Autocorrelation Function Based Mobile Velocity Estimation in Correlated Rayleigh MIMO Channels

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ABSTRACT

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In upcoming 4th generation mobile systems using multiple antennas, knowledge of the speed of the mobile will help allocate adaptively scarce system resources to users. Due to insufficient scattering in the propagation environment or insufficient antenna spacing on either the transmitter or receiver, Multiple Input Multiple Output (MIMO) channels are often correlated. Velocity estimation in MIMO channels has not received much attention up to now. On the other hand, a large number of schemes have been developed for velocity estimation in Single Input Single Output (SISO) systems. Some of these schemes can be categorized as Autocorrelation Function (ACF) based schemes. These ACF based schemes are easy to implement and give accurate velocity estimates. In this thesis, we focus on extending this existing class of ACF based velocity estimation schemes to correlated MIMO channels. This way, the benefits of ACF based schemes can be derived in commonly occurring correlated MIMO channels.

In the first part of the thesis, we first establish a performance reference by determining the performance of ACF based schemes in uncorrelated MIMO channels. Then we analyze the performance of ACF based schemes in correlated MIMO channel using the full antenna set. Some loss in the accuracy of velocity estimates is observed compared to the case of the uncorrelated MIMO channel. To recover this loss, we then present a channel decorrelation based recovery scheme.

The second part of the thesis studies the extension of ACF based schemes to the case of correlated MIMO channels with antenna selection. The performance of the ACF based schemes in this case is analyzed. In this case, a degradation of performance larger than the case of the full antenna set is noticed. Thereafter a recovery scheme based on channel decorrelation is presented. This scheme partially recovers the degradation in accuracy of velocity estimates. Thus the work performed in this thesis enables us to obtain accurate estimates of velocity in correlated MIMO channels.

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1 Introduction

1.1 Motivation

Until lately wireless communication meant transmission over a single link, i.e. with one transmit and one receive antenna, known as a single input single output (SISO) link. Recently the concept of multiple antennas on both the transmitter and receiver side has become wide spread. These multi-antenna systems are known as multiple input multiple output (MIMO) systems. The supremacy of the MIMO technology over earlier SISO systems can be explained as follows. The three basic parameters that comprehensively describe the quality and usefulness of a wireless link are speed, range and reliability. Prior to the advent of MIMO, improvement of one of these three parameters meant sacrificing the other two. For example an increase in speed means reduced range and reliability. Similarly, an extension of range means lesser throughput and less reliable communication. To achieve a more reliable communication, the speed and range of the system have to be reduced. MIMO technology has redefined the tradeoffs, clearly proving that it is capable of boosting all three parameters simultaneously [3]. With this capability, MIMO has already pushed its way into two broadband wireless access standards of IEEE, IEEE 802.16d for fixed broadband wireless access (FBWA) and IEEE 802.16e standard for mobile broadband wireless access (MBWA) also known as fixed and mobile WiMax respectively, in industry. Currently MIMO stands as the leading technology for upcoming 4G systems capable of delivering solutions for tomorrows communication needs.

The 4G systems should be capable of working efficiently in wide range of operating conditions, such as large range of mobile subscriber station (MSS) speeds, different carrier frequencies in licensed and license-exempt bands, various delay spreads, asymmetric traffic loads in downlink and uplink, and wide dynamic signal to- noise ratio (SNR) ranges. To deliver satisfactory performance to all users in dynamic conditions, a key feature of 4G systems is adaptive resource allocation (ARA). To keep the increasing number of subscribers demanding high speed services on their mobile devices satisfied at all times, the limited system resources will have to be very judiciously allocated to each subscriber. This will entail the operator's infrastructure to allocate resources to users adaptively, thus so called adaptive resource allocation. Velocity of a mobile terminal is a key parameter to aid in adaptive resource allocation.

On the receiver side, adaptive channel estimation techniques [2] are often used, in which the frequency of channel update depends on the mobile speed. For instance, the update rate is increased when the channel changes fast enough due to a high relative velocity between the mobile terminal and the base station. On the transmitter side, velocity estimation can be used to dictate adaptive coded modulation (ACM). To take the advantage of channel fluctuations, MBWA systems use adaptive modulation and coding. The concept of ACM is to transmit as high a data rate as possible when the channel is good, and to work at a lower rate when the channel is bad, in order to minimize dropped packets [3]. This is achieved by varying the coding rate, transmit power and constellation type. An example of the influence of the estimated velocity on ACM is that, pedestrians (with a slow varying channel) get 64 QAM whereas faster vehicles (with a faster varying channel) get QPSK in order to maintain the link quality.

Velocity estimation aids also in radio network control by influencing hand off and dynamic cell layer assignment algorithms. For example, rapid processing of handoff requests from fast moving users in microcellular networks can prevent calls from dropping. Thus, a velocity-adaptive hand off algorithm will give a robust performance in a severe propagation environment that is typical of an urban microcellular network. In hierarchical cell layer designs, faster moving mobiles are assigned to larger cells to avoid unnecessary handoffs, thus reducing computational burden on base station. On the other hand, slower moving pedestrians will be assigned pico cells so they can benefit from a higher data rate not limited by constraints arising from high speed. Other parameters like the direction of movement of the mobile and the position of the mobile can be closely used together with the velocity of the mobile for various purposes. These include mobile tracking and location. Enhanced 911 is a prime example of the practical usage of geolocation and tracking services in use today. However, the study of all of these parameters is outside the scope of this thesis and the interest reader is referred to [31] and [50] and references therein. We strictly appreciate the benefits of the magnitude of the velocity of the mobile, which makes it indispensible data in most mobile communication systems.

The usefulness of velocity estimation outlined above clearly demonstrates how effective it could be in aiding the very critical process of adaptive resource allocation (ARA). Since ARA is a key feature of upcoming 4G systems based on MIMO technology, velocity estimation in MIMO systems becomes a very important research topic, which is our focus in this thesis.

1.2 Scope and organization of the thesis

There exists a large class of ACF based velocity estimation schemes for SISO systems which deliver good performance and are computationally inexpensive [9]-[21]. We focus on extending this existing class of velocity estimation schemes for use in practical MIMO systems. Some papers have presented ACF based schemes which they claim to be readily extendable to MIMO channels [14],[15],[18],[20],[21]. Intuitively it occurs that for an ideal MIMO channel, i.e. an i.i.d. Rayleigh fading MIMO channel with $N = N_t \times N_r$ SISO channels (N_t=No. of transmit antennas, N_r=No. of receive antennas) applying an ACF based scheme to each SISO channel and then averaging the N velocity estimates obtained should give an accurate estimate of the MIMO mobile velocity. However, this stands true only as long as the MIMO channel remains ideal, i.e. all the SISO channels remain completely uncorrelated with each other. This is seldom realized in realistic MIMO channels. In practice, the channels between pairs of transmit-receive antenna exhibit correlation amongst them. This could be due to insufficient antenna spacing or scatter geometry around the transmitter/receiver. Such a channel is called a correlated MIMO channel. We study the extension of existing ACF based velocity estimation schemes to the correlated MIMO channel using a full set of antennas. Alongside, the high cost of RF equipment required to implement MIMO systems has recently triggered interest in transmitting and/or receiving over only selected antennas to reduce RF equipment cost, a phenomenon known as antenna selection. Considerable work has been done in this area, and it could very possibly come into widespread use in practical systems soon [5]. Hence, while conducting our study, we also take into consideration correlated MIMO channels with antenna selection.

The thesis is organized as follows. Chapter 2 presents some background material on the Rayleigh fading model of mobile wireless channels along with a discussion of the ideal MIMO channel, the correlated MIMO channel and the MIMO channel with antenna selection. ACF based velocity estimation schemes for SISO wireless systems are also reviewed in the chapter. Chapter 3 reveals the performance degradation of the ACF based velocity estimation in correlated Rayleigh fading MIMO channels using a full set of antennas. A channel decorrelation based scheme for recovering this performance loss is then presented. Simulation results support the loss in performance revealed and show that the proposed recovery scheme is capable of recovering 100% of the performance loss provided accurate channel state information (CSI) and correlation matrix estimates are available. Thus, by using the proposed recovery method presented in this chapter, ACF based schemes will give accurate velocity estimates when extended to correlated MIMO channels using a full set of antennas. Chapter 4 reveals the performance degradation of the ACF schemes in correlated Rayleigh fading MIMO systems using only a subset of antennas. A scheme for recovering this performance loss is also proposed in this chapter. Simulation results support the degradation of performance and illustrate that the proposed recovery scheme is capable of recovering approximately 50 % of the degradation. Thus the recovery scheme proposed in this chapter can be used to obtain good velocity estimates when ACF based schemes are extended for use in correlated MIMO channels using a subset of antennas. Chapter 5 summarizes the conclusions of the thesis and presents recommendations for future work.

1.3 Contributions

Specifically, the following is contributed towards in this thesis:

- First, the accuracy of velocity estimates obtained when ACF based velocity estimation schemes are extended to i.i.d MIMO channels using the full set of antennas is established. Next, it is disclosed that when ACF based velocity estimation schemes are extended to the case of correlated MIMO channels using either a full set of antennas or a subset of antennas, the resulting velocity estimates are less accurate than the case of the i.i.d channel using a full set of antennas. This reduced accuracy is seen as a higher Mean Squared Error (MSE) in the former case than the MSE obtained in the latter case.

- Two channel decorrelation based recovery schemes are proposed for reducing this increase in MSE for both cases, the case using the full set of antennas and the case where only a subset of antennas is used. For the former case, application of the proposed recovery scheme reduces the increase in MSE by 100 % whereas for the latter case the proposed recovery scheme partially reduces the increase in MSE.
- Simulation results are presented to validate the increase in MSE for both cases, the case of a full antenna set and the case of a subset of antennas. The reduction in MSE after applying the two proposed schemes is also validated by simulation results.

2 Background

This chapter presents some technical background material that is required to carry out further investigation of mobile velocity estimation in Chapters 3 and 4. It begins with the presentation of some of the important aspects of mobile wireless channels. The Rayleigh fading model for the wireless channel is then presented along with discussions on the variation of the mobile channel with changing vehicle speed. Further on, MIMO systems are introduced with a focus on uncorrelated MIMO channels, correlated MIMO channels and MIMO channels with antenna selection. Thereafter, a brief review of existing velocity estimation approaches ACF is presented. Lastly, the extension of ACF based methods to MIMO systems is discussed.

2.1 The Rayleigh fading model for the mobile wireless channel

Although in a mobile radio system the base stations (BSs) are usually laid out well above the local terrain to achieve reasonable coverage area, the immediate vicinity of the mobile stations (MS) is usually cluttered with objects. This means that there probably exists no line of sight between the BS and the MS antennas. Transmitted plane waves arrive at the mobile station after undergoing reflection, diffraction and scattering from many different directions and with different delays as shown in Figure 2.1. This phenomenon is called multipath propagation. The different plane waves add up as vectors at the MS antenna to produce a composite received signal.

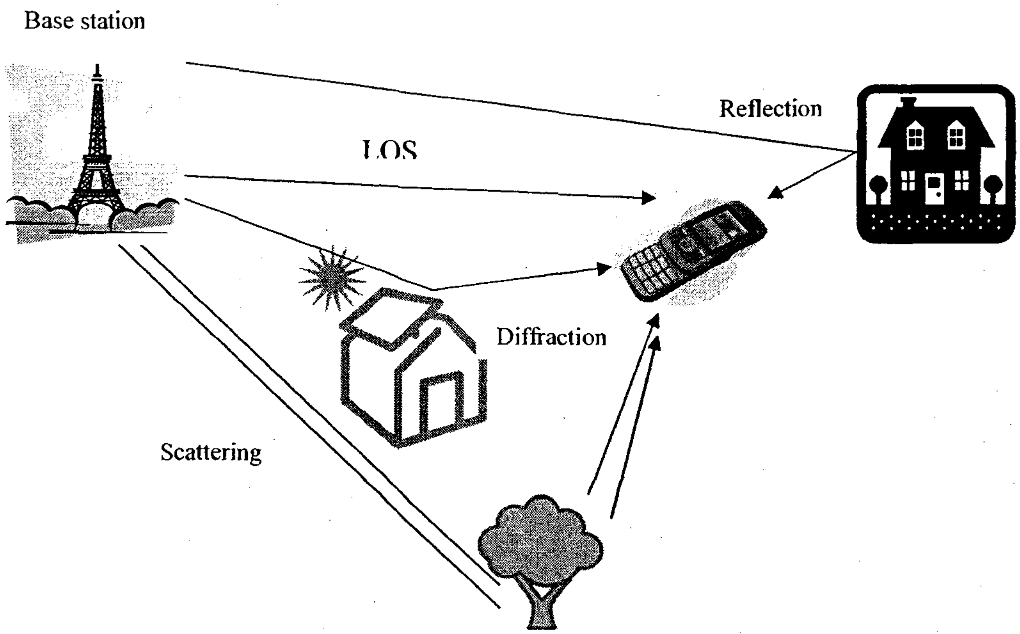

Figure 2.1 Propagation effects in a wireless channel

The short wave length of the carrier in current mobile radio systems causes small changes in the delays introduced by the moving MS, which produce large changes in the phases of the arriving plane waves. This results in constructive and destructive addition of the incident plane waves, leading to large variations in the envelope amplitude and phase of the composite received signal at the MS. These variations are known as signal amplitude variations with time at the MS and the phenomenon is called envelope fading.

Many models have been used to describe the signal amplitude variation in wireless communication channels. In this thesis, we use the Rayleigh fading model to describe the fading amplitude in flat fading channels between each pair of transmit and receive antennas in the MIMO system. The Rayleigh fading model can be easily described based on Clarke's model. The Clarke's model assumes that a stationary transmitter transmits a signal to a moving mobile and the electro magnetic field of the received signal is a result of scattering. At each mobile antenna, the incident field consists of N horizontally traveling plane waves of a random phase and equal average amplitude. The phase is assumed to be uniformly distributed between 0 and 2π. Moreover, it is assumed that the arriving amplitudes and phases are all statistically uncorrelated. The vertical component of the electromagnetic field, denoted by E_z can then be written as

$$E_z = \sum_{i=1}^{N} E_i e^{j\theta_i} = X + jY \tag{2.1}$$

where E_i and θ_i represent the amplitude and phase of the i-th arriving wave respectively. If N is sufficiently large, according to the Central Limit Theorem E_z approximates to a Gaussian Random Variable (RV). Thus, the in-phase and quadrature components of the vertical component of the electric field, denoted by X and Y respectively, are also Gaussian RVs with means and variances given by

$$\mathrm{E}[X]=\mathrm{E}[Y]=0,\ \sigma_{\mathrm{X}}^2 = \sigma_{\mathrm{Y}}^2 = \sigma^2 \tag{2.2}$$

where E[·] denotes the expectation operator and σ^2 is the total average received power from all multipath components. With the channel impulse response modeled as a zero-mean complex valued Gaussian random process as in Clarke's model, the received envelope $R = \sqrt{X^2 + Y^2}$ at any time instant is Rayleigh distributed [6]. Thus the magnitude of the received complex envelope has a Rayleigh probability density function (PDF)

$$f(r) = \frac{r}{\sigma}\exp\{-\frac{r}{2\sigma}\}, \quad r \geq 0 \tag{2.3}$$

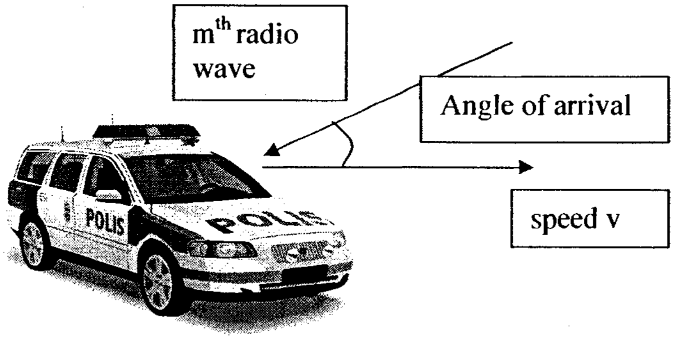

Figure 2.2 A moving mobile station causing doppler shift on the incident wave

For a moving mobile, the motion of the mobile station (MS) introduces a frequency shift known as the Doppler shift into the m^{th} incident plane wave as given by

$$f_m(t) = \frac{v}{\lambda}\cos\theta_m(t) \tag{2.4}$$

where v is the velocity of MS and θ_m is the angle of arrival of the wave relative to the direction of motion as shown in Figure 2.2. The Doppler shift can be translated to a relative velocity of the mobile, namely

$$v = \frac{c \cdot f_m}{f_c} \tag{2.5}$$

Where c = 3 * 10^8 (speed of light), f_m is the maximum doppler frequency and f_c is the carrier wavelength. The autocorrelation function of each of the quadrature components X or Y for a Rayleigh fading signal is a Bessel function as given by [24]

$$\varphi_{XX}(\tau) = \varphi_{YY}(\tau) = \sigma^2 J_0(2\pi f_m \tau) \tag{2.6}$$

As the speed of a mobile increases, the variation of the amplitude of the composite received signal in the Rayleigh fading channel increases. To illustrate fading in the Rayleigh channel with changing mobile speed, snapshots of the channel at velocities of 10 kmph, 50 kmph and 100 kmph are given over a period of 0.1 seconds. The respective autocorrelation functions are also given for the three speeds to display the correlation properties of the channel over time delays at different speeds.

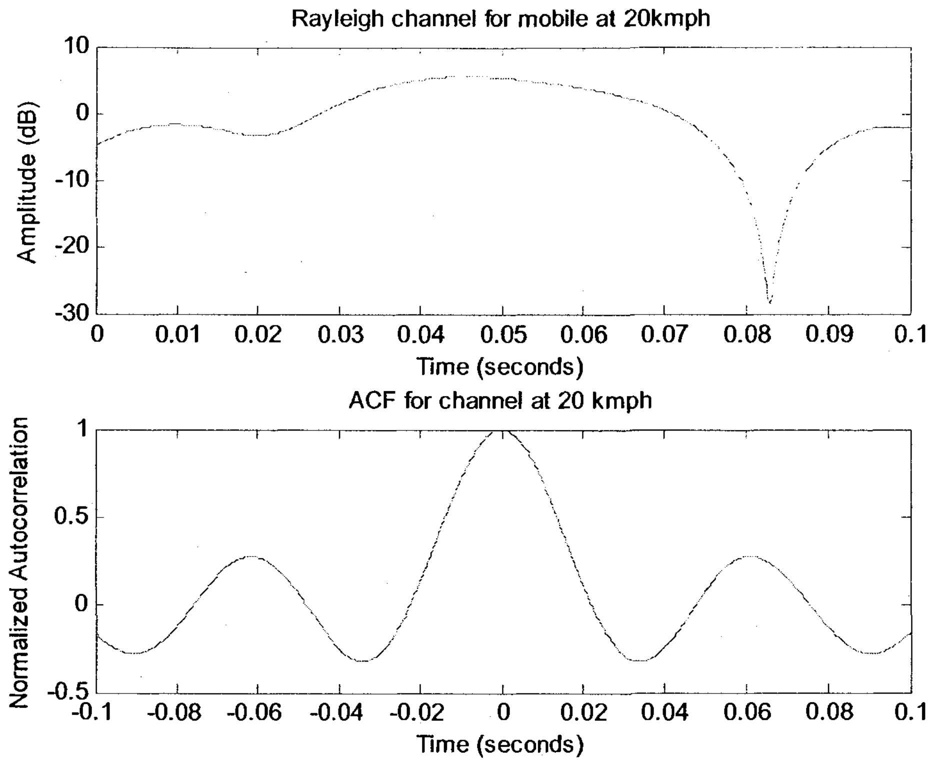

Figure 2.3 Snapshot of Rayleigh channel at 20 kmph and its corresponding auto correlation function

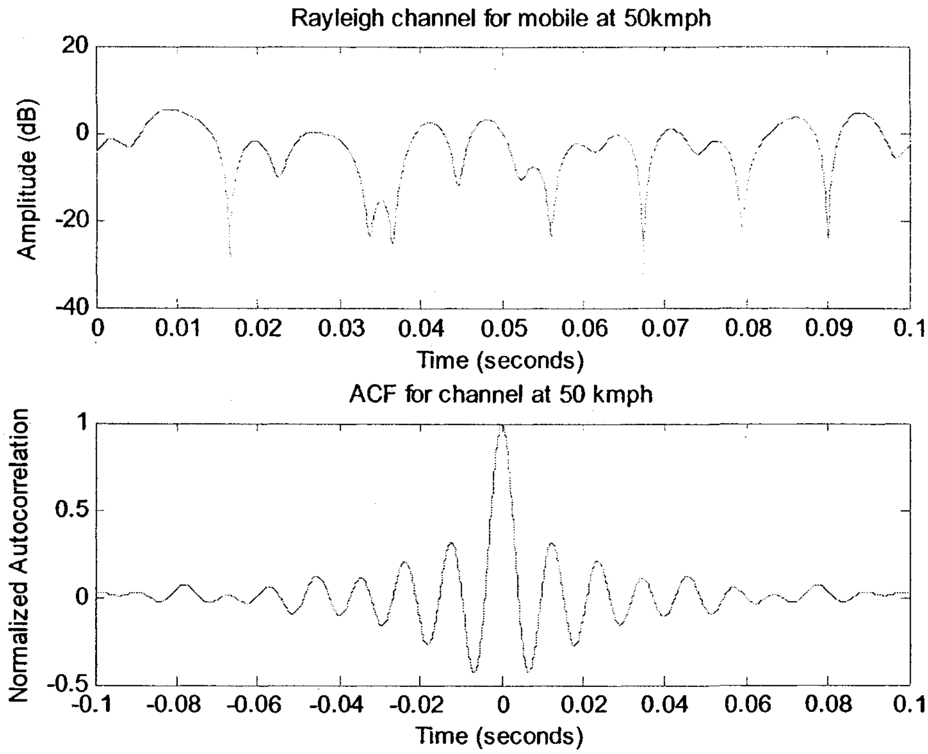

Figure 2.4 Snapshot of Rayleigh channel at 50 kmph and its corresponding auto correlation function

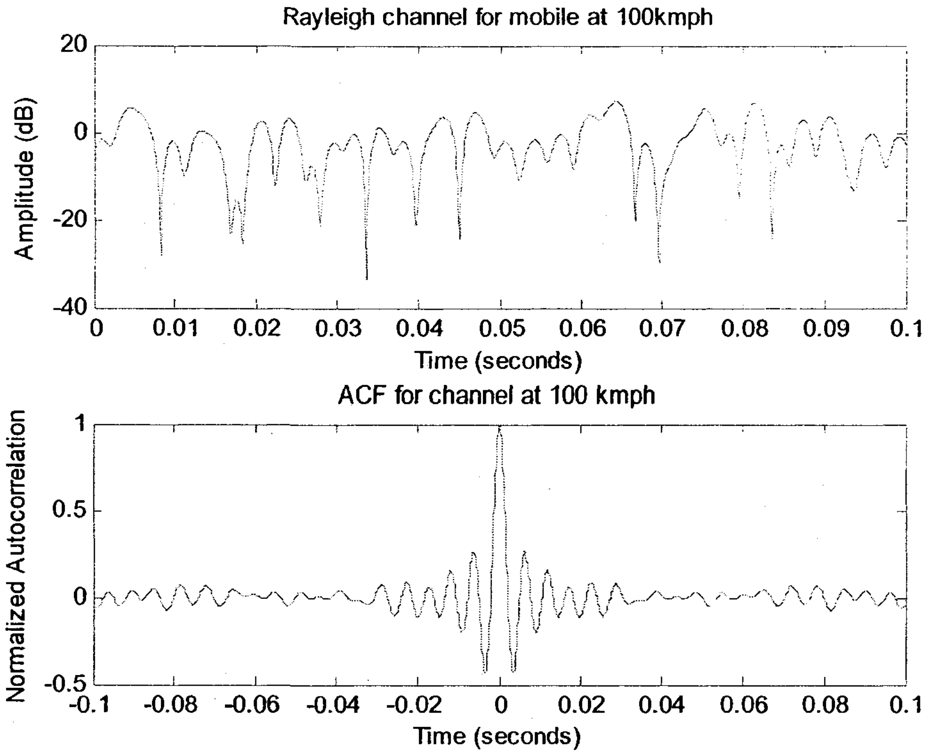

Figure 2.5 Snapshot of Rayleigh channel at 100 kmph and its corresponding auto correlation function

It can be noticed in the above figures that for a time interval of 0.1 seconds the change in the signal amplitude is more for a higher speed than for a lower speed. This also implies that the channel becomes uncorrelated faster at higher speeds. This can be seen in the autocorrelation graphs where for higher speeds the value of the Normalized autocorrelation drops to zero in lesser time than it does for lower speeds.

2.2 Multiple Input Multiple Output Systems

2.2.1 Benefits of MIMO systems.

Wireless applications are gradually shifting from voice-centric towards data-centric applications. The 4th generation (4G) wireless applications such as broadband internet access, interactive gaming and live television on hand held mobile devices require high throughput rates. As spectrum is both expensive and scarce, this demands a wireless technology with an increased spectral efficiency to be implemented for upcoming 4G systems. Similarly, guaranteed Quality of Service (QoS) will have to be maintained by infrastructure operators to maintain acceptability of services by customers. In current SISO systems, constructive and destructive addition of multipath components leading to random fading causes mobiles to be in "deep fades", i.e. mobiles are left with no reception at a certain location or time. This is very detrimental to achieveing desired QoS. Thus link reliability will have to be improved to achieve desired QoS in 4G systems. Moreover, 4G services will have to be available everywhere; for example high speed internet access will have to be available to passengers in a bus, not only in a cafe with a wireless access point close by. Thus the range of base stations will need to be extended.

MIMO technology is in favor of all the three needs i.e., higher throughput/capacity, improved link reliability and range extension, by providing multiple antennas at both the transmitter and receiver. Under a scatter rich environment, the channel paths between different transmit and receive antennas can be treated as independent channels due to the multipath effects caused by the scatterers. Thus, MIMO makes an effective use of the random fading and multipath delay spread to increase the transmission rate of the system. It is the exploitation of the additional spatial degree of freedom that increases the throughput and improves the performance of the system. More speficially, a MIMO system can provide three distinct gains:

1) Array Gain: Coherent combining of multiple antennas at the transmitter or receiver or both results in an average increase in the signal to noise ratio (SNR) at the receiver. This increase in SNR is called the array gain. Figure 2.6 shows an example of a single

input multiple output (SIMO) system. Assuming coherence distance i.e. the maximum spatial separation over which the channel response can be assumed constant, is maintained between the receive antenna elements, the received signal at each antenna will differ in phase due to the relative delay caused by the antenna separation. To maximize the energy of the received signal, an optimal receiver based on beam forming techniques is often used to account for the different delays of the multiple antennas and thus combine the received signals constructively. This will yield a M_r-fold power gain, where M_r is the number of receive antennas. Similarly, in the MIMO case, a M_tM_r-fold power gain can be achievable where M_t is the number of transmit antennas. For a system to have array gain on either the transmitter or the receiver, the channel has to be known to that side of the system [23]. Typically, the channel can be estimated at the receiver, but for the transmitter to know the channel, the channel state information (CSI) needs to be fed back causing some transmission overhead.

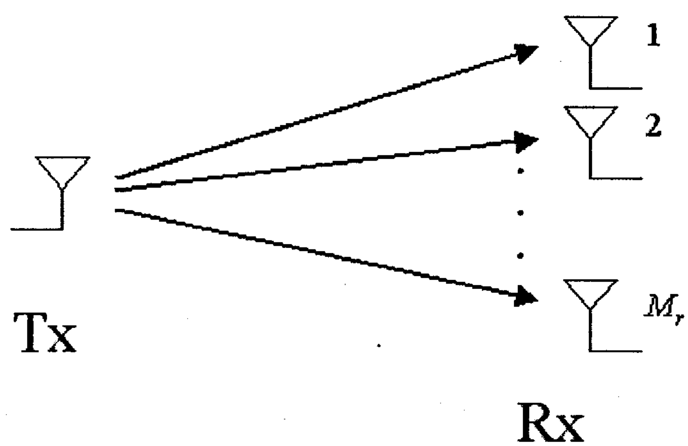

Figure 2.6 A single input multiple output system

2) Diversity gain: Signal fluctuation in a wireless channel happens across time, frequency and space. Diversity provides the receiver with multiple independent looks at the signal to enhance reception. Each of the different looks can be considered as a diversity branch. The more the branches the lesser the chance that all the branches will fade at the same time. Thus, diversity increases reliability of a system. Diversity can be obtained in time, frequency or space. Time diversity is based on the assumption that due to channel variation, two copies of the same signal transmitted with a delay greater than the channel coherence time will undergo different fading effects. Though time diversity has the benefit of not requiring additional hardware, it does require memory storage for the repeated signals to process [24]. Frequency diversity is achieved by transmitting the same signal on various independent carrier frequencies, where the carrier frequencies are separated by more than the coherence bandwidth of the frequency selective fading channel. Multiple antennas detect the signals at different carrier frequencies to select the one with the highest energy. Alternatively, a multi-antenna system can exploit the independent multipath channels to achieve spatial diversity, also called antenna diversity. The antenna diversity can be applied both at the receiver and the transmitter side. When applied only at the receiver, the replicas of the signals sent by a single transmit antenna are received by two apart antennas. The spacing of the antennas has to be more than the coherent distance to ensure independent fades across different antennas. The two replicas are then further processed with diversity combining techniques. Three main diversity combining techniques are selection combining, maximal ratio combining, and equal gain combining [23]. Selection combining selects the signal with the highest SNR

while maximal ratio combining gives a weighted average of the signals arriving at different antennas according to the received SNR. Equal gain combining simply averages all the received signals with equal weight.

Transmit diversity on the other hand is a newer phenomenon than the receive diversity and has become widely acceptable only in the early 2000s. In general, transmit diversity introduces controlled redundancy at the transmitter which can then be exploited by appropriate signal processing at the receiver side [23]. Transmit diversity is particularly attractive for the downlink of the systems based on infrastructure such as WiMax, since it shifts the burden for multiple antennas to the transmitter rather than at the receiver which imposes large constraints of space, power and costs on mobile terminals. For a MIMO system, the maximum spatial diversity gain is $M_t \times M_r$, where M_t is the number of transmit antennas and M_r is the number of receive antennas [23]. Transmit diversity schemes can be characterized as either open loop or closed loop. Open-loop systems do not require knowledge of the channel at the transmitter, whereas closed-loop systems do. The most popular open loop transmit diversity scheme is space/time coding, whereby data is encoded by a channel code and the encoded data is split into n streams that are simultaneously transmitted using n transmit antennas. The received signal at each receive antenna is a linear superposition of the n transmitted signals perturbed by noise. To decode the space/time code, the receiver must know the channel. However this is not a problem since the channel must be known for other decoding operations anyway. Though space/time codes are of many types, space/time block codes have attracted intense research interest since the late 1990s. Space time block codes with two transmit antennas or orthogonal codes for arbitrary number of transmit antennas achieve full diversity gain and linear low complexity decoding at the expense of lower transmission rate [25],[26].

3) Spatial Multiplexing gain: Multiplexing gain is achieved through transmitting different signals on independent channels in a MIMO system. The multiplexing gain order is the number of parallel independent spatial data links in the same frequency band between the transmitter and receiver. The signal is split into two or more parts and transmitted on two separate antennas. At each receive antenna a single signal from a specific transmit antenna will be detected and signals from other antennas will be seen as interference. Combining techniques are required at the receiver to eliminate the interference and to multiplex the signal back together. Thus capacity gain is achieved by reducing the transmission time without using additional bandwidth. As reported in [27], the capacity of MIMO systems equipped with N_{Tx} transmit and N_{Rx} receive antennas scales up almost linearly with the minimum of N_{Tx} and N_{Rx} in flat Rayleigh fading environments with fully uncorrelated scalar channels between each transmit and receive antenna pair. Since then several contributions illustrated that comparable throughputs can be achieved in many realistic environments [28],[29],[30].

To summarize, the use of MIMO offers many potential benefits. However it might not be possible to achieve all of the above benefits in a single system as some of them are mutually conflicting goals. In general a MIMO system could improve,

- Spectral efficiency/Capacity: Multiplexing gain
- Link reliability: Diversity gain

- Coverage: Diversity gain and Array gain

2.2.2 MIMO Channel Models

Since MIMO systems are equipped with multiple antennas at both link ends, the MIMO channel has to be described by the response between all transmit and receive antenna pairs.

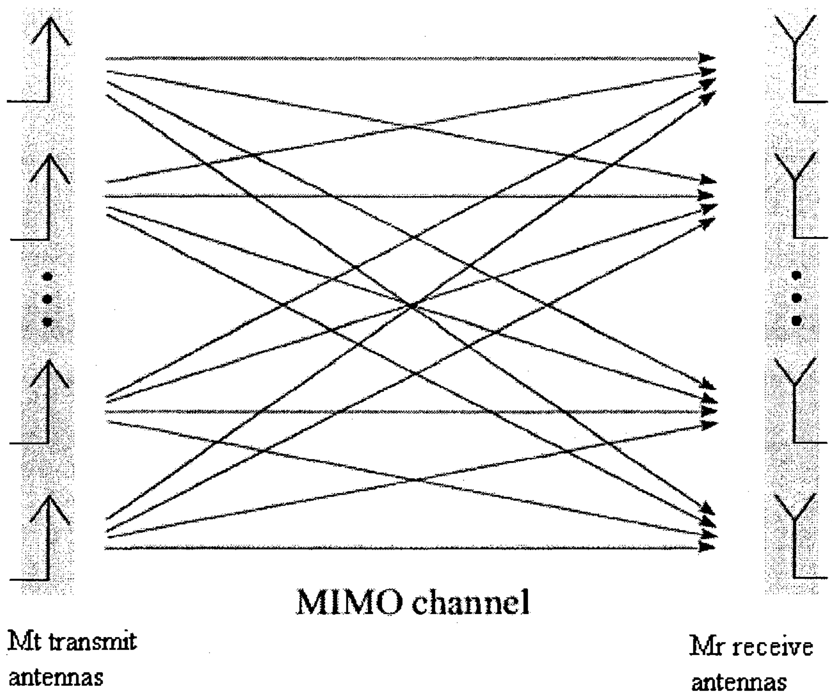

Figure 2.7 A MIMO system with M_t transmit and M_r receive antennas

Figure 2.7 shows a MIMO channel with M_t transmit and M_r receive antennas, where the channel response can be represented by the matrix $\mathbf{H}(t,\tau)$ of size $M_r \times M_t$.

$$
\mathbf{H}(t,\tau)=\begin{bmatrix} h_{11}(t,\tau) & h_{12}(t,\tau) & \cdots & h_{1M_t}(t,\tau) \\ h_{21}(t,\tau) & h_{22}(t,\tau) & \cdots & h_{2M_t}(t,\tau) \\ \vdots & \vdots & \ddots & \vdots \\ h_{M_t1}(t,\tau) & h_{M_t1}(t,\tau) & \cdots & h_{M_rM_t}(t,\tau) \end{bmatrix} \tag{2.7}
$$

where $h_{ij}(t,\tau)$ denotes the time-variant impulse responses between the *j-th* transmit antenna and *i-th* receive antenna, t denotes varying time and τ is the time delay. Since Eq. ((2.7) describes the channel response between the antennas at both link ends, it obviously depends on various parameters of the actual MIMO channel which it models. MIMO channel modeling is itself a vast topic which has received considerable attention over the past few years. To avoid irrelevant discussions, we restrict ourselves to the discussion of two MIMO channel models which suffice for the purpose of understanding the work presented in this thesis. The two channel models will then be followed by a discussion of antenna selection systems.

2.2.2.1 I.I.D flat fading model

Consider a MIMO channel with M_t transmit antennas and M_r receive antennas with the channel matrix denoted by **H.** Throughout our work we consider only flat fading channels, i.e. the impulse response is represented by a single impulse. Thus, τ in Eq. ((2.7) can be discarded in such a system. Thereafter in the flat fading i.i.d model, the elements of H are modeled as independent zero mean circularly symmetric complex

Gaussian (ZMCSCG) random variables[1]. We denote this channel as $\mathbf{H}_w$. $[\mathbf{H}_w]_{i,j}$ represents the element in the i_{th} row and the j_{th} column of the MIMO channel matrix. Some properties of such a channel are briefly summarized below.

First, the mean of every element in the matrix is zero, namely

$$E\{[\mathbf{H}_w]_{i,j}\} = 0, \tag{2.8}$$

The variance of every element of the matrix is equal to 1,

$$E\{\left|[\mathbf{H}_w]_{i,j}\right|^2\} = 1, \tag{2.9}$$

Also, the cross-correlation between any two elements of the matrix is zero,

$$E\{[\mathbf{H}_w]_{i,j}[\mathbf{H}_w]^*_{m,n}\} = 0 \; if \; i \neq m \; or \; j \neq n. \tag{2.10}$$

The MIMO channel **H** is reduced to SIMO and MISO channels when dropping either columns or rows, respectively. This ideal MIMO channel assumes an extremely rich scattering environment which is difficult to achieve in practice. Nevertheless, this is a very widely used model for developing, improving and testing signal processing algorithms.

2.2.2.2 Correlated MIMO channel model

In practice the i.i.d. MIMO channel model does not stand true even in the majority of indoor environments [4]. Inadequate antenna spacing, scatterer environment geometry and other similar factors cause the MIMO channel to behave more like correlated channels. This simply implies that the elements of **H** are correlated rather than

[1] A complex Gaussian random variable C=A+jB is ZMCSCG if A and B are independent real Gaussian random variables with zero mean and equal variance.

being completely independent of each other as in an i.i.d channel case . Such a correlated channel can be modeled by

$$vec(\mathbf{H}) = \mathbf{R}^{1/2} vec(\mathbf{H}_w), \tag{2.11}$$

Where vec denotes the vectorization operator, $\mathbf{H}_w$ is the spatial white M_r by M_t MIMO channel described earlier and $\mathbf{R}$ is the M_tM_r by M_tM_r covariance matrix defined as

$$\mathbf{R} = E[vec(\mathbf{H})vec(\mathbf{H})^H] \tag{2.12}$$

If $\mathbf{R} = I_{M_tM_r}$, then $\mathbf{H} = \mathbf{H}_w$. This means that when the correlation between any two different antenna elements reduces to zero the channel is i.i.d. Although the model above can capture any correlation effects between the elements of $\mathbf{H}$, a simpler model is often adequate. This simpler model, used in this thesis, models the effect of correlation by assuming that the channel can be characterized by the product of a ZMCSCG channel (represented by Eq.((2.10)) with two constant matrices that induce transmit and receive correlations. The interested reader is referred to [29] for complete details of this model. The mathematical representation is given by,

$$\mathbf{H} = \mathbf{R}_r^{1/2} \mathbf{H}_w \mathbf{R}_t^{1/2}, \tag{2.13}$$

where $\mathbf{R}_t$ is the $M_t \times M_t$ transmit covariance matrix and $\mathbf{R}_r$ is the $M_r \times M_r$ receive covariance matrix. This model has been verified through measurement campaigns and its validity has been thoroughly investigated [32],[33],[34]. Eq. (2.13) implies that the receive antenna correlation $\mathbf{R}_r$ is equal to the covariance of the $M_r \times 1$ receive vector channel when excited by any transmit antenna, and is therefore the same for all transmit antenna. This model holds when the angle spectrum of the scatterers at the receive array is identical for signals arriving from any transmit antenna. This condition arises if all the transmit antennas are closely located and have identical radiation patterns. These remarks also apply to the transmit antenna correlation $\mathbf{R}_t$. Note also that $\mathbf{H}_w$ is a full rank matrix with probability 1. In the presence of receive or transmit correlation, the rank of $\mathbf{H}$ is constrained by $\min(r(\mathbf{R}_r), r(\mathbf{R}_t))$, where $r(A)$ denotes the rank of A.

Often in the downlink, the mobile unit is in a well scattered environment whereas the base station is usually situated on a hill top or a tower. In such environments, the receive correlation matrix, $\mathbf{R}_r$ is usually identity. The absence of sufficient number of scatterers around the base station introduces transmit correlation so that the channel model becomes

$$\mathbf{H} = \mathbf{H}_w \mathbf{R}_t^{1/2} \tag{2.14}$$

In other words the covariance matrix of every row has the same correlation structure (given by $\mathbf{R}_t$).

2.2.2.3 MIMO systems with antenna selection

The many benefits of a MIMO system, make its implementation in current wireless systems extremely attractive to satisfy the demand for systems with increased throughput, reliability and communication range. However, these benefits come at the expense of an increased hardware cost, higher signal processing complexity, more power consumption and bigger component size at both the transmitter and receiver. This increased expense bluntly contradicts the fundamental norms of good wireless system design. A factor to which these expenses can be attributed is the increase in the number of radio frequency (RF) chains. In a system with M_t transmit and M_r receive antennas, if all the antennas are simultaneously used, a total of $M_t \times M_r$ RF chains are required, thus leading to increased costs. Antenna selection comes as a possible solution to overcome this drawback of MIMO systems. The idea is that, while the antenna elements are typically cheap, the RF chains are considerably more expensive and if reduced, will lower costs. Thus antenna selection systems have only a limited number of RF chains to process data. These RF chains are adaptively switched between a subset of the greater number of available antennas. Figure 2.8 shows a schematic diagram of an antenna selection system. Data to be transmitted is sent through a RF chain after necessary processing to produce signal for transmission through each transmit antenna. However, the number of RF chains is smaller than that of transmit antennas (i.e. $N_t \leq M_t$). The RF switch chooses the 'best' N_t antennas out of M_t. At the receiver, the RF switch chooses the 'best' N_r receive antennas ($N_r \leq M_r$). The channel seen by the selected subset of transmit and receive antennas is the submatrix $\tilde{\mathbf{H}} \in \mathbb{C}^{N_t \times N_r}$ which is obtained by selecting the rows and columns of the channel matrix that corresponding to the selected receive and transmit antennas, where $\mathbb{C}^{m \times n}$ is a m × n dimensional complex matrix space. There are $\binom{M_t}{N_t}\binom{M_r}{N_r}$ possible submatrices of **H**. The design of criteria choosing the antennas on either side of the system has been a topic of active research in the past years. Some prominent criteria are the system capacity maximization [35], SNR maximization [5] or union bound on error rate minimization [36] . Selection of receive antennas is done at the receiver side, whereas selection of transmit antennas is also often done at the receiver in which case and only the index numbers of the selected transmit antennas are fed back to the transmitter [5].

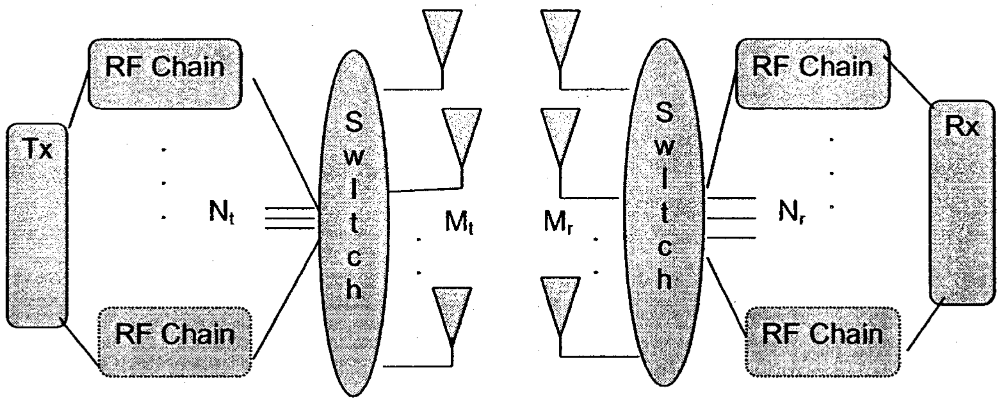

Figure 2.8 Schematic diagram of an antenna selection system

2.2.3 Signal Model

In this section we develop the signal model that will be utilized in the remainder of the thesis. The channel is modeled by a matrix **H** of dimension $M_r \times M_t$. The signal model is,

$$\mathbf{y}[k] = \mathbf{H}\mathbf{x}[k] + \mathbf{n}[k] \tag{2.15}$$

Where, y[k] is the received signal vector with dimension $M_r \times 1$, $x[k] = [x_1[k] \ldots . x_{M_T}[k]]^T$ is the transmit signal vector of size $M_t \times 1$ consisting of transmitted symbols and **n**[k] is the $M_r \times 1$ spatio-temporally white ZMCSCG noise vector with variance N_o in each dimension. Our system is memory less, i.e. the outputs do not depend on previous inputs. Thus we can drop out the time index k for clarity and express the input-output relation as

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n} \tag{2.16}$$

The **H** in Eq. (2.16) will vary depending on the scenario. It could represent an i.i.d MIMO channel, a correlated MIMO channel or an antenna selection system. Details of the **H** in each of the three cases have already been mentioned in Sections 2.2.2.1-2.2.2.3.

2.3 A review of ACF based velocity estimators for generic wireless systems.

The focus of this study is to extend the existing ACF based velocity estimation schemes for SISO systems to correlated MIMO channels. It is thus necessary to provide the reader with a brief review of these schemes in order to appreciate the contributions of the thesis. The common principle of these schemes is based on the ACF of the quadrature components of the given Rayleigh fading channel, $h(n) = X + iY$, which is rewritten below,

$$\varphi_{XX}(k) = \varphi_{YY}(k) = \sigma^2 J_0(2\pi f_m kT_s) \tag{2.17}$$

where T_s is the sampling interval, k is an integer. The first step in the ACF based schemes is to calculate the ACF of the channel by using channel estimates. Then, the ACF is used in different ways to obtain an estimate of the mobile velocity. We now group the ACF based velocity estimation schemes into three categories:

1. Estimation of exact mobile velocity using a single point on the ACF curve.
2. Estimation of exact mobile velocity using the complete ACF curve.
3. Estimation of the mode of the mobile using thresholds on the ACF curve.

In Section 2.1, it has been shown how the maximum Doppler frequency can be translated to velocity in a Rayleigh fading channel. Thus, for the purpose of brevity, in the following sections we show the estimation of Doppler frequency without repeating its translation to velocity every time. The general concept of the schemes in each category is given followed by an example of particular estimator.

2.3.1 Estimation of exact mobile velocity using a single point on the ACF curve

The schemes of this category use a single point on the ACF curve to estimate the velocity. Firstly, a specific value of correlation, $\varphi_{XX}(k_0)$, is chosen from the normalized ACF curve. Secondly, the ideal delay, k_0, at which this value occurs is found using the inverse of the Bessel function. Thirdly, an estimate of the actual delay $\hat{k}_0$, at which the value $\varphi_{XX}(k_0)$ occurs on the estimated ACF curve is obtained. This estimated delay $\hat{k}_0$ and the ideal delay, k_0, obtained using the inverse of the Bessel function are used to calculate the Doppler estimate using Eq. (2.18)

$$f_m = \frac{1}{2\pi \hat{k}_0 T_s} J_0^{-1}\left(\frac{\varphi_{XX}(k_0)}{\varphi_{XX}(0)}\right) \tag{2.18}$$

where $\varphi_{XX}(0) = \sigma^2$ is the average received power of the signal envelope. The inverse of $J_0(.)$ is difficult but we can adopt look-up tables [49].

As an example of the estimator belonging to this category we detail the estimator presented in [8]. The author chooses to use the first zero crossing point of the Bessel function to estimate velocity, i.e. $\varphi_{XX}(k_0)$ = 0 in this case. A look up table tells that the first zero crossing of the first order Bessel function occurs at x = 2.405, i.e. k_0 = $J_0^{-1}(0) = 2.405$. This is illustrated by Figure 2.9

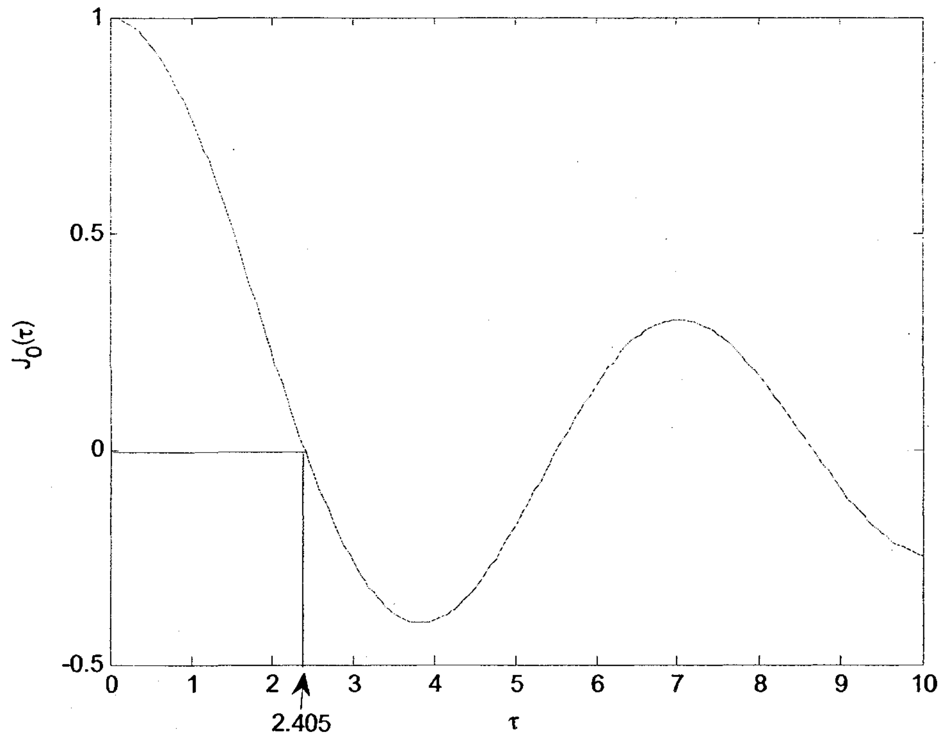

Figure 2.9 The zero crossing of the Bessel function

Next, the zero-crossing point, $\hat{k}_0$ of the estimated ACF curve $\hat{\varphi}_{XX}$, is estimated by searching for the pair k_1 and $k_2 = k_1+1$ such that $\hat{\varphi}_{XX}(k_1)$ and $\hat{\varphi}_{XX}(k_2)$ have different signs as illustrated by Figure 2.10.

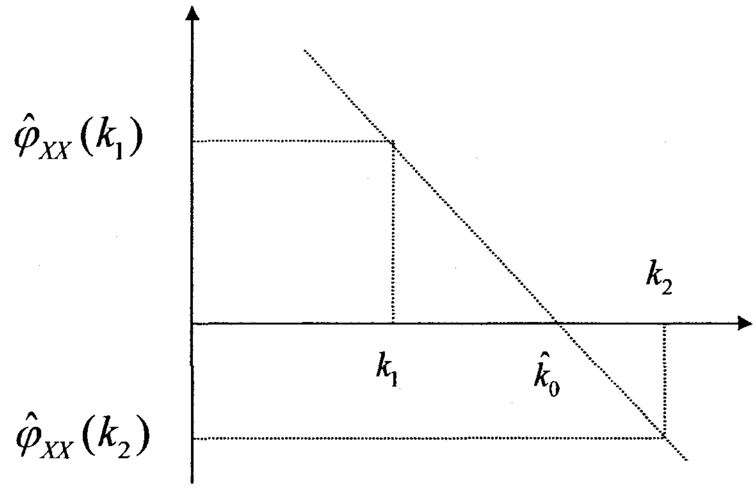

Figure 2.10 Interpolation to obtain an estimate of the zero-crossing

$\hat{k}_0$ is now determined by linear interpolation, i.e.,

$$\hat{k}_0 = k_1 - \frac{\hat{\varphi}_{XX}(k_1)}{\hat{\varphi}_{XX}(k_2) - \hat{\varphi}_{XX}(k_1)} \tag{2.19}$$

The estimated delay, $\hat{k}_0$ and the ideal delay, k_0 are then used to obtain an estimate of the maximum Doppler frequency following Eq. (2.18) as shown by Eq. ((2.20).

$$\begin{aligned} f_m &= \frac{1}{2\pi \hat{k}_0 T_s} J_0^{-1}\left(\frac{\varphi_{XX}(k_0)}{\varphi_{XX}(0)}\right) \\ f_m &= \frac{2.405}{2\pi \hat{k}_0 T_s} \\ f_m &= \frac{0.38}{\hat{k}_0 T_s} \end{aligned} \tag{2.20}$$

$\varphi_{XX}(0)$ is a normalizing constant whose value is 1 in this case since we are dealing with normalized ACF values. Thus an estimate of velocity is obtained using a single point on the estimated ACF curve. References [9]-[15] present schemes based on a similar approach.

2.3.2 Estimation of exact velocity using the complete ACF curve

In these schemes, hypothesis testing based velocity estimation is performed. The theoretical ACF curves for a set of Doppler values are calculated using Eq. (2.17) and stored in memory. Each curve is called a hypothesis. Depending on the desired accuracy of the estimator, the number of stored autocorrelation hypothesis can be more or less. The computational complexity of the algorithm will vary correspondingly. For higher accuracy, more hypotheses will have to be stored in memory and compared with the estimated ACF before making a decision and vice versa for lower accuracy. Then, an estimate of the ACF curve is obtained and the hypothesis to which this estimated ACF curve is most similar is searched for. The Doppler value which corresponds to this hypothesis is the estimated Doppler.

One such estimator is given in [16]. Let there be M Doppler values separated by f_{step} whose autocorrelation hypotheses are stored in memory. If $\hat{\varphi}_{XX}(k)$ gives the kth lag of the estimated ACF and $\varphi_{XX}(k;f_d)$ is the hypothesis of the Doppler f_d stored in memory then the estimate of the Doppler spread will minimize the cost function

$$F(f_d)=\sum_{k=1}^{N-1}\left|\frac{\hat{\varphi}_{XX}(k)}{\hat{\varphi}_{XX}(0)}-\varphi_{XX}(k;f_d)\right|^2 \quad f_d=1f_{step},2f_{step},\ldots\ldots Mf_{step} \tag{2.21}$$

Then, the Doppler value which corresponds to the hypothesis which provides minimum error is the estimated Doppler value as shown by Eq. ((2.22).

$$\hat{f}_d = \arg\min_{f_d} F(f_d) \tag{2.22}$$

Other estimators belonging to this category are given by [17][18]

2.3.3 Estimation of the mode of the mobile using thresholds.

These schemes are motivated by the fact that some receiver algorithms require knowledge of whether the mobile is in fast (F-mode), medium (M-mode) or slow (S-mode) rather than the exact velocity of the mobile. The Doppler range is divided into suitable smaller ranges and the Doppler spread estimator compares estimated correlation values at chosen delays with theoretical values of the correlation function at the same delays. Based on this comparison a decision of the mode of the mobile is made.

In [19] the author presents such a scheme for SISO wireless systems. First, the Doppler is divided in the ranges shown in Table 2.1. The maximum Doppler frequency, 500Hz corresponds to 270 km/h for a carrier frequency of 2GHz and is thus sufficient for most practical purposes.

Slow (S) mode	0 < fd < 60 Hz
Medium (M) mode	60 Hz < fd < 250 Hz
Fast (F)mode	250 Hz < fd < 500 Hz

Table 2.1 Doppler ranges

Next, two thresholds of ACF values are fixed at specific delay times. Now the algorithm is set up. To estimate the mode, the algorithm first uses one threshold at a specific delay time to decide between F-mode and S/M-Mode. If S/M mode is decided the second threshold is now used at a specific delay time to decide between the S-mode and the M-mode. The algorithm can be summarized by the following steps:

Step 1: Obtain the ACF of the channel using the channel estimates.

Step 2: For two specific delays k_1=18 and k_2= 50 compute the theoretical values given by the Bessel function as shown below. T_s= 1/15 kHz

$$T_1^{(18)} = J_0(2\pi.250.18.T_s) = 0.290$$

$$T_2^{(50)} = J_0(2\pi.60.50.T_s) = 0.645$$

These theoretical values make our thresholds. T_1 is the threshold for deciding between F and M/S mode and T_2 is the threshold for deciding between M and S modes.

Step 3: Use the following algorithm to decide the mode of the mobile:

$$\begin{bmatrix} \textit{if } \hat{\varphi}_{XX}(k_1 = 18) > T_1^{18}, \quad \text{declare M/S - mode} \\ \quad \textit{if } \hat{\varphi}_{XX}(k_2 = 50) > T_2^{50}, \quad \text{declare S - mode} \\ \quad \textit{else } \text{declare M-mode} \\ \textit{else } \text{declare F-mode} \end{bmatrix} \tag{2.23}$$

The algorithm can be easily followed by looking at Figure 2.11.

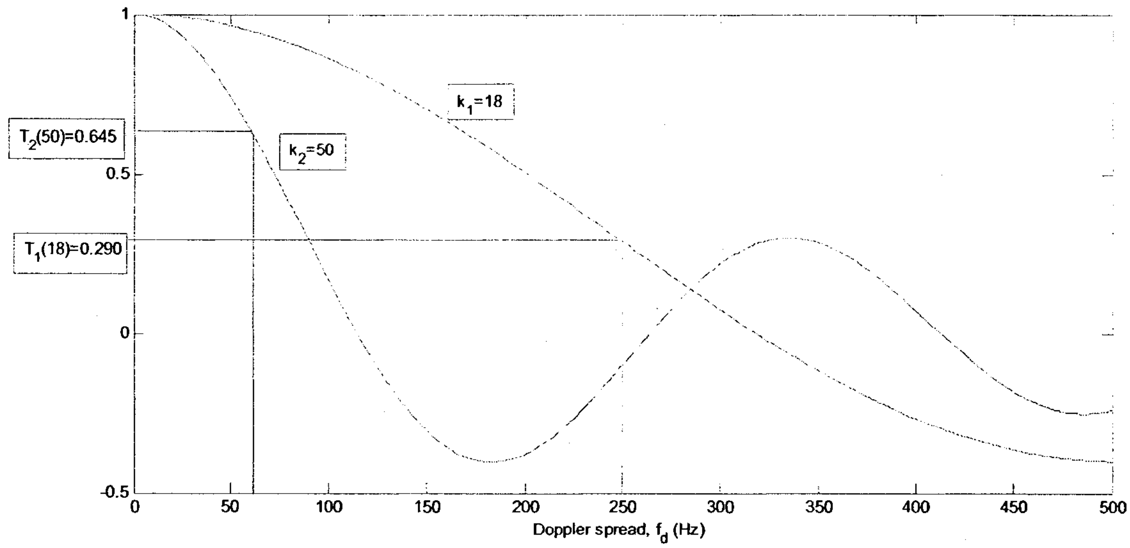

Figure 2.11 ACF at time indexes $k_1 = 18$ and $k_2 = 50$

The choice of the two delays k_1 and k_2 is based on optimizing the decision region between the different modes. A detailed description of this optimization is irrelevant here. In general, this could either be analytically done [19][21] or could be based on statistical data [20]. A system can be simulated and the estimation accuracy checked by setting different thresholds. The best ones can then be selected. If the algorithm is implemented and integrated into real cellular systems, then the selected thresholds based on simulation results can be used as a reference to fine-tune the thresholds for real cellular systems. The number of modes and velocity/doppler bins can be defined according to the user's requirement. Reference [20] presents a similar scheme with only two modes, slow and fast while [21] presents a scheme with three modes but different Doppler bins.

It can be noticed that the common factor amongst all the three categories of ACF based schemes is that they are all based on the knowledge that the ACF of a Rayleigh channel is ideally a zero-order Bessel function. In all schemes, as a first step, the ACF of the channel is estimated and then this ACF is used in different ways to estimate velocity as also demonstrated in the three examples above. Thus, the accuracy of the velocity estimates obtained using these schemes is always directly dependent on the accuracy of the estimated ACF. Also, these schemes give accurate results and are simple to implement [31]. All together they constitute a class of ACF based schemes for velocity estimation in SISO Rayleigh fading channels. Next, we look at the extension of this class of ACF based velocity estimation schemes to MIMO systems.

2.4 Extension of ACF based techniques to correlated MIMO channels

The extension of the large class of velocity estimation techniques for MIMO channels would allow their benefits to be derived in MIMO systems too. References [14],[15],[18],[20],[21] claim regarding their ACF based schemes that this extension can be done but do not provide supporting evidence. Intuitively, the extension of ACF based techniques to MIMO systems is straightforward for an ideal MIMO channel i.e. if the fading between any transmit and receive antennas is an independent Rayleigh random variable. In such a case, since fading between transmit-receive antenna pairs is completely uncorrelated, every pair acts like an independent SISO channel. Thus the velocity estimation can be performed independently for each individual SISO channel and all velocity estimates obtained averaged to get the MIMO mobile velocity.

In practice, however, ideal MIMO channels are hard to realize even in indoor environments with rich scattering [4]. Practically, the channels between pairs of transmit-receive antennas may be correlated. This correlation might cause a change in the performance of ACF based velocity estimation techniques in practical MIMO channels.

Moreover, as antenna selection appears to be an efficient solution to combat the high cost of RF chains in MIMO systems, it is expected to be incorporated soon into practical systems. How will ACF based velocity estimation techniques perform in correlated Rayleigh fading MIMO channels using the full set of antennas? How will ACF based velocity estimation techniques perform in correlated Rayleigh fading MIMO channels using antenna selection? If the performance degrades, is there a way to recover this degradation? These questions lead to our topic of study. Chapter 3 reveals the performance loss of ACF based schemes in correlated MIMO channels using the full antenna set and proposes a recovery scheme to fully recover this loss. Chapter 4 reveals the performance loss of ACF based schemes in correlated MIMO channels using a subset of antennas and proposes a recovery scheme to partially recover this loss.

3 Mobile velocity estimation using ACF based schemes in correlated MIMO channels.

As concluded in Section 2.3, the fundamental factor determining the accuracy of all auto-correlation function (ACF) based velocity estimation schemes is the accuracy of the estimated ACF of the channel. This implies that studying and improving the performance of one ACF based scheme would suffice the investigation of all the ACF based schemes. Thus, in this chapter, to make our study of velocity estimation using ACF based methods manageable, we choose to study and improve the performance of one particular ACF based scheme for velocity estimation in correlated MIMO channels, namely, the zero-crossing based velocity estimator as detailed in Section 2.3.1. The results obtained would be applicable to other ACF based velocity estimation schemes. First, we discuss the application of this method to the MIMO channel with i.i.d Rayleigh fading, i.e., the case when each SISO channel is independent. Thereafter, we move over to discuss the performance of velocity estimation in the more realistic case of the correlated MIMO channel. We consider three cases of the MIMO channel (1) MIMO channel with transmit correlation only; (2) that with receive correlation only and (3) that with both transmit and receive correlation. The performance of velocity estimation schemes based on the ACF method in uncorrelated channels is compared with their performance in correlated channels. Lastly, we propose methods to recover the performance loss incurred due to correlation present in the MIMO channel for all three cases mentioned above. Our simulation results support the disclosed performance difference between the uncorrelated MIMO channel and the correlated MIMO channel as well as the improvement achieved by our proposed methods.

3.1 Velocity estimation using ACF based schemes in i.i.d MIMO channels

The flat fading i.i.d Rayleigh MIMO channel can be represented by a channel matrix $\mathbf{H}_w(t)$

$$\mathbf{H}_w(t)=\begin{bmatrix} h_{11}(t) & h_{12}(t) & \cdots & h_{1M_t}(t) \\ h_{21}(t) & h_{22}(t) & \cdots & h_{2M_t}(t) \\ \vdots & \vdots & \ddots & \vdots \\ h_{M_t1}(t) & h_{M_t1}(t) & \cdots & h_{M_rM_t}(t) \end{bmatrix} \tag{3.1}$$

where $h_{ij}(t)$ represents the channel response between the i^{th} receive antenna and the j^{th} transmit antenna. For the i.i.d Rayleigh MIMO channel, elements in **H** are modeled as independent zero-mean circularly symmetric complex Gaussian (ZMCSCG) random variables[1] [6]. In practice two major factors influence this effect. Firstly, the antennas in the transmitter and those in the receiver are spatially separated sufficiently enough to avoid any correlation amongst them. Secondly, the geometry of the scatter environment is well-suited to provide independent uncorrelated paths between the different pairs of antennas of the MIMO link. These two factors, if present, will ensure that our channel is uncorrelated and can be modeled by the i.i.d. model as detailed in Section 2.2.3. Using the received signal y, an estimate of the MIMO channel can be obtained. For the i.i.d MIMO channel let this estimate be $\hat{\mathbf{H}}_w(t)$. We assume perfect channel estimates and

[1] A complex Gaussian random variable C=A+jB is ZMCSCG if A and B are independent real Gaussian random variables with zero mean and equal variance.

thus $\hat{\mathbf{H}}_w(t) = \mathbf{H}_w(t)$ at all times. Every element of $\hat{\mathbf{H}}_w(t)$, $h_{ij}(t)$ where $t=T_s \ldots sT_s$, $s>>1$, can be treated as an estimate of an independent SISO channel. Thus, for a particular i and j, ignoring noise at the receiver, the estimate of the velocity can be obtained by estimating the Autocorrelation function as [24]

$$E\{\hat{h}_{ij}(n)\hat{h}_{ij}^*(n+sT_s)\} = J_0(2\pi f_d sT_s) \tag{3.2}$$

Then, the ACF method described in Section 2.3.1 can be applied to obtain a velocity estimate $\hat{v}_{ij}$ from this estimated ACF. Likewise, a total of $N = M_r \times M_t$ velocity estimates can be obtained for all pairs of i and j. It must be borne in mind that although we have N separate velocity estimates, the mobile whose velocity is being estimated is moving at one particular velocity. So the question which remains to be answered is: Is there a criterion to select the best velocity estimate(s) from the total of N estimates? A few criteria have been attempted and validated by computer simulations. These criteria include:

1) The velocity estimate given by the highest impulse response out of the N impulse responses was chosen.
2) Two velocity estimates given by two pairs of transmit-receive antennas which are spatially most separated were averaged.
3) Out of N velocity estimates, the maximum and minimum values were averaged.
4) Out of N velocity estimates, two randomly selected estimates were averaged.
5) All the N velocity estimates obtained were averaged.

According to a large amount of computer simulations, it is found that the best estimate of the velocity of the mobile in the MIMO channel $\hat{v}_{MIMO}$ is given by the average of all the N estimates. This makes intuitive sense as the Rayleigh channel follows a random behavior. No criterion governs which particular pair of antennas (pair of a particular i and j) in a MIMO setup will give a better velocity estimate than others. Thus, the estimate of the MIMO mobile is calculated by

$$\hat{v}_{MIMO} = \frac{\sum_{i=1}^{M_r}\sum_{j=1}^{M_t}\hat{v}_{ij}}{N}, \qquad N = M_r \times M_t \tag{3.3}$$

For illustrating the above mentioned discussion Table 3.1 gives a set of $\hat{v}_{ij}$ values obtained for a 3 × 3 MIMO mobile moving at 100 kmph. The average value obtained using Eq. (3.3) in this case is 98.139 kmph. Thus, even though some of the values shown in the table are distant from the true velocity but averaging all the velocities gives us an estimate which is close to the true velocity.

i \ j	1	2	3
1	103.4774	92.6390	91.2241
2	93.5592	101.7008	107.8241
3	97.0553	100.2471	102.4978

Table 3.1 A set of velocity estimates obtained from the SISO channels.

Simulation was carried out to see the performance of the ACF zero-crossing method in i.i.d. Rayleigh fading MIMO cannels. The normalized mean square error (NMSE) is used as a performance measure for the velocity estimation. It is calculated as

$$\frac{E[(\hat{v}_{MIMO}-v_{MIMO})^2]}{v_{MIMO}^2}=\frac{\sum_{n=1}^{N}(\hat{v}_{MIMO}(n)-v_{MIMO})^2}{N}\times\frac{1}{v_{MIMO}^2} \qquad N=1000 \text{ in our simulation} \tag{3.4}$$

A 3 × 3 MIMO system is simulated. Velocity, v_{MIMO}, is varied from 10 Kmph to 100 Kmph in steps of 10. Each point on the graph is averaged over 1000 velocity estimates, i.e. N = 1000. The number of symbols used to compute an ACF, i.e. s in Eq. (3.2), was 1000. The result of the simulation is shown by the graph below.

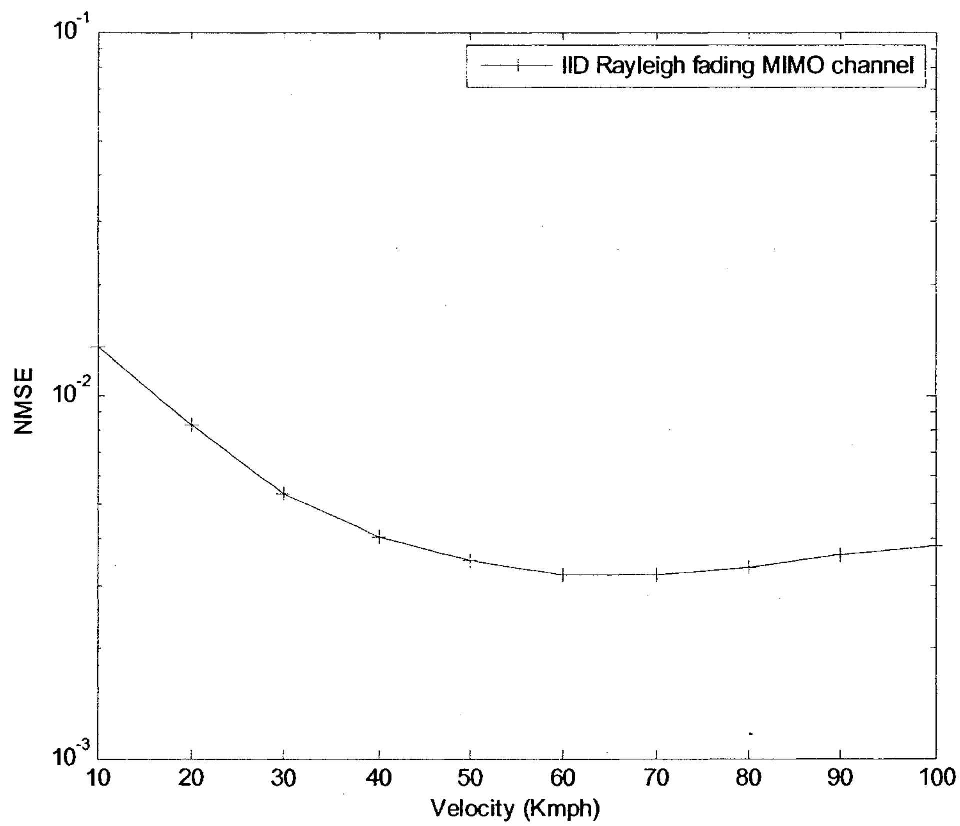

Figure 3.1 Velocity estimation performance of ACF method implemented in an i.i.d. Rayleigh fading MIMO channel

As can be seen from Figure 3.1, the NMSE of the velocity estimate keeps between 10^{-2} and 10^{-3} over the entire range of velocity. Thus averaging the individual velocity estimates of the SISO channels obtained using the ACF method gives fairly accurate results in an i.i.d. Rayleigh fading MIMO channel. Next, we discuss the performance of velocity estimation using the ACF method in correlated Rayleigh fading MIMO channels. Hereon, we use the term, i.i.d. MIMO channel to refer to the i.i.d Rayleigh fading MIMO channel and the term correlated MIMO channel for the correlated Rayleigh fading MIMO channel.

3.2 Velocity estimation using ACF based schemes in correlated MIMO channels

The i.i.d MIMO channel discussed in Section 3.1 can be realized in practice if the antenna spacing is large enough and the scatterer geometry around the transmitter and receiver is such that all paths between the different pairs of transmit and receive antennas are independent. In the real world, a base station could be high above with low buildings in the surrounding. This absence of sufficient scatterers can cause correlation on the transmitter side. On the other hand, the two antennas on a small user device could be close enough, causing receive correlation. This leads us to a practical situation where MIMO channels almost always deviate to correlated channels. Thus, it becomes important to study the performance of velocity estimation in correlated MIMO channels.

In conforming to the focus of this thesis, we study the performance of ACF based velocity estimation schemes in correlated Rayleigh fading MIMO channels. The study of correlation in MIMO antenna arrays is a vast topic in itself [29]. A large number of models have been presented in the past years which account for correlation in MIMO channels [29]. We restrict ourselves to using the Kronecker model [29]. The authors of [33] have validated this model and identified the scenarios where the model is applicable. Thus, the study conducted in this thesis is applicable to all physical scenarios which have a geometrical structure that can be characterized by the Kronecker model. The Kronecker model views the correlated Rayleigh fading MIMO channel as

$$\mathbf{H} = \mathbf{R}_r^{1/2}\mathbf{H}_w\mathbf{R}_t^{1/2} \tag{3.5}$$

where $\mathbf{R}_t$ is the $M_t \times M_t$ transmit covariance matrix, $\mathbf{R}_r$ is the $M_r \times M_r$ receive covariance matrix and $\mathbf{H}_w$ is the $M_r \times M_t$ i.i.d matrix with characteristics given by Eqs. (2.8-(2.10).

3.2.1 Performance in correlated MIMO channels

To clarify the presentation we first consider receiver correlation and then the transmit correlation, followed by the correlation at both transmit and receive side. For convenience, we call the first two cases as receive correlated and transmit correlated channels, respectively.

3.2.1.1 Receive correlated channels

For receive correlated scenarios, the $\mathbf{R}_t$ matrix assumes an identity matrix. The Kronecker model thus becomes

$$\mathbf{H} = \mathbf{R}_r^{1/2}\mathbf{H}_w \tag{3.6}$$

Clearly the channel $\mathbf{H}$ is no longer equal to $\mathbf{H}_w$, the i.i.d MIMO channel, rather it is modified by the receive correlation effect of the channel. When the channel is estimated at the receiver, the estimate of the channel will not be an estimate of $\mathbf{H}_w$ but that of $\mathbf{H}$, whose elements do not have purely Rayleigh fading characteristic. This will result in a difference between the ACF obtained using the estimates of the correlated channel and the correct ACF given by the purely Rayleigh fading channel for that velocity. As an example, a comparison of the ACF obtained using the channel values of a receive correlated channel and that of an uncorrelated channel with purely Rayleigh fading characteristic for a velocity of 10 Kmph is shown in Figure 3.2. It can be noticed that the two curves are slightly different. Since the velocity estimates directly depend on the ACF (on the zero-crossing in our specific case) this slight difference will cause the resulting velocity estimates obtained using the ACF of the receive correlated channels to be less accurate.

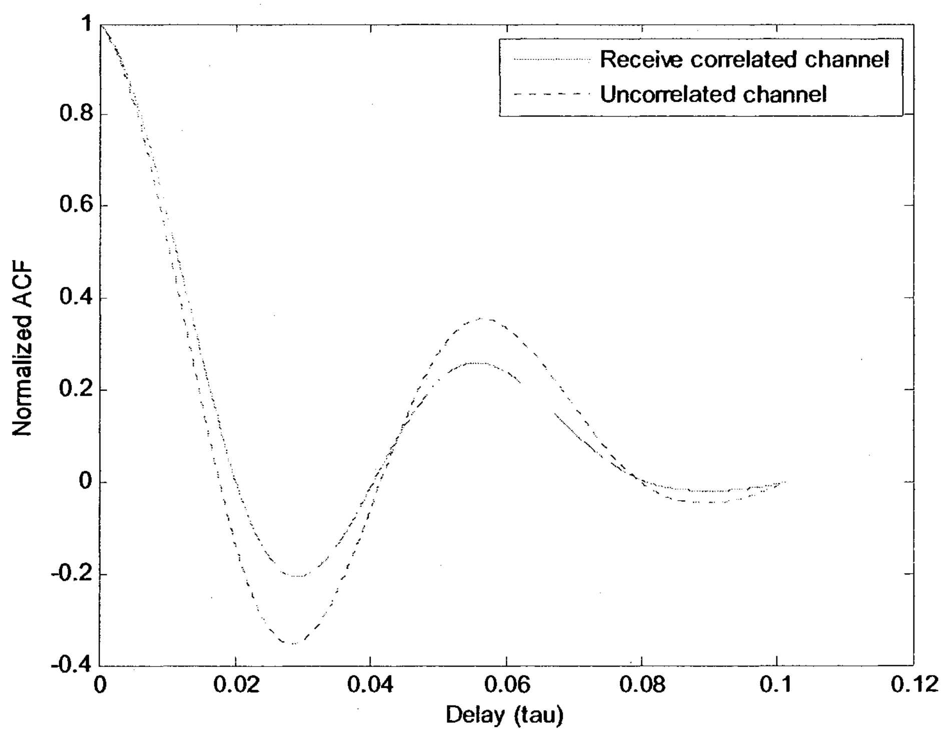

Figure 3.2 Comparison of the ACF obtained using the estimated receive correlated channel with that from the uncorrelated channel

3.2.1.2 Transmit correlated channels

In transmit correlated scenarios, the receive correlation matrix $\mathbf{R}_r$, is an identity matrix. The channel $\mathbf{H}$ thus becomes

$$\mathbf{H} = \mathbf{H}_w \mathbf{R}_t^{1/2} \tag{3.7}$$

Obviously, $\mathbf{H}$ is no longer equal to $\mathbf{H}_w$, the i.i.d MIMO channel. Thus the channel estimate obtained will not be the estimate of $\mathbf{H}_w$. It will now be the estimate of the new $\mathbf{H}$ which is modified due to the presence of the transmit correlation in the channel. The usage of the ACF method for velocity estimation though, is based on the assumption that the channel undergoes pure Rayleigh fading and thus has the Bessel function as its ACF. This does not hold anymore because of the induction of the transmit correlation effect in the channel matrix. Figure 3.3 illustrates the slight difference between the estimated ACF of an uncorrelated channel and that of a transmit correlated channel. The ACF method, if now used with the channel estimate $\hat{\mathbf{H}}$, will give less accurate estimates of velocity. This follows the same reasoning detailed in Section 3.2.1.1. Hence, the performance of velocity estimation using the ACF method will degrade in the presence of transmit correlation in the MIMO channel.

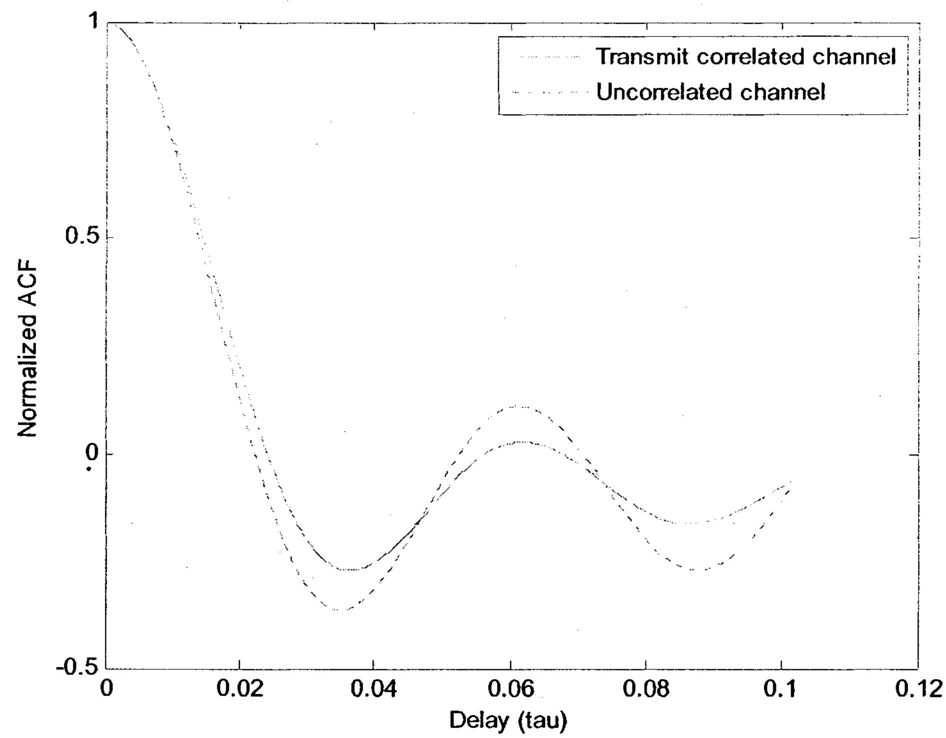

Figure 3.3 Comparison of the ACF obtained using estimated transmit correlated channel with that from the uncorrelated channel

3.2.1.3 MIMO channels with both transmit and receive correlations

In a scenario with both transmit and receive correlation, the channel **H** will become

$$\mathbf{H} = \mathbf{R}_r^{1/2}\mathbf{H}_w\mathbf{R}_t^{1/2} \tag{3.8}$$

In this case, the elements of **H** are not i.i.d because $\mathbf{H}_w$ is multiplied with the transmit and receive correlation matrices. Therefore, the estimate of the channel will also not be an estimate of $\mathbf{H}_w$, rather will be an estimate of **H**, the effective channel. When the ACF of this effective channel is obtained it will be different from the ACF of the uncorrelated channel. Figure 3.4 illustrates this difference. It can be noticed that the difference in the two ACF curves is larger than in the previous two cases where the correlation existed at only one side of the channel. This is due to the increased deviation of the effective channel from the purely Rayleigh fading channel in the presence of correlation at both the transmitter and the receiver as compared to the correlation at only one side of the channel. Thus, the performance of the velocity estimation methods based on ACF would degrade seriously in MIMO channels with transmit and receive correlation.

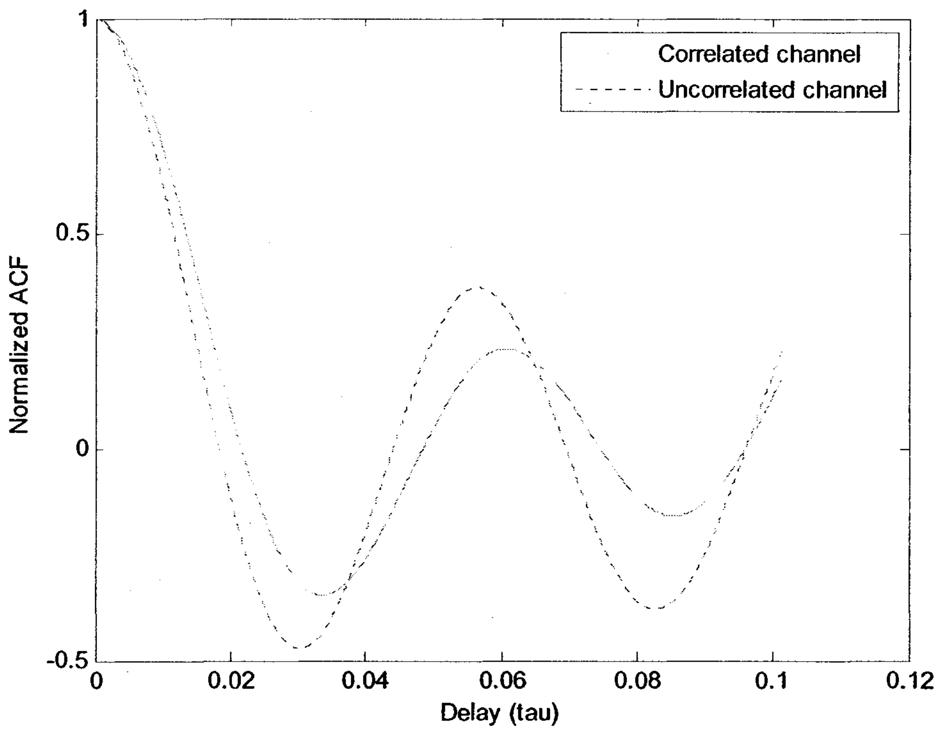

Figure 3.4 Comparison of the ACF obtained using estimated correlated channel with that of the uncorrelated channel

3.2.2 Recovery of performance loss based on channel decorrelation

As discussed earlier in Section 3.2, wireless channels in the real world are seldom i.i.d and often experience correlation. Thus, to achieve good velocity estimates using the

ACF function in correlated channels, the performance loss revealed in Section 3.2 has to be recovered. Otherwise, ACF schemes will give inaccurate velocity estimates. In this section, we present decorrelation based methods for recovering the loss of velocity estimation performance in the receive correlated channel, the transmit correlated channel, and the channel with both transmit and receive correlations.

3.2.2.1 Receive channel decorrelation

The receive correlated channel model is given by

$$\mathbf{H} = \mathbf{R}_r^{1/2}\mathbf{H}_w \tag{3.9}$$

If we can somehow get $\mathbf{H}_w$ back, we can recover the performance lost due to the presence of receive correlation. We propose to left-multiply the estimated channel $\hat{\mathbf{H}}$ by the inverse of the receive correlation matrix. This operation can easily be done as follows.

$$\mathbf{H}_{\mathbf{recov}} = (\mathbf{R}_r^{1/2})^{-1}\mathbf{H} = (\mathbf{R}_r^{1/2})^{-1}\mathbf{R}_r^{1/2}\mathbf{H}_w = \mathbf{H}_w, \tag{3.10}$$

where we have assumed that a perfect channel estimate is available. Now if we use $\mathbf{H}_{\mathbf{recov}}$ instead of $\mathbf{H}$ to estimate the velocity using the ACF method, we should recover the loss of velocity estimation performance experienced due to correlation of receive antennas.

3.2.2.2 Transmit channel decorrelation

The transmit correlated channel model is given by

$$\mathbf{H} = \mathbf{H}_w\mathbf{R}_t^{1/2} \tag{3.11}$$

If the effect of transmit correlation on the i.i.d channel can be undone the performance loss due to presence of transmit correlation can be recovered. We propose to right multiply the estimated channel $\hat{\mathbf{H}}$ by the inverse of the transmit correlation matrix i.e.,

$$\mathbf{H}_{recov} = \mathbf{H}(\mathbf{R}_t^{1/2})^{-1} = \mathbf{H}_w \mathbf{R}_t^{1/2}(\mathbf{R}_t^{1/2})^{-1} = \mathbf{H}_w \tag{3.12}$$

Eq. (3.12) shows that right multiplication of the estimated channel matrix by the inverse of the transmit correlation matrix will give us $\mathbf{H}_W$ back. Now if $\mathbf{H}_{recov}$ is used to estimate the velocity of the mobile, we will recover the loss of performance incurred due to the transmit correlation.

3.2.2.3 Decorrelation of both receive and transmit channels

The Kronecker model describes a scenario with both transmit and receive correlations as

$$\mathbf{H} = \mathbf{R}_r^{1/2}\mathbf{H}_w \mathbf{R}_t^{1/2} \tag{3.13}$$

It was revealed in Section 3.2.1.3 that the velocity estimation performance will be severely degraded in a channel with transmit as well as receive correlation because the channel is no longer i.i.d.. Removing this effect and using the resulting channel for velocity estimation will recover the loss in velocity estimation performance incurred. This can be achieved by left-multiplying the estimated channel matrix $\hat{\mathbf{H}}$ with the inverse of the received correlation matrix and right-multiplying it with the inverse of the transmit correlation matrix, as shown below.

$$\mathbf{H}_{recov} = (\mathbf{R}_r^{1/2})^{-1}\mathbf{H}(\mathbf{R}_t^{1/2})^{-1} = (\mathbf{R}_r^{1/2})^{-1}\mathbf{R}_r^{1/2}\mathbf{H}_w \mathbf{R}_t^{1/2}(\mathbf{R}_t^{1/2})^{-1} = \mathbf{H}_w \tag{3.14}$$

Here again, a perfect channel estimate is assumed. It is seen from Eq. (3.14) that multiplying the estimated channel with the correlation matrices in the above mentioned manner undoes the correlation effect of the channel and leaves us with the $\mathbf{H}_w$ matrix. Using this $\mathbf{H}_w$ matrix for velocity estimation will deliver the same performance as the uncorrelated channel. Thus, through simple multiplications, we have recovered the loss of velocity estimation performance experienced due to the presence of transmit and receive correlations in the MIMO channel.

3.3 Simulation results

Computer simulations were carried out to validate two distinct aspects. Firstly through simulations we reveal the degradation in velocity estimation performance when the ACF method is used to estimate velocity in correlated MIMO channels. Secondly, we apply the methods proposed in Section 3.2.2 to show the recovery of this performance loss by the application of these methods. To avoid repetition, we will present the details of the parameters used in the simulations before proceeding to present the two sets of results.

Consider a system with 3 transmit and 3 receive antennas using uniform linear arrays on both sides with a distance between consecutive antennas equal to $\delta = \frac{d}{\lambda}$, where d is the absolute antenna spacing and $\lambda = c / f_c$ is the wavelength of a narrowband signal with center frequency f_c. The narrowband fading and the GWSSUS model [37] for correlated fading with Gaussian distributed angles of arrival are assumed. Suppose there are L clusters arriving at the receiver with angles of arrival distributed as per $\theta_l \sim N(\theta_{m_l}, \sigma_{\theta_l})$ where θ_{m_l} and σ_{θ_l} are the mean and variance of the angle of arrival of the l^{th} path, respectively. The receive correlation matrix due to the l^{th} cluster is denoted as R_{R_l} with the $(i,j)^{th}$ entry given by [43]

$$\rho_l(s\delta,\theta_{ml},\sigma_{ml}) = e^{-j2\pi s\delta\cos(\theta_{m_l})}e^{-\frac{1}{2}(\pi s\delta\sin(\theta_{m_l})\sigma_{\theta_l})^2} \tag{3.15}$$

where $s = i - j$. Since our system is narrowband, the cluster paths arrive at the same time and the net receive correlation matrix has entries as sums of Eq. ((3.15) weighted by the fraction of power in the corresponding cluster. Thus if $|\beta_l|^2$ is the fraction of power in the l^{th} path, then each element of the net correlation matrix contains summations of Eq. (3.16).

$$|\beta_l|^2 \; e^{-j2\pi(i-j)\delta\cos(\theta_{m_l})}e^{-\frac{1}{2}(\pi(i-j)\delta\sin(\theta_{m_l})\sigma_{\theta_l})^2} \tag{3.16}$$

For our correlated system we choose δ to be 0.5, $M_r = M_t = 3$ and the parameters are given in Table 3.2.

Table 3.2. Parameters of correlated MIMO channels

θ_{m_1}	θ_{m_2}	σ_{θ_1}	σ_{θ_2}	$\lvert\beta_1\rvert^2$	$\lvert\beta_1\rvert^2$
π/6	π/2	π/20	π/40	0.5	0.5

We assume the receive and transmit correlation matrices to be equal for the purpose of simplicity. Eq. (3.15) & (3.16) give the correlation matrices as,

$$\mathbf{R_r} = \mathbf{R_t} = \begin{pmatrix} 1.00 & 0.2e^{0.86\pi j} & 0.8e^{-0.26\pi j} \\ 0.2e^{-0.86\pi j} & 1.00 & 0.2e^{0.86\pi j} \\ 0.8e^{0.26\pi j} & 0.2e^{-0.86\pi j} & 1.00 \end{pmatrix} \tag{3.17}$$

The measure used to evaluate the accuracy of the velocity estimate is the NMSE as given by Eq. (3.4). Each value of the NMSE is computed by averaging over 1000 velocity estimates. To compute every velocity estimate, the ACF is computed using estimates of 1000 channel realizations. We assume the channel and the correlation matrix are perfectly known at the receiver. Here onwards, the velocity estimation is undertaken using the zero-crossing based ACF method as described in Section 2.3.1. The first set of results illustrates the performance loss in correlated channels and the second set illustrates the recovery of this performance loss.

3.3.1 Performance loss due to receive correlation

Figure 3.5 compares the performance of velocity estimation in a correlated MIMO channel with the performance in an uncorrelated MIMO channel. It can be seen that the NMSE of the correlated channel is higher than the NMSE of the uncorrelated channel for all velocities. This confirms the statement made in Section 3.2.1.1 that the correlation on the receive side of the MIMO system reduces the performance of the ACF-based velocity estimation schemes. This reduction occurs because of the deviation of the channel matrix from the i.i.d channel matrix due to the presence of receive correlation in the channel. Next we look at the performance of ACF based velocity estimation schemes in MIMO channels with transmit correlation.

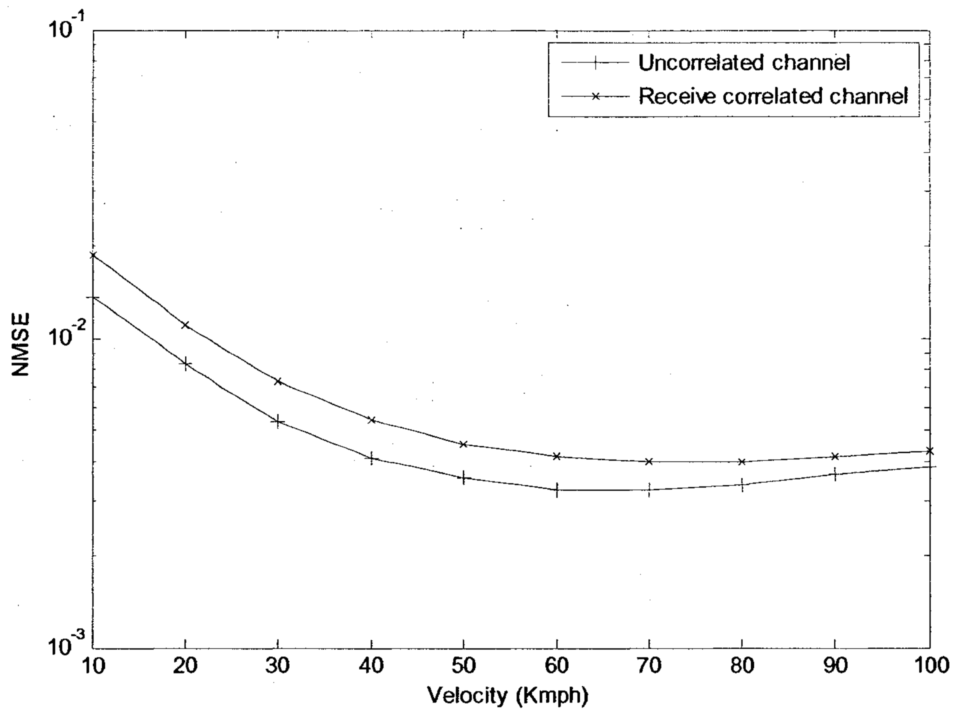

Figure 3.5 Degradation of velocity estimation performance due to receive correlation in a 3 by 3 MIMO system

3.3.2 Performance loss due to transmit correlation

Figure 3.6 compares the performance of velocity estimation for two cases

1) An uncorrelated MIMO channel.

2) Transmit correlated MIMO channel.

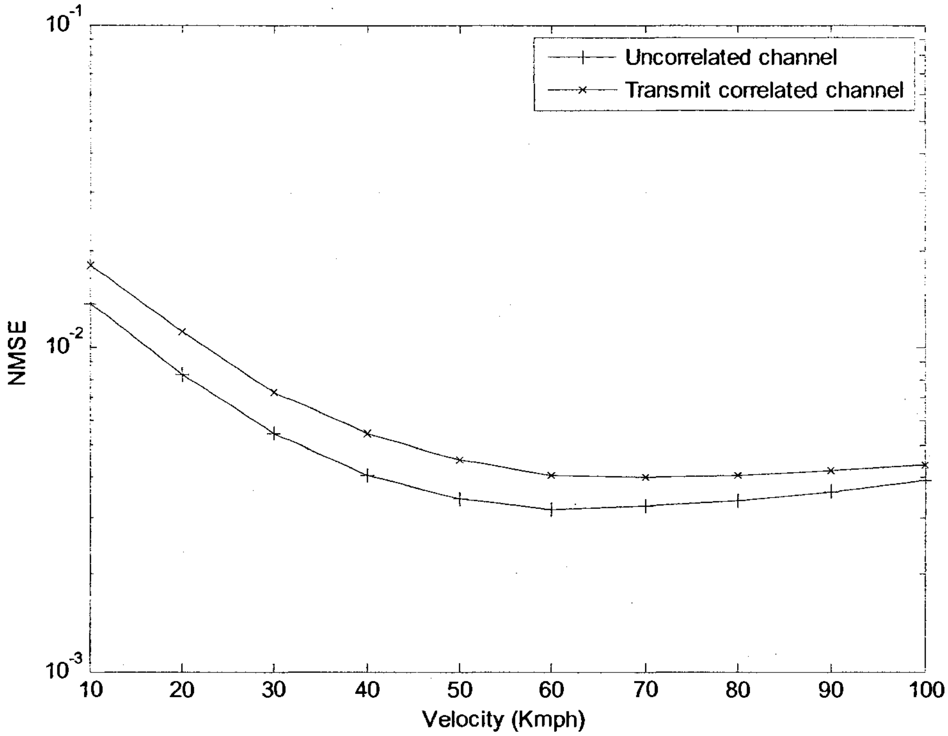

Figure 3.6 Degradation of velocity estimation performance due to transmit correlation in a 3 by 3 MIMO system

The simulation results show that the NMSE of the correlated channel is greater than the NMSE of the uncorrelated channel for all velocities. This clearly displays that a loss in the accuracy of velocity estimation occurs due to the presence of correlation on the transmit side of the MIMO system.

3.3.3 Performance loss due to presence of both transmit and receive correlation.

Figure 3.7 compares the performances of velocity estimation for two MIMO channels

1) An uncorrelated channel
2) A channel with correlation at the transmitter and the receiver.

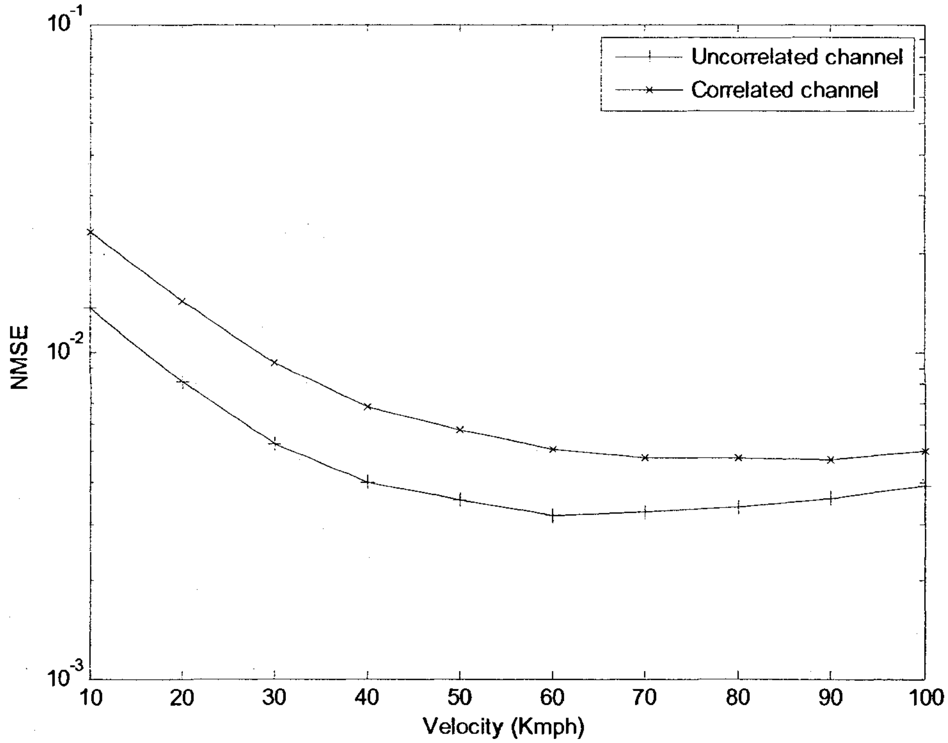

Figure 3.7 Degradation of velocity estimation performance due to correlation at both transmit and receive sides of a 3 by 3 MIMO system

The NMSE of the correlated MIMO channel is greater than the NMSE of the uncorrelated channel for all velocities. Thus, the performance of velocity estimation in the correlated channel has worsened due to the presence of both transmit and receive correlations in the channel. It should be noticed that the two curves in Figure 3.7 are further apart than the curves in both the previous two figures, Figure 3.5 & Figure 3.6. This shows that performance degradation in the presence of transmit and receive correlations is more than the case where correlation is present at one side only. Thus, an increase in the correlation of the channel leads to an increased degradation of the performance of velocity estimation.

Next, we move on to present the second set of simulation results, i.e. the recovery of the performance loss of velocity estimation using the methods proposed in Section 3.2.2. We first present results for the receive correlated MIMO channel, followed by the transmit correlated channel, and lastly the results for MIMO channels with both transmit and receive correlation.

3.3.4 Recovery of performance loss in receive correlated MIMO channel.

Figure 3.8 compares the NMSE of the velocity estimation for the uncorrelated channel and the receive correlated channel as well as the performance achieved after applying the performance recovery scheme proposed in Section 3.2.2.1. It can be seen that after applying the recovery scheme, the performance of velocity estimation reverts back to the performance of the uncorrelated channel. Thus, the loss in velocity estimation performance due to the presence of receive correlation in the channel is recovered. However it must be remembered that we have assumed a perfectly known receive correlation matrix in our simulations. This causes the loss due to correlation being fully recovered when we use this correlation matrix to recover our performance degradation. As the estimation of the receive correlation matrix becomes inaccurate, the percentage recovery of performance loss will also reduce.

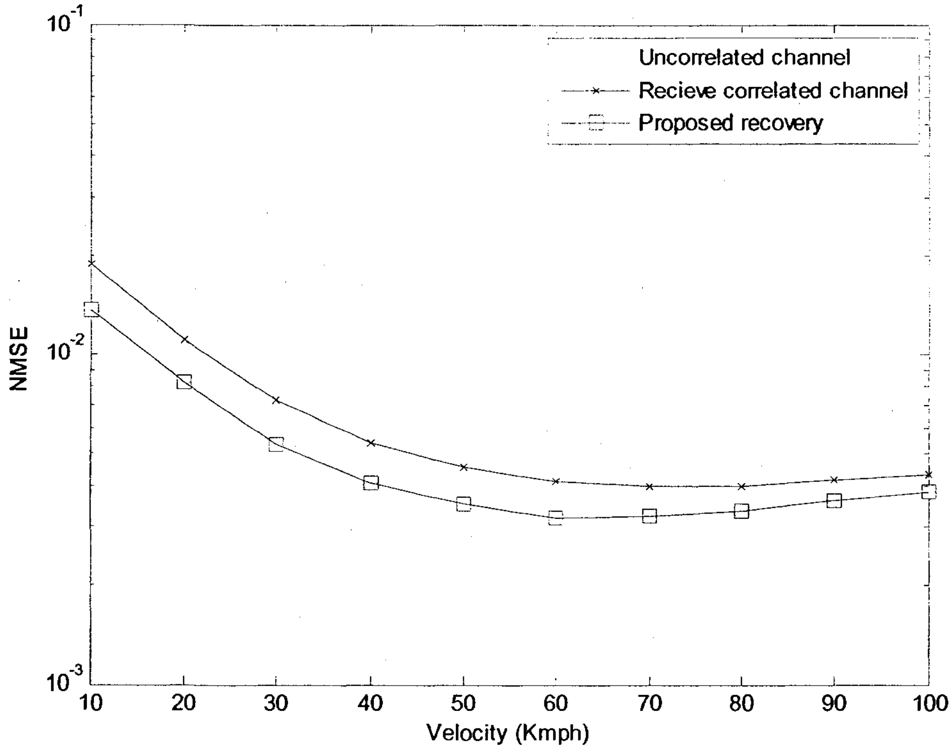

Figure 3.8 NMSE versus velocity curves for the uncorrelated channel, the receive correlated channel and after the recovered /decorrelated channel

3.3.5 Recovery of performance loss in transmit correlated MIMO channel

Figure 3.9 compares the NMSE of velocity estimation for an uncorrelated channel, a transmit correlated channel, and the decorrelated channel obtained using the loss recovery technique presented in Section 3.2.2.2. It can be seen that the proposed method fully recovers the loss in performance occurring due to the presence of transmit correlation in the MIMO channel. As mentioned in Section 3.3.4, 100 % recovery of the loss of estimation performance occurs due to perfect knowledge of the transmit correlation matrix at the receiver. It is to be noted here that we have assume that correct knowledge of the transmit correlation matrix can be maintained at the receiver. This assumption is valid as the correlation matrix is based on the second order statistics of the channel and not the instantaneous channel realization. These second order statistics, being a function of the local scattering environment, vary on a much slower time scale than the channel itself, thus allowing the transmit correlation matrix to be fed to the receiver at time intervals which are separated well enough to avoid causing excessive overhead due to feedback.

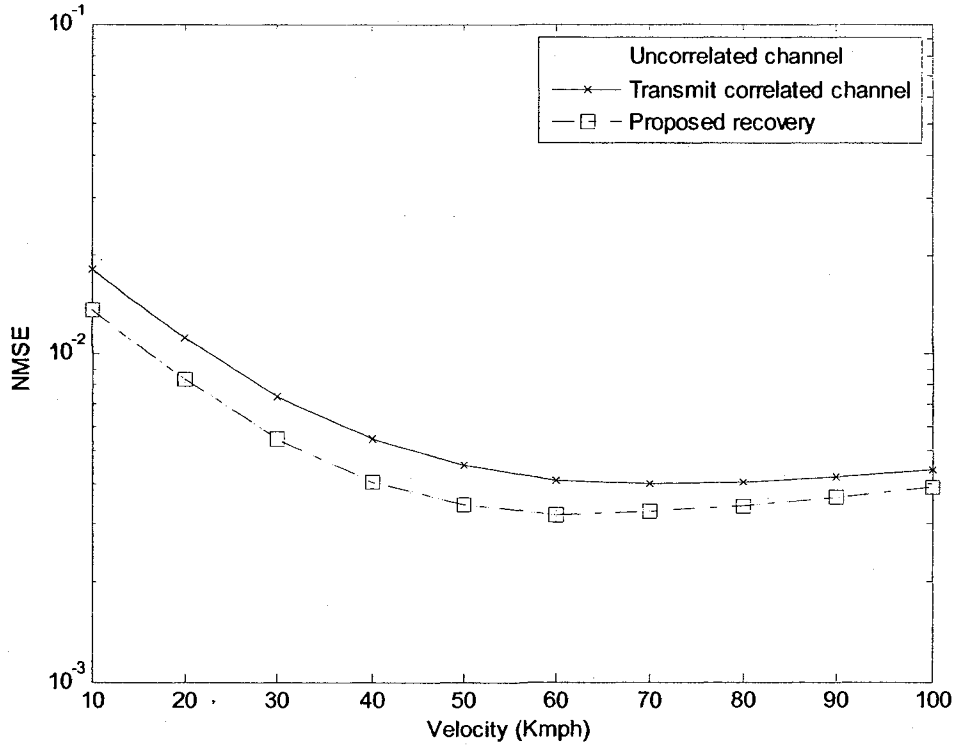

Figure 3.9 NMSE versus velocity curves for uncorrelated channel, transmit correlation channel and after applying proposed recovery method

3.3.6 Recovery of performance loss in MIMO channel with both transmit and receive correlations.

Figure 3.10 compares the NMSE of velocity estimation for the uncorrelated channel, the channel with correlation at transmitter and receiver and the decorrelated channel using the recovery technique proposed in Section 3.2.2.3. The curves show that the loss in velocity estimation performance is completely recovered.

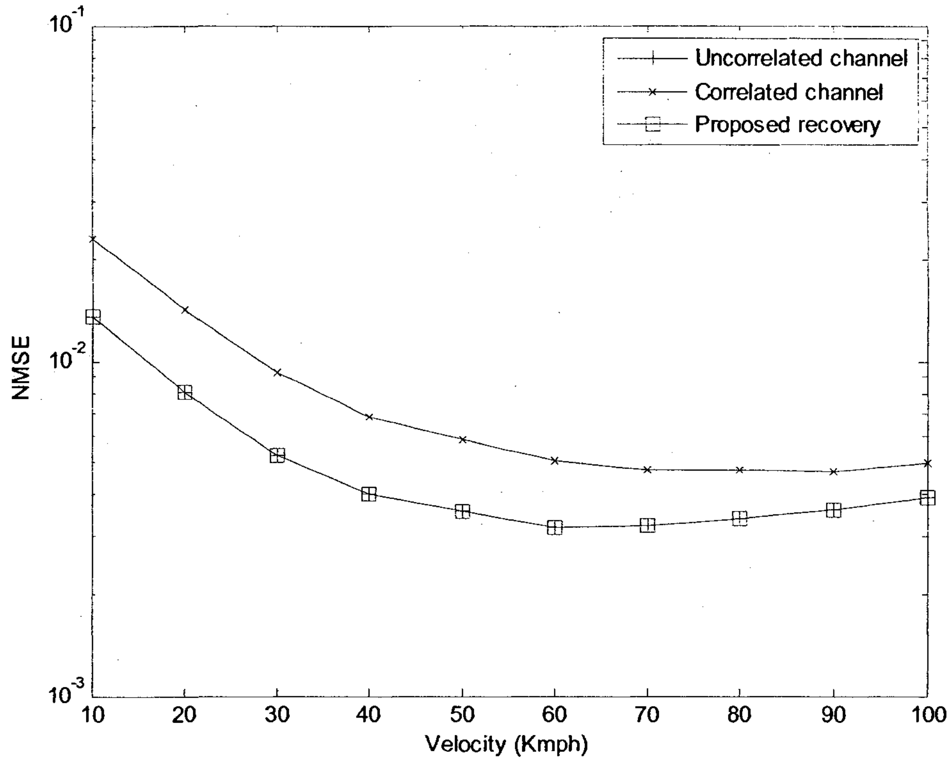

Figure 3.10 NMSE versus velocity curves for uncorrelated channel, correlated channel and decorrelated channel

It is also noticed in Figure 3.5-Figure 3.10 that the NMSE decreases with increasing velocity to a certain point and then increases. This is influenced by two factors which independently affect the accuracy of the estimate of the ACF obtained. The first factor can be explained as follows. Our estimation is based on the zero-crossing of the ACF of the estimated channel. Practically, the zero-crossing represents the delay at which the channel becomes completely uncorrelated. For a slow moving mobile, the channel will vary slowly and thus this delay will be larger. Lets say τ_1=100ms. On the other hand, for a fast moving mobile the channel will vary faster and thus this delay will be shorter. Lets say τ_2=10ms. If we estimate the velocity every 1 second, i.e. a new ACF is calculated using the channel estimates for the duration of every one second, then the value of the ACF obtained at the zero crossing for the fast channel would be an average of 100 correlation values (1s/10ms) whereas the value of the ACF obtained at the zero crossing for the slow channel would be an average of only 10 correlation values (1s/100ms). This will result in more accurate estimate of ACF value at the zero crossing for fast moving mobiles than for slow moving mobiles. Likewise, for a fixed interval after which the velocity estimate is updated using the ACF method, the values of the estimated velocity for fast moving mobiles will generally be more accurate than velocity estimates for slow moving mobiles.

The other factor influencing the accuracy of the estimated ACF is the sampling frequency. The higher the sampling frequency the better the channel variation is captured. This eventually leads to an accurate estimate of ACF. But a high sampling frequency also burdens the system. Recall that we target to update our velocity estimate every 1 second. For a high sampling frequency, say 1 MHz, the number of samples required to capture 1 second of channel variation is 1×10^6. This will require a lot of storage space and will make it computationally heavy to calculate the ACF every one second using 1×10^6 samples. Thus, the sampling frequency cannot be increased arbitrarily. At high speeds this means that the channel is not captured most accurately and thus the accuracy of velocity estimates obtained decreases. This causes the slight increase in NMSE as seen in Figure 3.5-Figure 3.10 at higher mobile velocities.

3.4 Conclusion

In this chapter, firstly the performance of ACF based velocity estimation schemes in correlated Rayleigh fading MIMO channels was compared with the performance of ACF based velocity estimation technique in uncorrelated Rayleigh fading MIMO channels. This comparison was conducted for three cases: 1) Correlation at transmit side only, 2) Correlation at receive side only 3) Correlation at both transmit and receive side. It was revealed that in all these three cases of correlated MIMO channels, the performance worsens compared to the uncorrelated channel. Next, a recovery method based on decorrelation of the estimated MIMO channel matrix was proposed to recover this performance loss. Simulation results verified the performance loss in velocity estimation for correlated MIMO channels and also revealed that the proposed recovery methods are capable of recovering the performance loss completely, provided that the perfect knowledge of the transmit and receive correlation matrices is available at the receiver.

4 Velocity estimation using ACF based schemes in correlated MIMO channels with antenna selection.

In this chapter we study the application of the ACF based methods to correlated MIMO systems with antenna selection. We continue to use the zero-crossing based ACF method introduced in Section 2.3.1 to conduct our study. Since the fundamental factor determining the accuracy of all ACF based techniques is the accuracy of the estimated ACF, the same results will apply to all ACF based velocity estimation methods. We start the chapter with a discussion on antenna selection for fast moving mobiles. What follows is a comparison of the performance of velocity estimation in antenna selection systems with the performance of velocity estimation in MIMO systems using the full antenna set. Thereafter, we propose a decorrelation based method to partially recover the performance loss of velocity estimation in antenna selection systems.

4.1 Antenna selection in fast moving mobiles

When we talk about velocity estimation our target application is of course the moving mobile. The moving mobile implies a fast changing channel. This section is dedicated to discussing which kinds of antenna selection techniques are feasible for use with moving mobiles? Antenna selection can be based either on the instantaneous channel realization or on channel statistics. This is detailed in the following two sections.

4.1.1 Selection based on instantaneous channel realization

In this type of selection, the criterion to select antenna is based on the instantaneous channel realization. An example of a technique based on this criterion is the truly optimum selection of the antenna elements [38] . This entails an exhaustive search of all possible combinations for the one that gives the best SNR (for diversity) or capacity (for spatial multiplexing). This algorithm becomes prohibitively complex with increasing antennas. The simplest selection algorithm in this category is the one that chooses the antenna elements with the largest power, i.e. the largest Frobenius column (or row) norm [35]. Another algorithm called the correlation based method (CBM) [39] chooses the two rows (or columns) of the channel matrix which are most correlated and removes the one which has less power. It continues to do so until the needed number of antennas remains. In this way the matrix remains with rows (or columns) which have minimum mutual information and maximum power. More work on selection based on instantaneous channel realization can be given in [40]-[42]. The purpose of mentioning some of the existing techniques for selection based on instantaneous channel realization above is for the reader to realize that for a fast varying channel, the selection performed by such techniques will have to be updated very frequently. Criteria such as SNR and capacity of the channel could change for the different subsets of the MIMO antennas with every realization of the channel, thus causing a change in the selected antennas.

A simulation was carried out to observe the rate at which the selection of the antennas changes for the CBM method mentioned above. The simulation was set up to select 3 out of 8 receive antennas where the number of transmit antennas was 3. A total of 10000 symbols were transmitted and the index of selected antennas (eg. 1,2 and 5) compared for two consecutive symbols, i.e. two consecutive channel realizations. For every symbol transmission i.e. every channel realization, the number of newly selected antennas which were different from antennas selected for the previous symbol was recorded on the y-axis. So if for symbol 1, the selected antennas was 1,4 and 6 and for symbol 2 the selected antennas was 1, 3 and 6 then the y axis recorded a 1 for a value of 2 on the xaxis because the number of newly selected antennas is 1 (antenna 3 instead of antenna 4). Figure 4.1 shows the result of the simulation.

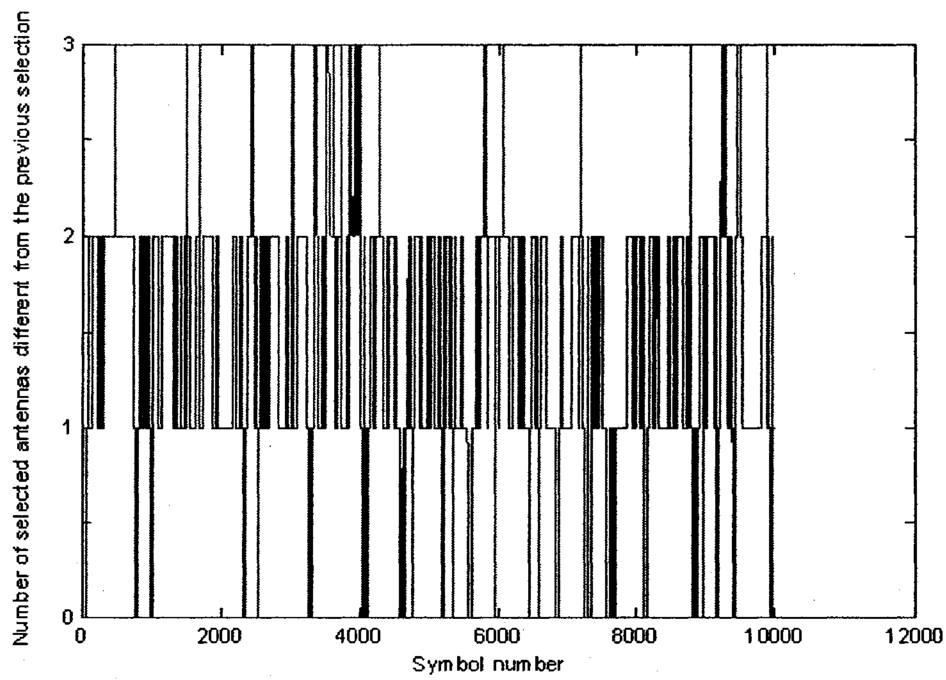

Figure 4.1 Number of selected antennas different from the previous selection vs symbol number

It can be seen in Figure 4.1 that there are very few occurrences where the set of selected antennas has not changed. Almost every symbol, there is a change of one or more selected antennas. This fast change in selected antennas could cause two problems in fast moving mobiles. First, for transmit selection systems in general, delays in the feedback path (when transmit antennas are selected at the receiver side and only their index is fed back) could cause decision errors because the channel might have changed by the time the selection is actually done on the transmit side. The second problem concerns the ACF based velocity estimation technique directly. Recall from Section 3.1 that for calculating the velocity of the mobile the first step is to calculate the ACF using the channel estimates of every individual SISO channel. To estimate the ACF of a particular SISO channel we need to have continuous channel estimates of this SISO channel for a certain amount of time. But with the antenna selection changing almost every symbol we cannot have continuous channel estimates of a particular SISO channel for a time period which is enough to give us a good ACF. Thus for these two reasons, to perform antenna selection in fast moving mobiles, we need to look towards antenna selection algorithms which change the selected antennas on a rather slower scale. Firstly, this will help avoid decision errors in transmit selection systems based on feedback. Secondly, the usage of the ACF based velocity estimation schemes will be possible as the availability of continuous channel estimates will allow the estimation of an ACF for each SISO channel and thus the estimation of velocity of the MIMO mobile. The second category of selection techniques where selection is based on statistical channel knowledge helps us achieve this.

4.1.2 Selection based on statistical channel knowledge.

Unlike the instantaneous channel realization, the channel statistics are usually more stable. They depend on large scale scatterers/distance between the transmitter and receiver and change slowly over time even in mobile environments [36]. Therefore, in scenarios, where 'deterministic selection', i.e., the antenna sets be selected per channel instance, is not possible, we can resort to channel statistics based selection. In this kind of selection the optimal antenna subset is selected based on second order channel statistics so as to minimize the average probability of error. The selected subset will not minimize the instantaneous probability of error for every channel instance. It will however, be a subset that is 'optimal on average' in the sense that the average probability of error for that selection is lower than that for any other selection of antennas. A handful of techniques present statistical selection methods in current literatures [43]-[48]. As not all of them are relevant to our topic, we do not detail all these methods here. Rather we restrict ourselves to discussing only the antenna selection method we use in our simulations.

We use the statistics based antenna selection method given in [43] for our simulations. It can be explained as follows. Let N_t and N_r denote the number of selected transmit antennas and that of receive antennas, respectively and out of M_t transmit and M_r receive antennas. Further, let $\mathbf{R}$ ($M_tM_r \times M_tM_r$) be the correlation matrix of the vectorized channel between the M_t transmit and M_r receive antennas and $\mathbf{R}_{sel}$ ($N_tN_r \times N_tN_r$) be the correlation matrix of the vectorizeed channel between the selected antennas. The joint selection rule is to choose the principle submatrix $\mathbf{R}_{sel}$ of $\mathbf{R}$, corresponding to N_t transmit and N_r receive antennas which maximizes det($\mathbf{R}_{sel}$), the determinant of the submatrix $\mathbf{R}_{sel}$. This guarantees that the average probability of error is minimum among all possible selections. For high SNRs the joint selection rule decouples, allowing us to select transmit and receive antennas independent of each other. The rule then says "If $\mathbf{R}_t$ is the transmit correlation matrix and $\mathbf{R}_r$ is the receive correlation matrix, then at the transmit end, choose the ($N_t \times N_t$) submatrix $\mathbf{R}_{tx\_sel}$ of $\mathbf{R}_t$ with the highest determinant and at the receive side choose the ($N_r \times N_r$) submatrix $\mathbf{R}_{rx\_sel}$ of $\mathbf{R}_r$ with the highest determinant"

4.2 Velocity estimation using ACF based schemes in correlated MIMO channels with antenna selection

In this section we study the extension of velocity estimation methods based on the ACF to correlated MIMO channels with antenna selection. To start, we compare the performance of the extension under study to that of velocity estimation in the i.i.d MIMO channel case.

4.2.1 Performance in correlated MIMO channels with antenna selection

To clarify presentation we first consider correlation and selection at transmit side only, followed by correlation and selection at receiver side only and lastly we consider correlation and selection at both transmitter and receiver side. It is recalled from chapters 2 & 3 that the ideal MIMO channel is the Rayleigh fading uncorrelated MIMO channel using the full antenna set and is represented by $\mathbf{H}_{\mathbf{w}}$. We use the notation of N_t for selected transmit antennas, N_r for selected receive antennas and M_t and M_r for total transmit and receive antennas respectively. Notations of $\mathbf{R}_{tx\_sel}$ and $\mathbf{R}_{rx\_sel}$ are used for the selected sub matrices of the complete transmit correlation and the complete receive correlation matrices, respectively. For all further discussions, correlation of channel will go with selection of antennas, i.e. the channel is correlated at the side where selection is being performed and uncorrelated where selection is not to be performed. This mention will not be repeated every time.

4.2.1.1 Selection at transmit side only

The transmit selection channel, which does not take correlation at the transmitter and receiver into account (follows i.i.d distribution), can be represented by $\mathbf{H}_w^{tx\_sel}$ where the size of $\mathbf{H}_w^{tx\_sel}$ is M_r by N_t. After accounting for transmit correlation in the channel, the effective channel matrix can be written as,

$$\mathbf{H} = \mathbf{R}_{tx\_sel}^{1/2}\mathbf{H}_w^{tx\_sel} \tag{4.1}$$

It must be noticed in Eq. ((4.1) that now the channel **H** has deviated from the ideal MIMO channel $\mathbf{H}_w$ in two ways. Firstly, the size of **H** has reduced from $M_r \times M_t$ to $M_r \times N_t$. This is because the antenna selection has reduced the number of columns in **H** from M_t to N_t. Secondly, the elements which make up **H** are no longer i.i.d random variables, rather they are modified due to the transmit correlation in the channel. Thus, we have degradation in the performance of velocity estimation. To explain the first reason, we repeat, from Section 3.1, the equation for calculating the velocity of a mobile in a $M_t \times M_r$ MIMO system

$$\hat{v}_{MIMO} = \frac{\sum_{i=1}^{M_r}\sum_{j=1}^{M_t}\hat{v}_{ij}}{N}, \qquad N = M_r \times M_t \tag{4.2}$$

which says that that the calculation of the velocity of a mobile in a MIMO system using the ACF method is performed by averaging the velocity estimates of the N SISO channels which make up the MIMO channel. The random nature of the Rayleigh fading channel implies that the greater the value of N, the better will be the velocity estimate. Remembering that $N_t < M_t$, that in the case of transmit antenna selection N would reduce from $M_r \times M_t$ (as in the case of the full MIMO channel) to $M_r \times N_t$. This reduction in N would effectively reduce the accuracy of the MIMO velocity estimate. The second reason for degradation in performance of velocity estimation is that even the remaining elements of the reduced matrix **H** no longer represent a pure Rayleigh fading. Rather the presence of transmit correlation in the channel causes them to undergo multiplication with the transmit correlation matrix as shown in Eq. (4.1). This results in deviation of the channel from a pure Rayleigh channel. The ACF obtained from the estimated channel $\hat{\mathbf{H}}$, would represent the corresponding Rayleigh channel inaccurately. This will lead to an inaccurate estimate of velocity using ACF based schemes as the key to accurate velocity estimation in ACF based methods is an accurate estimate of the ACF. Thus, the performance of velocity estimation using ACF based methods will deteriorate in correlated MIMO channels with antenna selection on the transmitter side.

4.2.1.2 Selection at receive side

We can denote the receive selection channel which does not take correlation at the transmitter and receiver side into account as $\mathbf{H}_w^{rx\_sel}$ with size N_r by M_t. Accounting for receive correlation in the channel, the effective channel matrix would be,

$$\mathbf{H} = \mathbf{H}_w^{rx\_sel} \mathbf{R}_{rx\_sel}^{1/2} \tag{4.3}$$

It is to be noted that $\mathbf{H}$ has now deviated from the ideal MIMO channel, $\mathbf{H}_w$ in two ways. Firstly the size of $\mathbf{H}$ has reduced from $M_r \times M_t$ to $N_r \times M_t$. This is because of the reduction of receive antennas from M_r to N_r in the process of receive antenna selection. Secondly the elements of $\mathbf{H}$ are no longer ZMCSCG random variables[1]. This will cause degradation in the velocity estimation performance. Primarily the reduction of receive antennas due to receive selection will cause N in Eq. (4.2) to be reduced. This will lead to the MIMO velocity estimate being calculated by averaging over the lesser number of SISO velocity estimates, thus reducing accuracy of the obtained MIMO velocity estimate. The second reason for the degradation of performance will be that even the fewer elements which remain in $\mathbf{H}$ do not represent the pure Rayleigh channel any more due to the effect of receive correlation in the system. As the fundamental assumption of ACF

[1] A complex Gaussian random variable C=A+jB is ZMCSCG if A and B are independent real Gaussian random variables with zero mean and equal variance.

based velocity estimation methods is that the wireless channel undergoes purely Rayleigh fading, this deviation of **H** from the pure Rayleigh channel will eventually result in less accurate estimates of velocity as already detailed in Section 4.2.1.1.

4.2.1.3 Selection at both transmit and receive

The channel, not taking correlation into account, with transmit and receive selection can be denoted by $\mathbf{H}_w^{tx\_rx\_sel}$ with size M_r by M_t. After accounting for correlation on the transmitter and receiver side, the channel can be represented by

$$\mathbf{H} = \mathbf{R}_{tx\_sel}^{1/2}\mathbf{H}_w^{tx\_rx\_sel}\mathbf{R}_{rx\_sel}^{1/2} \tag{4.4}$$

Similarly, the effective channel matrix **H** deviates from the ideal MIMO channel matrix $\mathbf{H}_w$ in two ways. Firstly, the number of elements in the matrix has reduced from $M_r \times M_t$ to $N_r \times N_t$. This is because antenna selection removes M_r - N_r antennas from the receiver side and M_t - N_t antennas from the transmit side. Secondly, the variation of every element in **H** with time no longer represents pure Rayleigh fading due to the matrix $\mathbf{H}_w^{tx\_rx\_sel}$ being multiplied by the transmit and receive correlation matrices of the channel. These two deviations will degrade the velocity estimation performance. The reduction in the number of antennas on both sides will reduce the total number of SISO velocity estimates which are averaged over to obtain the MIMO velocity estimate. This reduction, equivalent to a reduction in N of Eq. (4.2) will now cause the velocity estimates obtained after averaging to be less accurate as reasoned in Section 4.2.1.1. On the other hand, the deviation of the elements of **H** from pure Rayleigh fading characteristic will cause the estimated ACF at a specific velocity to deviate considerably from the correct ACF for that velocity. The correct ACF for a specific velocity is always given by a Bessel function as previously explained in Section 2.3. Thus, in correlated MIMO channels with antenna selection on both transmit and receive sides, not only is N reduced in Eq. (4.2 but each of the individual velocity estimates, v_{ij}, is now less accurate, leading to a degraded performance when velocity is estimated using ACF based schemes. Next, we move on to present some new schemes for the recovery of the performance loss of velocity estimation occurring in correlated MIMO channels with antenna selection.

4.2.2 Recovery of performance loss in correlated MIMO channels with antenna selection.

Lately, tremendous interest has grown in antenna selection algorithms. The idea is being seen as a very viable solution to the high cost of RF equipment associated with implementing a MIMO system in practice. As the usage of MIMO becomes widespread antenna selection might very soon become a common feature on wireless devices and/or base stations. For velocity estimation techniques to be used in practice in the commonly occurring correlated MIMO channels with antenna selection they will need to be accurate. This section is devoted to proposing techniques which can partially recover the performance loss due to the use of the ACF based methods in correlated MIMO systems with antenna selection. We first propose the recovery techniques for the case of transmit antenna selection followed by the case of receive antenna selection and finally the case where selection is performed at both transmit and receive sides.

4.2.2.1 Recovery of performance loss in transmit selection systems

The channel model for transmit selection systems as given in Section 4.2.1.1 is

$$\mathbf{H} = \mathbf{R}_{tx\_sel}^{1/2} \mathbf{H}_w^{tx\_sel} \tag{4.5}$$

Recall that two distinct losses of velocity estimation performance occur due to two distinct reasons: the reduction in the number of elements in $\mathbf{H}$ and the deviation of each element from pure Rayleigh fading characteristic. We found that the loss due to the deviation from pure Rayleigh characteristic can be recovered by left multiplying the estimated channel by the inverse of $\mathbf{R}_{tx\_sel}^{1/2}$, the selected sub matrix of the complete transmit correlation matrix. Assuming perfect channel estimation, i.e. $\mathbf{H} = \hat{\mathbf{H}}$, we have

$$(\mathbf{R}_{tx\_sel}^{1/2})^{-1} \mathbf{H} = (\mathbf{R}_{tx\_sel}^{1/2})^{-1} \mathbf{R}_{tx\_sel}^{1/2} \mathbf{H}_w^{tx\_sel} = \mathbf{H}_w^{tx\_sel} \tag{4.6}$$

Eq. (4.6) shows that the multiplication gives back $\mathbf{H}_w^{tx\_sel}$ whose elements exhibit pure Rayleigh fading. Thus, we have partially recovered the loss of velocity estimation. The other part of the degradation still remains as the number of elements in $\mathbf{H}_w^{tx\_sel}$ is still less than $\mathbf{H}_w$. This loss cannot be recovered because in practice channel estimation will always be done only for the channels between the active subset of antennas. It would be highly inefficient to undertake the computationally heavy task of channel estimation in the full MIMO system just for the sake of velocity estimation. Thus channel estimates will not be available for the inactive subset of antennas and therefore the number of elements in $\mathbf{H}$ will remain to be less, implying that the loss resulting due to reduced elements in $\mathbf{H}_w^{tx\_sel}$ cannot be compensated for. Nevertheless, using the proposed technique, a partial recovery of the loss in velocity estimation performance in correlated MIMO channels with transmit selection can be achieved.

4.2.2.2 Recovery of performance loss in receive selection systems

The correlated MIMO channel with receive antenna selection is represented by

$$\mathbf{H} = \mathbf{H}_w^{rx\_sel}\mathbf{R}_{rx\_sel}^{1/2} \tag{4.7}$$

The loss of velocity estimation performance is attributed to two factors. One is the reduction in the number of elements in **H** and the other is the deviation of the remaining elements of **H** from pure Rayleigh fading characteristic. We propose a partial recovery of the performance loss by right multiplying the estimated channel matrix $\hat{\mathbf{H}}$ by the inverse of $\mathbf{R}_{rx\_sel}^{1/2}$, the selected sub matrix of the complete receive correlation matrix. Assuming perfect channel estimation, i.e. $\mathbf{H} = \hat{\mathbf{H}}$, the result of the matrix multiplication is given as

$$\mathbf{H}(\mathbf{R}_{rx\_sel}^{1/2})^{-1} = \mathbf{H}_w^{rx\_sel}\mathbf{R}_{rx\_sel}^{1/2}(\mathbf{R}_{rx\_sel}^{1/2})^{-1} = \mathbf{H}_w^{rx\_sel} \tag{4.8}$$

The resulting $\mathbf{H}_w^{rx\_sel}$ is the channel matrix of the selected channel which does not include correlation effects of the channel. Using this channel matrix for velocity estimation will allow us to partially recover the loss incurred because now the elements of the matrix represent a purely Rayleigh fading channel. We can now expect the ACF calculation using each of these elements to be close to the actual Bessel function and thus give accurate velocity estimates for each SISO channel. This will eventually result in an accurate velocity estimate of the MIMO mobile. However, the number of SISO velocity estimates averaged to obtain the MIMO velocity estimate remains to be less due to the reduction in number of receive antennas. Thus, we remain incapable of recovering the loss incurred due to reduction in the number of active receive antennas as detailed in Section 4.2.2.1.

4.2.2.3 Recovery of performance loss in systems with selection at both transmitter and receiver

When antennas are selected at both transmitter and receiver in correlated MIMO channels we model the system as

$$\mathbf{H} = \mathbf{R}_{tx\_sel}^{1/2} \mathbf{H}_w^{tx\_rx\_sel} \mathbf{R}_{rx\_sel}^{1/2} \tag{4.9}$$

The performance degradation of velocity estimation will occur due to two different reasons. Firstly, the number of elements in **H** has reduced and secondly the elements of **H** no longer represent purely Rayleigh fading because of the induction of transmit and receive correlation effects in the channel. The reduction in the number of elements in **H** is inevitable in antenna selection systems. Antenna selection on both transmitter and receiver will always reduce M_t - N_t and M_r - N_r antennas on the transmit and receive sides, respectively. This will entail estimation of only the channels of the active subset of antennas, thus reducing the number of elements in **H**. This loss incurred due to the reduction in elements of **H** cannot be recovered. However, we can recover the loss in velocity estimation performance which occurs due to the induction of transmit and receive correlation effect in the selected channel matrix $\mathbf{H}_w^{tx\_rx\_sel}$. If we can undo the effect of this correlation on the channel matrix, the performance loss can be recovered. We propose to do this by left-multiplying the estimated channel matrix by the inverse of $\mathbf{R}_{tx\_sel}^{1/2}$ and right multiplying it by the inverse of $\mathbf{R}_{rx\_sel}^{1/2}$, which under the assumption of perfect channel estimation, gives

$$
\begin{aligned}
(\mathbf{R}_{tx\_sel}^{1/2})^{-1}\mathbf{H}(\mathbf{R}_{rx\_sel}^{1/2})^{-1} &= (\mathbf{R}_{tx\_sel}^{1/2})^{-1}\mathbf{R}_{tx\_sel}^{1/2}\mathbf{H}_{w}^{tx\_rx\_sel}\mathbf{R}_{rx\_sel}^{1/2}(\mathbf{R}_{rx\_sel}^{1/2})^{-1} \\
&= \mathbf{H}_{w}^{tx\_rx\_sel}
\end{aligned}
\tag{4.10}
$$

Obviously the multiplication undoes the correlation effect on the channel matrix, resulting in the matrix $\mathbf{H}_{w}^{tx\_rx\_sel}$. The channel matrix now has elements which represent purely Rayleigh fading. These elements, when used to estimate velocity, will give accurate estimates as reasoned in Section 4.2.2.1. Thus the proposed recovery technique allows partial recovery of the performance loss in velocity estimation in correlated MIMO channels with antenna selection at both transmit and receive sides.

4.3 Simulation results

Simulation results presented in this section validate two aspects. The first set of results validates the performance degradation of velocity estimation using ACF based methods in correlated MIMO channels with antenna selection. Thereafter, the second set of results validates the recovery of this performance loss using the methods presented in Section 4.2.2. Both sets of results consider cases of receive antenna selection, transmit antenna selection and selection at both transmitter and receiver. All simulations are based on a 3×3 MIMO system. The correlation matrix used at the transmitter and/or receiver is given by

$$
\mathbf{R_r} = \mathbf{R_t} = \begin{pmatrix} 1.00 & 0.2e^{0.86\pi j} & 0.8e^{-0.26\pi j} \\ 0.2e^{-0.86\pi j} & 1.00 & 0.2e^{0.86\pi j} \\ 0.8e^{0.26\pi j} & 0.2e^{-0.86\pi j} & 1.00 \end{pmatrix} \tag{4.11}
$$

This matrix is identical to the one used in Chapter 3. Details of the scenario simulated by the matrix have already been given in Section 3.3 and will not be repeated. For antenna selection two of three antennas are selected based on the rule "If $\mathbf{R}_t$ is the transmit correlation matrix and $\mathbf{R}_r$ is the receive correlation matrix then at the transmit end, choose the ($N_t \times N_t$) submatrix $\mathbf{R}_{tx\_sel}$ of R_t with the highest determinant and at the receive side choose the ($N_r \times N_r$) submatrix $\mathbf{R}_{rx\_sel}$ of R_r with the highest determinant" where N_t and N_r are the number of selected transmit and receive antennas respectively. This rule has been discussed in detail in Section 4.1.2. We choose $N_t = N_r = 2$ for our simulations, i.e. 2 out of 3 antennas are selected on either side of the 3 × 3 MIMO system. Further on, the velocity estimation refers to the estimation using the zero crossing ACF based method as discussed in Section 2.3.1.

4.3.1 Degradation of velocity estimation performance in systems with receive antenna selection

Figure 4.2 compares the performance of the velocity estimation when using all antennas in an uncorrelated channel with the case of having only selected antennas at the receiver in a receive correlated channel. It can be observed that the performance degrades in the case of the selected antennas. This degradation is due to two reasons. Firstly, the reduction in the number of SISO channels due to antenna selection reduces the number of SISO velocity estimates that are averaged to get the MIMO mobile velocity. Secondly, the presence of receive correlation in the channel causes the channel to deviate from the purely Rayleigh fading characteristic. This causes the ACF based method to give inaccurate estimates of velocity, since the ACF method is based on the assumption that fading in the channel is purely Rayleigh.

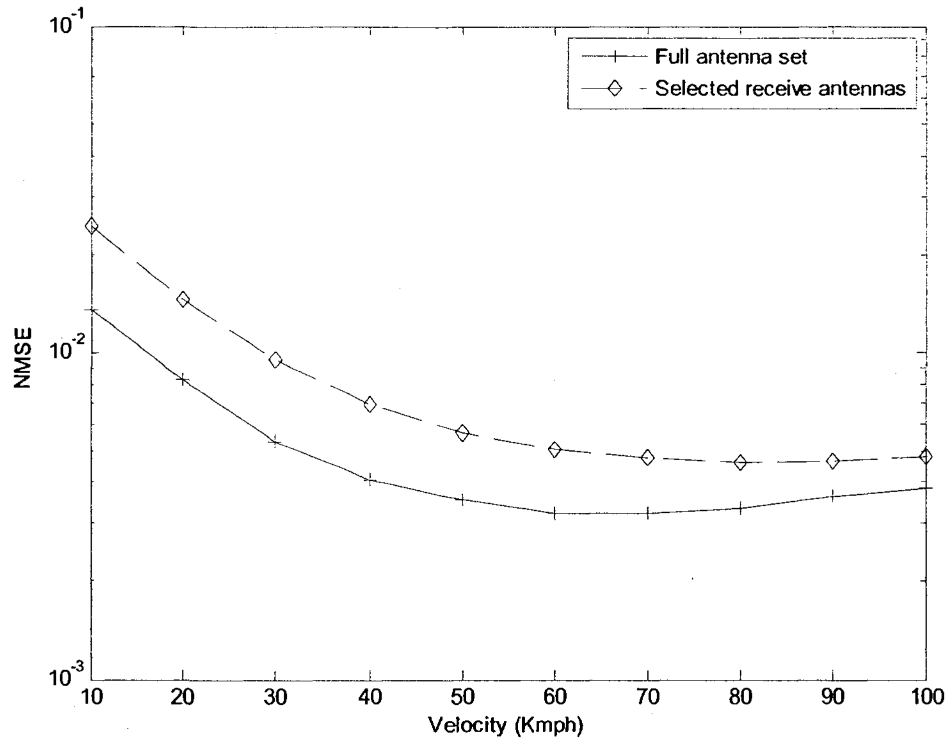

Figure 4.2 NMSE vs velocity for uncorrelated full MIMO channel and correlated MIMO channel with receive antenna selection

4.3.2 Degradation of velocity estimation performance in transmit selection systems

Figure 4.3 compares the performance of velocity estimation using all antennas in an uncorrelated channel with the performance of velocity estimation employing only selected transmit antennas in a transmit correlated MIMO channel. It can be seen that the performance of velocity estimation has degraded in the case of antenna selection compared to the case of the channel using the full set of antennas. Again, this degradation occurs due to two distinct reasons. Firstly, the transmit antenna selection reduces the number of antennas from 3 to 2. This reduces the total number of SISO channels from $3 \times 3 = 9$ to $2 \times 3 = 6$. Thus, the MIMO velocity estimate now obtained has been averaged over 6 SISO velocity estimates instead of 9. This has reduced the accuracy of the estimated MIMO velocity. Secondly, each SISO channel is no longer a perfect Rayleigh channel due to the induction of transmit correlation effects in the MIMO channel matrix. Since the ACF based methods are based on the assumption that the channel is purely Rayleigh, this deviation from Rayleigh fading characteristic causes each SISO velocity estimate obtained to be less accurate. Thus, these two factors jointly degrade the performance of velocity estimation using ACF based methods in transmit correlated MIMO channels with transmit antenna selection as compared to the performance in uncorrelated MIMO channel using the full set of antennas.

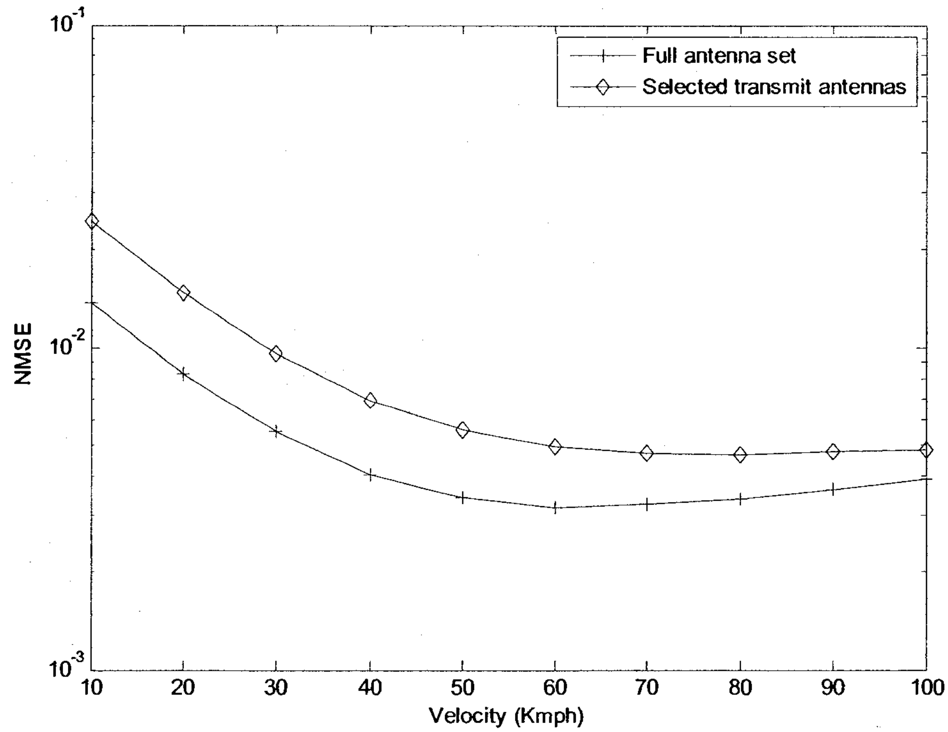

Figure 4.3 NMSE vs velocity for all antennas of uncorrelated channel compared with selected antennas of transmit correlated channel

4.3.3 Degradation of velocity estimation performance in systems with transmit and receive antenna selection

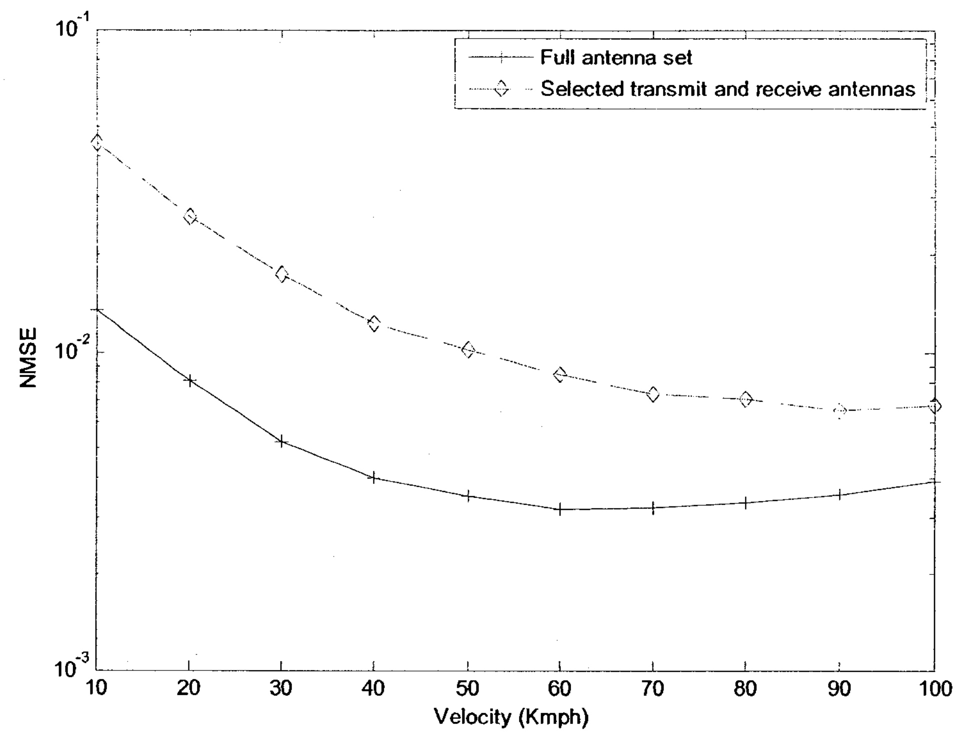

Figure 4.4 NMSE vs velocity for the uncorrelated channel using the full set of antennas and the correlated channel with antenna selection at the transmitter and receiver

Figure 4.4 compares the NMSE of velocity estimation achieved in uncorrelated MIMO channels using the full set of antennas with the NMSE achieved in correlated MIMO channels using antenna selection at the transmitter and receiver. It can be seen that the degradation of NMSE in this case is worse than the case where selection is performed only at one side, the transmitter or receiver. This is because in this case the number of SISO channels reduces from $3 \times 3 = 9$ to $2 \times 2 = 4$ as opposed to 6 in the case where selection is performed at one end only. Thus, the number of velocity estimates averaged to obtain the MIMO velocity estimate also reduces to 4, leading to worse MIMO velocity estimates than the case of one sided selection and causing performance degradation in the accuracy of MIMO velocity estimates. As an example we tabulate the values of the $\hat{v}_{ij}$ values for the 2×2 system for a mobile moving with velocity 100 kmph.

j / i	1	2
1	99.5705	94.5927
2	94.5202	92.6416

Table 4.1. Velocity estimates of SISO channels in the antenna selection case.

In this case the average value obtained using Eq. (4.2) is 95.3313 kmph. It must be recalled that a value of 98.139 kmph was estimated in Section (3.1) when all the antennas were being used. Thus the reduction in number of antennas has lead to degradation in velocity estimation performance. Along side, the effects of correlation are present on both sides of the channel in this case. This increases the deviation of the fading from the Rayleigh channel characteristic even more, making the velocity estimates provided by the four SISO channels even less accurate in this case. These four inaccurate individual velocity estimates eventually average to provide an inaccurate MIMO velocity estimate.

4.3.4 Recovery of performance degradation in receive antenna selection systems.

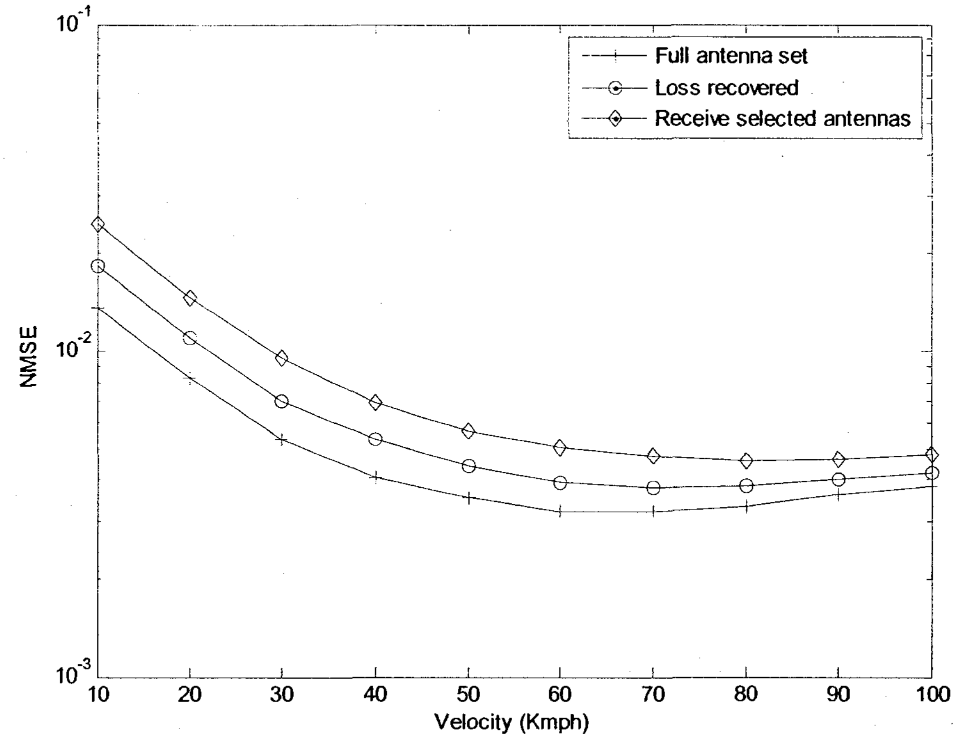

Figure 4.5 Recovery of performance degradation in receive antenna selection system using the proposed method

Figure 4.5 compares the performance achieved from the recovery technique proposed in Section 4.2.2.2 with performance achieved by the full MIMO channel and the selected channel without applying the recovery technique. A partial recovery of the velocity estimation performance is observed. Recall from Section 4.3.1 that the degradation of performance was due to the reduced number of SISO channels and the deviation of SISO channels from Rayleigh fading characteristic. The recovery technique is successful in recovering the loss due to the latter reason. It achieves this by undoing the effects of receive correlation in the channel. However, the reduction of SISO channels follows the removal of antennas which is inevitable during receive antenna selection. Thus, the loss occurring due to reduction in SISO channels cannot be compensated for and has to be borne with. In summary, the recovery technique proposed in Section 4.2.2.2 is capable of partially recovering the performance degradation of velocity estimation in correlated MIMO channels with antenna selection at the receiver side.

4.3.5 Recovery of velocity estimation performance in transmit antenna selection systems.

Figure 4.6 compares the NMSE of velocity estimation achieved from the recovery technique proposed in Section 4.2.2.1 with the NMSE resulting from an uncorrelated channel using the full set of antennas as well as the NMSE achieved in a transmit correlated MIMO system with transmit antenna selection. It can be seen that the recovery technique is able to partially recover the degradation of performance in the correlated channel with transmit antenna selection. The loss recovered is the degradation which occurs due to the induction of transmit correlation in the channel. The recovery scheme undoes this correlation effect on the selected channels and thus gets back the pure Rayleigh fading characteristic of the selected channels. These selected SISO channels, when used to estimate the velocity, then give accurate estimates of velocity. Nevertheless, the degradation in accuracy of the MIMO velocity estimate due to reduction in number of SISO channels from $3 \times 3 = 9$ to $2 \times 3 = 6$ remains. This degradation cannot be recovered as we are unable to acquire the estimates of the 3 SISO channels which are not active after antenna selection and thus the number of velocity estimates to average remains to be 6. As a consequence, the algorithm proposed in Section 4.2.2.1 is capable of partially recovering the performance loss of velocity estimation in correlated MIMO channels with transmit antenna selection.

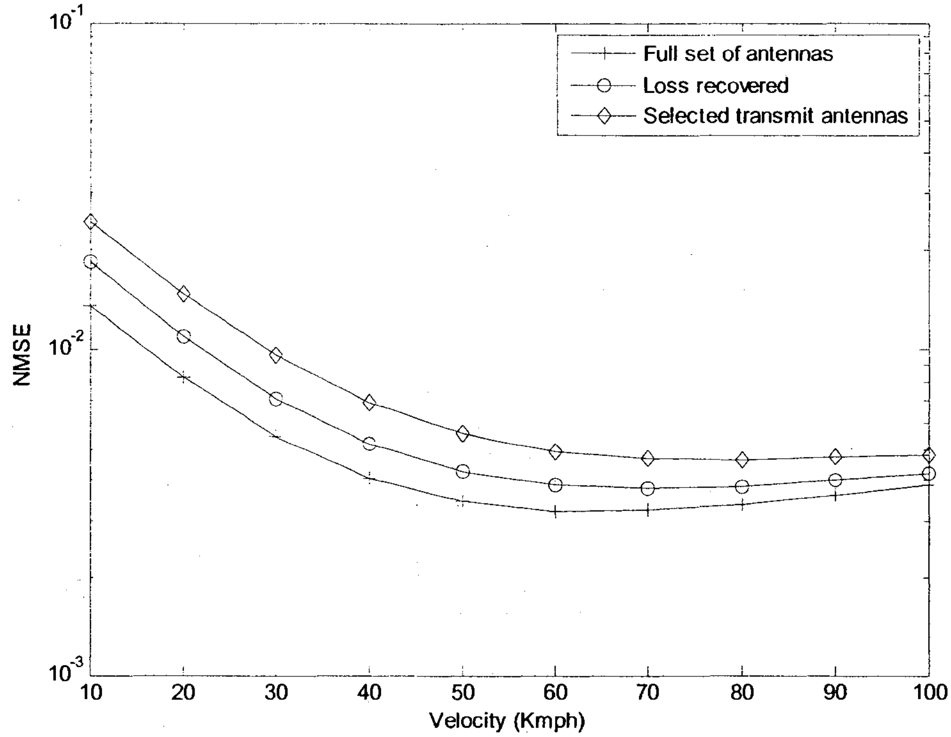

Figure 4.6 Recovery of performance degradation in transmit antenna selection systems using the proposed method

4.3.6 Recovery of velocity estimation performance in systems with transmit and receive selection

Figure 4.7 compares the NMSE of the velocity estimation achieved by applying the performance recovery technique proposed in Section 4.2.2.3 with the case when the recovery technique is not applied to the correlated MIMO channel with antenna selection as well as the case when the full set of antennas is used in an uncorrelated channel.

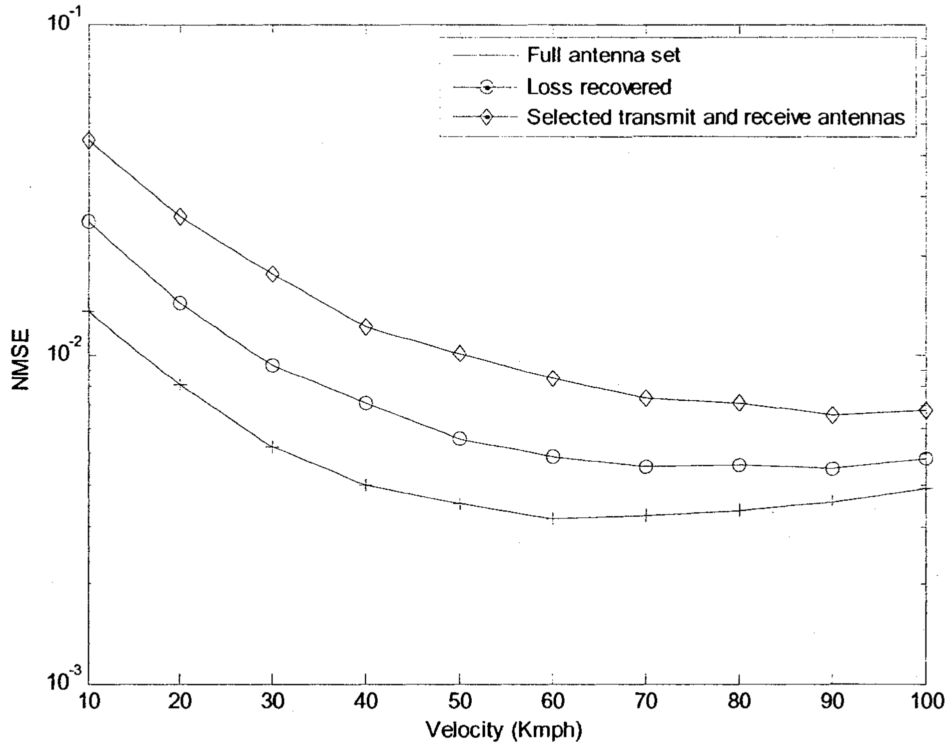

Figure 4.7 Recovery of performance degradation in correlated MIMO systems with antenna selection at both transmitter and receiver

It can be observed in Figure 4.7 that the NMSE curve given by the recovery technique lies in between that of the uncorrelated channel using the full set of antennas and that of the correlated channel using the selected subset. This translates to recovery of almost one-half of the performance degradation benefited from the recovery technique. The theoretical basis of partial recovery of degradation can be explained as follows. The number of SISO channels in the MIMO system has reduced from $3 \times 3 = 9$ to $2 \times 2 = 4$. This directly implies that the number of SISO velocity estimates available to be averaged over to obtain the MIMO velocity estimate is 4 instead of 9. Averaging the lesser SISO channels leads to worse MIMO velocity estimates thus degrading velocity estimation performance, which is unavoidable in antenna selection systems. The partial recovery is achieved because the proposed technique is able to successfully undo the correlation effect induced by the channel. Thus, if perfect channel correlation matrix estimates are assumed, the channel estimates used to estimate the individual velocities of the SISO channels now follow a purely Rayleigh fading characteristic. This will cause the zero crossing ACF based estimator to give accurate velocity estimates because of the assumption of pure Rayleigh fading. This regain of accurate velocity estimates obtained for the selected SISO channels makes up the partial recovery of performance achieved. Thus the recovery technique proposed in Section 4.2.2.3 is able to partially recover the performance loss of velocity estimation using ACF based techniques in correlated MIMO channels with antenna selection at both transmitter and receiver.

It must be noted that in correlated MIMO channels with antenna selection, the percentage of loss that can be recovered using the proposed recovery scheme is dependent on the ratio of the number of selected antennas to the number of total antennas. The closer this ratio is to one, the higher the percentage of recovery. This is because as the number of selected antennas keeps reducing, the number of velocity estimates to be averaged also keeps reducing. The random nature of Rayleigh fading implies that the higher the number of Rayleigh channels available to estimate velocity, the better the averaged final MIMO velocity estimate. And the fact is that each time an antenna is removed by transmit or receive selection the number of channels lost is M_r (total number of receive antennas) or M_t (total number of transmit channels) respectively. Thus a higher ratio of the number of selected antennas to the number of total antennas in correlated MIMO channels will enable higher percentage recovery of velocity estimation performance loss.

4.4 Summary

In the beginning of the chapter we discussed antenna selection in fast moving mobiles and concluded that the statistical selection is the feasible approach to antenna selection in fast moving mobiles. Then, an analysis of the performance of ACF based techniques in correlated MIMO channels with antenna selection at the transmitter and/or receiver was conducted. In all the three selection cases, namely the transmit antenna selection only, receive antenna selection only and the selection of both of transmit and receive antennas, it was deduced that the performance in correlated MIMO channels with antenna selection will degrade compared to the performance in uncorrelated MIMO channels using the full set of antennas. A recovery technique for compensating for this performance loss was then proposed. It has been illustrated how this technique could partially recover the performance degradation which occurred in all the three cases of correlated MIMO channels with antenna selection. It has been shown that the performance achieved by the recovery technique is better than the correlated channel with antenna selection but still not as good as the uncorrelated MIMO channel using the full set of antennas. The last part of the chapter has validated the proposed technique using Monte-Carlo simulations.

5 Conclusions

5.1 Summary of the work

In this thesis, we have studied the extension of the existing class of ACF based schemes for velocity estimation in Rayleigh fading channels to mobile correlated Rayleigh MIMO channels. The MIMO channel using the full set of antennas as well as that using only a subset of antennas are both considered.

In the second chapter we laid technical background which would help the reader appreciate the work done in Chapters 3 & 4. This started with briefing the Rayleigh model and its behavior with increasing mobile velocity. Thereafter, the motivation for using multiple antennas in wireless communication links was thoroughly discussed followed by a discussion of the ideal MIMO channel, the correlated MIMO channel and the MIMO channel with antenna selection. This is followed by a review of the existing ACF based velocity estimators for generic wireless systems. Lastly, the extension of ACF based estimators to correlated MIMO channels is discussed.

The third chapter studied the estimation of velocity using the ACF based method in correlated Rayleigh fading MIMO channels using the full set of antennas. In the first part of the chapter, we concluded that when the ACF based methods are used to estimate the velocity in correlated MIMO channels with the full set of antennas, the estimation performance degrades compared to that in uncorrelated channels using the full set of antennas. The degradation, when correlation is present on both sides of the channel, is more than when the channel is correlated only on one side of the channel. Next, we developed a channel decorrelation based performance recovery scheme to recover this performance loss. It is shown that our performance recovery scheme is capable of recovering the performance loss completely provided that perfect estimates of the concerned correlation matrix are available. Lastly, the degradation in the performance of velocity estimation in correlated MIMO channels and the recovery of this performance loss using the proposed scheme is verified by simulations.

Chapter 4 has studied the performance of velocity estimation using the ACF based schemes in correlated Rayleigh MIMO channels with antenna selection. We started with a discussion on antenna selection for fast moving mobiles and conclude that statistical based antenna selection is more feasible for antenna selection in fast moving mobiles. Thereafter, we analysed the performance of velocity estimation using ACF based method in correlated MIMO channels with antenna selection. We have shown that compared to the case of the uncorrelated channel using the full set of antennas, the performance in the case of correlated channels with antenna selection degrades. The degradation in this case was found to be more than in the case of correlated MIMO channels using the full set of antennas discussed in Chapter 3. To compensate for the performance degradation, a channel decorrelation based recovery scheme was then proposed. It was shown that this recovery technique is able to partially recover the performance loss which occurs when ACF based methods are used for velocity estimation in correlated MIMO channels with antenna selection.

5.2 Future research directions

Further extensions of this research could possibly be in the following directions:

- The extension of the ACF based techniques to correlated channels studied in this research applies to correlated channels which can be modeled using the

Kronecker model. Similarly, the extension to correlated MIMO channel scenarios which can not be modeled by the Kronecker model or can otherwise more accurately be modeled using another model could be studied.

- It apparently seems that the conclusions made and techniques developed in this research for flat fading channels can be easily extended to frequency selective channels. Nevertheless, this can be verified in future work.
- The focus of this thesis was the extension of the already existing class of ACF based velocity estimation techniques for Rayleigh channels to some practical MIMO channels. Similarly, the extension of other already existing classes of velocity estimation techniques to practical MIMO systems can be studied. This will give MIMO wireless system designers more options of velocity estimation techniques to choose from.

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