CHAPTER 1

INTRODUCTION

A wireless system is expected to fulfil two important requirements. One of those requirements is, the system should provide maximum bits/s for 1 Hz and the other one of the two requirements is, there should be minimum bit error rate (BER) in reception. Multi-element antenna (MEA) systems provide solutions to these two important requirements. These systems have been in research and implementation under two broad categories. They are

(i) Smart antenna systems and
(ii) Multiple-input - multiple-output (MIMO) systems.

Smart antenna systems are the ones, which have MEA at either receiver or transmitter. Smart antennas have been in active research and implementation since the classic paper published by Widrow (1967) on receive-adaptive antennas. A receive-smart antenna is one, which combines signals from different elements by using an adaptive algorithm. A transmit-smart antenna is one, which creates different signals for different antenna elements by using an adaptive algorithm. Smart antennas are used for fulfilling various objectives. The objectives include,

(i) Capacity increase
(ii) Increase of coverage
(iii) BER improvement
(iv) Decrease of delay dispersion
(v) Angle of arrival estimation

MIMO systems employ MEA at both receive side and transmit side. These systems are employed for fulfilling four broad objectives. They are

(i) Spatial Multiplexing
(ii) Diversity
(iii) Interference suppression
(iv) Beamforming

Fundamentally, the last three purposes in these four are the same as those of smart antenna systems. Spatial Multiplexing (SM) is a novel concept, which allows direct improvement of capacity by simultaneous transmission of multiple data streams. As spectrum became more and more precious, the necessity came up for ways of achieving high data rate without using additional bandwidth. It is possible to achieve high data rate with less spectrum using MEA at both receiver and transmitter. That is, it is possible to achieve high capacity in bits/s/Hz with MIMO systems.

Though MIMO systems are attractive, the systems demand high signal processing and hardware complexity and cost. An important contributor to the complexity and cost is radio-frequency chains (RFCs) in transmitter and receiver. An RFC in a transmitter consists of a digital-to-analog converter, an upconverter, and a power amplifier and an RFC in a receiver consists of a low-noise amplifier, a downconverter and an analog-to-digital converter. Antenna selection is a technique, which addresses some of the hardware complexity and cost issues of MIMO systems. In this technique, available RFCs are fewer in number than the available antenna elements. Out
of the available antenna elements, only as many antenna elements as equal to the number of RFCs will be selected. The selection must be such that its speed must be fast enough and it must fetch maximum capacity. Hence, it is necessary to devise good performance/complexity tradeoff fetching algorithms. Antenna selection scheme has been applied in wireless standards such as IEEE 802.11n and WiMax.

Wireless communication started with the works of Maxwell and Hertz. They laid the basis for the understanding of the transmission of electromagnetic waves. Not long after, Tesla and Markoni demonstrated wireless communication. In the subsequent years, radio and television become widespread. 1940s and 1950s saw the development of citizens band mobile telephone system and the cellular principle. However, cellular telephony did not pick up in 1960s. The launch of sputnik by Soviet Union fostered research in satellite communications.

The interest in cellular communications revived in 1970s. The deployment of Global System for Mobile Communication (GSM) was started in 1990s. Further in 1990s cordless phones started replacing normal phones. Wireless Local Loop (WLL) was introduced in 1990s. Then came the Third Generation (3G) cellular systems and Third Generation Partnership Project (3GPP). The development of 3GPP and the introduction of IS-95 CDMA (Code Division Multiple Access) system sparked a lot of research into CDMA. Further in 1990s multicarrier techniques and multiuser techniques were introduced. Finally, multi-antenna systems saw an enormous growth since 1995.

The concept of MIMO can be traced back to as long as 1970s. Kaye and George (1970) proposed and investigated an optimum linear receiver for a frequency-selective MIMO system. Brandenburg & Wyner (1974) investigated the information capacity limits of MIMO channels and derived
an analytical expression for a frequency-selective MIMO channel with perfect channel state information at the transmitter. Linear equalisation for a 2 x 2 MIMO radio systems was studied by Amitay & Salz (1984). Winter (1987) was the first person to carry out the analysis for a MIMO cellular scenario and formulate a capacity expression.

The enormous complexity of hardware and signal processing hindered and demotivated implementation of MIMO systems, though the benefit of MIMO systems compared to the single-input - single-output (SISO) systems was known for decades. In this tight situation, Paulraj & Kailath (1994) demonstrated a practical application of MIMO for digital TV broadcast.

Foschini (1996) introduced the concept of Layered Space-Time (LST) architecture. In his paper, Foschini (1996) proposed an architecture for a point-to-point MIMO communication system, where the data stream required to be transmitted was split to several branches. This system was called as Diagonal Bell Labs Layered Space-Time (D-BLAST). In D-BLAST, code blocks were dispersed diagonally in space-time. The system fetched significantly good increase in the data rate However, it was difficult to implement the system. In this scenario, came another BLAST, called Vertical BLAST (V-BLAST) (Wolniansky et al 1998). V-BLAST struck a compromise between complexity and capacity. Telatar (1999) is the first person to provide a general framework for analysing the ergodic and non-ergodic capacities of MIMO channels. The papers of Foschini (1996), Wolniansky et al (1998) and Telatar (1999) created enormous research interest in MIMO systems. Now, in the world systems involving MIMO concept have been implemented in wireless standards like IEEE 802.11n and LTE, and it is believed that in future wireless systems MIMO concept will play a huge role. MIMO systems can be designed with the sole objective of
maximising capacity or maximising reliability or striking a compromise between the two, called, diversity-spatial multiplexing tradeoff. A MIMO system can be assessed in terms of the following gains:

1. Spatial multiplexing gain
2. Diversity gain
3. Array gain

This research work focuses on MIMO-based capacity maximisation. Capacity maximisation is achieved through a concept called spatial multiplexing. Spatial multiplexing can be of two variants.

(i) Spatial multiplexing with full antennas at both transmitter and receiver.

(ii) Spatial multiplexing with antenna selection.

The basic principle behind spatial multiplexing by a MIMO system is explained by Figure 1.1. In this chapter, in section 1.1, a brief review on spatial multiplexing with full antennas at both transmitter and receiver is given. Section 1.2 introduces spatial multiplexing with antenna selection approach. Section 1.3 gives a literature survey on MIMO antenna selection scheme. Section 1.4 defines the problems. Section 1.5 is on the objective of the research. Section 1.6 outlines the thesis.

![Figure 1.1 Basic principle of spatial multiplexing](image)
1.1 SPATIAL MULTIPLEXING WITH FULL ANTENNAS AT BOTH TRANSMITTER AND RECEIVER

In this scheme, all the antennas available at either the transmitter or the receiver are used. The capacity of a single-input - single-output (SISO) systems for single user channel with random input $X$ and random output $Y$ is defined to be the maximum mutual information of the channel. The mutual information of this case is given by equation (1.1) (Ezio Biglieri et al. 2007)

$$I(X ; Y) = \int_{s_x,s_y} f(x, y) \log_2 \frac{f(x, y)}{f(x)f(y)} \, dx \, dy$$  \hspace{1cm} (1.1)

where, $f(x, y)$, is the joint probability density function of $X$ and $Y$, $f(x)$ is the probability density function of $X$, $f(y)$ is the probability density function of $Y$. $I$ is the mutual information between $X$ and $Y$ and $s_x$ and $s_y$ are the supports over which the integration is done. Shannon (1948) proposed that the channel capacity of the most of the channels is equal to the mutual information of the channel maximized over all possible input distributions. That is,

$$C = \max_{f(x)} I(X ; Y)$$  \hspace{1cm} (1.2)

Using 1-1 in 1-2, we get

$$C = \max_{f(x)} \int_{s_x,s_y} f(x, y) \log \left( \frac{f(x, y)}{f(x)f(y)} \right) \, dx \, dy$$  \hspace{1cm} (1.3)

For a time-invariant additive white Gaussian noise (AWGN) channel with bandwidth $B$ and receive-SNR $\rho$ the maximum-giving
distribution is Gaussian and the channel capacity results in equation (1.4) (Ezio Biglieri et al 2007).

\[ C = B \log_2(1 + \rho) \text{ bps} \]  \hspace{1cm} (1.4)

The capacity limits of a single-user MIMO system can be modelled as follows.

(i) Perfect channel state information at receiver (CSIR) and no channel state information at transmitter (CSIT).

(ii) Perfect CSIR and perfect CSIT.

(iii) Perfect CSIR and channel distribution information at transmitter (CDIT).

(iv) Perfect CSIR and limited feedback to transmitter.

1.1.1 Channel State Information at Receiver (CSIR) and No Channel State Information at Transmitter (CSIT)

For a MIMO system of transmitter symbol vector \( s \) and received symbol vector \( y \), it has been shown by Telatar (1999) that mutual information in bits/s/Hz is

\[ I(s ; y) = \log_2 \det \left( \frac{E_s}{M_T N_0} H R_{ss} H^H + I_{M_R} \right) \]  \hspace{1cm} (1.5)

where, \( I \) is the mutual information between the symbol vectors \( s \) and \( y \), \( E_s \) is the total symbol energy available over a symbol period, \( M_T \) is the number of transmit antennas, \( N_0 \) is the variance of noise, \( H \) is channel matrix, \( R_{ss} \) is autocorrelation matrix of the transmit signal vector , \( H^H \) is the Hermitian transpose of \( H \), and \( I_{M_R} \) is unit matrix of \( M_R \) dimension. Then, the capacity in bps/Hz, based on (1.2) is given by equation (1.6) (Paulraj et al 2003).
$$C = \max_{T_r(R_{SS})=M_T} \log_2 \det \left[ \frac{E_S}{M_T N_0} H R_{SS} H^H + I_{M_T} \right]$$  

(1.6)

where the maximization, which was with respect to \( f(S) \) is now with respect \( R_{SS} \), with a total power constraint of \( E_S \) and \( T_r(R_{SS}) = M_T \). \( T_r(R_{SS}) \) refers to trace of \( R_{SS} \). In the present case, there is no CSIT, hence, the best way is to distribute equal power to all the antennas. In such a case, \( R_{SS} \) becomes \( I_{M_T} \). That is, the capacity in bps/Hz can be written as (1.7) (Paulraj et al 2003).

$$C = \max_{T_r(R_{SS})=M_T} \log_2 \det \left[ \frac{E_S}{M_T N_0} H H^H + I_{M_T} \right]$$  

(1.7)

### 1.1.2 Perfect CSIR and Perfect CSIT

This model is mostly impractical. In this case, since there is CSIT, we can find a way in which the power can be distributed among the antennas so that there can be array gain. Presence of array gain means increase in SNR at the receiver. The optimal power distribution problem is solved by an algorithm called water filling algorithm (Paulraj et al 2003).

It can be shown by applying singular value decomposition (SVD) on \( H \) matrix and with the assumption that the power can be distributed among the transmit-antennas in the desired way using the channel knowledge, the capacity can be written as

$$C = \max \sum_{i=1}^{\tau} \log \left[ \frac{E_S \gamma_i}{M_T N_0} \lambda_i + 1 \right] \text{bps/Hz}$$  

(1.8)

\( \tau \) is the number of non-zero eigen values of \( HH^H \), \( \gamma_i \) is the transmit-energy in the \( i \)th sub-channel and the constraints are

- total power = \( E_S \) and
- \( \sum_{i=1}^{\tau \cdot \max} \gamma_i = M_T \)
The optimal powers for individual antennas are found by waterfilling algorithm (Paulraj et al 2003).

1.1.3 Statistical Characterisation of Capacity

The discussions in sections (1.1.1) and (1.1.2) are for instantaneous capacity. This means that they were for single channel realisation. But, in general, channels will be time-varying. The variation may be fitted into classifications of fast-varying and slow-varying. Under fast-changing channel conditions the channel that is measured at the receiver cannot be fed back to the transmitter before the channel changes its state. Since the channel is not constant during the whole time of interest, its Shannon capacity cannot be stated considering only a single channel realisation. In such cases, the Shannon capacity must be represented by an average. The average is called ergodic capacity. The channel must be sufficiently fast-varying for the ergodic capacity concept to be a useful one. The ergodic capacity will be the expectation of the channel capacity random variable. For example, the ergodic capacity of a perfect CSIR / perfect CSIT case is

\[ C = E\left\{ \sum_{i=1}^{r} \log \left[ \frac{E_s \gamma_i^{\text{opt}}}{M_T N_0} \lambda_i + 1 \right] \right\} \text{ bps/Hz} \quad (1.9) \]

where the part within the braces is a random variable and \( \gamma_i^{\text{opt}} \) reflects the optimum power distribution policy.

Under slow-changing channel conditions, the average concept may not be a good representative. In such cases, a concept called outage capacity is used. Outage capacity is the capacity that is guaranteed with certain level of reliability. The \( p \% \) outage capacity is defined as the information rate that is guaranteed for \( (100-p) \% \) of channel realisations. That is, \( P(C \leq C_{\text{out}}) = p \).
Figure 1.2 shows ergodic capacity of five different CSIR/no CSIT MIMO configurations. \(4 \times 4, 2 \times 2, 1 \times 1, 1 \times 2\) and \(2 \times 1\), where the first number of a configuration refers to the number of receive antennas and the second number refers to the number of transmit antennas. In these, it can be seen that the last three are respectively (SISO), single-input - multiple-output (SIMO) and multiple-input - single-output (MISO) configurations. These configurations are special cases of MIMO configurations. Before going through the important observations those may be noted from Figure 1.2, it is necessary to understand the terms array gain and multiplexing gain.

Array gain is the average increase in the SNR at the receiver due to the coherent combination effect of multiple antennas at the receiver or the transmitter. Intuitively multiplexing gain is the number of parallel spatial data pipes between the transmitter and the receiver. The maximum multiplexing

![Figure 1.2](image)

**Figure 1.2** Plot illustrating ergodic capacities of various MIMO configurations with CSIR and no CSIT

gain \( t_{\text{max}} \) that can be achieved over a MIMO channel is given by the asymptotic slope of the ergodic capacity plotted as a function of the SNR on a linear-log scale. That is
\[ r_{\max} = \lim_{\rho \to \infty} \frac{C(\rho)}{\log \rho} \]

Important points to be observed from the plots are as follows.

1. All the configurations have multiplexing gains; the first one has the highest.

2. Cases 4×4, 2×2 and 2×1 have receive-array gain, but not transmit-array gain because of respectively informed receiver and uninformed transmitter, whereas case 1×2 has neither of the two array gains, though there are multiple antennas at the transmitter. Case 1×1, which is a SISO, has no receive-array gain and transmit-array gain.

3. The multiplexing gains are high at high SNRs.

1.1.4 Capacity with Perfect CSIR and CDIT

Perfect CSIR and CDIT case is applicable for the scenario, where the channel state can be accurately tracked at the receiver, but, it is not possible to accurately do at the transmitter. The inability to track at the transmitter occurs when the channel is fast-varying. In such cases, only the statistics of the channel is conveyed to the transmitter. The channel is modelled to be one of the following.

(i) Zero-mean spatially white (ZMSW) model.

(ii) Channel mean information (CMI)-based model.

(iii) Channel covariance information (CCI)-based model.

Channel capacity under covariance feedback has been discussed in (Jafar et al 2001) and (Jorsweik et al 2004).
1.1.5 Capacity with Limited Feedback

Another way of informing a transmitter is using limited feedback concept. Channel distribution feedback causes more overhead. Without an explicit feedback it is possible to access the channel when frequency division duplexing (FDD) and time division duplexing (TDD) are used. When FDD is used we can have a channel access, but the frequencies used are different for the two links. Hence, the channel information will not be of use. TDD will be of use provided the time difference between the two links is less than the coherence time of the channel.

The receiver may estimate the channel based on training or blind estimation method. Blind techniques are based on concepts such as cyclostationarity, finite alphabets and constant modulus. Blind techniques for multi-antenna systems have been discussed in (Boleskei, H 2002) Semi-blind methods mix training and blind techniques. In limited feedback approach, codebook concept is used very much. The receiver obtains the channel knowledge. Using this knowledge, the receiver can quantise $\mathbf{H}$. The receiver can determine a rate-maximising input covariance matrix corresponding to the quantised $\mathbf{H}$ and feed the index of the covariance matrix back to the transmitter. For this, codebooks are maintained at both transmitter and receiver. Here, the codebook is a set of covariance matrices

$$\mathbf{R}_s = \{ \mathbf{R}_{ss_1}, \mathbf{R}_{ss_2}, \ldots, \mathbf{R}_{ss_B} \}$$

where $B$ is the number of bits of the index of the matrix. Only the indices of the covariance matrix will be sent to the transmitter. The index that will be sent to the transmitter will satisfy,

$$C = \max \log_2 \det \left[ \frac{E_S}{M_{RN_0}} \mathbf{H} \mathbf{R}_{ssn} \mathbf{H}^H + \mathbf{I}_{M_R} \right]$$  \hspace{1cm} (1.10)
where \( 1 \leq n \leq 2^B \)

The corresponding \( R_{ssn} \) will be named as \( R_{ssn, opt} \).

The corresponding maximum achievable rate in bps/s will be ergodically

\[
\begin{align*}
C &= E \left\{ \max_{R_{ssn}} \log_2 \det \left[ \frac{\sigma^2}{M^2 N_0} H R_{ssn} H^H + I_{M_R} \right] \right\} \\
\end{align*}
\]

(1.11)

\( R_{ssn} \in R_{ss} \)

where \( R_{ss} \) is the set of covariance matrices. The covariance codebook may be fixed or dynamic. Fixed codebook design has been discussed in (Lau et al 2004). Random approaches to codebook design have been proposed in (Dabbagh et al 2006). It has been shown in (Dabbagh et al 2006) that rate loss decreases exponentially with the number of feedback bits.

1.1.6 Capacity in Spatial Fading Correlation Condition

Correlation of channel elements \( [H]_{i,j} \), where \( [H]_{i,j} \) stands for individual elements of \( H \), exists when there is no rich scattering, there is insufficient inter-antenna element spacing and when using polarized antennas. For the case, in which there is CSIR, no information at transmitter and there is correlation among channel coefficients of \( H \), Kronecker model may be used. This is a simple model, but, a reasonable one.

The channel is modeled as follows (Paulraj et al 2003)

\[
H = R_r^{1/2} H_w R_t^{1/2}
\]

(1.12)

where \( R_r \equiv \) Receive antenna correlation matrix of \( M_R \times M_R \)
\[ R_t \equiv \text{Transmit antenna correlation matrix of } M_T \times M_T \]

\[ H_w \equiv \text{Spatially white channel} \]

Receive-correlation is dependent on the scattering objects present close to the receive-antenna and receive-antenna inter-element spacing. Transmit-correlation is dependent on scattering objects present close to the transmit-antenna and transmit-antenna inter-element spacing.

\[ \mathbf{R}_r \text{ and } \mathbf{R}_t \text{ are normalised such that} \]

\[ [\mathbf{R}_r]_{i,i} = 1 \]

where \( i = 1,2,3,\ldots,M_R \)

\[ [\mathbf{R}_t]_{j,j} = 1 \]

where \( j = 1,2,3,\ldots,M_T \)

On using Equation (1.12)

the capacity in bps/Hz for no CSIT becomes

\[ C = \log_2 \det \left[ \mathbf{I}_{M_R} + \frac{E_S}{M_T N_0} \mathbf{R}_r^{1/2} \mathbf{H}_w \mathbf{R}_t \mathbf{H}_w^H \mathbf{R}_r^{1/2} \right] \]  \hspace{1cm} (1.13)

For the case of equal number of transmit- and receive-antennas and high \( \rho \) values, capacity can be approximated to be

\[ \log_2 \det \left[ \frac{\rho}{M} \mathbf{H}_w \mathbf{H}_w^H \right] + \log_2 \det(\mathbf{R}_r) + \log_2 \det(\mathbf{R}_t). \]  \hspace{1cm} (1.14)

It can be shown that \( \det(\mathbf{R}_r) \) and \( \det(\mathbf{R}_t) \) are always less than or equal to zero, where the case of being equal to zero will be a special and rare
one. What is being informed is, the capacity goes for a decrease due to the existence of correlation.

1.2 SPATIAL MULTIPLEXING WITH ANTENNA SELECTION APPROACH

MIMO systems are attractive; but, high signal processing and hardware complexities and cost are involved in them. An important contributor to the complexity and cost is Radio-frequency chains (RFCs) in transmitter and receiver. Because of the huge cost involved in RFCs, it becomes necessary to have less number of them. But, cost factor should not be an obstruction for capacity and it is necessary to find a mechanism of attaining maximum capacity with the given number of RFCs. One can have larger number of space links at his/her disposal and select the best as many number of links as equal to the number of the RFCs. Having larger number of space links will mean having larger number of antennas, and selecting the best links will directly transform to the best antennas. The best links may change with prevailing channel conditions. Hence, it is necessary to go for different antenna subsets at different times as it may be necessary.

The hardware cost may be a concern only for the transmitter implementation or only for the receiver implementation or for both transmitter and receiver implementations. Figure 1.3 describes the antenna selection carried out at both the transmitter and receiver. In this system, there are \( M_T \) antennas and \( I_T \) RFCs at the transmitter and \( M_R \) antennas and \( I_R \) RFCs at the receiver. Since the numbers of RFCs are only \( I_T \) and \( I_R \), only \( I_T \) and \( I_R \) antennas need to be selected at respectively the transmitter and the receiver. Channel information will be obtained by the receiver and then an algorithm will identify which antennas must be selected at the transmitter and the receiver. The indices of the selected transmit antennas will be transmitted to the transmitter from the receiver through a wireless feedback link. The indices
of the selected receive-antennas will be sent to the RF switch of the receiver. The links within the receiver and the link from the receiver to the transmitter are shown in the figure.

![Diagram of antenna selection](image)

**Figure 1.3 Antenna selection both at the transmitter and the receiver**

Antenna selection may be carried out on the basis of either instantaneous channel measurement or the channel statistics measurement. Instantaneous channel measurement-based selection is usually done for sufficiently slow-varying channel conditions. In instantaneous selection method, in order to select the best subset, all the $M_T M_R$ links corresponding to all possible transmitter and receive antenna pairs need to be sounded, even though only $L_T$ and $L_R$ elements at the transmitter and receiver, respectively, will eventually be used for data transmission. In general, such sounding can be achieved with a switched approach. For simplicity, it may be assumed that $R_T = M_T/ L_T$ and $R_R = M_R/ L_R$ are integers. Then the available transmit (receive) antenna elements can be divided into $R_T$ ($R_R$) disjoint sets. The switched antenna sounding now repeats $R_T R_R$ times a standard training sequence that is suitable for an $L_R \times L_T$ MIMO system. During each repetition of the training sequence, the transmit (receive) RF chains are connected to different sets of antenna elements. Thus, at the end of the $R_T R_R$ repetitions, the complete channel has been sounded.
Channel statistics measurement-based selection may be done for fast-varying channels. In this method, selection can be done on the basis of channel statistics (for example, fading correlations), whose variation is orders of magnitude slower than that of fading. It was shown in (Zhang&Dai 2004) that such an antenna selection approach is effective in highly correlated channels.

This research work is on antenna selection for sufficiently slow-varying channel conditions. The antenna selection corresponding to sufficiently slow-varying channel conditions is instantaneous antenna selection. There are various types of algorithms for doing instantaneous antenna selection. The algorithms are expected to be of low complexity and high performance. Performance and complexity tradeoff plays an important role in deciding on the algorithm. The algorithms can be classified to be

(i) Decremental or incremental successive algorithms (greedy algorithms)

(ii) Correlation or uncorrelation-based algorithms

(iii) Norm-Based algorithms

1.3 LITERATURE SURVEY

Starting from year near 2000, the antenna selection approach of maximizing capacity has been advocated. Antenna selection may be only at the transmit side or only at the receive side or at both sides. Majority of the papers were devoted for single-side selection. Various algorithms of different tradeoffs and different varieties such as norm-based ones, correlation and norm-based ones and greedy ones have been proposed in the literature for single side selection. For a system, which has $M_R$ total receive antennas and $M_T$ total transmit antennas, to select $L_R$ antennas for maximising capacity, the optimal way is to carry out determinant calculation $\binom{M_R}{L_R}$ times as required by
the capacity formula given by Telatar (1999) and arrive at the highest capacity-giving antenna subset. Such an exhaustive search method was used by Winter & Win (2001) for diversity reception. Similar argument is applicable for transmit side also. Surely, \(\binom{M_R}{L_R}\) computations of determinants will demand prohibitively large amount of time. To alleviate this complexity problem, yet, gain the advantages of antenna selection concept, sub-optimal algorithms, in which a compromise is struck between the computation complexity and the capacity performance, have been developed. Various capacity-based single-sided antenna selection problems have been discussed in the literature. In (Gore et al 2000) antenna selection was considered at the transmitter for a low rank channel. In that paper, there was no mention of RF chain constraint concept with regard to antenna selection, rather, an optimization criterion was built up for maximising the capacity and the algorithm of antenna selection was left as a future direction. In (Heath et al 2001) a signal-to-noise (SNR)-based criterion was developed for antenna selection in transmit side for spatial multiplexing systems using ZF-based linear receivers. In (Molisch et al 2001), the concept of antenna selection with respect to the RFC was introduced. In that paper, an analytical bound for the capacity was derived. The system was called hybrid selection MIMO (H-S/MIMO), where in the case of standard diversity, it is called as hybrid selection-maximum ratio combining (H-S/MRC). In (Gore et al 2002), a selection rule for maximising the average throughput was given for transmit-antenna selection of spatial multiplexing system.

A norm-based antenna selection algorithm for transmit side was suggested by Gore et al (2001) for the Alamouti space-time coding system. In this, antennas of largest Euclidean norms were selected. Norm-based selection can also be used for capacity criterion as suggested in (Sanayeii & Nosratinia
2004). But, the algorithm itself was not stated by either Gore et al (2001) or Sanayei & Nosratinia (2004).

A high-capacity achieving sub-optimal antenna selection algorithm, whose performance in terms of capacity is very close to that of the optimal one, and in terms of computational complexity is not that promising, was given by Gorokhov (2002). This algorithm started with the full set of antennas and one by one deleted the least capacity-contributing antenna. It directly dealt with the exact capacity expression. It changed the problem of finding determinant into finding an inverse for the purpose of reducing the computational complexity. However, the inverse lemma used in the algorithm demands a huge number of flops. The complexity of this algorithm was calculated to be \( O(M_T^3 + M_T^2 M_R^2) + O(M_R^2 M_T^2) + O(M_R^2) + O(M_T^2 M_R^2) + O(M_T M_R^2) \) in (Gharavi & Gershman 2004) for receive-side selection. A follow-up to Gorokhov (2002) was made by Gharavi & Gershman (2004), who introduced an addition-based sub-optimal algorithm for receive-side selection. In that paper, the authors followed the procedure of starting with empty set of antennas and then adding one by one maximum-capacity-contributing antenna. They used the well known capacity Equation (2.1) for their algorithm. Gharavi & Gershman (2004) also changed the problem of finding determinants to finding inverse as done in (Gorokhov 2002), but, the difference is that computation for finding the inverse was dramatically reduced by using a lemma that finds the inverse by an iterative procedure, which involves addition and matrix multiplication. The similarity between the two is that both come under the classification of greedy algorithms.

A computationally and constructionally simple algorithm was given by Molisch et al in (2005). This algorithm does not directly deal with Equation (2.1); it comes under the classification of fast selection sub-optimal
algorithms, where it is understood that this kind of algorithms do not use directly Equation (2.1) and surely there will be a small compromise on capacity. Clearly, this algorithm is simple, but, there is considerable penalty in terms of capacity. A comprehensive performance analysis of MIMO systems with transmit antenna selection and stochastic power allocation for the spatially correlated fading channels has been carried out in (Liang 2009). An efficient suboptimal transmit antenna selection was proposed for MMO relay networks by Tarkhan et al(2011). Computationally efficient antenna selection schemes were proposed for amplify-and-forward MIMO relay systems in (Heesun et al 2012.)

Various articles have been published on the antenna selection at both sides for capacity maximisation. However, the joint or combined antenna selection has received considerably less attention than the single-side selection has received. The articles published have dealt with decoupled transmit/receive antenna selection and greedy joint selection. The concept of both-side selections was first proposed in (Gorokhov et al. 2004). The authors suggested optimal search separately on receive-antenna and transmit-antenna sides, reducing the otherwise required calculation of $\binom{M_R}{L_R}\binom{M_T}{L_T}$ determinants to calculation of $\binom{M_R}{L_R} + \binom{M_T}{L_T}$ determinants without affecting the capacity much. Further in (Sanayeit et al. 2004), the decoupling concept was suggested in terms of greedy algorithm of (Gharavi & Gershman 2004) at both sides. But, the algorithm was not developed for the transmit-side and the complete algorithm with complexity involvement was not given. A greedy joint algorithm, efficient joint transmit and receive antenna selection (EJTRAS) for capacity maximisation was proposed by Chiao-En Chen (2010). This algorithm may give very little improvement over the decoupled version of algorithm given by Gharavi & Gershman (2004), whereas the
computation requirement is much higher. Hanif et al. (2012) proposed a joint antenna selection scheme for MIMO cognitive radios. In this one of the two objectives was maximizing data rate.

1.4 PROBLEM STATEMENT

MIMO systems are attractive, but, high signal processing and hardware complexities and cost are involved in them. An important contributor to the complexity and cost is Radio-frequency chains (RFCs) in transmitter and receiver. Because of the huge cost involved in RFCs, it becomes necessary to have less number of them. But, cost factor should not be an obstruction for capacity and it is necessary to find a mechanism of attaining maximum capacity with the given number of RFCs. One can have larger number of space links at his/her disposal and select the best as many number of links as equal to the number of the RFCs. Having larger number of space links will mean having larger number of antennas, and selecting the best links will directly transform to the best antennas. The best links may change with prevailing channel conditions. Hence, it is necessary to go for different antenna subsets at different times as it may be necessary.

Antenna selection is applicable for sufficiently slow-fading channels, where there is time to do selection. However, the channel has to be identified before the training preample is completed and selection must be done fast. Hence, speed of the algorithm matters. Hence, the following questions arise. How do the existing algorithms tradeoff exactly capacity performance with complexity? In what context the existing algorithms do well and in what contexts their performance/complexity tradeoffs may be poor? How do the performance/complexity tradeoffs work when the algorithms are extended as transmitter/receiver algorithms? Are there any other schemes,
which can do a different tradeoff between capacity performance and complexity? An attempt has been made to answer these questions.

1.5 OBJECTIVE OF THE RESEARCH WORK

Instantaneous antenna selection is applicable for block fading or sufficiently slow-fading channels, where there is sufficient time to do selection. A training sequence preamble, which is known to the receiver, is used in transmission of data. The training sequence duration must be low as far as possible, because, the sequence is an overhead. The channel must be identified within the training sequence time and selection must be done fast. Hence, the speed of the algorithms used for antenna selection is important. With speed, the capacity performances of the algorithms also are important. The research work focuses on proposing low complexity algorithms for antenna selection for capacity maximisation, calculating the exact complexity of the existing and the proposed algorithms and pointing out the capacity performance/complexity tradeoffs of the algorithms. In terms of complexity calculation, a novel contribution of calculating the real-real complexity is done. The objectives of this research work are as follows.

(i). To develop low complexity receive-only antenna selection algorithm for instantaneous antenna selection.

(ii). To analyse the performance/complexity tradeoff of the existing algorithms and the proposed algorithm.

(iii). To extend the receive-only algorithms as transmit/receive algorithms.

(iv). To analyse the performance/complexity tradeoff of the extended algorithms.

(v). To propose new joint and decoupled algorithms.

(vi). To analyse the proposed new joint and decoupled algorithms for
their performance/complexity tradeoffs.

(vii). To make a comparative study on the performance/complexity tradeoffs of all the transmit/receive algorithms.

The contributions in this thesis can be divided broadly into two parts

(i) A receive-only uncorrelation-based antenna selection algorithm and its performance/complexity tradeoff with the existing ones and

(ii) Decoupled and joint transmit/receive antenna selection algorithms and their capacity/complexity tradeoffs.

1.5.1 Receive – Only Selection Algorithm

Gharavi & Gershman (2004) suggested an incremental successive selection algorithm for receive-side selection for capacity maximisation. The algorithm’s exact complexity is, in this research work, analysed and it is concluded that this algorithm places a constraint on the number of antennas that can be selected with less complexity. Molisch et al (2005) suggested correlation and norm-based algorithm for capacity maximisation. The pseudo-statements have been framed for this algorithm and complexity has been calculated. The algorithm is more sub-optimal than Gharavi & Gershman algorithm (2004). An uncorrelation-based algorithm, which performs considerably better than Molisch et al (2005) algorithm and is less complex than Gharavi & Gershman algorithm (2004) is proposed through proper development. The pseudo-statements have been formed and the exact complexity is calculated. The superiority of the algorithm is pointed out through simulation and complexity analysis.
1.5.2 Decoupled and Joint Transmit/Receive Antenna Selection Algorithms and their Performance/Complexity Tradeoffs

The algorithms proposed for the single-side selection can be extended to be transmitter/receiver antenna selection algorithm by doing separate selection for the receiver first and then repeating the selection for the transmitter. In this, for the transmitter case, the effective $H$ matrix will change. Hence, among the algorithms the relations of complexities may change. In this view, the existing and proposed receive-only selection algorithms that were discussed in the previous section have been extended in a decoupled way as transmit/receive antenna selection algorithms and the capacity/complexity tradeoffs are investigated. Three norm-based joint and decoupled algorithms are proposed and the capacity/complexity tradeoffs are analysed. Finally, all the joint and decoupled algorithms are compared together for their capacity/complexity tradeoffs.

1.6 THESIS OUTLINE

The thesis consists of four main chapters. The above-mentioned contributions are split into four chapters. One chapter has been devoted for receiver-only selection algorithms and three chapters have been devoted for transmit/receive algorithms. Outlines of the chapters are as follows.

**Chapter 2** makes a discussion on two existing algorithms and then proceeds to propose an uncorrelation-based antenna selection algorithm for capacity maximisation. It consolidates the complexities of the three algorithms in terms of real-real flops, gives simulated results on performances and complexities.

**Chapter 3** extends the algorithms of chapter 2 as transmit/receive ones. For all the algorithms, the pseudo-statements are framed and
complexities are consolidated in terms of real-real flops and simulated results are given for performances and complexities.

**Chapter 4** proposes simple norm-based decoupled and joint transmit/receive algorithms. The complexities are calculated and simulated results are given for performances and complexities.

**Chapter 5** puts together the complexities and performances of all the decoupled and joint transmit/receive algorithms and a unified comparison is brought out on the performance/complexity tradeoffs.

**Chapter 6** provides the conclusion. This chapter summarises main results of the thesis, discusses the implementations of antenna selection scheme in wireless standards briefly and gives the future directions.