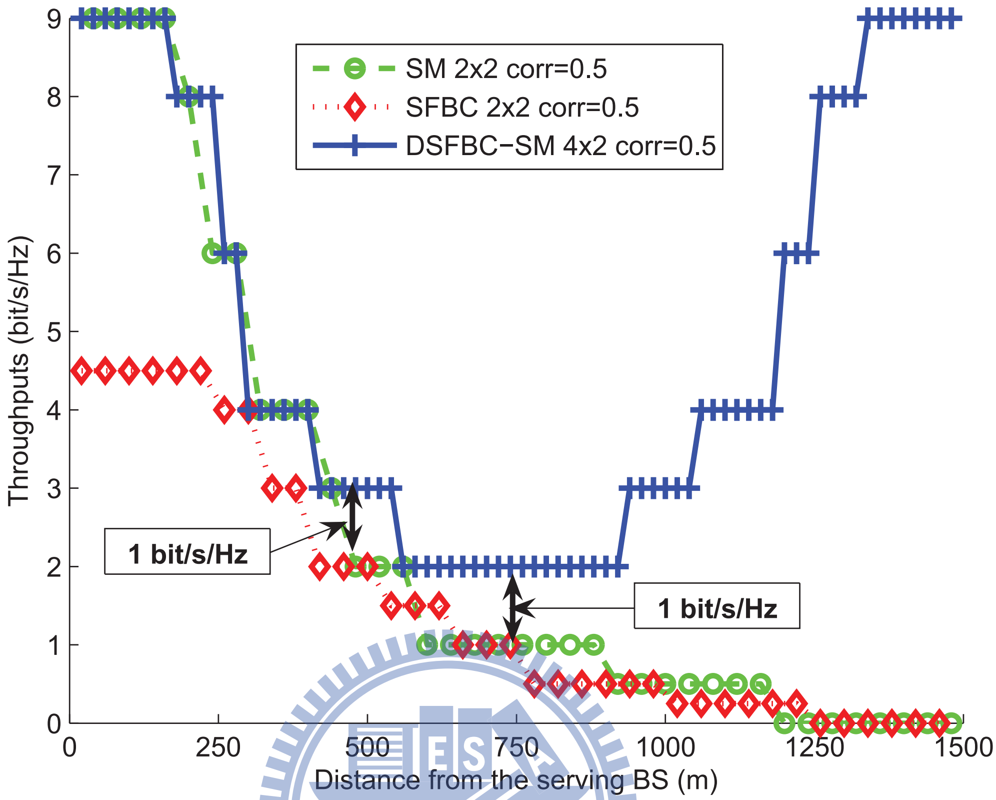

Figure 4.5: Throughputs of SM 2x2 , SFBC 2x2 and DSFBC-SM 4x2 with $\rho_{tx} = 0.5$ at each BS.

scheme can also provide higher throughput than the conventional SFBC and SM schemes with $\rho_{tx} = 0.7$. For $\rho_{tx} = 0.9$, the throughput of the SFBC macro-diversity combining with SM scheme is the same as that of the conventional SFBC scheme. It is evident that the performance of SFBC macro-diversity combining with SM scheme is more robust than the conventional SM scheme as spatial correlation increases.

When the distance between a mobile station and the serving base station is two thirds of the cell radius, Fig. 4.8 shows that SFBC macro-diversity combining with SM scheme can provide higher throughput than the conventional SM and SFBC schemes for

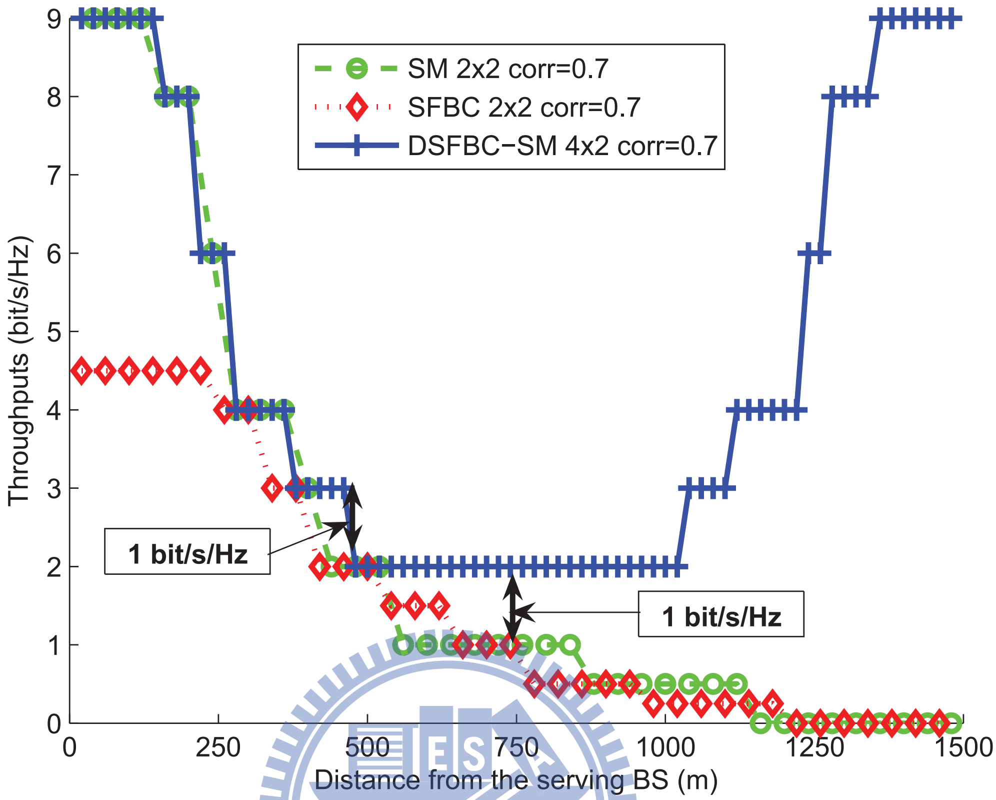

Figure 4.6: Throughputs of SM 2x2 , SFBC 2x2 and DSFBC-SM 4x2 with ρ_{tx} = 0.7 at each BS.

$\rho_{tx} \leq 0.7$. For $\rho_{tx} = 0.9$, the throughput of the conventional SFBC scheme is higher than SFBC macro-diversity combining with SM scheme and the conventional SM scheme. At the two thirds of the cell radius, the performance of SFBC macro-diversity combining with SM scheme is not effective due to the longer distance from the adjacent base station. Because of path loss, the received signal strength from the adjacent base station is decreased seriously. When the distance between a mobile station and the serving base station is a cell radius. Fig. 4.9 shows that the throughput is quickly getting worse for the conventional SM and SFBC schemes. However, the performance of SFBC macro-diversity combining

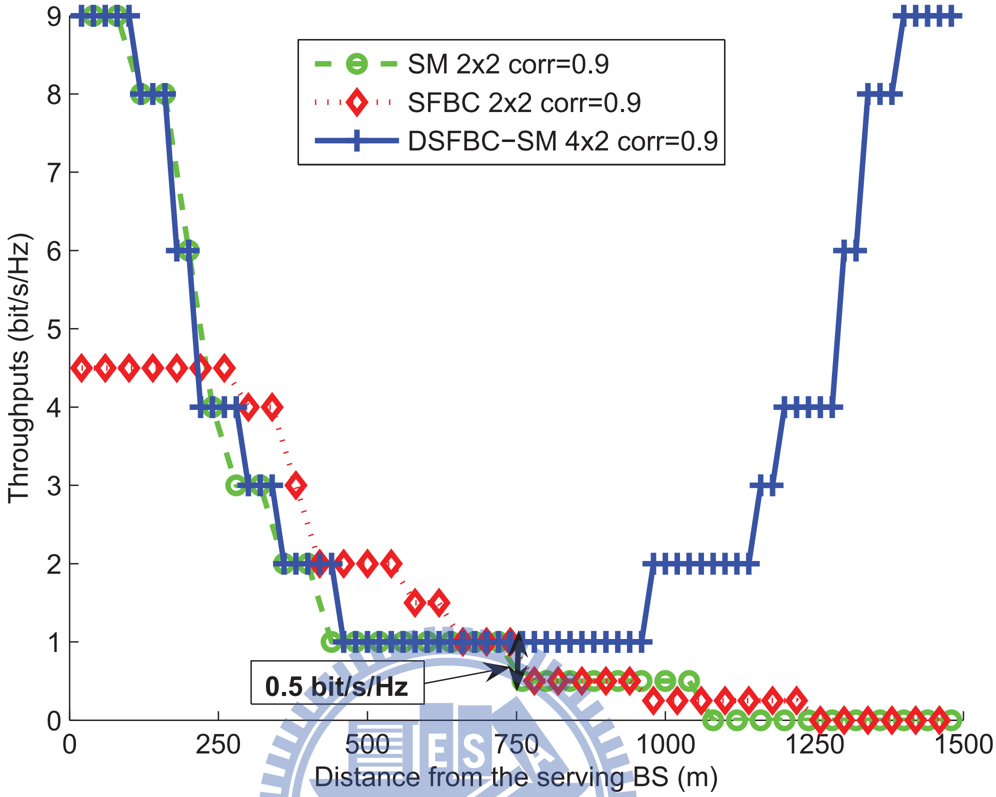

Figure 4.7: Throughputs of SM 2x2 , SFBC 2x2 and DSFBC-SM 4x2 with $\rho_{tx} = 0.9$ at each BS.

with SM scheme at the cell boundary is better than that at the two thirds of the cell radius. Because the distance from the serving base station is almost equal to the distance from the adjacent base station, the mobile station receives the equal signal strength from the two base stations. At the cell boundary, SFBC macro-diversity combining with SM scheme can offer higher throughputs than the conventional SM and SFBC schemes under different spatial correlations. Obviously the improvement of distributed SFBC is great,

In Table 4.2, we show increased throughputs of SFBC macro-diversity combining with SM scheme compared with the conventional SM scheme when a mobile station is at

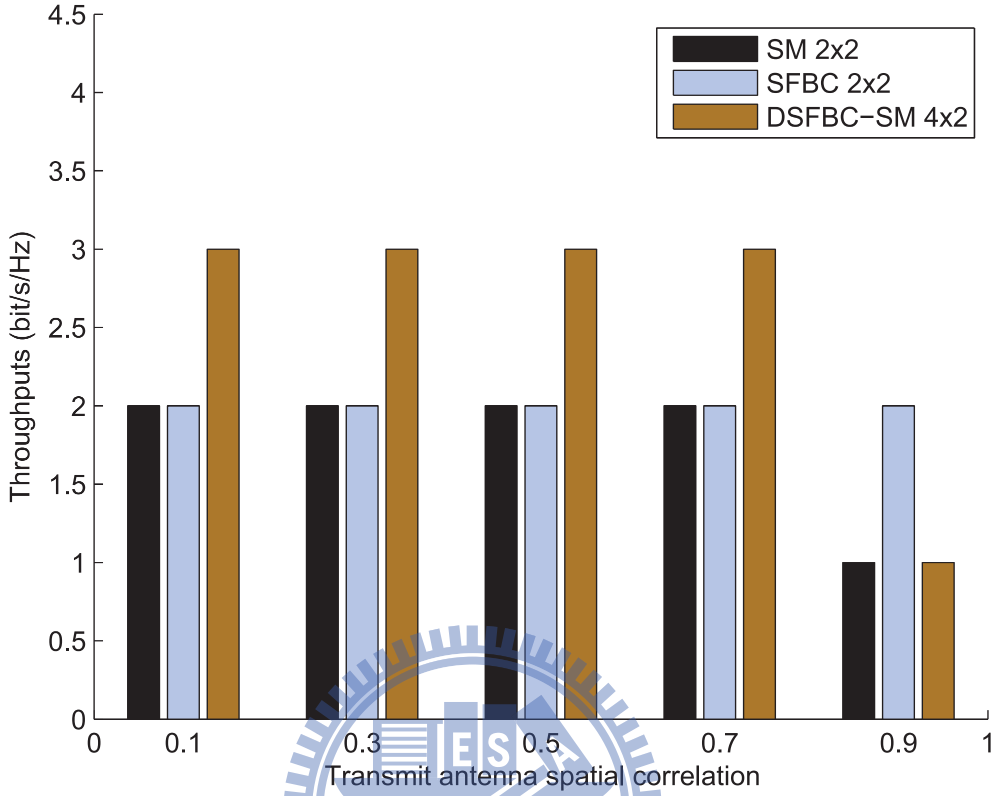

Figure 4.8: Throughputs of SM 2x2, SFBC 2x2 and DSFBC-SM 4x2 schemes for different ρ_{tx} with the distance from the serving BS equal to 500m (2Rc/3).

the two-thirds of the cell radius and a cell radius (Rc). It is shown that the improvements of throughput by SFBC macro-diversity combining with SM scheme is remarkable under spatially correlated channels. SFBC macro-diversity combining with SM scheme can offer higher data throughput for a mobile station at the cell boundary. Hence, the handover performance can be enhanced greatly.

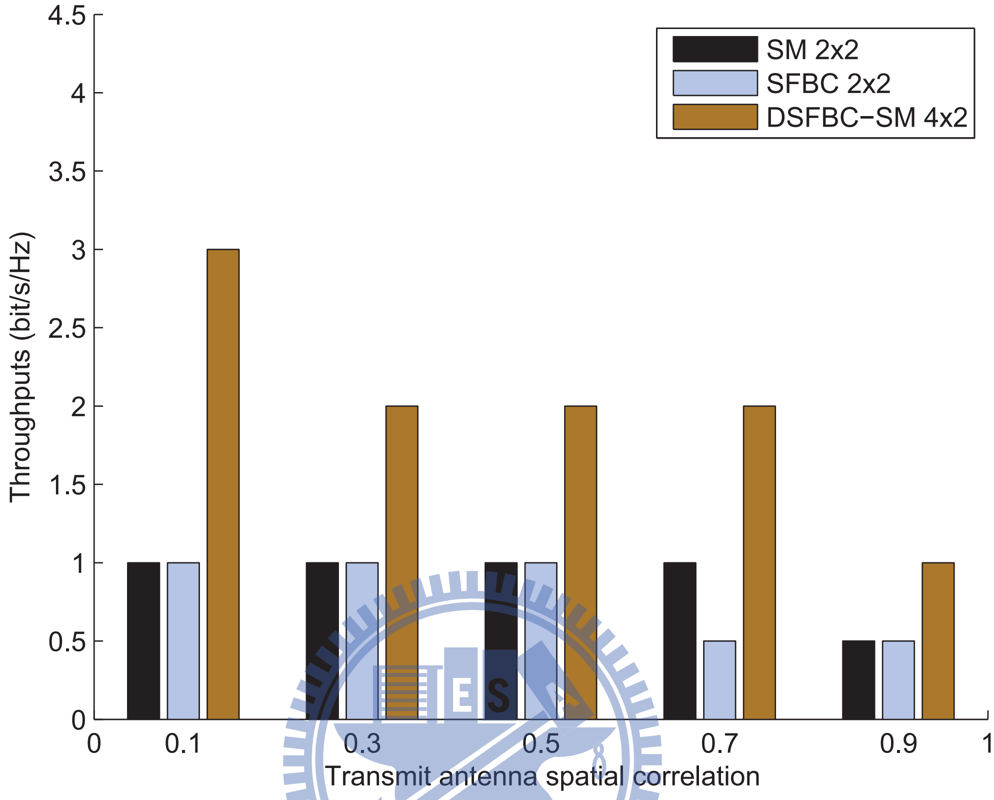

Figure 4.9: Throughputs of SM 2x2, SFBC 2x2 and DSFBC-SM 4x2 schemes for different ρ_{tx} with the distance from the serving BS equal to 750m (Rc).

Table 4.2: Throughputs Improvement by DSFBC-SM Compared with The Conventional SM.

Increased Throughputs by DSFBC-SM (bit/s/Hz)	ρ_{tx}= 0.1	ρ_{tx}= 0.3	ρ_{tx}= 0.5	ρ_{tx}= 0.7	ρ_{tx}= 0.9
Distance from the serving BS 500m (2Rc/3)	1	1	1	1	0
Distance from the serving BS 750m (Rc)	2	1	1	1	0.5

CHAPTER 5

Cyclic Delay Macro-Diversity Combining for MIMO OFDM Cellular Mobile Networks

In this chapter, we replace space-frequency block code (SFBC) with cyclic delay diversity (CDD) to increase transmit diversity at the adjacent suitable base stations. CDD can be viewed as a space-time block code. In contrast to SFBC, it is not necessary to assume constant channel properties over several sub-carriers or symbol and the number of transmit antennas. CDD is an efficient way to achieve diversity in a flat fading channel. Applying CDD only requires changes at the transmitter and the receiver remains changeless. The complexity of implementing CDD is very minimal. CDD inserts virtual echoes on the channel response. That increases the frequency selectivity of the channel seen by the receiver [17] [22]. Thus, it reduces the likelihood of deep fading. CDD can achieve desirable transmit diversity gain over uncorrelated channel. Because the distance between the adjacent is far enough for CDD free from spatial correlation, applying CDD at the adjunct base station sides is a more efficient way than at the transmit antenna sides of each base station. Hence, we introduce the cyclic delay macro-diversity combining with spatial multiplexing scheme.

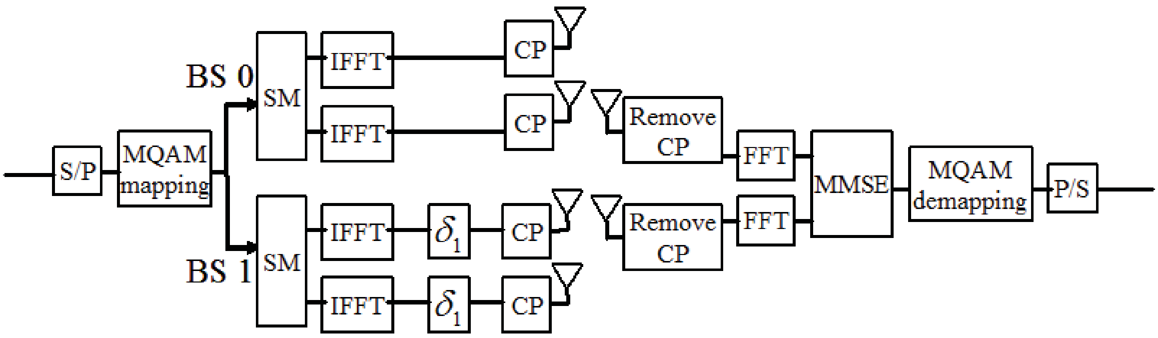

Figure 5.1: The Block Diagram of Cyclic Delay Macro-Diversity Combining with Spatial Multiplexing Scheme.

5.1 CDD Macro-Diversity Scheme

Fig. 5.1 shows the block diagram of two adjacent base stations apply CDD technique and each base station uses two antennas to perform spatial multiplexing. The signals are transmitted over the adjacent base stations, whereas it is only different with a specific cycle shift. After cyclic shifting, a cyclic prefix in add to avoid the ISI and maintain sub-carriers orthogonality for multi-path channels. δ_i denotes the cyclic shift of the i^{th} base station in the time domain and it can be regard as a phase factor as

$$\theta_k = e^{-j\frac{2\pi}{N_{FFT}}\delta_i k} \; . \tag{5.1}$$

This phase factor linearly increase with the sub-carrier index k for each base station.

5.2 SINR Performance

Both the serving base station (BS 0) and the target base station (BS 1) use two transmit antennas to perform spatial multiplexing. Because we apply CDD with a cyclic shift at the adjacent base stations side, the cyclic delay could be chosen according to [35].

$$\delta_0 = 0\ ,$$
$$\delta_i = \frac{N}{N_{bs}} + \delta_{i-1}\ . \qquad (5.2)$$

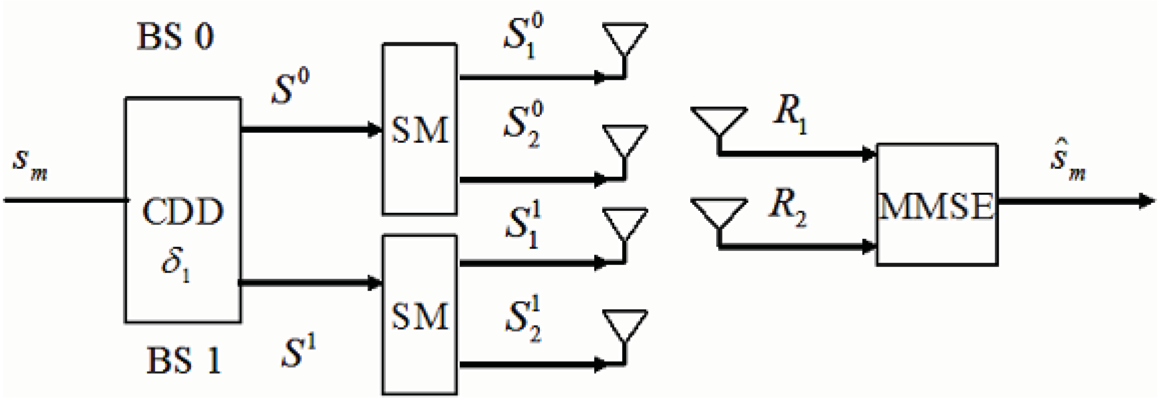

Figure 5.2: DCDD-SM Simplified System Model.

As depicted in Fig. 5.2, N is the number of used sub-carriers in the OFDM system and N_{bs} is the number of base stations in the scheme. We can get the cyclic shift $\delta_1 = N/N_{bs}$ for BS 1, and denote those modulated symbols as s_m. The sequences of s_m encoded by CDD can be separated into two groups for each base station as vectors S^0 and S^1 :

$$S^0 = [s_1\ s_2\ s_3\ s_4 \ldots\ldots\ s_{2N-3}\ s_{2N-2}\ \ s_{2N-1}\ s_{2N}]\ ;$$
$$S^1 = \left[s_1 e^{-j\frac{2\pi k\delta_1}{N}}\ \ s_2 e^{-j\frac{2\pi k\delta_1}{N}}\ \ \ldots\ldots\ \ s_{2N-1} e^{-j\frac{2\pi k\delta_1}{N}}\ \ s_{2N} e^{-j\frac{2\pi k\delta_1}{N}}\right]\ .$$

For the next SM branches, S^0 is split into two vectors S_1^0 and S_2^0. Also, S^1 is split into two vectors S_1^1 and S_2^1 for the transmit antennas of each base station. Thus, the output signals of the transmitters becomes

$$S_1^0 = [s_1\ s_3\ s_5\ s_7 \ldots\ldots\ s_{2N-3}\ s_{2N-1}]$$
$$S_2^0 = [s_2\ s_4\ s_6\ s_8 \ldots\ldots\ s_{2N-2}\ s_{2N}]$$
$$S_1^1 = \left[s_1 e^{-j\frac{2\pi k\delta_1}{N}}\ \ s_3 e^{-j\frac{2\pi k\delta_1}{N}}\ \ s_5 e^{-j\frac{2\pi k\delta_1}{N}}\ \ s_7 e^{-j\frac{2\pi k\delta_1}{N}}\ \ldots\ldots\ s_{2N-3} e^{-j\frac{2\pi k\delta_1}{N}}\ \ s_{2N-1} e^{-j\frac{2\pi k\delta_1}{N}}\right]$$
$$S_2^1 = \left[s_2 e^{-j\frac{2\pi k\delta_1}{N}}\ \ s_4 e^{-j\frac{2\pi k\delta_1}{N}}\ \ s_6 e^{-j\frac{2\pi k\delta_1}{N}}\ \ s_8 e^{-j\frac{2\pi k\delta_1}{N}}\ \ldots\ldots\ s_{2N-2} e^{-j\frac{2\pi k\delta_1}{N}}\ \ s_{2N} e^{-j\frac{2\pi k\delta_1}{N}}\right]\ .$$

where $k = 1, 2, 3, ..., N$

$$\begin{bmatrix} R_1(k) \\ R_2(k) \end{bmatrix} = \begin{bmatrix} H_{11}^0(k) \ + \ H_{11}^1(k)e^{-j\frac{2\pi k\delta_1}{N}} & H_{12}^0(k) \ + \ H_{12}^1(k)e^{-j\frac{2\pi k\delta_1}{N}} \\ H_{21}^0(k) \ + \ H_{21}^1(k)e^{-j\frac{2\pi k\delta_1}{N}} & H_{22}^0(k) \ + \ H_{22}^1(k)e^{-j\frac{2\pi k\delta_1}{N}} \end{bmatrix} \times$$

$$\begin{bmatrix} S(2k-1) \\ S(2k) \end{bmatrix} + \begin{bmatrix} n_1(k) \\ n_2(k) \end{bmatrix} . \tag{5.3}$$

In short, we can represent (5.3) as

$$R_{dcddsm}(k) = H_{dcddsm}(k)S_{dcddsm}(k) + N_{dcddsm}(k) \ , \tag{5.4}$$

$$R_{dcddsm}(k) = \begin{bmatrix} R_1(k) \\ R_2(k) \end{bmatrix} ,$$

$$H_{dcddsm}(k) = \begin{bmatrix} H_{11}^0(k) \ + \ H_{11}^1(k)e^{-j\frac{2\pi k\delta_1}{N}} & H_{12}^0(k) \ + \ H_{12}^1(k)e^{-j\frac{2\pi k\delta_1}{N}} \\ H_{21}^0(k) \ + \ H_{21}^1(k)e^{-j\frac{2\pi k\delta_1}{N}} & H_{22}^0(k) \ + \ H_{22}^1(k)e^{-j\frac{2\pi k\delta_1}{N}} \end{bmatrix} ,$$

and

$$S_{dcddsm}(k) = \begin{bmatrix} S(2k-1) \\ S(2k) \end{bmatrix} , N_{dcddsm}(k) = \begin{bmatrix} n_1(k) \\ n_2(k) \end{bmatrix} .$$

The same way to detect the signals as distributed SFBC combining with SM with a linear MMSE receiver, the receive signal vector $\mathrm{R}_{dcddsm}(k)$ is multiplied with$G^{MMSE}(k)$, the MMSE detector minimizes the mean square error between actually transmitted symbols and the output of the receiver,

$$\hat{S}_{dcddsm}(k) = G^{MMSE}(k)\mathrm{R}_{dcddsm}(k) \tag{5.5}$$

$$G_e^{MMSE}(k) = (H_{dcddsm}^*(k)H_{dcddsm}(k) + (M_t\frac{N_0}{E_s})I_{2M_t})^{-1}H_{dcddsm}^*(k), \tag{5.6}$$

where H^* is the Hermitian transpose of H, the total power transmitted on M_t antennas at one symbol time is E_s at each base station. We extend SINR calculations in the narrowband

MIMO systems [32] to the CDD macro-diversity combining with SM in OFDM system. Given the equivalent MIMO channel $H_{dcddsm}(k)$, the per-tone SINR calculation at the s^{th} sub-carrier is given by

$$SINR_s^{MMSE} = \frac{E_s}{M_t N_0 \left[(H^*_{dcddsm}(k) H_{dcddsm}(k) + (M_t \frac{N_0}{E_s}) I_{2M_t})^{-1} \right]_{s,s}} - 1. \qquad (5.7)$$

After the SINR evaluation of MMSE detector, we can apply the EESM approximation method to get the effective SINR r_{eff} from (5.7) and then decide the MCS to the same block error rate (BLER) by a lookup table through an AWGN curves as Table 3.1. We can find the throughputs with the decided MCS of the CDD macro-diversity combining with SM scheme.

5.3 Simulation Results

As SFBC macro-diversity combining with SM scheme in Chapter 4, the parameters used in the simulation are listed in Table 4.1. When the mobile station moves from the serving base station (BS 0) to the adjacent base station (BS 1) as shown in Fig. 3.1, we calculate the throughputs for different spatial correlations of the transmit antennas at each base station and compare with the single base station using SM or SFBC. The separation of each base station is far enough to ignore the spatial correlation between the transmit antennas of BS 0 and BS 1. The main goal of this simulation is to show that the throughput gain can be achieved by adopting CDD macro-diversity combining with SM around the cell edge compared with that of the conventional centralized MIMO-OFDM scheme and SFBC macro-diversity combining with SM scheme. Perfect channel state information at receivers is assumed in our simulations. Particularly, we are interested in the performance comparison between CDD macro-diversity combining with SM scheme and SFBC macro-diversity combining with SM scheme.

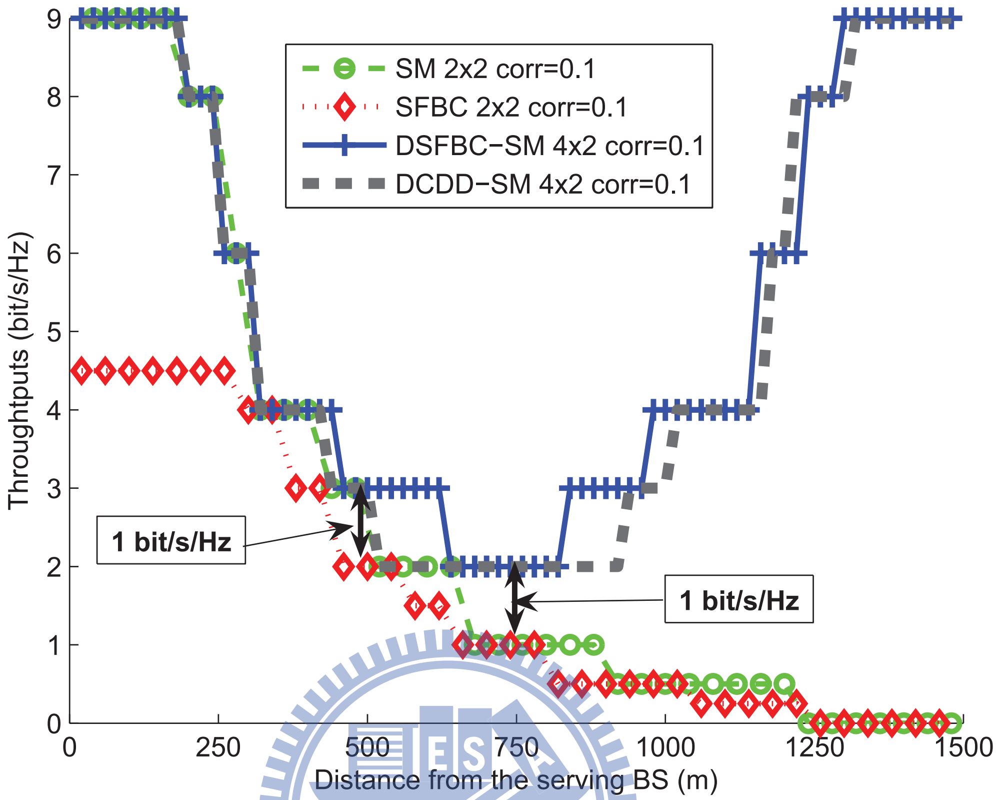

Figure 5.3: Throughputs of SM 2x2 , SFBC 2x2 , DSFBC-SM 4x2 and DCDD-SM 4x2 with ρ_{tx} = 0.1 at each BS.

From Fig. 5.3, the poor throughput of the conventional SM scheme around the cell edge is improved obviously by applying the distributed CDD techniques at the adjacent base stations sides. Because CDD can not achieve the optimal diversity gain as SFBC, distributed SFBC outperforms distributed CDD slightly. Using transmit diversity at the base station side increases SINR effectively around the cell edge. It allows us to choose higher order modulation and coding schemes (MCS). Therefore, the CDD macro-diversity combining with SM scheme can also overcome the drawbacks of the single base station using SM and maintain the large throughput for the mobile station around the cell edge. It can be concluded that distributed CDD is another effective scheme to get spatial diversity gain in cellular networks as distributed SFBC.

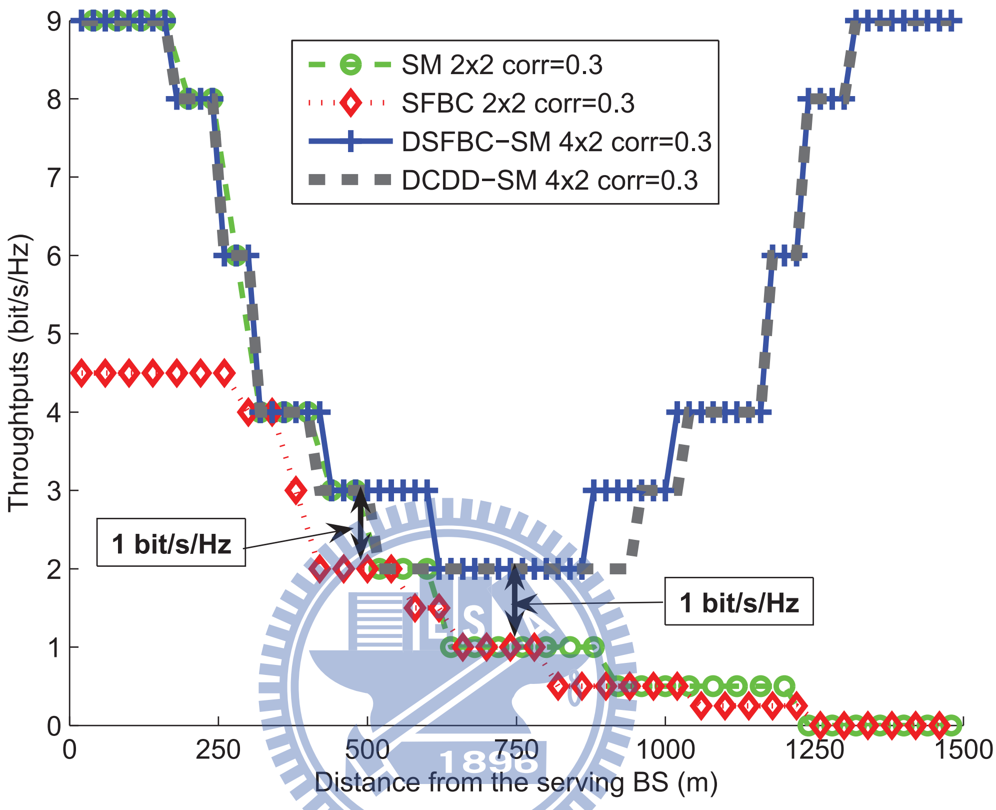

Figure 5.4: Throughputs of SM 2x2 , SFBC 2x2 , DSFBC-SM 4x2 and DCDD-SM 4x2 with $\rho_{tx} = 0.3$ at each BS.

As Figs. 5.4, 5.5, 5.6 and 5.7 show the effects of increasing spatial correlation of each transmitters for the CDD macro-diversity combining with SM scheme. It is shown that it can provide higher throughput than the conventional SFBC and SM schemes with $\rho_{tx} = 0.7$. The variations of throughputs between CDD macro-diversity combining with SM scheme and SFBC macro-diversity combining with SM scheme are getting small at the cell boundary as spatial correlation increases. For $\rho_{tx} = 0.9$, the throughputs of the two

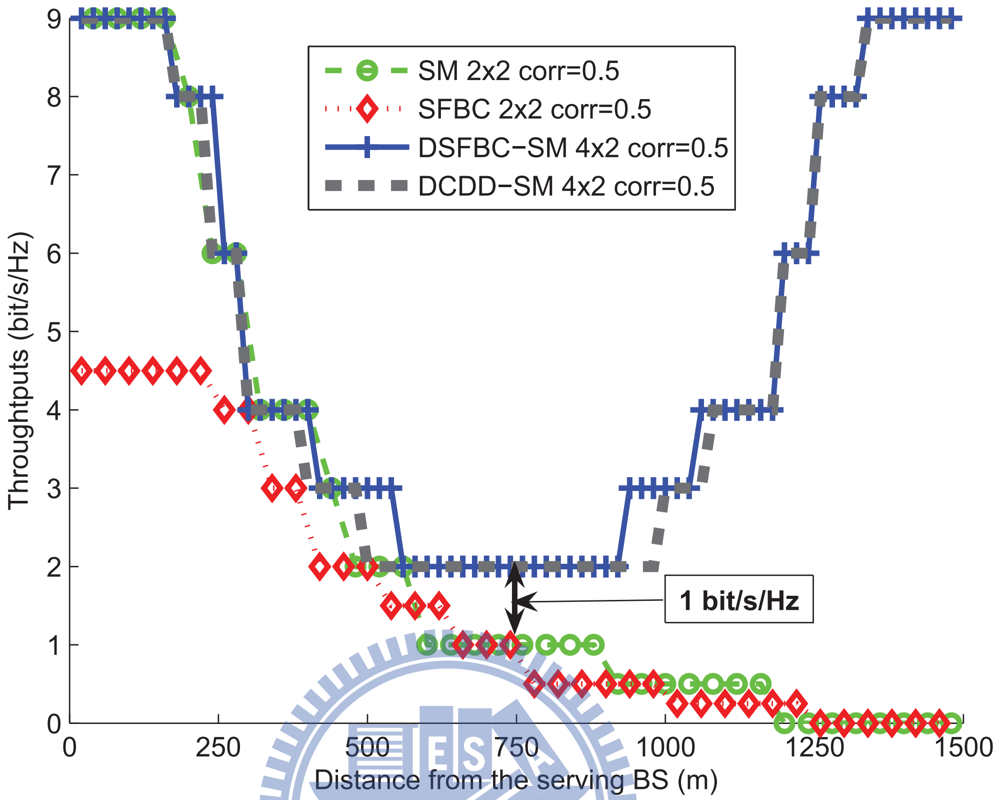

Figure 5.5: Throughputs of SM 2x2 , SFBC 2x2 , DSFBC-SM 4x2 and DCDD-SM 4x2 with $\rho_{tx} = 0.5$ at each BS.

schemes are the same at cell boundary.

When the distance between a mobile station and the serving base station is two thirds of the cell radius, Fig. 5.8 shows that the performance of CDD macro-diversity combining with SM scheme is the same as SFBC macro-diversity combining with SM scheme and better than the conventional SFBC and SM schemes with $\rho_{tx} \leq 0.3$. SFBC macro-diversity combining with SM scheme also outperforms the CDD macro-diversity combining with SM scheme for higher ρ_{tx} values. At the cell boundary, Fig. 5.9 shows that the CDD macro-diversity combining with SM scheme performs similar to the SFBC

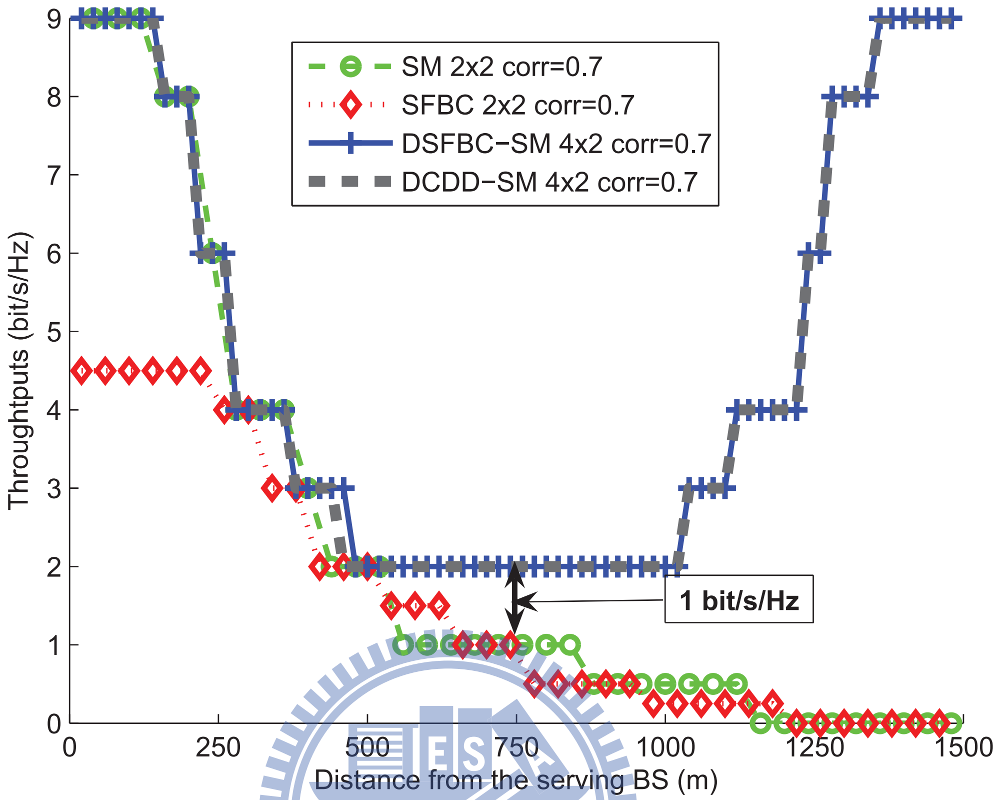

Figure 5.6: Throughputs of SM 2x2 , SFBC 2x2 , DSFBC-SM 4x2 and DCDD-SM 4x2 with $\rho_{tx} = 0.7$ at each BS.

macro-diversity combining with SM scheme. It can also provide higher throughput than the conventional SFBC and SM schemes.

Table 5.1 shows the increased throughputs of CDD macro-diversity combining with SM scheme compared with the conventional SM scheme. It shows that CDD macro-diversity combining with SM scheme can also effectively improve the throughput under spatially correlated channels and can offer higher data throughput for a mobile station at the cell boundary. Hence, the handover performance can be enhanced greatly.

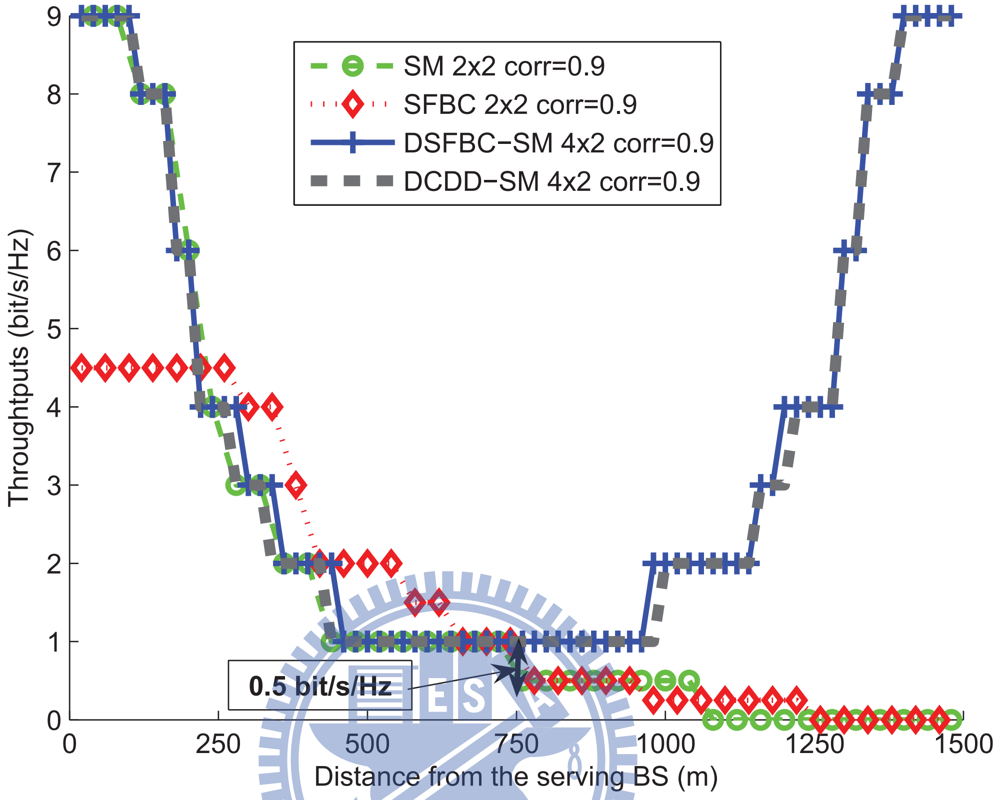

Figure 5.7: Throughputs of SM 2x2 , SFBC 2x2 , DSFBC-SM 4x2 and DCDD-SM 4x2 with $\rho_{tx} = 0.9$ at each BS.

Table 5.1: Throughputs Improvement by DCDD-SM Compared with The Conventional SM.

Increased Throughputs by DCDD-SM (bit/s/Hz)	ρ_{tx}= 0.1	ρ_{tx}= 0.3	ρ_{tx}= 0.5	ρ_{tx}= 0.7	ρ_{tx}= 0.9
Distance from the serving BS 500m (2Rc/3)	1	1	0	0	0
Distance from the serving BS 750m (Rc)	1	1	1	1	0.5

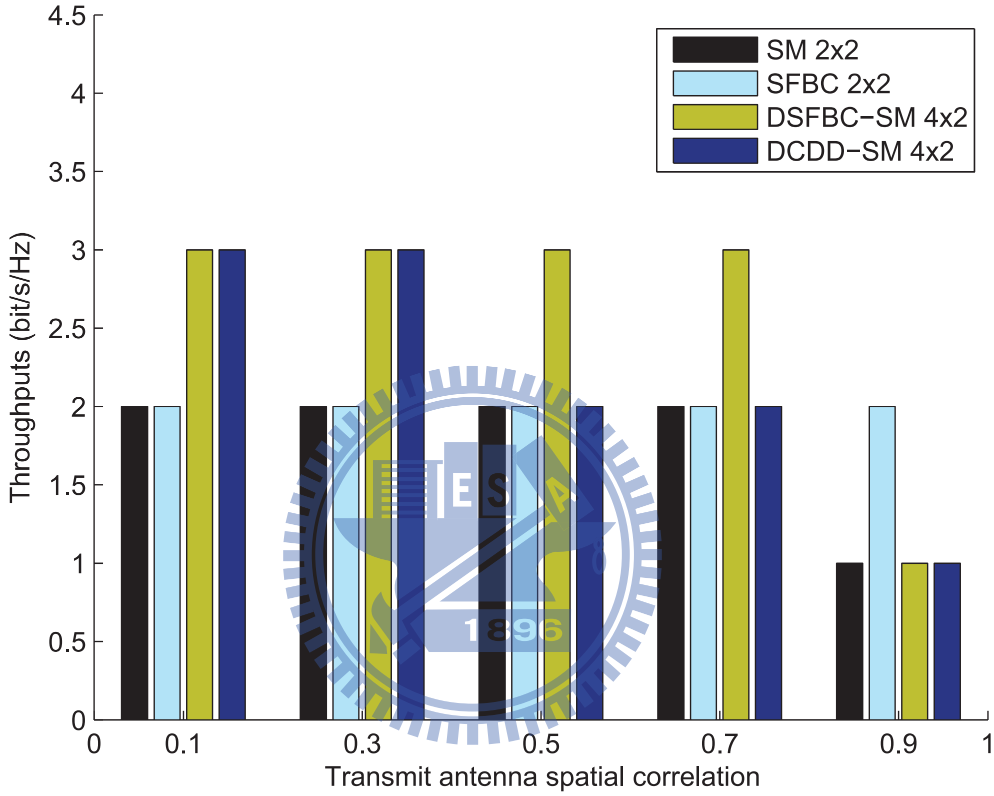

Figure 5.8: Throughputs of SM 2x2, SFBC 2x2, DSFBC-SM 4x2 and DCDD-SM 4x2 schemes for different ρ_{tx} with the distance from the serving BS equal to 500m (2Rc/3).

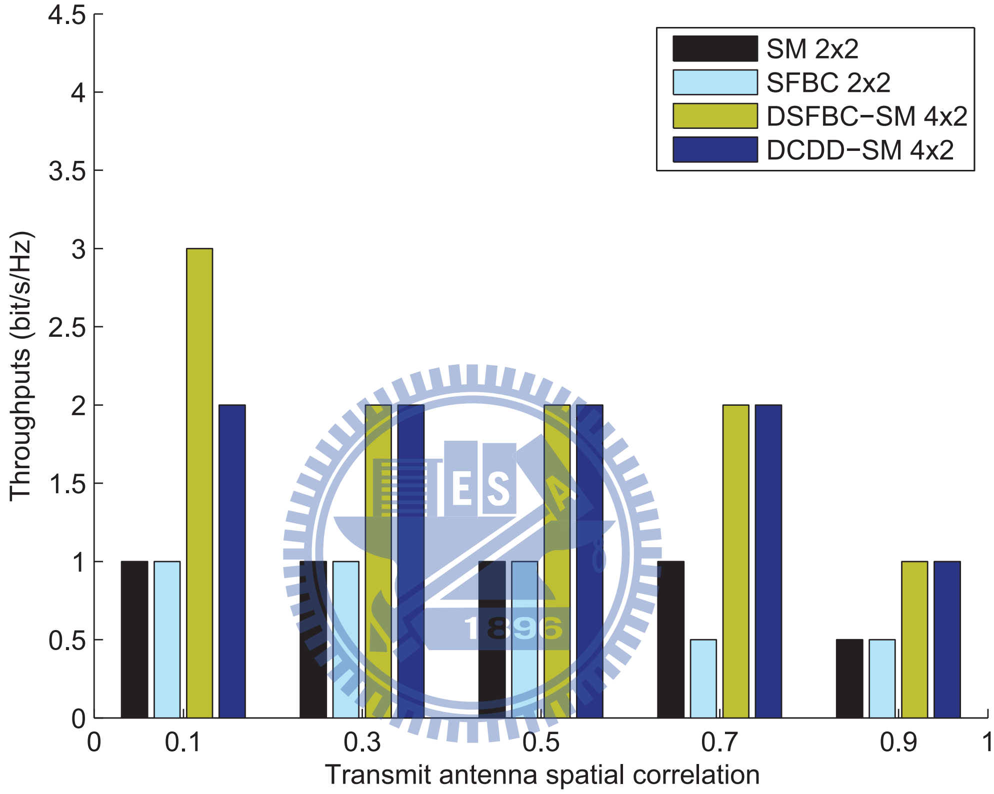

Figure 5.9: Throughputs of SM 2x2, SFBC 2x2, DSFBC-SM 4x2 and DCDD-SM 4x2 schemes for different ρ_{tx} with the distance from the serving BS equal to 750m (Rc).

CHAPTER 6

Conclusions

In this thesis, we introduce two new schemes for increasing the throughput of the mobile station around the cell edge of MIMO OFDM cellular mobile networks: space-frequency block code macro-diversity combining with spatial multiplexing scheme and cyclic delay macro-diversity combining with spatial multiplexing scheme. We also evaluate the impacts of transmit antenna spatial correlation. These schemes overcome the drawbacks of the single base station using SM to offer high data rate for the mobile station. However using SM reduces the coverage of base stations. Without increasing the transmit power or the number of antennas of base stations, we apply the transmit diversity at the base station sides to increase the SINR of the mobile station around the cell edge in the downlink case. The receiver of a mobile station performs diversity combining to increase SINR. By using SM, the serving base station can provide high throughput for the mobile station close to the serving base station, while the mobile station moves to cell area. The two schemes adopt different transmit diversity techniques at the base station sides. The adjacent base stations transmit the same signal to mobile station with cooperation. The mobile station can combine the receive signals to get the spatial diversity gain and increase the SINR around the cell edge in the downlink case. In addition, the impacts of spatial correlation at the transmitter are considered. The performance of SM-MIMO system seriously degreases, especially if there is non-trivial spatial correlation among the transmit antennas. The two schemes are more robust than the conventional SM scheme of the single base station in spatially-correlated channels.

An EESM-based approach is proposed to evaluate the system-level performance. The simulation results in Chapters 4 and 5 show that the two macro-diversity schemes can significantly improve performance compared with the conventional SM scheme of the single base station around the cell edge. Distributed SFBC outperforms distributed CDD slightly under low spatially correlated channels. The variations of throughputs increasing between CDD combining with SM scheme and SFBC combining with SM scheme are getting small at the outer cell area in high spatially-correlated channels. The throughput of the two schemes are about the same at the cell boundary with ρ_{tx} = 0.9. Their performances are quite similar. While the increased throughput satisfies the requirement of mobile stations around the cell edge, there will be no call-dropped case occurred at the cell boundary. This decreases handover frequency and relieves the ping-pong effect [12]. The handover performance in OFDM cellular networks is also enhanced greatly.

To get the improvement of throughput, more complicated decoders are required for SFBC. In contrast to SFBC macro-diversity combining with SM scheme, CDD macro-diversity combining with SM scheme can be designed for arbitrary base stations and no modification at the receiver is necessary. Due to the quite similar improvement, lower complexity and compatibility to existing wireless communication systems, we prefer to adopt the CDD macro-diversity combining with SM scheme instead of SFBC macro-diversity combining with SM scheme for MIMO OFDM cellular mobile networks. CDD macro-diversity combining with SM scheme can provide huge throughput for the mobile stations near the serving base station. When the mobile station moves to the cell edge, it can perform macro-diversity combining with MDHO to increase SINR and improve the poor throughput of mobile stations.

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