A Survey of Geometrically-Based MIMO Propagation Channel Models

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ABSTRACT: The paper presents a classification of multiple-input multiple-output (MIMO) geometry-based stochastic channel models (GSCM). Based on the shape of the scatterers, the models are distinguished between regular-shaped GSCM (RS-GSCM) and irregular-shaped GSCM (IS-GSCM). The proposed models for regular shaped scattering environments, such as, one-ring, two-ring, and elliptical along with the ones for irregular shaped scattering environments, such as, streets and tunnels are reviewed extensively. The specification of each model in terms of appropriateness to be deployed for narrowband and/or wideband channels will be investigated. To give an insight into GSCM, the wideband geometric modeling of a hollow-disk scattering environment is represented. The cross-correlation function (CCF) of the mobile station (MS) and the base station (BS) antenna elements is computed and then calibrated/verified with the one achieved by the Radio-wave Propagation Simulator (RPS). Finally, the capacity of the channel calculated by RPS is compared with the one derived from the channel model matrix. The numerical results show that the capacity curves are very close.

Key words: MIMO channels, geometry-based stochastic channel model, regular-and irregular-shaped scattering environment,

INTRODUCTION

The multiple-input multiple-output (MIMO) technology has been deploying widely in recent telecommunication systems. MIMO technology enhances the throughput and robustness by improving spectral efficiency and increasing space diversity. Characterizing MIMO channel and quantifying its gain are tied to the specifications of the radio propagation channel. Therefore, specific care should be devoted to the modeling of MIMO channels in order to raise the accuracy of the performance evaluation and system design (Verma et al., 2008).

MIMO propagation channel models are classified into physical and analytical models. Physical models focus on the double-directional propagation mechanisms between the location of the mobile station (MS) and the base station (BS) regardless of antenna configuration. Analytical models capture physical wave propagation and antenna configuration simultaneously by describing the impulse response (equivalently, the transfer function) between the antenna arrays at both link ends (Almers et al., 2007). Geometry-based stochastic channel models (GSCM) are among the physical models where the statistical distributions of the angles of arrival/departure (AOA/AOD) and delays of multipath components (MPC) can be obtained by the geometry of the scatterers (Intarapanich et al., 2007). The scatterers are located stochastically with a certain probability density function (PDF). The model is derived by applying the fundamental laws of reflection, diffraction and scattering, according to the position of the scatterers (Matthaaiou). GSCMs are advantageous in the sense that they allow the spatial structure of the channel to be considered in a convenient way and with low complexity (Czink et al., 2007).

GSCMs are divided into regular-shaped GSCM (RS-GSCM) and irregular-shaped GSCM (IS-GSCM), based on the shape of the scatterers. In this paper, the proposed models for regular-shaped scattering environments, such as, one-ring, two-ring, and elliptical, and the ones for irregular shaped scattering environments, such as, streets and tunnels are investigated. To calibrate/verify GSCM with a real environment model, the propagation channel model of the Electrical and Computer Engineering Department, University of Sistan and
Baluchestan is computed by Radio-wave Propagation Simulator (RPS) package. The analytical and the numerical results are compared in terms of cross correlation function (CCF) of MIMO links and the achieved capacity. We show that the capacity of the hollow-disk model, proposed in the paper (Latinovic et al., 2003), is close to the one achieved by the simulator.

The rest of this paper is organized as follows. In Section II, MIMO systems are explained. Section III provides a classification of MIMO models. Section IV, is devoted to MIMO propagation effects. A survey of GSCM is presented in Section V. In Section VI, regular-shaped GSCMs (RS-GSCMs) are reviewed. We investigate irregular-shaped GSCM (IS-GSCM) in Section VII. Simulation results are presented in Section VIII. The paper is concluded in Section IX.

### MIMO SYSTEMS

Conventional communication systems contain one transmit and one receive antenna, but in MIMO systems multiple antennas exist at the wireless link input and output (actually the name MIMO comes from this fact). Therefore, a MIMO channel model should describe all transmit and receive antenna pairs. Consider an \(N \times M\) MIMO system, where \(M\) and \(N\) are the number of transmit and receive antennas, respectively. From a system level perspective, a linear, time-varying MIMO channel is then represented by an \(N \times M\) channel matrix

\[
H(t, \tau) = \begin{pmatrix}
    h_{11}(t, \tau) & h_{12}(t, \tau) & \ldots & h_{1m}(t, \tau) \\
    h_{21}(t, \tau) & h_{22}(t, \tau) & \ldots & h_{2m}(t, \tau) \\
    \vdots & \vdots & \ddots & \vdots \\
    h_{m1}(t, \tau) & h_{m2}(t, \tau) & \ldots & h_{mm}(t, \tau)
\end{pmatrix},
\]

where \(h_{ij}(t, \tau)\) denotes the time-varying impulse response between the \(j\)th transmit antenna and the \(i\)th receive antenna. Each element of the matrix \(H(t, \tau)\) has to be replaced by a polarimetric submatrix describing the coupling of vertically and horizontally polarized modes, where polarization is to be included (Almers et al., 2007).

### MIMO CHANNEL MODELS CLASSIFICATION

A variety of MIMO channel models have been proposed in the literature so far. The proposed models can be classified in various ways. The models can be distinguished with regard to the type of channel being considered, i.e., narrowband (flat fading) versus broadband, time variant versus time invariant. A classification of MIMO channels and propagation models is shown in Table 1.

<table>
<thead>
<tr>
<th>Physical wave propagation</th>
<th>MIMO channel matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical models:</td>
<td>Analytical models:</td>
</tr>
<tr>
<td>(i) deterministic:</td>
<td>(i) correlation-based:</td>
</tr>
<tr>
<td>- ray tracing</td>
<td>- i.i.d. model</td>
</tr>
<tr>
<td>- stored measurements</td>
<td>- Kronecker model</td>
</tr>
<tr>
<td>(ii) geometry-based stochastic:</td>
<td>- Weichsel Berger model</td>
</tr>
<tr>
<td>- GSCM</td>
<td>(ii) propagation-motivated:</td>
</tr>
<tr>
<td>(iii) non geometrical stochastic:</td>
<td>- finite-scatterer model</td>
</tr>
<tr>
<td>- Saleh-Valenzuela type</td>
<td>- maximum entropy model</td>
</tr>
<tr>
<td>- Zwick model</td>
<td>- virtual channel representation</td>
</tr>
</tbody>
</table>

Standardized models:
(i) 3GPP SCM
(ii) COST 259 and 273
(iii) IEEE 802.11 n
(iv) IEEE 802.16 e / SUI
(v) WINNER

Generally, MIMO channel models are classified into physical and analytical models. Physical channel models consider an environment which describes the double-directional multipath propagation of electromagnetic waves between the location of the MS array and the location of the BS array. The wave propagation parameters, such as, complex amplitude, DOD, DOA, and delay of MP Care modeled explicitly. Physical models reproduce radio propagation accurately, with different levels of complexity, independent of the antenna configurations (antenna pattern, number of antennas, array geometry, polarization, mutual coupling) and the system bandwidth (Almers et al., 2007).
Physical MIMO channel models are divided into deterministic models, geometry-based stochastic models, and non-geometric stochastic models. In deterministic models, physical propagation parameters are definite, for instance, traced rays data or measured data. In geometry-based stochastic models, the impulse response of the channel is characterized by the laws of wave propagation applied to specific MS and BS element, and the stochastically-chosen scatterer geometries (Almers et al., 2007). In contrast, non-geometric stochastic models, for instance, the extensions of the Salah-Valenzuela model (Steinbauer, 1998), describe and determine physical parameters, such as, DOD, DOA, and delay, in a complete stochastic way without assuming an underlying geometry. To ease MIMO systems performance evaluation or design, several reference MIMO channel models have been characterized. Examples of such reference models are the ones proposed within 3GPP (3GPP2 Spatial Channel Model Ad-hoc, 2003), COST 259 (Molisch et al., 2006), COST 273 (Sirkova, 2006.), IEEE 802.16a,e (Erceg et al. 2001), and IEEE 802.11n (Erceg et al., 2004).

In contrast to physical models, analytical channel models characterize the impulse response of the channel between the individual MS and BS antennas analytically without respecting the wave propagation. The individual impulse responses appear in the MIMO channel matrix.

Analytical models are split to propagation-motivated models and correlation-based models. The propagation-motivated models determine the channel matrix via propagation parameters. Examples are finite scatterer model (Burr, 2003), maximum entropy model (Debbah and Muller, 2005) and virtual channel representation model (Sayeed, 2002). Correlation-based models characterize the MIMO channel matrix statistically in terms of the correlations between the matrix entries. Conventional correlation-based channel models are Kronecker model (Chuah et al., 1998), and Weichsel Berger model (Weichsel Berger et al., 2006).

Despite the mentioned classification, some of the suggested models can be assumed as both analytical and physical models. Geometry-based models are of these models which have many properties of analytical and physical models. This paper focuses on these models. Some specific properties of Geometry-based models are:

These models are very compatible to real environments as their important parameters are usually determined according to simple geometrical considerations.

Most effects are implicitly reproduced; for instance, small scale fading is created by spontaneous-positioning of waves from individual scatterers while DOA and delay drifts caused by MS movements are determined implicitly.

Each parameter depends on a primary cause in the distribution of scatterers; hence, the interactions between the power delay profile (PDP) and angular power spectrum (APS) do not affect the modeling.

MS/BS and scatterer movements, shadowing, and the appearance/disappearance of the propagation path can be easily implemented; this fact allows the inclusion of long-term channel correlations in a straightforward way. GSCMs do not depend on the types of the antennas at the MS or BS.

**MIMO PROPAGATION EFFECTS**

Propagation effects which are critical for MIMO performance include: (i) single scattering around the MS and BS, (ii) scattering by far clusters, (iii) double-scattering, (iv) wave guiding, and (v) diffraction by roof edges.

**A. Single Scattering around the BS and MS**

The single-scattering process can be modeled by locating the scatterers around the BS and MS. Each scatterer’s location determines the DOA and the delay of the MPC propagated via this scatterer. The distance of the scatterer, characterizing the delay, is correspondent to the physical MPC that undergoes single scattering (Molisch, 2004).

**B. Double Scattering**

The AOA of single bounce channel models can be related to the AOD and the time of arrival (TOA) of the multipath components. Moreover, the single bounce scattering model does not provide a rich enough multipath signal, especially in pico-cells and indoor environments.

Double and multiple bounce models have been suggested in (Kuipers et al., 2007) to solve these problems. It has been investigated how a geometry-based single bounce channel model can be developed into a multiple bounce model. Double scattering is one of the most important factors in MIMO systems. Keyhole or pinhole effect may appear if the distance between a BS and an MS is much larger than the effective radius of the scatterers around the BS and MS. Keyhole effect describes the situation where the channel capacity is less than what has been investigated by the correlation matrix of the received signals (more details in (Gesbert et al., 2000)). In addition, different amplitude statistics will be produced by keyholes. MS scatterers are assumed effectively as point sources with a Rayleigh amplitude statistics for each scatterer at the BS. The scatterer locations
obtained for the scattering around the BS and MS remain valid in double scattering simulation. The angles and delays are again obtained from geometrical properties (Molisch, 2004).

**C. Scattering via Far Clusters**

The position of far scatterers are fixed at a definite position in space in contrast to the local scatterers which are always centered around the MS. Far scatterers, such as, high-rise buildings and mountains, are far away from both MS and BS (Fuhl et al., 1998). Therefore, scatterers in the vicinity of a BS may be considered, specifically if the BS antenna is below the rooftops, e.g., micro- and pico-cells (Molisch et al., 1999).

**D. Wave guiding and Diffraction**

Considering the waveguide propagation at some point between the MS and BS is challenging. Waves can be coupled into a street canyon (waveguide) either directly from the BS, or after reflection by near or far scatterers (Toeltsch et al., 2001; Kuchar et al., 2000). In addition, waves can propagate from the MS or BS via a (horizontal) roof-edge directly or via other scatterers. These two propagation mechanisms play an important role in MIMO systems since the associated propagation matrices are both rank deficient (Chizhik et al., 2000). However, there are two differences:

1) The waveguide usually adds delay dispersion, while a roof-edge does not.
2) Although the horizontal roof-edge is rank-deficient (usually with rank one) with respect to vertical antenna arrangements, it does not restrict the rank.

The rank relies on the specific circumstances of propagation. The waveguide is typically ranked deficient with a rank higher than the one in the horizontal dimension. The number of modes that a street (or corridor) can support defines the rank when there is pure wave guiding along the street. If the wave guiding involves diffraction around one corner, then the rank is united with respect to horizontal antenna arrangements. For a typical street crossing, all four corners neighboring the intersection are involved, so the rank tends to be increased. Waveguide dispersion causes different modes to propagate with different speeds, so it couples the rank and delay dispersion, but primary simulations of frequency-selective MIMO channels in (Molisch, 2002) show that negligible influence on the capacity distribution exists. Wave guiding do not need to be implemented as a multiple-diffraction process. Therefore, random matrices multiplied by a rank reducing matrix reproduce the statistical properties of the propagation in the waveguide (Molisch, 2002).

Statistical analysis of clusters in radio propagation requires clustering methods which perform reliable and reproducible results simultaneously. It is important to estimate the optimal number of clusters with respect to the separability and compactness of the individual clusters. Further more, the clustering should perform independently from the underlying propagation condition for large channel data processing, e.g., outdoor or indoor (Schneider et al., 2009). Pico-, micro- and macro-cells are three basic scenarios which have been considered in terms of the relative position between the BS and MS. In contrast to macro-cell, pico- and micro-cell environments consider the line-of-sight (LOS) propagation between the BS and MS. The scattering area in micro-cell environments is modeled by an ellipse, representing a street environment, while the pico- and macro-cell ones are modeled by circles. Another difference is in the location of the BS and MSs. They are all located inside the scattering area in the pico- and micro-cell environments, but in macro-cell, only MSs are located inside this area and the BS is located outside. The BS and MSs can be located anywhere inside the circle in pico-cell environments, while in the micro-cell, both the BS and MSs are located in the foci of the ellipse, the MS is located at the center of the circle in the macro-cell cases (Kuipers and Correia).

**TYPES OF GSCM**

There are different geometry-based channel model representations. GSCM can be further classified as regular-shaped (RS-GSCM) and irregular shaped (IS-GSCM) depending on whether effective scatterers are placed on regular shapes or irregular shapes (Wang and Cheng, 2009). Such models can be easily adapted to different scenarios by changing the shape of the scattering region.

**RS-GSCM**

The RS-GSCM are divided into the following four models:

1) one-ring model
2) two-ring model
3) elliptical model
4) combined models and three-dimensional models (3-D)

**A. One-Ring Model**
The model describes an environment where the BS has little or no scatterer surrounding it while the MS surrounded by scatterers assumed to exist on a ring around the MS. One-ring model is suggested for suburban environments where the distance between the BS and MS is considerable and the BS is at a height much higher than the MS one. The BS is usually placed on a very elevated point, e.g., a hill, mountain or tower, and the MS is placed at a much lower point, e.g., average human height. One-ring model can be applied to a mobile-to-mobile (M2M) communication system, such as, the communication environment of an airplane or helicopter with a ground vehicle. One-ring model is appropriate for the fixed wireless communication scenario, where the BS is elevated (Shiu et al., 2000). The model (Shiu et al., 2000) is a widely used one for studying outdoor MIMO communications where the scatterers are placed on a ring while the MS is placed at the center. Generally, a single scatterer placed on the ring represents a group of scatterers which are responsible for incident rays from a particular direction. The radius of the ring is determined by the angular spread subtended at the BS in the uplink (Paul and Bhattacharjee, 2006).

In 1993, Jakes (Jakes, 1993) introduced an SISO model based on one-ring model. The model has further been extended in (Shiu et al., 2000) and (Jakes, 1993), where it was proposed as an appropriate stochastic model for a narrowband MIMO Rayleigh fading channel. The model has been used in (Patzold and Hogstad, 2004) as a starting point for the derivation of a reference model for a $2 \times 2$ MIMO channel (Hogstad and Patzold, 2004). The geometry-structure of one-ring modeling is shown in Figure 1. The previous described narrowband models do not take the different propagation delays of all incoming waves into account. The delays are supposed to be equal and small in comparison to the data symbol duration. In wideband systems, this statement is not true and the propagation delay differences cannot be neglected. Consequently, the channel becomes frequency selective (Patzold and Hogstad, 2006).

To describe the frequency selectivity of the channel, the narrowband channel models (Luo et al., 2008) are modified differently:

- It is assumed that the number of segment pairs equals the number of different propagation paths."L". Each pair of segments is assigned to a single discrete propagation delay according to a fixed rule (more detail in (Patzold and Hogstad, 2006) and (Hakimi et al., 2008)).

Using multiple rings of scatterers around the MS with different radii is a realistic approach, specifically in combination with clusters of scatterers (Patzold and Hogstad, 2006). In (Luo et al., 2008) and (Latinovic et al., 2003) the hollow-disk model is proposed to model the signal statistics of a wideband MIMO channel. In this model all scatterers are located on the hollow-disk.

**B. Two-Ring Model**

In one-ring model, it is often assumed that each received wave is scattered only once, so these models are sometimes called single-bounce models. Measurements have shown that multiple reflections or multiple scattering instants are important in pico-cell and indoor environments (Molisch et al., 1999; Svantesson 2002). When the height/vertical position of the BS is not as high as the one in one-ring model, it is as summed that the BS is surrounded by scatterers existing on a ring. Therefore, two rings surrounding the BS and MS, respectively. This
model, in the case of M2M communications, can represent a helicopter, flying low above a city, communicating with a ground vehicle.

Geometry-based channel models may consider two scattering instants per path, in order to model indoor and pico-cell environments. One group of scatterers are located in the vicinity of the BS and another group around the MS (Svantesson, 2002). Modified two-ring models are presented in (Bakhshi et al., 2008; Patzold), where only single-bounce rays are considered and multiple bounces are treated as secondary effects. The frequency selectivity of two-ring model, where two hollow-disks are considered, one around the MS and another one around the BS, is investigated in (Shen et al., 2010). The geometry-structure of two-ring modeling is shown in Figure 2.

![Figure 2. Geometrical two-ring model (Ma and Patzold)](image)

**C. Elliptical Model**

Geometry-based elliptical model (GSEM) assumes that scatterers are uniformly distributed within an ellipse where the MS and BS are the foci of the ellipse for wideband modeling, multiple ellipses surround the MS and the BS. The MS and BS have equal antenna heights in this model, which is suitable for indoor systems. This model represents micro-cell environments where antenna heights are relatively low. Therefore, multipath scattering near the BS is similar to multipath scattering near the MS. The model assumes that a single scattering situation and multiple scattering lead to larger delay than the one’s of the previous models. In rural macro-cells, a typical difference of approximately 30m exists between antenna heights, and in urban micro-cells, the difference is about 15m. To be able to include such differences in antenna heights, a 3-dimensional model is proposed (Norklit and Andersen, 1998). The geometry of elliptical modeling is shown in Figure 3.

GSEM is a spatial geometry-based model. It is used for the cases in which both MS and BS are surrounded by clutter and scatterers, i.e., micro-cell and pico-cell systems. The well-defined geometry of the model leads to find the important parameters, such as, the pdf of direction-of-arrival (DOA) analytically (Intarapanich et al., 2004). Extended GSEM is suggested for indoor LOS MIMO channel using polarization diversity at 8GHz bands. The model creates spatial channel parameters for each environment, separately. It suggests a 3-dimensional geometry for indoor environments and considers array antennas by using spatial correlation. Moreover, scattering and reflection mechanisms are considered using the patch scattering model (Moon et al., 2007).

(Oestges et al., 2003) suggests a physical scattering model for MIMO channel characterizing. First, system bandwidth, antenna beam width and a valid power-delay profile are defined for a specific range. Then, scatterers are assumed to be located on ellipses to fit this power delay profile. Ultimately, the effects of range and antenna beam width on delay spread, channel correlations, Demmel condition number are simulated according to the model.
D. Combined Models and 3-Dimensional Models

In two-dimensional models, it is assumed that the field incident on MS or BS antenna is composed of a number of waves travelling only in the horizontal plane. However, the assumption is not true for urban environments where MS and BS antenna arrays are often located in close proximity to and lower than surrounding buildings. Scattered waves do not necessarily travel horizontally since they may propagate by diffraction from the top of buildings down to the street.

Two-cylinders (Zajic and Stuber, 2007), two-spheres (Bakhshi et al., 2009) and a spheroid (Janaswamy, 2002) have been proposed as 3-dimensional models where the distribution of the scatterers is assumed to be on the surfaces of cylinders around the MS and BS, on the surface of the two-spheres around the BS and the user, and on a semi-spheroid around the MS, respectively. Also (Ozdemir et al., 2004) presents a 3-dimensional multipath scattering model for MIMO channels. The model is derived from a 2-dimensional one for the purpose of generating uncorrelated channels.

The presented model in (Cheng et al., 2010) combines a two-sphere model and an elliptical cylinder model. It is the first 3-dimensional RS-GSCM that has the ability to investigate the impact of the vehicular traffic density (VTD) on channel statistics and jointly considers the azimuth and elevation angle. This 3-dimensional model comprises a single- and double-bounce two sphere model, so the model is adaptive to a wide variety of scenarios (Cheng et al., 2010).

The proposed model in reference (Cheng et al., 2009) combines a two-ring model and an ellipse model, where the sum of LOS, single- and double-bounced rays with different energies construct the receiving signal. In fact, the model is compatible with a variety of M2M scenarios, such as, macro-, micro-, and pico-cells. Moreover, the model is the first GSCM that studies the impact of VTD on channel characteristics (Cheng et al., 2009).

A GSCM for wideband MIMO Rician fading channels is proposed based on the tapped delay line (TDL) structure (Cheng et al., 2009). The proposed wideband model is the first GSCM that has the ability to study the impact of the VTD on channel statistics for different time delays.

A new wideband MIMO fading channel model for V2V communications is proposed in (Zhiyi et al., 2009). The model, called T-model, represents the propagation effects when vehicles move toward a junction with a side road and corner buildings. Assuming the single- and double-bounce scattering is the first step toward derivation of T-model.

A novel channel model of the relay MIMO cooperative communication based on geometry-based double-bounce model (GDBM) is proposed in (Jie et al., 2010). Generally, there is a strong direct path between the relay node (RN) and the destination node (DN), thus the LOS path must be considered as two-ring model. In MIMO cooperative communication systems, both DN and RN are in motion. This model is analyzed in the Rician fading environment (Jie et al., 2010).
Table 2. GSCM models available in the literature along with some specification

<table>
<thead>
<tr>
<th>Reference</th>
<th>Channel model</th>
<th>SB</th>
<th>NB</th>
<th>Rayleigh</th>
<th>2D</th>
<th>(M_T \times M_R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Shiu et al., 2000)</td>
<td>RS-GSCM (one-ring)</td>
<td>SB</td>
<td>NB</td>
<td>Rayleigh</td>
<td>2D</td>
<td>(2 \times 2)</td>
</tr>
<tr>
<td>(Paul and Bhattacharjee, 2006)</td>
<td>RS-GSCM (one-ring)</td>
<td>SB</td>
<td>NB</td>
<td>Rayleigh</td>
<td>2D</td>
<td>(2 \times 2)</td>
</tr>
<tr>
<td>(Patzold and Hogstad, 2004)</td>
<td>RS-GSCM (one-ring)</td>
<td>SB</td>
<td>NB</td>
<td>Rayleigh</td>
<td>2D</td>
<td>(2 \times 2)</td>
</tr>
<tr>
<td>(Hong and Patzold, 2004)</td>
<td>RS-GSCM (one-ring)</td>
<td>SB</td>
<td>NB</td>
<td>Rice</td>
<td>2D</td>
<td>(2 \times 2)</td>
</tr>
<tr>
<td>(Abdi, 2004)</td>
<td>RS-GSCM (one-ring and two-ring)</td>
<td>SB</td>
<td>NB</td>
<td>Rice</td>
<td>2D</td>
<td>(2 \times 2)</td>
</tr>
<tr>
<td>(Abdi and Kaveh, 2002)</td>
<td>RS-GSCM (one-ring)</td>
<td>SB</td>
<td>NB</td>
<td>Rayleigh</td>
<td>2D</td>
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<tr>
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<td>(M_T \times M_R)</td>
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<td>(Hakimi et al., 2008)</td>
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<tr>
<td>(Latinovic et al., 2003)</td>
<td>RS-GSCM (one-ring)</td>
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<td>(Svantesson 2002)</td>
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<td>(Tang and Mohan, 2003)</td>
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</tr>
<tr>
<td>(Tong and Zekavat, 2008)</td>
<td>RS-GSCM (two-ring)</td>
<td>DB</td>
<td>NB</td>
<td>Rayleigh</td>
<td>2D</td>
<td>(2 \times 2)</td>
</tr>
<tr>
<td>(Norkilt and Andersen, 1998)</td>
<td>RS-GSCM (elliptical)</td>
<td>SB</td>
<td>WB</td>
<td>Rayleigh</td>
<td>2D</td>
<td>(M_T \times M_R)</td>
</tr>
<tr>
<td>(Patzold and Hogstad, 2006)</td>
<td>RS-GSCM (elliptical)</td>
<td>SB</td>
<td>NB</td>
<td>-</td>
<td>2D</td>
<td>(M_T \times M_R)</td>
</tr>
<tr>
<td>(Bakhshi et al., 2009)</td>
<td>RS-GSCM (two-spheres)</td>
<td>SB</td>
<td>NB</td>
<td>Rayleigh</td>
<td>3D</td>
<td>(2 \times 2)</td>
</tr>
<tr>
<td>(Zajic A.G. Stuber G.L. 2007)</td>
<td>RS-GSCM (two-cylinders)</td>
<td>MB</td>
<td>WB</td>
<td>Rayleigh</td>
<td>3D</td>
<td>(2 \times 2)</td>
</tr>
<tr>
<td>(Zajic and Stuber, 2007)</td>
<td>RS-GSCM (two-cylinders)</td>
<td>MB</td>
<td>WB</td>
<td>Rayleigh</td>
<td>3D</td>
<td>(2 \times 2)</td>
</tr>
<tr>
<td>(Jie et al., 2010)</td>
<td>RS-GSCM (two-ring)</td>
<td>DB</td>
<td>NB</td>
<td>Rice</td>
<td>2D</td>
<td>(2 \times 2)</td>
</tr>
<tr>
<td>(Hong-Dang and Xiao-Yan, 2008)</td>
<td>IS-GSCM (tunnel model)</td>
<td>SB</td>
<td>NB</td>
<td>Rayleigh</td>
<td>2D</td>
<td>(M_T \times M_R)</td>
</tr>
<tr>
<td>(Chelli and Patzold, 2007)</td>
<td>IS-GSCM (street model)</td>
<td>SB</td>
<td>NB</td>
<td>Rayleigh</td>
<td>2D</td>
<td>(M_T \times M_R)</td>
</tr>
<tr>
<td>(Liberti and Rappaport, 1999)</td>
<td>RS-GSCM (two-ring)</td>
<td>DB</td>
<td>NB</td>
<td>Rayleigh</td>
<td>2D</td>
<td>(2 \times 2)</td>
</tr>
<tr>
<td>(Cheng et al., 2012)</td>
<td>RS-GSCM (three-ring)</td>
<td>SB</td>
<td>DB</td>
<td>MB</td>
<td>Rice</td>
<td>2D</td>
</tr>
<tr>
<td>(Cheng et al., 2010)</td>
<td>RS-GSCM (two-sphere and an elliptic-cylinder)</td>
<td>SB</td>
<td>DB</td>
<td>NB</td>
<td>Rice</td>
<td>3D</td>
</tr>
<tr>
<td>(Bakhshi et al., 2008)</td>
<td>RS-GSCM (one-ring)</td>
<td>SB</td>
<td>WB</td>
<td>Rayleigh</td>
<td>2D</td>
<td>(M_T \times M_R)</td>
</tr>
<tr>
<td>(Zhiyi et al., 2009)</td>
<td>IS-GSCM (T-model)</td>
<td>SB</td>
<td>-</td>
<td>Rayleigh</td>
<td>2D</td>
<td>(2 \times 2\times 2)</td>
</tr>
<tr>
<td>(Intarapanich et al., 2007)</td>
<td>RS-GSCM (elliptical model)</td>
<td>SB</td>
<td>NB</td>
<td>-</td>
<td>2D</td>
<td>(2 \times 2)</td>
</tr>
</tbody>
</table>

**IS-GSCM MODELS**

In IS-GSCM, effective scatterers are placed on irregular shapes. Some authors assume that a tunnel, due to its properties, such as, long and narrow space, complex structure of the walls, and poor smoothness, provides great scattering. Geometric distribution of the scattering in the tunnel is very different from the ones’ of the microdistrict and the indoor environment because of its property of generally contributing on both sides (Hong-Dang and Xiao-Yan, 2008).

A new geometric street scattering model is proposed in (Chelli and Patzold, 2007), where the street model consists of an infinite number of scatterers existing on the left and/or right hand side of the street.

A reduced-complexity cluster modeling method for channel models, based on the third generation partnership project (3GPP) channel modeling, is presented in (Xiao and Burr, 2008). It simulates the time variation of spatially correlated wideband MIMO channels. The main novelty is that while modeling the time-variant
wideband MIMO channels, only the change in the center AoA for each of the clusters is tracked instead of tracking the changes in the AoAs of all the MPCs defined (Xiao08).

In (Zhang and Kuo, 2007), a novel GSCM has been extracted from a new unified cooperative MIMO channel model process. The proposed multiple-ring GSCM is compatible with a wide variety of cooperative MIMO propagation scenarios. Furthermore, the model is the first to investigate the effect of local scattering density (LSD) on channel statistics.

The performance of GSCM’s terms of the diversity gain for cooperative communication through spatial correlation properties of GBSMs is investigated in (Cheng et al., 2012). In particular, a two-ring scattering model is derived to study the performance of cooperative diversity protocols in an M2M environment. Both the source nodes (SNs) and destination nodes (DNs) are surrounded by a large number of local scatterers, i.e., indoor environments. The path loss limits the contribution of remote scatterers to the total channel energy in this model. Therefore, only local scattering is considered.

A novel approach based on the concept of twin clusters has been suggested in (Hofstetter et al., 2006). MPCs originate from the BS, travel to the first cluster, are transmitted to a corresponding interacting object in the twin cluster and finally to the MS. The position of the clusters is chosen in a way that both the DOD and the DOA are reproduced correctly. The transferring between the two clusters adds a delay that also matches the measured delay of the MPCs.

Many different proposed GSCMs have been reviewed so far, and many more exist in the literature. A comprehensive characteristic list of these models are brought in Table 2. The models are compared in terms of the channel models (RS-GSCM, IS-GSCM), frequency selectivity (wideband (WB) or narrowband (NB)), number of reflections (single- double (SB), double-bounced (DB) or multiple-bounced (MB)), Rayleigh or Rice channel in 2D/3D.

Knowledge of channel statics is essential for the analysis and design of communication systems. In many of these papers, the statistical properties, such as, CCF, autocorrelation function (ACF), spatial correlation or joint effect spatial and temporal correlation were derived, and in some references, the MIMO channel capacity is computed.

### SIMULATION RESULTS

In this section, the capacity and the CCF, of a hollow-disk model proposed in paper (Latinovic et al., 2003) and has been shown in Figure 4, are investigated. First, the parameters of the mathematical CCF are calibrated according to the CCF obtained by conducting some simulations on RPS. The simulated environment in RPS is the one-story building of Electrical and Computer Engineering School at the University of Sistan and Baluchestan shown in Figure 5. The BS is located outdoor and equipped with an array antenna with twoisotropic elements mounted at a height of 5m. The user’s array antenna is similar to BS’s array antenna but at height of 1.5m, the values of $k$ and $\mu$ are determined according to the simulated CCF to project the specifications of the propagation channel into the mathematical CCF. Second, the capacity of the hollow-disk model is computed for performance evaluation of the model.

The CCF is computed as follows:

$$\rho_{lp, mq}(\Delta f, \Delta t) \approx \frac{D_n}{\Omega_0(k)} \int_{R_1}^{R_2} \exp[jc_{pq} \cos(\alpha_{pq}) + je(1 + DR^{-1})] \times I_0(\{k^2 - a^2 - b^2_m - e^2 - c^2_{pq} \Delta^2 \sin^2(\alpha_{pq})$$

$$+ 2a b_m \cos(\beta_{lm} - \gamma) + 2c_{pq} \Delta \sin(\alpha_{pq})] \{a \sin(\gamma) - b_m \sin(\beta_{lm})\} + 2ae \cos(\gamma) - 2b_m \cos(\beta_{lm})$$

$$- j2k[a \cos(\mu - \gamma) - b_m \cos(\mu - \beta_{lm}) - c_{pq} \Delta \sin(\alpha_{pq}) \sin(\mu - e \cos(\mu))]^{1/2}] R^{-n} f(R) dR$$

(1)

where $\lambda$ is the wavelength, $f_D = v/\lambda$ is the maximum Doppler shift, $n$ represents the path loss exponent, $\Omega_{lp}$ is the power transferred through the $BS_p - U_1$ link, $\Omega_{lp} = \Omega_{mq} = \Omega$. The other parameters, i.e., $D$, $R_1$, $R_2$, $\delta_{pq}$, $d_m$, $\alpha_{pq}$, $\beta_{lm}$ and $\gamma$ are the distances and the angles shown in Figure 4.

$a = 2\pi f_D \Delta t$, $b_m = 2\pi d_m/\lambda$, $c_{pq} = 2\pi \delta_{pq}/\lambda$ and $e = 2\pi R \Delta f / c$. For a given $f(R)$, the CCF in (1) is calculated numerically. The expected capacity is computed according to the following formula:
\[ C = E\{\log_2 | I_2 + \frac{SNR}{n} H H^H |\}, \quad (2) \]

where \(| . |\) denotes the determinant, \(I_2\) is the \(2 \times 2\) identity matrix, \(SNR\) represents the signal-to-noise ratio, \(n\) is the number of antenna elements, \(H\) is the channel impulse response matrix and \((.)^H\) denotes the complex conjugate transpose operator. Note that the capacity \(C\) is a stochastic process, since the AOA is a random variable (Sarris and Nix. 2007). The following parameters are chosen for the models: the angles of antenna array at the BS and the MS \(\alpha_{pq} = \beta_{lm} = \pi/2\), \(n = 1.8\), \(f = 700 MHz\) and \(\Delta f = 0\). Assuming \(D = 93 \lambda\) and the reasonable assumption of \(D \gg R_2 \gg R_1 \gg \delta_{lm}\), the value of the inner and the outer diameter of the disk are computed as \(R_1 \approx 2.3 \lambda\), \(R_2 \approx 9.3 \lambda\), and \(0 < \delta_{lm}/\lambda < 0.25\), where \(\delta_{pq}/\lambda = 1\).

First, the CCF is obtained by calculating the integral of (1), numerically, and then the simulated CCF is obtained according to RPS simulations. The calibrated mathematical CCF and the simulated one, shown in Figure 6, are very close. The increasing of the distance of the MS antenna elements, \(0 < \delta_{lm}/\lambda < 0.25\), reduces the magnitude of the CCF. Therefore, the channel capacity grows up as shown in Figure 7. Comparing the capacities of the hollow-disk model and the simulated one shows that the results are close with negligible error.

Figure 4. Geometrical configuration of a 2×2 hollow-disk channel with local scatterers around the MS (Latinovic et al., 2003)

CONCLUSION

In this paper, a comprehensive investigation on the geometry-based MIMO channel models was presented. These models were very compatible with real environments as their important parameters were normally determined according to the simple geometrical considerations. The geometric models were divided into different categories according to the shape of the scattering region, i.e., RS-GSCMs and IS-GSCMs, depending on whether effective scatterers were placed on regular or irregular shapes. Different RS-GSCMs and IS-GSCMs models proposed in the literature for different environments and applications were reviewed in this paper. Finally, the CCF of a hollow disk model calibrated with the information of a simulated ones was presented. According to the CCF parameters, \(k\) and \(\mu\), the capacity was computed. Comparing the mathematical and simulated values of the capacity showed that the capacity of the hollow-disk model is close to the capacity achieved by the simulator.
Figure 5. The simulated environment

Figure 6. The $|CCF|, |\rho_{1,21}(\Delta f)|$, of hollow-disk model, $(k = 15, \mu = 1.7 \text{ rad})$

Figure 7. The channel capacity of the hollow-disk model, $SNR = 100dB, k = 15, \mu = 1.7 \text{ rad}$


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