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# MIMO Channel Modeling: A Review

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## Abstract

Channel modeling plays an important role in understanding the behavior and designing of communication systems for different environments. In this paper, we make a brief review of the different channel modeling techniques used to model a multiple-input-multiple-output (MIMO) wireless channel.

**Keywords**

*Channel modeling, MIMO channels, multi-antenna channels.*



## 1. Introduction

The two most important requirements for a modern day wireless communication system are to support high data rates within the limited available bandwidth and to offer the maximum reliability. Multiple Input Multiple Output (MIMO) technology, which exploits the spatial dimension, has shown potential in providing enormous capacity gains and improvements in the quality of service (QoS) [1-5]. In any communication system, the capacity is dependent on the propagation channel conditions, which in turn are dependent on the environment. In a MIMO system consisting of $N_T$ transmit and $N_R$ receive antennas, theoretical investigation has shown that for a rich scattering environment, the ergodic capacity of the system is the sum of the capacities of N (=$min(N_T, N_R)$, is the spatial parameter defining the degrees of freedom) virtual single-input-single-output (SISO) channels. It has further been shown that for $N_T = N_R =$ N and N being very large, the ergodic capacity increases linearly, with the increasing signal to noise ratio. Appropriate modeling of the MIMO channel behavior helps in efficient and proper designing of a MIMO system, with reference to code design, power allocation at the transmitter antennas, modulation schemes etc. It also aids in evaluating the performance before actual deployment. Channel modeling is an area of active research and several models have been developed to predict, simulate and design a high performance communication system.

Channel models can be classified into two broad categories, namely site specific physical models and analytical models as shown in Figure 1.

Site specific physical models help in network deployment and planning, while site independent models are mostly used for system design and testing. The physical models may be further classified into deterministic and stochastic models. A deterministic model tries to reproduce/replicate the actual physical radio propagation process for a given environment along with the reflection, diffraction, shadowing by discrete obstacles, and the wave guiding in street canyons. Recorded impulse response and ray tracing techniques are some of the examples of deterministic channel modeling techniques. The stochastic models are based on the fact that the wireless propagation channels are unpredictable and time varying in nature but its parameters, like the Angle of Arrival (AOA), Angle of Departure (AOD), time delay profiles etc., follow a defined stochastic/statistical behavior, depending on the environment. The stochastic channel models are generally computationally efficient. Most stochastic models have a geometrical basis; however, a few non-geometric correlation based or parametric stochastic models can also be found in the literature [6]. In the realm of geometrically based stochastic models, large variants of the model have been proposed, but the basic philosophy remains the same. Different geometrically based stochastic models reproduce different sets of environments like indoor or outdoor scenarios, and narrow band or wide band environments. Usually, the models are validated by comparing the values or distributions of certain physical parameters like AOA, AOD, Time of arrival (TOA), and power spectrum etc., obtained through the model with those acquired through measurements under specific conditions.

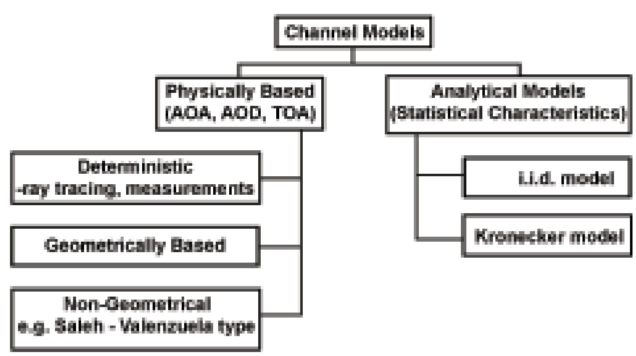


**Figure 1:** Channel model classification.

## 2. MIMO Channel Model

A MIMO system consisting of M transmit antennas and N receive antennas is shown in Figure 2.

The received signal y(n) at dicreet time n is related to the transmitted signal x(n) by

$$\mathbf{y}(n) = H(n) * \mathbf{x}(n) + \mathbf{w}(n) \tag{1}$$

Here, $\mathbf{y}(n)$ is an $N \times 1$ vector, $\mathbf{x}(n)$ ia an $M \times 1$ vector. $\mathbf{w}(n)$ is an $N \times 1$ vector, which represents additive white gaussian noise (AWGN) and H(n) is the channel matrix, giving the channel impulse response at any discreet time *n*. For a $M \times N$ MIMO system, H(n) is a $N \times M$ dimensional matrix.

If the signal bandwidth is assumed to be sufficiently smaller than the coherent bandwidth of the channel, which is often the situation in case of communication at lower data rates, then the channel matrix remains constant over the frequency of operation. For a flat fading channel, eqn. 1 can be written as,

$$y = Hx + w \tag{2}$$

where the time index n has been suppressed to simplify the notation. For a frequency flat channel, the individual elements of the channel matrix are given as:

$$h_{mn} = \alpha_{mn} j\varphi_{mn} \tag{3}$$

where, $h_{mn}$ refers to the channel between the $m^{th}$ transmit antenna and the $n^{th}$ receive antenna. $\alpha_{mn}$ and $\varphi_{mn}$ are the corresponding channel gains and phase shifts respectively. The distribution of $\alpha_{mn}$ depends on the environment. For a macrocellular environment, having no line of sight between the transmitter and the receiver, the transmitted signal reaches the receiver after being scattered by different scatterrers (e.g. buildings, trees etc) surrounding the receiver. Thus, multiple copies of the transmitted signal are received from different directions, with different delays and phase shifts. This has been modeled as a complex gaussian random process.

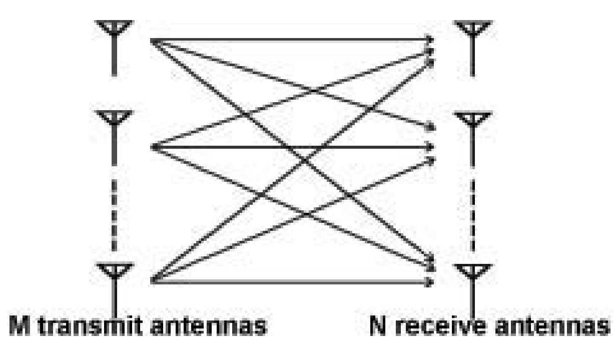


**Figure 2:** A MXN MIMO channel.

The amplitude distribution for such a process is given by Rayleigh distribution. Hence, for a macrocellular environment, with no line of sight path between the transmitter and the receiver, $\alpha_{mn}$ is taken to be Rayleigh distributed. If a line of sight exists between the transmitter and the receiver, then the distribution is given by Rician distribution. Often the channel gains are assumed to be Nakagami-*m* distributed, as it can represent both Rayleigh and Rician distributions depending on the value of the *m* parameter. The phase is generally assumed to be uniformly distributed between 0 and $2\pi$.

The objective of any channel modeling technique is to model the channel matrix H efficiently. The elements of the channel matrix are often assumed to be independent and identically distributed, thus having very little or no correlation between them and offering the maximum capacity gains. But in actual practice, the elements of the channel matrix have a finite correlation due to the limited spacing between the antennas. The correlation is inversely proportional to the distance of separation between the antenna elements. The coherence distance gives the separation between the antennas below which the correlation between the channel elements is significant. The rule of thumb is to take the coherence distance to be $\lambda/4$, where $\lambda$ is the operating wavelength.

### 2.1 Deterministic Models

The deterministic channel modeling techniques try to replicate the actual physical scenario between the transmit and the receive arrays. Most often, the antenna parameters like the antenna patterns, array size and geometry, the effects of mutual coupling between the array elements, polarization etc. are not accounted for [6]. Ray tracing softwares and techniques are one of the most popular ways for modeling the channel deterministically. In ray tracing softwares, the geometry and the electromagnetic characteristics of any particular scenario/environment is stored in files. These files are later used for simulating the electromagnetic propagation process between the transmitter and the receiver. These models are fairly accurate and may be used in place of measurement campaigns, when time is at premium. In ray tracing techniques, flat top polygons of different sizes and shapes are generally used to represent buildings. The ray tracing softwares are basically based on the phenomenona of geometrical optics like reflection, refraction, diffraction etc. For urban scenarios, geometrical optics can be aptly applied, as the wavelength of operation is much smaller than the dimension of the obstacles.

### 2.2 Geometrically based Channel Models

Geometry based channel models may be thought of as a simplification of the deterministic channel models (e.g. ray tracing). Deterministic channel models require to handle a huge database of the environment and its propagation conditions. In geometry based channel models, the scatter locations are considered to be random and governed by some well defined probability distribution functions, depending on the scenario. The channel impulse response in these models is obtained based on phenomenona of geometrical optics, after positioning of the scatterers.

Figure 3 shows a typical geometrically based channel model for a macrocellular scenario. In a macrocellular scenario, the base station is generally placed on an elevated platform or on the top of a hill and, hence, is devoid of scatterers. Whereas, the mobile station is surrounded by scatterers from all sides. The scenario has been reproduced in Figure 3 by placing a ring of scatterers around the mobile station (*MS*). The model parameters are –

1) The distance of separation between the base station and the mobile station (*D*).
2) Radius of the scattering circle at the *M*S (*R*).
3) Distribution of the scatterers around the *M*S ($p(\varphi_{ms})$).
4) Inter element separation of the *B*S and *M*S antenna arrays ($d_{bs}$, $d_{ms}$).
5) Orientation of the transmit and receive arrays ($\alpha_{bs}$, $\alpha_{ms}$).
6) Direction of movement of the *M*S with respect to a reference plane (e.g. the line joining the *B*S and *MS*)($\alpha_v$). It is assumed that any wave from the *BS*(*MS*) reaches the *MS*(*BS*), after getting scattered by a single scatterer. Multiple scattering is generally neglected, as the energy contributed by a multiple scattered wave is marginal. Based on the assumption, D >> R >> max $\{d_{bs}, d_{ms}\}$, each incoming wave may be considered as a plane wave and, hence, justifies the application of geometrical optics. With reference to Figure 3, the time of arrival and angle of arrival statistics depend grossly on the distance of separation between the *B*S and the *MS*, the radius of the scattering circle at the MS and the distribution of the scatterers. Geometrical based models depicting other scenarios, e.g. mobile to mobile communication and indoor channels, have been reported in literature. The reference and simulation model for a mobile to mobile communication scenario is dealt with in [7,8]. The geometric model for indoor channels is dealt with in [9]. In this model, the transmitter and the receiver are positioned at the foci of an ellipse. The scatterers are assumed to be scattered inside the ellipse. A geometrical based approach, where scatterers are represented by antenna elements with appropriate load conditions, was proposed in [10]. Further investigation on such models has been reported in [11]. Mutual coupling between the antenna elements effects the MIMO system capacity. Incorporation of mutual coupling effects in MIMO channel models has been addressed in [12,13].

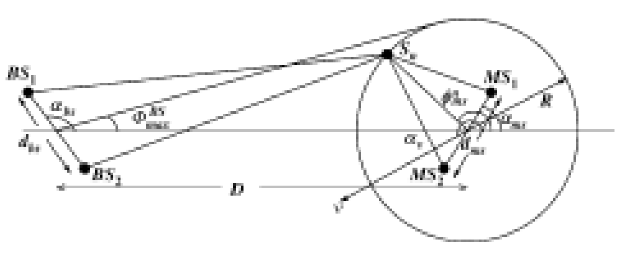


**Figure 3:** Geometry based one ring model.

### 2.3 Non-Geometrical Physical Models

In a non geometrical physical model, there is no reference to the geometry of the scenario it depicts. The Saleh Valenzuela model and its extensions [14] make a typical example for the non geometrical physical model. In this model, the multipath components are assumed to arrive in clusters. The rate of decay of the multipath components, within a cluster and among the clusters, is governed by well defined statistical distributions. In this model, the discrete channel impulse representation is employed. The channel impulse response is given as,

$$h(t) = \sum \beta k e^{j\theta_k} \delta(t - tau_k) \quad (4)$$

where,

k = number of multipaths, ideally k extends from 0 to ∞.

$\beta_k$ = real positive gain of the $k^{th}$ multipath.

$tau_k$ = propagation delay of the $k^{th}$ multipath.

$\theta_k$ = phase shift associated with the $k^{th}$ multipath, and is assumed to be uniformly distributed and statistically independent over $(0, 2\pi)$.

$\delta(.)$ = Dirac delta function.

### 2.4 Independent and Identically Distributed Model

The independent and identically distributed (iid) channel model [2] is the simplest of all the analytical channel models. The correlation matrix between the channel elements is defined as,

$$R_H = E[hh^H] \quad (5)$$

For an *iid* channel, the correlation matrix is given as $R_H = \rho^2 I$, where I is the unity matrix.

Thus for an iid channel, the correlation matrix is a diagonal matrix, with each element equal to $\rho^2$. The non diagonal elements of the correlation matrix gives the cross correlation between the channel elements and are all equal to zero. This represents a scenario with rich scattering, where all the channel matrix elements are mutually independent. $\rho^2$ gives the variance of the MIMO channel elements H and also the channel power. Early works for capacity evaluation for MIMO systems used *iid* channel models.

### 2.4 Kronecker Model

The Kronecker model [1] was developed on the basic assumption that the transmitter and the receiver correlations are separable. Thus, the channel correlation matrix $R_H$ may be written as the Kronecker product of the transmitter correlation matrix ($R_{Tx}$) and the receiver correlation matrix ($R_{Rx}$).

$$R_H = R_{Tx} \varnothing R_{Rx} \quad (6)$$

where Ø denotes the Kronecker product. The transmitter and the receiver correlation matrices are given as,

$$R_{Tx} = E\,[H^H H] \text{ and } R_{Rx} = E\,[HH^H]$$

It has been shown that the channel matrix H is given as,

$$H = R_{Rx}^{1/2} G R_{Tx}^{1/2} \quad (7)$$

where, G = unvec(g) and g is a $nm\ X\ 1$ vector with *ii*d gaussian elements having zero mean and unity variance. The eqn. 7 is widely used for theoretical analysis and MIMO channel simulation.

### 2.5 Some Special Cases and Their Modeling

Under some special circumstances, an effect called keyhole or pinhole effect can be observed. In this phenomenon, scattering is present both at the transmitter and the receiver ends. But all the rays from the transmitter have to pass through a small keyhole or pinhole, before reaching the receiver, as shown in Figure 4. The scenario is similar to a multiple-input-single-output (MISO) system cascaded with a single-input-multiple-output (SIMO) system. This process reduces the degrees of freedom and thus resulting in a rank deficient channel matrix [15]. Hence, despite of having scatterers and enough separation between the antenna elements at the transmitter and the receiver, the capacity of a keyhole channel gets reduced due to the rank deficiency of the channel matrix.

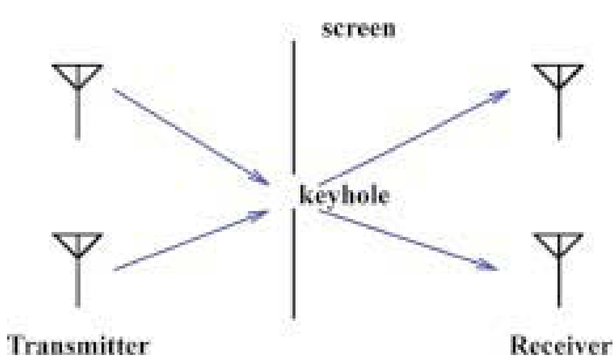


**Figure 4:** A keyhole MIMO channel.

## 3. Conclusion

In this paper, we present a brief overview of some of the important MIMO channel modeling techniques that have been reported in literature. Better knowledge of the channel helps in better system design. Research in the field of MIMO channel modeling involves refinement of the existing models and introduction of new models for better understanding and representation of MIMO channel.

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