Overview of MIMO Channel Modelling

Daljeet Singh, Manwinder Singh, Kamal Kumar Sharma

School of Electronics & Electrical Engineering

Lovely Professional University, Phagwara,Punjab, India

Abstract:

The technology of using multiple antennas at both link ends in wireless communications systems has been introduced as an effective way to meet the user demand for high data rate applications, and is known as MIMO technology. This technology can potentially achieve higher bandwidth efficiency by the creation of orthogonal transmission channels between the link ends. The efficiency of MIMO technology directly depends on the propagation environment between the transmitter and the receiver, i.e. the MIMO channels.

1. Introduction:

Wireless communications has become more and more popular in our daily lives. With the fast growing industry in this area, all kinds of wireless communications products supporting data transmission have greatly increased. The most common wireless communications is the mobile phones. Since Claude E. Shannon's formula to describe the bandwidth efficiency (expressed as $bits=s=Hz$) based on information theory, possible methods to increase the capacity of system are to broaden the bandwidth, or to improve the SNR. However, there is still a gap between the theoretical proof of the potential capacity gain of MIMO technology and the practical realisation of obtaining this gain by the MIMO technology. This is partly because the theoretical capacity gain presented by Telatar is based on the assumption that the MIMO channels are all independent complex Gaussian values, which is intended to model a Rayleigh flat fading channel and applies in the situation where there exist enough scatterers and enough physical separation within the Tx and Rx antennas; therefore, these conditions cannot be satisfied in many realistic scenarios; much research in this area have revealed that the realistic performance of MIMO systems in capacity degrades significantly with the spatial correlation of channels between the Tx and Rx antenna pairs.

In fact, not only the capacity gain, but also the potential benefits of using the MIMO technology lie in the diversity gain and antenna gain for combating many realistic transmission difficulties. In order to explore all of these potential benefits brought by MIMO technology, on the one hand it is essential for us to obtain knowledge of MIMO channels under realistic conditions by setting up field measurements, and on the other hand, we need to develop practical techniques for MIMO systems to realize effective and efficient wireless transmission.

The work covered by MIMO channel modeling is like a bridge connecting the realistic knowledge of MIMO channels under different conditions and the development of practical transmission techniques for MIMO systems. To mimic realistic MIMO channels, MIMO channel modeling incorporates channel knowledge under different realistic circumstances into mathematical models, and thus enables us to test the performance of various newly developed MIMO techniques before applying them into practice, without performing costly measurements each time. MIMO channel modeling helps us save the cost of field measurements, while effectively evaluating the performance of a range of MIMO transmission techniques. Therefore, MIMO channel modeling provides us an effective and efficient method to evaluate the development of MIMO transmission techniques, and it is among the most fundamental and important work for the development of MIMO technology.

2. MIMO System Model

In contrast to conventional SISO systems, as a consequence of multiple antennas at both link ends, the MIMO channel need to be described for all Tx and Rx antenna pairs. In a system with *nT* Tx antenna elements and *nR* Rx elements, the received signal may be represented by a column vector:

r = Hs + n

Note that these elements *hij* may be complex values, representing simple attenuation and phase shift, and may vary with time or be functions of time delay corresponding to different propagation scenarios in reality. The derivation of these elements is based on the mechanism of double-directional radio propagation. The value of each of these elements is actually the double-directional channel impulse response between a pair of the Tx and Rx antennas.

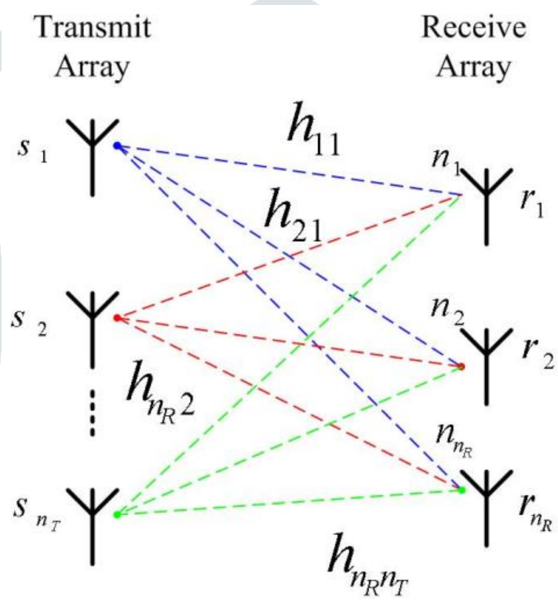

Fig. 1: Matrix Model of MIMO Channel

3. Importance of MIMO Channel Modeling

The capacity presented by Telatar is based on the assumption that the entries of matrix H are all independent complex Gaussian values, which is intended to model a Rayleigh flat fading channel. In reality, this assumption applies in a rich scattering environment with enough physical separation within the Tx and Rx antennas. Therefore, these conditions cannot be satisfied in many scenarios that are without enough scatterers, such as the outdoor environments, or the Tx and Rx antennas are not well separated. Many studies in this area have revealed that the realistic performance of MIMO systems in capacity significantly degrades with the spatial correlation of channels between the Tx and Rx antenna pairs [22] [23] [24] [25].

Furthermore, in real wireless communications systems, the effect of multi-paths propagation of radio waves determined by the inherent physical properties of wireless systems makes the radio signals interfere with each other, which gives rise to the phenomena of fading and time dispersion of the transmitted signals. These

phenomena may have adverse influence on the performance of MIMO systems. Therefore the achievable capacity of MIMO channels is limited due to the need for transmission techniques such as coding, to conquer these practical transmission problems.
All in all, it is worth investigating the physical behaviour of radio signals in the propagation environment and the spatial properties of MIMO channels, and developing mathematical models to accurately characterise the properties of these behaviours for different propagation circumstances in practice, by which various MIMO schemes can be validated before being applied to the practical systems without setting up costly field measurement for the purpose of test all the time. Hence, the modeling of MIMO radio channels has attracted much attention.

4. Classification of MIMO Channel Modeling

To model the MIMO radio channels, a variety of approaches have been developed in the recent years [26] [27] [28]. Different approaches have different advantages when modeling MIMO channels. The advantages of a specific approach in characterising some aspects of the MIMO channels, may imply a reduction of performance in capturing some other properties. Therefore, we need choose appropriate method for MIMO channel modeling according to different research and application purposes. Based on the main approach taken in MIMO channel modeling, there are two fundamental groups of MIMO channel models, which are the physical models and non-physical models.

Physical models aim at describing the propagation of radio signals between the Tx and Rx on the basis of the double-directional impulse response. Modeling radio signals as rays, we can visualise that different propagation paths with different angles-of-departure (AoDs) and angles-of-arrival (AoAs) occur depending on the position of the scatterers. The received signals, or the impulse response, consists of contributions from all individual paths, which are identified by some important physical features of theirs, such as AoD, AoA, time delay of arrival (TDoA) and complex amplitude. Thus it motivates us to characterise the radio channels in MIMO system by the crucial physical parameters of the multi-path components (MPCs) between the Tx and the Rx.

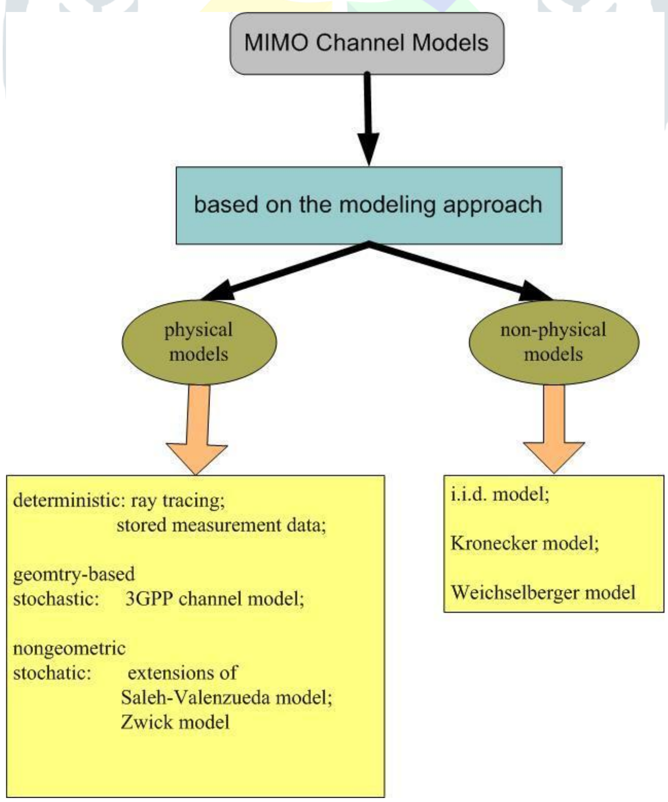

Fig. 2: Classification of MIMO Channel Models based on the Modeling Approach

The narrowband channels assume that the channel has the same response over the entire system bandwidth, while the wideband channels take the propagation channel as frequency selective, which means that different frequency divisions have different channel responses. Time-variant channels as apposed to time-invariant ones, describe the temporal evolution of the channel impulse response according to certain Doppler characteristics. Although these classifications differentiate the radio channel from the frequency domain and the time domain respectively, the radio channel can have a combination of the characteristics from the two categories, for example, the radio channel could be narrowband time-variant or wideband time-variant.

Since the presence of time-variant radio channels is quite common in practice, the characteristic of time variation is an important characteristic to be included in channel modeling. In the following, the main properties based on which we model the time variation of channels are outlined for both narrowband and wideband channels.

4.1 Narrowband Fast Fading

The multi-path propagation gives rise to the phenomenon of *fading* of the received signal. This is because the received signal that consists of a large number of MPCs arriving in different phase relations to one another, which may combine in phase or in anti-phase. In other words, the MPCs arriving at the Rx interfere with each other. Figure 3.1 illustrates the resultant received signal by a phasor diagram, from which we can see that the resultant signal (denoted by the grey arrow) is determined by the MPCs with random amplitudes and phases (denoted as the black arrows), that is, if these components are in anti-phase to each other, the received signal suffers from deep fading, and if these components are in phase with each other, the received signal is an enhanced version of the transmitted signal.

4. 2 Wideband Fast Fading

In the narrowband channel, the MPCs come to the Rx at about the same time, so all the frequencies of the signal are affected in the same way by the fading channel. However, if there exist far scatterers in the propagation environment, the time differences between the MPCs to arrive at the Rx may be significant compared to the duration of unit of the information transmitted.

4.3 Statistical Characterisation with MIMO Correlation Functions

In principle, the radio channel can be characterised by deterministic methods. However, a deterministic characterisation may not possible when there are a huge number of factors influence the channel. Thus it is more feasible to describe the channel by statistical methods.

4.4 Application of the CMD Metric in Closed-Loop MIMO Systems

In a closed-loop MIMO system [57], it is often assumed that the Rx estimates the channel information and sends updates on the channel state back to the Tx, then the Tx can optimise the transmission by adapting to the time variant channel [58] [59] [60]. There are many forms of the channel knowledge fed back by the Rx to the Tx, varying from statistical channel knowledge such as the spatial correlation matrices [61] [62], to exact channel knowledge, for example, the exact channel matrix, the changes in the channel matrix, or the eigenvectors from the EVD. In some cases, the codebook labels are sent back instead of the exact channel knowledge [63] [64].

Since the CMD metric is able to predict the time variation in the spatial correlation matrices, it also indicates the changes in the channel matrices. As the spatial correlation matrices become more and more uncorrelated, the CMD increases to a relatively large value and tends to unity. Taking advantage of the property of this metric, we could calculate the instantaneous time variation of the channel matrix at the Rx using the CMD metric, and when the CMD exceeds a predefined threshold, which is a relatively high value and depends on the requirement for the bit error ratio (BER) performance, we should send the updates on the channel state back to the Tx, and then

the Tx could optimise its transmission according to the latest channel state.

For the purpose of demonstration and simulation, we take a 2 £ 2 system with wideband fast fading channels based on the ITU-B Pedestrian channel model [65] as an example. In the simulation, the technology of OFDM together with SVD transmission is applied to the uncoded QPSK transmitted symbols. The system bandwidth is 10 MHz and FFT size is 256. Figure 3.10 shows a study on the relationship between the change of CMD and the time variant channel at a speed of 10 km/hr when the predefined threshold is 0.6. Here the detailed procedures to generate a plot like figure 3.10 are addressed as follows:
1. Take the spatial correlation matrices of all the frequencies at time zero R*H* (*t*0*; f*) as reference, refer to which the CMDs at the following time instants are calculated.

2. Record the time instant *t*x when the CMD has exceeded a predefined threshold, and make it as the time instant at which we feedback updates on the channel information; meanwhile reset R*H* (*t*0*; f*) as R*H* (*t*x*; f*), i.e. R*H* (*t*0*; f*) = R*H* (*t*x*; f*), therefore the CMDs at the following time instants can be calculated referring to the updated R*H* (*t*0*; f*).

3. Repeat 2 to obtain all the feedback instants during the whole transmission period.

To evaluate the proposed application of the CMD metric in controlling the feedback interval in a closed-loop MIMO system, we compare the performance in overhead by using the CMD metric with that by using a predefined feedback interval, when the two controlling metrics provide the same BER performance for the system. A comparison of the BER Performance with Predefined and with CMD Controlled Feedback Interval is shown in Fig. 3.

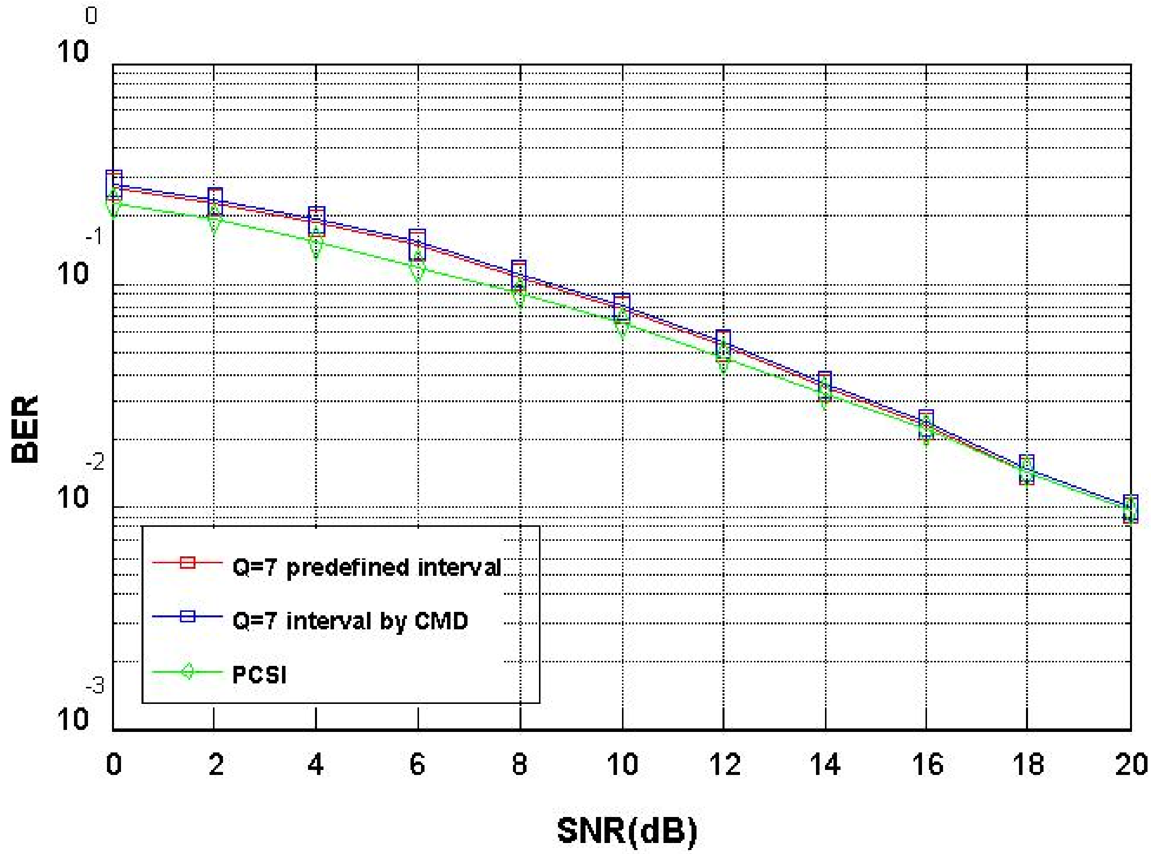

Figure 3: Comparison of the BER Performance with Predefined and with CMD Controlled Feedback Interval

5. Conclusion

In this paper, we have introduced the major features of the narrowband fast fading channel and the wideband fast fading channel. In order to describe different types of channels by mathematical tools, we have presented the deterministic characterisation and statistical characterisation of MIMO channels based on the first set of Bello's functions. Especially, a simplified statistical description of MIMO channels has been developed based on the spatial structure of the system, named the spatial matrix of MIMO channels. Based on the definition of the spatial matrix, a CMD metric has been introduced and extended to measure the time variation of the spatial structure of MIMO channels.