CHAPTER I

INTRODUCTION

1.1 Background and Motivation

In the past decade, growing demand for mobile multimedia communications has rapidly accelerated the research and development for high capacity wireless systems. As a result, the third Generation (3G) for mobile communication, International Mobile Telecommunications 2000 (IMT-2000) included W-CDMA, UMTS, and CDMA2000. NTT DoCoMo launched 3G services called ‘FOMA’ based on W-CDMA technology in Japan in October 2001, which supports high quality voice and high speed with the maximum data rate of 384 Kilobit per second (Kbps). Thereafter, High Speed Downlink Packet Access (HSDPA) was introduced in which a data rate of 3.6 Megabit per second (Mbps) in 2006. Technical specifications for HSPDA called for a maximum downlink data rate of approximately 14 Mbps. Since then there have been a number of operators working not only in Europe, but in North America and Asia as well. The 3rd Generation Partnership Project (3GPP), which has been developing technical specifications for W-CDMA, aims to increase the uplink data rate to 5.7 Mbps. However, looking further into the future, demands for long term vision with higher data rates for downloading of ever increasing volume of information will become stronger in mobile networks as well, which has leading the wireless communication industry to establish super-3G concept in early 2004 to steer the Long Term Evolution (LTE) of the 3G system. Currently, studies on the LTE are ongoing in the 3GPP. The research activities and developed technologies to achieve the targets for set by the International Telecommunication Union Radio-communication sector (ITU-R) for super-3G, which is very important for providing a smooth path for 4th Generation (4G) mobile networks. The 4G mobile networks support extremely high-speed packet data services of, for example, 100M-1Gbps [1]. The mobile networks have evolved from 1G to 3G and now it will further evolve into 4G mobile systems as shown in Figure 1.1.

Table 1.1 shows service requirements for 4G systems proposed by NTT DoCoMo [2], Bit rate of 3G system is around ten times higher than that of 2G systems. Thus, 4G systems may be expected to provide about ten times higher speed in communication than 3G system. In order for many customers to use high bit rate services, capacity or spectrum efficiency utilization must be higher than 3G system. Generally, requirement for spectrum efficiency depends on the bandwidth that will be available for 4G. Therefore, the super-3G mobile system is expected to employ much broader frequency bandwidths than the current 3G system. Meanwhile, due to the spectrum bands that have already been assigned to legacy systems and new wireless standards such as wireless LANs (W-LANs), the availability of spectrum resource for the super-3G cellular system is being exhausted. *Therefore, we need to develop technologies that significantly increase the spectrum efficiency to provide efficient mobile wireless systems.*

The *channel capacity* is known as the maximum error-free data rate that a channel can support. Channel capacity plays an important role in communications over fading channels, especially Multiple-Input Multiple-Output (MIMO) antenna technology at both the transmitter and the receiver.

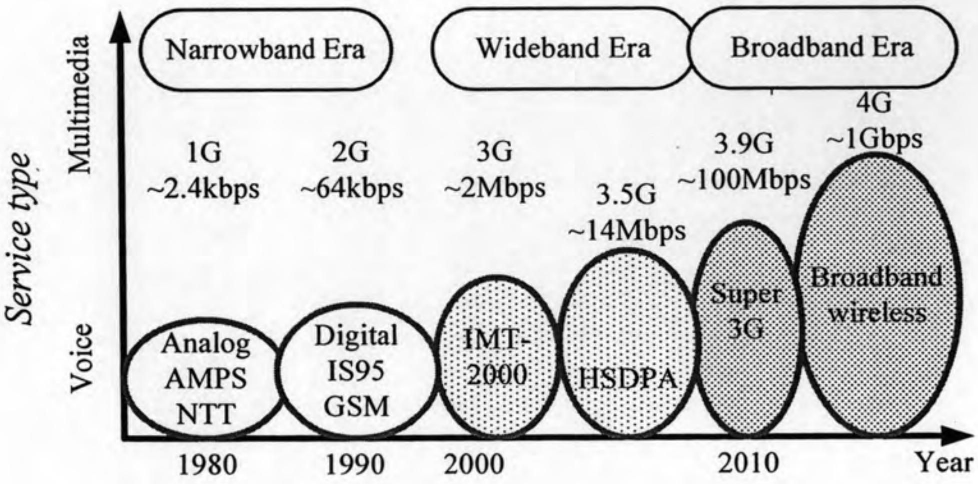

Figure 1.1 Evolution of the mobile and communication systems

Table 1.1 Expectations for 4th generation systems (*proposed by NTT DoCoMo* [2])

- High speed (vehicular: 2Mbps, pedestrian/indoor: 20Mbps)
- Next generation Internet support (IPv6, QoS, Mo-IP)
- High capacity: 5 to 10 times higher than 3G
- Seamless services
- Flexible for providing new services
- Higher frequencies Utilization (microwave: 3 to 8 GHz)
- Lower system cost (1/10 or IMT2000)

1.2 Smart Antennas and MIMO Concept

In order to improve dramatically the spectrum efficiency, research activities using antenna arrays in wireless communications have been forced as a new technology, which by itself is a century old idea. In December 1901, Marconi received the world's first long-distance radio transmission at Newfoundland, of 3.592Km from a transmitter which was situated at Poldhu on the Atlantic coast of England [3]. Here, John Ambrose Fleming sent the Morse code signal for 'S' from a gigantic antenna system consisting of about 400 wires suspended in an inverted cone from a 60m circle of twenty 60m high masts.

Since then, antenna arrays have been used in almost all fields of wireless communication [4], from satellite ground station to GSM [5] and 3G networks [6]. Antennas arrays, conventionally also known as smart antennas, are able to exploit the different replicas of the same signal at the multiple antenna elements by combining them before transmission or after reception according to the specific signal processing technique [7]. However, antenna arrays need not be limited to a set of separate elements. They can also be constructed by using collocated antennas with different polarizations or even different antenna modes.

A typical wireless communications consist of a transmitter, radio channel, and receiver. It can be categorized by the numbers of inputs and outputs, which are quantified by the number of transmitting and receiving antenna elements, respectively. A system with a single element at each end will form the fundamental Single Input Single Output (SISO) configuration. Systems with antenna array at either transmitter or receiver only are known as Multiple Input Single Output (MISO) or Single Input Multiple Output (SIMO) systems, respectively. Naturally, *Multiple Input Multiple Output (MIMO)* wireless systems consist of antenna arrays at both the transmitter and receiver. The top diagram of Figure 1.2 which comprises N_T transmitting and N_R receiving antennas configured an MIMO channel respond matrix, the bottom photo depicts the configuration of the testing MIMO system at the Araki-Sakaguchi Laboratory (Tokyo Institute of Technology, Japan) which using 4 antennas at the transmitter and 4 antennas at the receiver sides each [8].

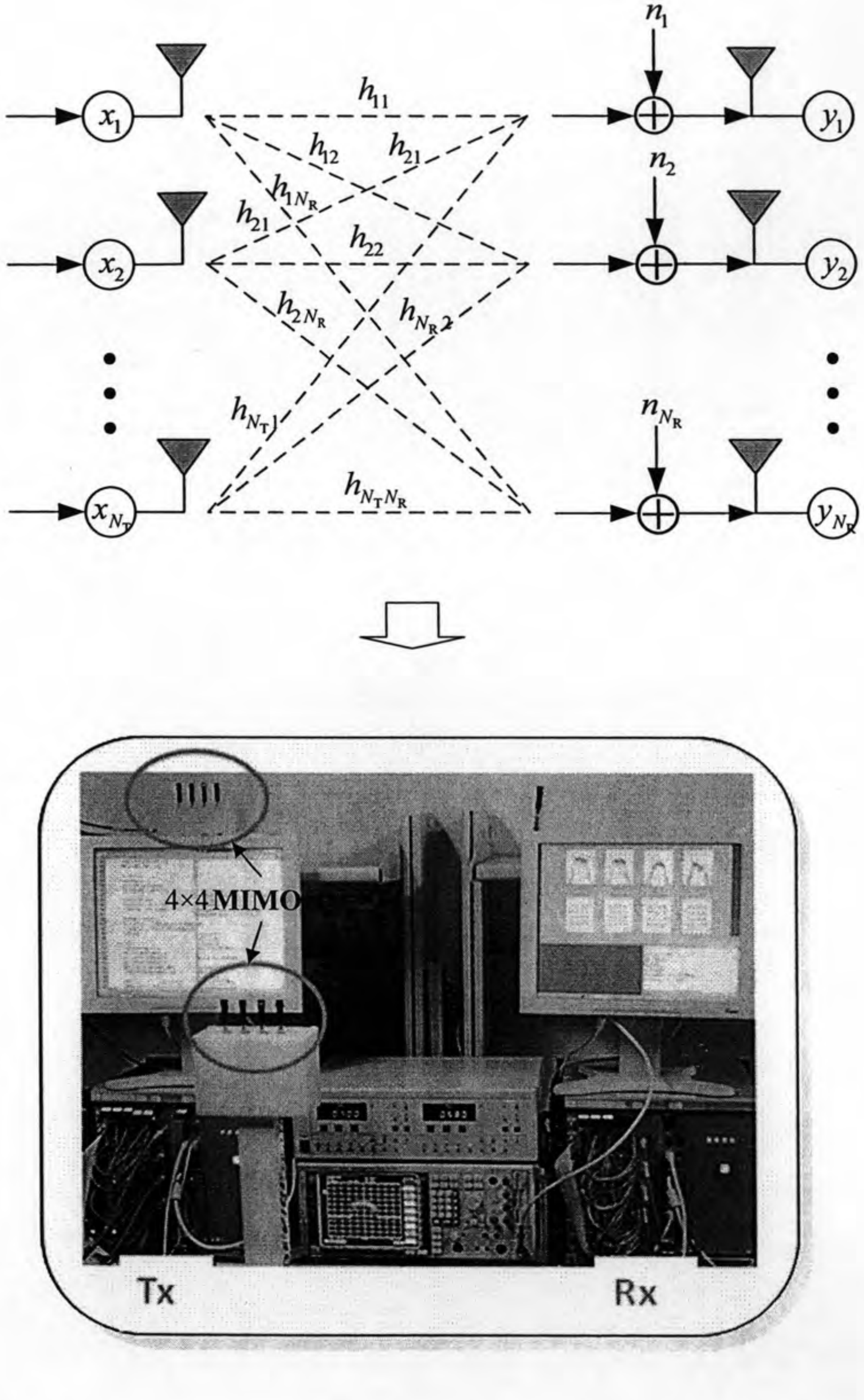

Figure 1.2 MIMO channel respond matrix and the real MIMO channel mesuarement system at Araki-Sakaguchi Laboratory

In conventional smart antenna terminology, only the transmitter or receiver is equipped with more than one antenna elements, forming a MISO or SIMO system. Smart antenna systems operating on the MISO or SIMO configuration are however not able to fully exploit the spatial domain inherent in the wireless channel.

Intuitively, a MIMO system with multiple antennas at both ends will perform much better than smart antenna systems and indeed the advantages offered by a MIMO link go far beyond that of the array and diversity gains in a MISO or SIMO link [7], [9], [10], [11], [12]. A MIMO link produces a matrix channel, which creates a new dimension of transmission through the spatial modes of the MIMO channel on the same time-frequency slot, thus promising an exciting increase in the spectral efficiency. By tapping on the different spatial signatures inherent in a typical wireless channel with rich scattering, MIMO systems are able to exploit the multipath propagation environment rather than just mitigating the fading effects as in MISO and SIMO links.

Although an explosion of research on MIMO systems, spearheaded by Bell Laboratories [10], [11], [12], started in the earlier 1990s, the first known publication hinting at the tremendous potential of MIMO systems was published by Winters [9] in 1987.

1.3 Fundamental Limits of Channel Capacity

According to Shannon's information capacity theory, capacity of conventional single-input single-output (SISO) system, C_{SISO}, is defined as [13], [14]

$$C_{\text{SISO}} = \log_2\left(1+\frac{P}{\sigma^2}|h|^2\right), \qquad [\text{b / s / Hz}], \qquad (1.1)$$

where

- $P\,[\text{W}]$ is the total transmitted power,
- $\sigma^2\,[\text{W}]$ is the variance of the Additive White Gaussian Noise (AWGN) at each receiver,

- h is the complex gain of a realization of a random channel.

However, high transmitting power is not desirable because it increases interference to adjacent channels and requires high performance power amplifier, etc. If possible, other solutions are requested in that sense. Therefore, multiple antennas technology is a possible solution for this issue.

In a SIMO system with N_{R} antennas at the receiver, the corresponding capacity, C_{SIMO} , can be expressed as

$$C_{\mathrm{SIMO}} = \log_2\left(1+\frac{P}{\sigma^2}\sum_{i=1}^{N_{\mathrm{R}}}|h_i|^2\right), \qquad [\mathrm{b/s/Hz}], \qquad (1.2)$$

where

- h_i denotes the complex response from the transmitter antenna to the ith receiver antenna.

Although an improvement in capacity is achieved through the use of N_{R} antennas at the receiver, it should be noted that this increase in Eq. (1.2) is only logarithmic manner with respect to an increase in N_{R}.

Similarly for a MISO system with N_{T} antennas without Channel State Information (CSI) at the transmitter, its capacity, C_{MISO}, can be expressed as [15]

$$C_{\mathrm{MISO}} = \log_2\left(1+\frac{P}{N_{\mathrm{T}}\sigma^2}\sum_{j=1}^{N_{\mathrm{T}}}|h_j|^2\right), \qquad [\mathrm{b/s/Hz}], \qquad (1.3)$$

where

- h_j denotes the complex channel response from the j^{th} transmitter antenna to the receiver antenna.

This Eq. (1.3) is similar to the SIMO case in Eq. (1.2) where there is only a logarithmic increase in capacity with respect to N_{T}. Furthermore, due to the absence of coherent combining available, the capacity expression for MISO is identical to Eq. (1.2).

Now, combined N_{T} antennas at the transmitter and N_{R} antennas at the receiver which used for MIMO system, the channel capacity C_{MIMO} is given by [12], [15], [16]

$$C_{\mathrm{MIMO}} = \log_2\left[\det\left(\mathbf{I}_{N_{\mathrm{R}}} + \frac{P}{N_{\mathrm{T}}\sigma^2}\mathbf{H}\mathbf{H}^H\right)\right], \qquad [\mathrm{b/s/Hz}], \qquad (1.4)$$

where

- $\det(\cdot)$ denotes the determinant of a matrix,
- $\mathbf{I}_{N_{\mathrm{R}}}$ is a $N_{\mathrm{R}} \times N_{\mathrm{R}}$ identity matrix,
- $\mathbf{H} \in \mathbb{C}^{N_{\mathrm{R}} \times N_{\mathrm{T}}}$ is the MIMO channel matrix,
- $(\cdot)^H$ represents the Hermitian transpose.

In Eq. (1.4), assume that P is distributed equally among the transmitter antennas.

1.4 Rayleigh Fading Channel

In this dissertation, Rayleigh fading channels with additive Gaussian noise will be studied. This means that channel alters the transmitted signal (s) by multiplying it by a random complex number (h, drawn from a particular distribution), then adding another random number n, forming the received signal r:

$$r = hs + n \qquad (1.5)$$

The noise term n can arise from other electromagnetic signal uncorrelated to r. It is assumed a Gaussian random variable (rv) by the central limit theorem, because it is considered as the sum of a large number of identically distributed rv's.

The transmission is successful if the receiver can accurately determine s from r, otherwise, an error in transmission has occurred. The receiver has knowledge of the code and statistics of h and n, but not necessarily their values.

Fading is a phenomenon in wireless transmission whereby a signal travels along many paths and combines constructively or destructively at the receiver. As a result, the signal net received varies with amplitude and phase over the time in an unpredictable manner. The number of symbols in which this variation is considered minimal is known as the *coherence interval*. The received signal also varies with distance, as a second receiver placed at a short distance away may experience a different sum of paths.

Suppose a message signal is modulated at some carrier frequency (i.e. multiplied by a sinusoidal signal) and transmitted over a channel that exhibits multipath fading. If there is no direct Line-of-Sight (LoS) between the transmitter and receiver, the phases of the paths can be represented by a complex number. By applying the central limit theorem, it can be shown in [17] that the real and imaginary parts of this complex number tend to be independent with zero-mean Gaussian random variables each having the same variance, as the number of paths tends to reach infinity. This leads to the random number h in Eq. (1.5) representing the *fade* of the communication system. Normalizing h to have unit variance, h is drawn from the complex Gaussian distribution $\mathbb{C}N(0, 1)$ and its probability density function (*pdf*) is given by

$$pdf(h) = \frac{e^{-|h|^2}}{\pi}, \qquad h \in \mathbb{C} \tag{1.6}$$

The magnitude of h has a Rayleigh probability distribution [18]. Hence, the Rayleigh distribution represents a behavior of multipath fading channel without direct LoS transmission. This model best applies to indoor or urban environments, where signal attenuation due to distance is less significant. We assume h is fixed during a coherence interval before changing to a new independent value.

Also note that the distribution of $r = |h|^2$ is exponential as

$$f(r) = e^{-r}, \qquad r > 0 \tag{1.7}$$

This property makes the analysis of Rayleigh fading channel attractive, and therefore this model has been studied extensively. Figure 1.3 depicts the Rayleigh distribution. The review paper [19] describes the communication and information theory related to fading channels in details.

The type of fading described in the earlier is known as a form of flat fading because the previous analysis assumes that the channel gain response is constant over the bandwidth of the signal. The signals arriving from multipaths are not delayed (related to a symbol period) in time. Due to the bandwidth of the signal is narrow compared with that in which the channel behaves the same, flat fading systems are also known as *narrowband* systems.

Rayleigh fading severely degrades the bit error probability performance of wireless systems. This is because there is a significant probability that in Eq. (1.5) is small in magnitude (known as an outage), resulting in the failure of two faded symbols hs_1 and hs_2 to be successfully distinguished when corrupted by noise. While error probability for a Gaussian channel without fading decays exponentially in the SNR, it decays only inversely in the SNR for a Gaussian channel with Rayleigh fading. It is shown in the Figure 1.4, where the error probability is plotted as a function of Signal-to-Noise Ratio (SNR) with and without fading (Additive White Gaussian Noise-AWGN). This is done by simulating Equation (1.5) with h is drawn from a $\mathbb{C}\mathcal{N}(0,1)$ distribution and setting r to $+\sqrt{\text{SNR}}$ or $-\sqrt{\text{SNR}}$ as SNR varies from 1 to 100. In the no fading case, set h equal to one, in the fading case h is drawn from $\mathbb{C}\mathcal{N}(0,1)$ distribution. With this scheme, an error occurs if $|r-hs| > |r+hs|$.

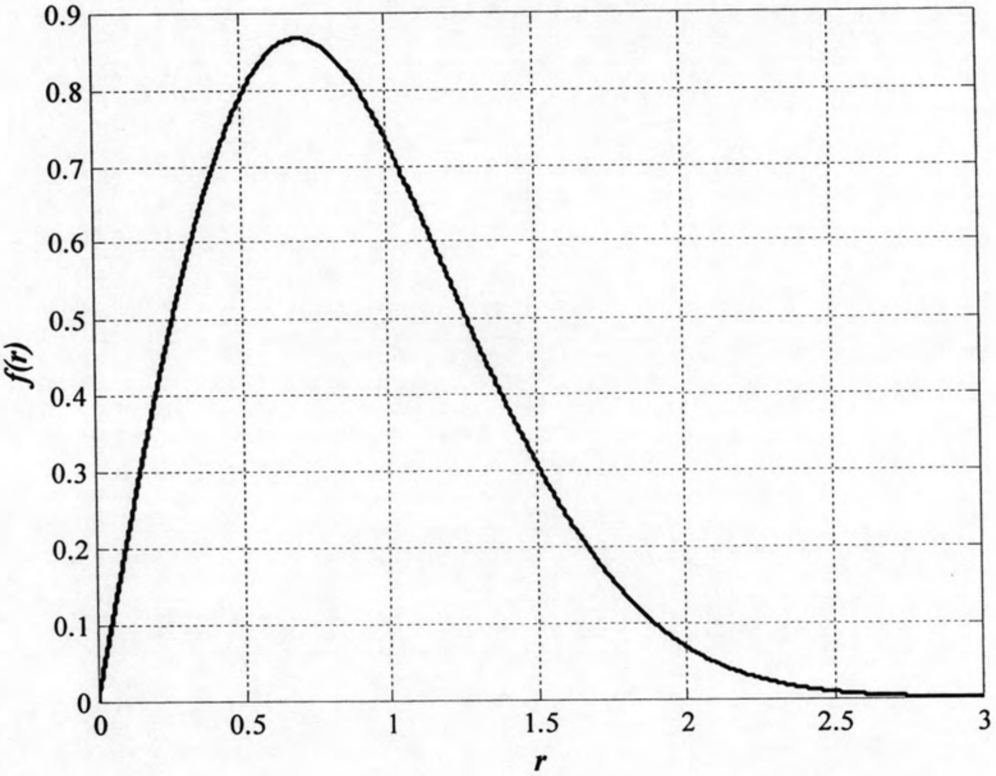

Figure 1.3 Rayleigh distribution

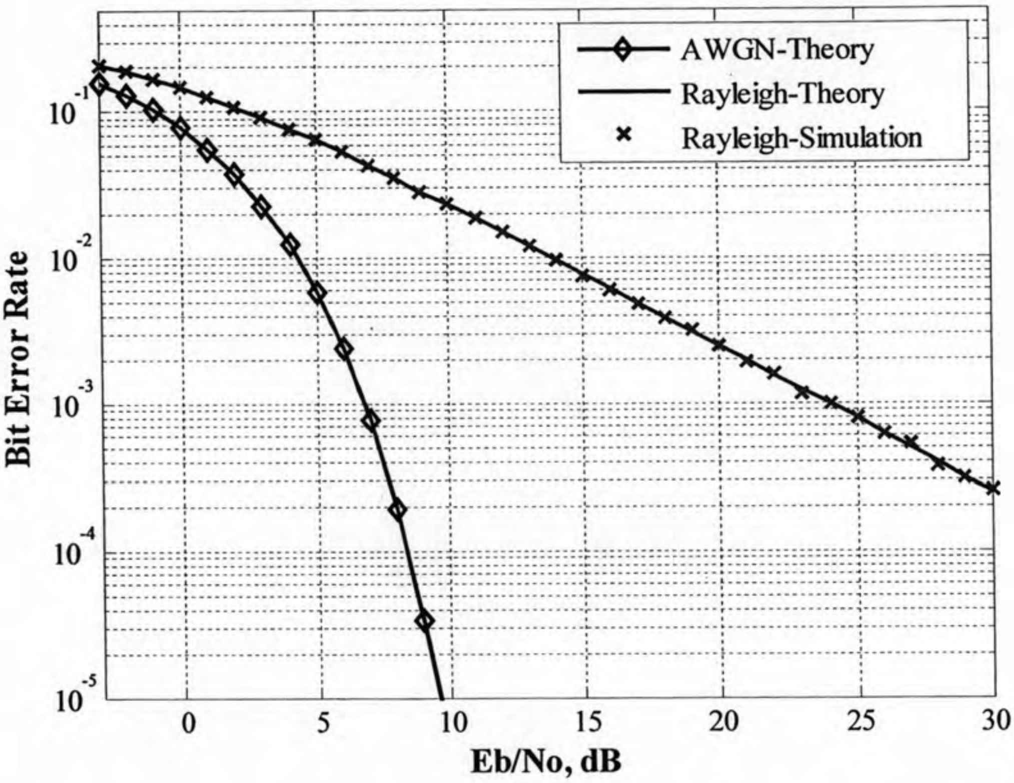

Figure 1.4 Bit Error Rate (BER) performance and SNR of Binary Phase Shift Keying (BPSK) modulation with Rayleigh fading and without fading

1.5 Research Interests of MIMO Technologies

Motivated by the great potential of the MIMO channel capacity, intense research and development have been conducted to enhance the practical feasibility of the MIMO schemes, and a significant number of new results have proposed and reported over the last decade. Unlike conventional wireless technologies, research on MIMO technologies is spreading over a wide range of topics. Figure 1.5 classifies the major MIMO research interests in two six categories: capacity analysis, transmission schemes, receiver schemes, antennas and propagations, hardware implementations and multi-user schemes. A list of specific research topics is given in each category. Due to closed relation of each category, comprehensive knowledge concerning *information theory, coding theory, matrix theory, signal processing, and propagation theory* is required for specific research. In the following explanations, each research category is briefly introduced with some pioneering investigations.

In the field of capacity analysis, investigations on capacity limits of various types of MIMO channels are research interests. Capacity limits of single- or multi-user MIMO channel with various assumptions on CSI at the transmitter and the receiver are summarized in [20]. The investigation on capacity analysis based on random matrix theory and multivariate statistics is a recent interest research [21], [22], [23].

Regarding the transmission schemes, efficient signaling schemes in terms of diversity-multiplexing trade-off [24] and the amount of required feedback information or CSI have been actively studied. When there is no CSI at the transmitter, signaling schemes related to diversity or space-time coding [25], [26], [27] and multiplexing or Bell labs Layered Space Time (BLAST) [28], [29] are major topics. In the case of perfect CSI at the transmitter, beamforming or precoding [30], [31] is comprehensively studied. For the case of the partial CSI, power allocation and adaptive modulation and coding techniques among multiple transmit antennas [32], [33], antenna selection techniques [34], and codebook precoding techniques [35], [36], [37], [38], [39] are also important topics. For signal transmission in frequency selective fading channel, Multiple Input Multiple Output – Orthogonal Frequency Division Multiplexing (MIMO-OFDM) systems [40], [31], [41] are actively investigated. MIMO relaying has recently been a focus of attention as a target for coverage extension in wireless networks [42], [43], [44], [45].

In the field of antenna and propagation, channel modeling and antenna design are two essential interests. The enormous capacity of MIMO channels is based on the assumption of rich scattering propagation environments that make each MIMO channel link uncorrelated to the others. However, in practical propagation environments, the rich scattering assumption does not always exist, and physical antenna configuration affect correlation properties of the MIMO channel. Thus, extensive studies have been conducted on channel modeling using various antenna configurations through channel measurement campaigns [46], [47], [48], [49].

In the area of receiver design, interference suppression techniques for MIMO spatial multiplexing systems are the most important issue. Combined interference cancellation and Linear Minimum Mean-Squared Error (LMMSE) detection [10], [50] is a key topic. Iterative detection and decoding for further performance improvement has been actively investigated [10], [51], [52].

For multi-user environments, advanced precoding and scheduling [53], [54], [55], [56], [57], and the Medium Access Control (MAC) protocol [58], [59] are actively studied.

Hardware implementations of MIMO technologies have been performed on Digital Signal Processing (DSP) [60], Field Programmable Gate Arrays (FPGAs), [61] and Application Specific Integrated Circuits (ASICs) [62].

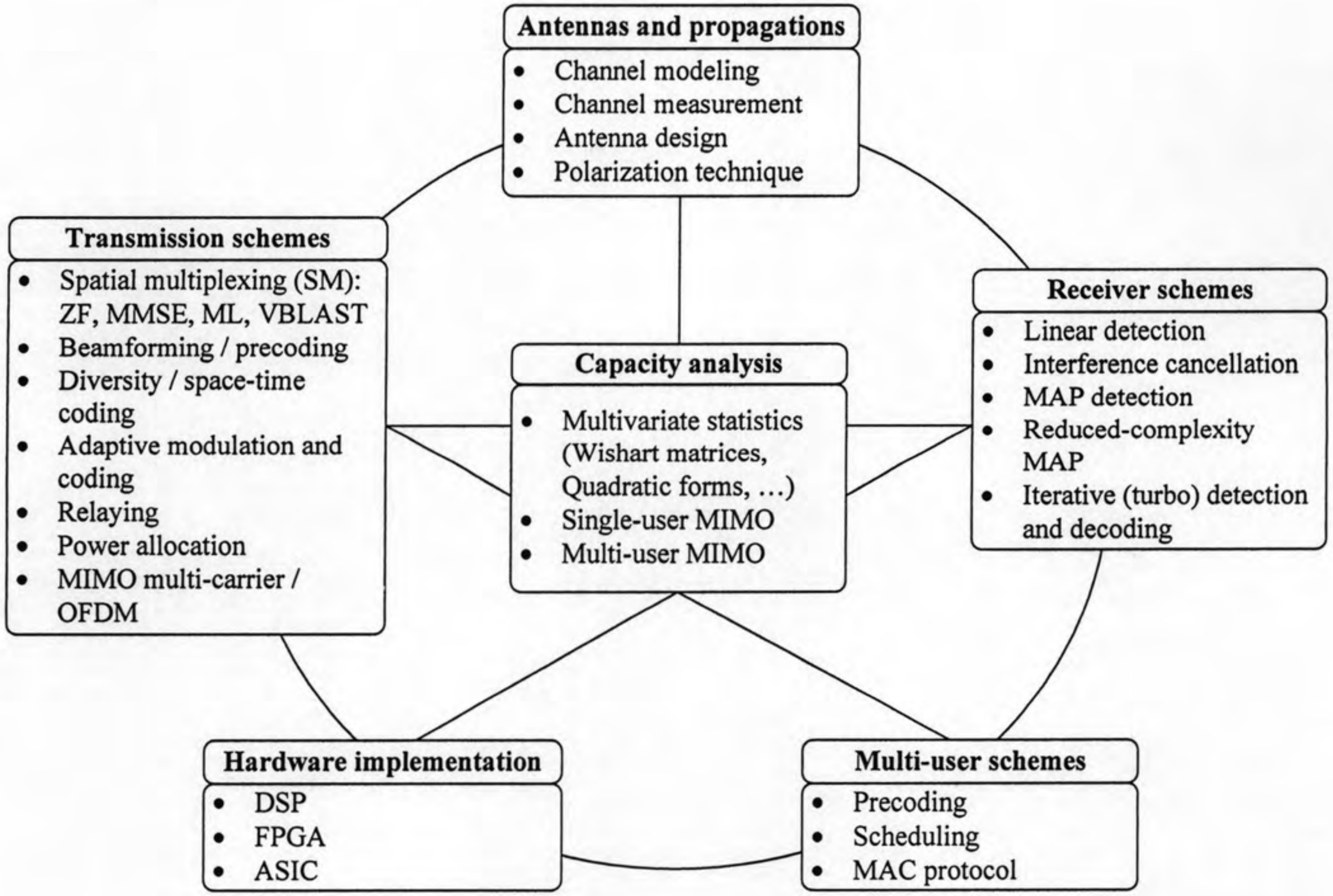

Figure 1.5 Block diagram of principal research topics in MIMO technologies

1.6 Scopes and Goals of Research

The final goal of the research is to study MIMO analysis technologies that can dramatically enhance the spectrum efficiency toward building broadband super-3G wireless systems. The specific target is at the right corner of Figure 1.1, namely, achieving a very high data rate in broadband era with relatively voice and multimedia service types. In particular, this research aims with regard to an aspect of capacity analysis in the center of Figure 1.5 and focus on multivariate statistic with theory of quadratic form on complex random matrices, single-user MIMO with the following scopes:

1. Statistical distributions of the eigenvalues of correlated complex random Wishart matrices are investigated to know the total performance of the system.
2. Analytical evaluations of the channel ergodic capacity in relations with number of transmitter and receiver antennas, the SNR's, and taken into account characteristic of spatial fading correlation in multipath environment.
3. Closed-form ergodic channel capacity expression and / or BER for general M-ary Phase Shift Keying (M-PSK) and M-ary Quadrature Amplitude Modulation (M-QAM) schemes take into account channel estimation errors, feedback delay, and spatially correlated fading channel.
4. Computer simulations are verified for the effectiveness of analysis.

1.7 Contributions of Research

This research has given benefits as follows

1. Provide spatial fading correlation characteristics in uplink mobile communications.
2. Derive the analytical expressions for evaluating the ergodic capacities of an MIMO channel in cases of the spatial fading correlation at the receiver side (known as semi-correlated at one side) and un-correlation at both the transmitter and the receiver.
3. Propose the integral closed-form expression in term of Meijer's-*G* function for simply evaluating the difficulty of the multidimensional integral form.

4. Derive channel ergodic capacity bounds and / or approximation of BER of spatial multiplexing MIMO Rayleigh channels with Zero-Forcing (ZF) receiver operating under practical conditions:
    - Spatially correlated fading channel,
    - Channel estimation errors at the receiver, and
    - Delayed feedback to the transmitter

1.8 Literature Review

An important problem in MIMO systems is to obtain analytical expressions for the channel ergodic capacity of MIMO wireless channels. In a Rayleigh flat fading environment, a MIMO communication link has a asymptotic capacity that increases linearly with the number of the transmitter and the receiver antennas if the complex-value propagation coefficients between all pairs of the transmitter and the receiver elements are statistically independent, known to the receiver antennas and are not correlated [15], [16], [63], and [64].

However, in many practical MIMO wireless transmission environments, correlation between signals transmitted and / or received at the different antenna elements can arise when these elements are not sufficiently spatially separated and / or lack of scattering. The channel coefficients from two different transmitter antennas to a signal receiver antenna can be correlated with the covariance matrix $\mathbf{\Psi}_\mathrm{T}$ while the channel coefficients from a single transmitter antenna to two different receiver antennas can be correlated with covariance matrix $\mathbf{\Psi}_\mathrm{R}$. Some analytical expressions have mostly been considered for the MIMO channel ergodic capacity and outage capacity under correlation frequency flat-Rayleigh fading condition, by using a variety of channel models and analytic techniques [65], [66], [21], [67], [68], [69], [70], [71], and [72].

A number of studies indicate that these correlations degrade the channel capacity, which depends on the physical parameters of the MIMO system and the scattering characteristics. The physical parameters include antenna arrangement and spacing, the Angle-of-Arrival (AoA), the Angle-of-Departure (AoD), etc. Correlation can arise if the antenna elements are not spaced sufficiently far apart. For example, Chuah, et al. early shown in [65] that for antenna spacing equal to half of the wavelength, the simulated average capacity is only 88.5% of the predicted value based on independent fading assumptions, the effect of correlations on total capacity is smaller when the antenna spacing is increased. If the spacing between the antennas is less than half of the wavelength, the correlations become highly dependent. This leads to the concept of *spatial fading correlations*. Also, Lee in [73] pointed out that in order to obtain a correlation coefficient at adjacent elements less than 0.7, the elements must be spaced by about 12-20 wavelengths in the broadside case and 70 wavelengths in the inline case. The presence of a dominant LoS component can also affect the capacity. Therefore, it is important to understand the impact of these factors on the MIMO system channel capacity.

In [67], based on determination of the Moment Generating Function (MGF) of the Mutual Information (MI), M. Kang presented capacity results for MIMO semicorrelated Rayleigh channels when the receiver had perfect CSI. The results illustrate that there is no significant decrease in channel capacity when the spatial correlation is below 0.5. Chiani et al. derived in [74] a concise closed-form expression for the distribution in terms of characteristic function of MIMO system capacity with arbitrary correlation on one side among the transmitter antennas or among the receiver antennas. For exponential correlation model, [74] is also shown that the capacity loss is negligible even with a correlation coefficient between two adjacent antennas as large as 0.5. A set of more interesting results for semi-correlated flat fading channels can be found in [75], [76], and [77].

On the other hand, H. Shin in [68] and [70] analyzed the capacity of MIMO Rayleigh fading channels in the presence of spatial correlation at both the transmitter and the receiver antennas using the correlation model based on realistic channel measurements as well as the classical exponential correlation model. Various recent contributions have been aimed at characterizing the MI distribution under isotropic Gaussian input of MIMO systems for non-correlated channel [78], fully correlated Rayleigh [79] and Rician channels [80].

Recently, most of the analyses involving MIMO systems reported assuming that a perfect or no CSI at the receiver and / or at the transmitter [40], [81], [8], [72]. However, perfect CSI does not exist [82], and therefore it is necessary to fully take into account the practical conditions of imperfections in CSI, and the spatially correlated fading channel during the evaluation of MIMO systems. With *channel* *estimation errors*, the received signal consists of three terms: a signal component, a noise component, and a cross-product term formed by the useful signal and detrimental channel estimation error. Bounding techniques are pioneering work of Medard [83], in which the product term is treated either as part of the signal component or as part of the noise component leading to an upper or lower capacity bound, respectively. It is shown that this lower bound can be achieved by appropriately designing a nearest neighbor decoder-based receiver [84]. The same methodology of [83] is subsequently extended by Yoo [85] to solve the problem with MIMO Rayleigh channels leading to results, again in the form of upper and lower bounds.

1.9 Outline of Dissertation

This dissertation is organized in details in five chapters as follows:

In Chapter I, introduction and research background are presented. This chapter includes the fundamental limits of channel capacity, description of Rayleigh fading channel, research interests in various areas of MIMO technologies, scopes, goals, and contributions of the research.

In Chapter II, the density of non-central quadratic form on complex random matrices and their joint eigenvalues are derived for applications to information theory.

In Chapter III, beginning with model configuration of spatial fading correlation for mobile wireless communications. The MIMO system model and problem definition in the channel capacity are raised when evaluating the integral form for cases of spatial correlation at the receiver and spatial uncorrelated channel. The closed-expression for simply evaluating the integral form is then proposed.

In Chapter IV, a spatial multiplexing MIMO system with zero-forcing receiver operating in conditions that are more practical is proposed. A lower bound of the mutual information is derived for the system.

In Chapter V, significant findings and recommendations are concluded.

Finally, this dissertation is included by a list of references. Appendices A, B are mathematical definition and proof. A complete list of abbreviations and mathematical notations can be found in Appendix C. A list of publication is presented in Appendix D.