Comparison and Implementation of the Directional Geometric-Stochastic Based Channel Model

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I. Introduction

A mobile radio channel model is an essential prerequisite for the simulation, development and accurate testing of mobile radio systems. The European Co-operation in the Field of Scientific and Technical Research (COST) projects have a long history of research about channel models. The COST 207 project in the 1980s and in the early 1990s played an important role in the development and approval of the GSM system. In the mid 1990s the COST 231 project focused mainly on the path loss of different radio environments. The third and the fourth generation of mobile radio systems take advantage of larger complex systems, like multiple-input and multiple-output (MIMO) systems. Therefore more detailed information about the radio channel has to be considered that was not addressed before, like:

• The information about direction-of-arrivals (DoAs) at both ends of the radio system, and
• Movements of the mobile station (MS) within a cell change the directional properties of the radio channel, like slow- and fast-fading, distinct signal paths appear and vanish again.

In order to meet these needs the European research project COST 259 (successor of the COST 207 and COST 231 projects) has developed a directional channel model (DCM). This model uses as a basis a geometry-based stochastic channel model (GSCM) [1], [7].

The directional channel model proposed in the COST 259 project defines a set of various cell types. The major difference between the three cell types are the different topographical and electrical properties referred to the channel models. The macro cell type covers urban and rural areas. Micro cells cover areas within buildings, as well as very local areas in urban regions, like crossings. Pico cells deal with indoor scenarios like office and corridor areas. These cell types are further divided into sets of parameters that represent a different more detailed radio environment. Each radio environment is then further divided into different propagation scenarios. In this paper a macro cell type model based on [1] is further developed and then implemented for a macro cell environment in the Java programming language.

The remaining part of the paper is organized as follows. In Section II the WSSUS channel model is described. Then in Section III the structure of the GSCM is presented and some important parameters. In Section IV the implementation issues of the GSCM model for macro cells in Java are discussed. Finally the conclusions are drawn in Section V.

II. WSSUS Channel Model

In this section we describe the Wide-Sense Stationary Uncorrelated Scattering (WSSUS) channel model as our reference channel model.

The main effects that cause and influence multipath propagation are reflection, scattering, shadowing, diffraction and path loss. The multipath propagation results in frequency and time selective fading of the received signal at the receiver.

Time- and frequency selective fading of the signal occurs during the propagation. It is characterized with statistical channel models, as for example with the WSSUS channel model proposed by Belo [2]. The time varying weight function of a WSSUS process can be approximated by [3]:

\[
h(\tau, t) = \lim_{N \to \infty} \frac{1}{\sqrt{N}} \sum_{n=1}^{N} e^{i\theta_n} e^{i(2\pi f_d \tau_n + \delta(\tau - \tau_0))} \quad (i)
\]

The time-continuous model described by (i) is used in a transmission system shown in Figure 1.a). It can be transformed into a discrete-time model, which suits better into a simulation model Figure 1.b) shows the discrete tap-delay model. The implementation of the tap-delay model is simple, but it does not cover distinct DoA information or the effects of the movement of the MS, like dynamically appearing or vanishing signal paths. The GSCM considers these non-stationary effects, and is presented in the next section.

Figure 1: a) Time continuous linear transmission system  
b) Time discrete-time model (tapped-delay).

III. Geometry-Based Stochastic Channel Model (GSCM)

Another way to model multipath propagation is to use a directional channel model. The GSCM is a directional channel. It describes the scatterers, base station and mobile station geometrically in polar coordinates. The sources,
reflectors and the receiver are distributed with different probability density functions (pdfs) in a fixed 2-dimensional coordinate system. This motivates to apply a simple (computing efficient) ray tracing approach to calculate all multipath values at the receiver.

Figure 2 shows the GSCM model, based on the cluster representation of the scatterers. Each scatterer represents a single multipath component. It has been observed [5] that in the real propagation environment scatterers usually occur not independently distributed, but in groups. These groups of scatterers are called clusters. There is always one cluster around the MS that moves with the MS, the near cluster. It represents the multipaths that are caused from the scatterers around the MS. All other clusters are called far clusters. They simulate the influence of the more distant objects such as: mountains, buildings, etc. Far clusters are distributed throughout the cell by using the following pdf [6]:

\[
f(r, \varphi_c) = \begin{cases} 0 & r_c < R_{\text{min}} \\ \frac{1}{2\pi \sigma_r} \exp \left( - \frac{r - R_{\text{min}}}{\sigma_r} \right) & r_c \geq R_{\text{min}} \end{cases}
\]  

(ii)

Values \( r_c, \varphi_c \) represent the polar coordinates of the center of the cluster. Values for \( R_{\text{min}} \) and \( \sigma_r \) from (ii) are given in Table 1.

The described approach enables as to model the channel as [1]:

\[
Y = H_{\text{LOS}} X + \sum_{k=0}^{N_{\text{NS}}} [H_{\text{NS}}(k) X] + \sum_{a=0}^{N_{\text{FC}}} \sum_{m=0}^{N_{\text{FS}}} [H_{\text{FS}}(n, m) X]
\]  

(iii)

In (iii) \( X \) is the input signal, \( Y \) the output signal, \( N_{\text{NS}} \) is the number of the scatterers in the near cluster, \( N_{\text{FC}} \) is the number of the far clusters, \( N_{\text{FS}} \) is the number of the scatters in the far cluster. \( H_{\text{LOS}}, H_{\text{NS}}, \) and \( H_{\text{FS}} \) represent the channel impulse response for the line of sight, the near cluster and for the far cluster respectively.

Figure 2: A Geometry based stochastic channel model (GSCM).

Each far cluster has certain visibility regions. Figure 3 shows how the visibility regions are defined. Each visibility region is the area that is visible from the corresponding cluster for the MS on its way through the cell. Circular regions are defined as the visibility regions over the MS route. When the MS enters a visibility region, the far cluster becomes ‘visible’ and scatterers start to create additional paths at the receiver. When the MS leaves this region the cluster is made inactive. The number of visibility regions assigned to the cluster can be approximated by Poisson distribution with the mean value of one.

Figure 3: Illustration of the visibility regions. Black squares represent far clusters, white circles corresponding visibility regions, and the gray circle the visibility region of the near cluster.

Depending on the macro-cell type the visibility regions cover a specific part of the MS route. This part of the path, \( p \), covered by the influence of the additional clusters is given in Table 1 as mean number of far clusters. As illustrated in Figure 4, the distance between points \( A \) and \( B \) plus the distance between points \( C \) and \( D \) has to be \( p\% \) of the MS route (in this case the MS route is the distance between \( \text{MS start} \) and \( \text{MS end} \)).

Figure 4: Illustration of the deployment of the visibility regions over the path.

The COST 259 project defines four macro-cell radio environments: Generalized Typical Urban (GTU), Generalized Bad Urban (GBU), Generalized Rural Area (GRA) and Generalized Hilly terrain (GHT). Some, of the specific parameters for these macro-cells are given in Table 1. Most of the parameters result out of different channel measurement campaigns [5].

<table>
<thead>
<tr>
<th></th>
<th>GTU</th>
<th>GBU</th>
<th>GRA</th>
<th>GHT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical MS to BS distance</td>
<td>500 m</td>
<td>500 m</td>
<td>5000 m</td>
<td>5000 m</td>
</tr>
<tr>
<td>Mean number</td>
<td>0,17</td>
<td>1,18</td>
<td>0,06</td>
<td>1</td>
</tr>
<tr>
<td>of far clusters - ( p )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radius of</td>
<td>100 m</td>
<td>100 m</td>
<td>300 m</td>
<td>300 m</td>
</tr>
<tr>
<td>visibility region - ( R_c )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min distance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>of the cluster - ( R_{\text{min}} )</td>
<td></td>
<td></td>
<td></td>
<td>1000 m</td>
</tr>
<tr>
<td>Variance of the cluster distance - ( \sigma_r )</td>
<td>1500 m</td>
<td>1500 m</td>
<td>5000 m</td>
<td>5000 m</td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>900 / 1800 MHz</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Characteristic parameters for macro cells in COST259.
IV Implementation Aspects

The described GSCM was developed as a software simulator block in the Java programming language. The given input signal (given as a Java object) is a discrete time signal with a specific sample rate. The channel object has all the received signals from each signal scatterer or signal source and each signal path at a specific sampled time. To keep results in a Java object is very useful because it can be easily sent over the network and used by other computers for further computing.

Except the received amplitude and phase of each path at the receiver we have certain additional information. These information are for each distinct signal path: direction-of-arrival, signal distance, Doppler shift and path loss.

It is computationally ineffective to update the channel impulse response for every bit. Therefore, a lot of effort was devoted to an efficient and still reliable update procedure. The parameters are divided in two main groups:

- short scale update parameters contain the fast changing variables. The recalculating in a short scale update procedure (SS-Update) is done every half of the wavelength movement of the MS. Fast changing parameters are for example: movement of the MS, path loss, signal distance, direction of arrival and Doppler shift;
- large scale update parameters contain the less frequent changing variables. A large scale update (LS-Update) is performed every 10<sup>th</sup> SS-Update. Although we are updating parameters less often, still computational effort is quite high because of intensive geometrical calculations. LS-Update parameters are: the visibility regions, the delay spread and the azimuth spread of the cluster.

In macro-cells, the delay spread, azimuth spread and shadowing of each cluster are correlated stochastic processes. The correlation can be performed by calculating a Cholesky decomposition of the specified correlation matrix \( \mathbf{G} \), where \( \mathbf{G} \) is equal to [5]:

\[
\mathbf{G} = \begin{bmatrix}
1 & -0.75 & -0.75 \\
-0.75 & 1 & 0.5 \\
-0.75 & 0.5 & 1
\end{bmatrix}
\]

The Cholesky decomposition of \( \mathbf{G} \) is defined as an inverse transformation of:

\[
\mathbf{G} = \mathbf{C} \cdot \mathbf{C}^T
\]

The resulting matrix \( \mathbf{C} \) is then multiplied by a 3 dimensional vector of independent random variables. The result of the multiplication contains in each row values of the delay spread, angular spread and shadowing with needed correlation properties. Delay spread and angular (azimuth) spread will be introduced in subsections C and D (correlation properties). Delay spread and angular spread, angular spread and shadowing with needed multiplication contains in each row values of the delay vector of independent random variables. The result of the multiplication contains in each row values of the delay vector of independent random variables. The resulting matrix is then multiplied by a 3-dimensional vector of independent random variables. The result of the multiplication contains in each row values of the delay spread, angular spread and shadowing with needed correlation properties. Delay spread and angular (azimuth) spread will be introduced in subsections C and D (correlation properties).

\[ \mathbf{G} = \begin{bmatrix}
1 & -0.75 & -0.75 \\
-0.75 & 1 & 0.5 \\
-0.75 & 0.5 & 1
\end{bmatrix} \]

Indices \( i,j \) show that we are calculating DoA of j-th scatterer in the i-th cluster. \( \text{DoAangle} \) is calculated from simple geometry as the direction of arrival that corresponds to the center of the cluster. It is constant for all the scatterers inside of the specific cluster. While angle \( \varphi_{\text{add},i,j} \) gives an additional shift of the DoA for the j-th scatterer. This angle can be represented with the Laplacian pdf:

\[
f(\varphi_{\text{add},i,j}) = \begin{cases} 
0 & \text{for } \varphi_{\text{add},i,j} > \pi, \varphi_{\text{add},i,j} < -\pi \\
\frac{1}{\sqrt{2}} \exp\left(\frac{-\varphi_{\text{add},i,j}^2}{2}\right) & \text{for } -\pi < \varphi_{\text{add},i,j} < \pi 
\end{cases}
\]

The signal distance is a SS-Update parameter, therefore the signal phase is also recalculated at each SS-Update.

B. Phase of the signal

The signal phase of each path at the receiver is calculated by using the knowledge of the corresponding signal distance (description of the signal distance is given in subsection D). The following equation introduces the correct phase shift of the specific path:

\[ \varphi = 2\pi f_s s/c \]

Where \( f_s \) is the carrier frequency, \( s \) is the signals distance and \( c \) is the speed of light.

The signal distance is a SS-Update parameter, therefore the signal phase is also recalculated at each SS-Update.

C. Direction of arrival

The direction of arrival (DoA) is a SS-update parameter. DoA is separately calculated for the scatterers inside of the near clusters and for the scatterers inside of the far clusters. For the scatterers in the near cluster (NC) we use the following pdf:

\[
f(\varphi_{\text{NC},i,j}) = \begin{cases} 
0 & \text{for } \varphi_{\text{NC},i,j} > \pi, \varphi_{\text{NC},i,j} < -\pi \\
\frac{1}{2\pi} & \text{for } -\pi < \varphi_{\text{NC},i,j} < \pi 
\end{cases}
\]

As we can see in equation (iv) the DoA of each scatterer in the NC is chosen from an uniform distribution. The reason for this is that the near cluster is always around the mobile station, so scatterers can come from any possible angle. Index i shows that the i-th scatterer of a NC is chosen.

DoA of the scatterers from the far clusters (FC) are calculated by:

\[ \varphi_{\text{FC},i,j} = \text{DoAangle} + \varphi_{\text{add},i,j} \]

D. Signal distance

The signal distance is a SS-Update parameter. It is calculated for each visible path (scatterer) at every time sample. The signal distance is calculated as:

\[ s_{i,j} = s_{\text{CL},i} + s_{\text{add},i,j} \]

Indices \( i,j \) denote the j-th scatterer within the i-th cluster. The \( s_{\text{CL},i} \) represents the signal distance of the center of the i-th cluster, and \( s_{\text{add},i,j} \) is additional signal distance of the j-th scatterer.

Value \( s_{\text{CL},i} \) is the distance between the BS and the center of the cluster plus the distance between center of the cluster and the current MS position.
The additional signal distance of the scatterer $s_{add,i,j}$ is equal to additional time distance of the scatterer $t_{add,i,j}$ multiplied with the speed of light. Laplacian pdf can be used to represent $f(t_{add,i,j})$:

$$f(t_{add,i,j}) = \begin{cases} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{1}{2} \cdot \frac{t_{add,i,j}}{\sigma^2}\right) & \text{for } t_{add,i,j} < -t_{\text{max},i}, t_{add,i,j} > t_{\text{max},i} \\ \frac{1}{\sqrt{2\pi}} & \text{for } -t_{\text{max},i} < t_{add,i,j} < t_{\text{max},i} \end{cases}$$

The value $t_{\text{max},i}$ represents the maximum delay of multi path components within specific cluster. For each of the paths we assign one random Laplacian distributed value from $(-t_{\text{max},i}, t_{\text{max},i})$ for scatterers in the far clusters and from $(0, t_{\text{max},i})$ for scatterers in the near clusters. $t_{\text{max},i}$ is the delay spread of the i-th cluster and is correlated with the azimuth spread value ($S_{\text{az},i}$).

### E. Doppler shift

The Doppler shifts are calculated for each signal by:

$$f_d = \frac{\partial S}{\partial t} f_c \frac{1}{c}$$

Where $\partial S$ is the change of the signal distance over the time $\partial t$, $f_c$ is the carrier frequency and $c$ the speed of light. The Doppler shift is calculated for each multipath component.

### F. Path loss

The path loss is a short scale update parameter. It is calculated for each visible path (scatterer) in each time sample. The path loss is calculated separately for the near and for the far clusters.

The path loss of the near cluster ($L_{\text{nearscluster}}$) is calculated from COST 231 – Hata for rural area and hilly terrain types of macro cell and from COST231 – Walfisch-Ikegami-Model for bad and typical urban types of macro cell (models are described in more detail in [4, pp 134]). The path loss for the scatterers within the near cluster are calculated by adding the additional traveling time $t_{\text{add}}/\mu s$ to the $L_{\text{nearscluster}}$. The path loss is calculated from the corresponding additional signal distance of the scatterer.

The path loss of the far clusters ($L_{\text{farscluster}}$) is calculated from [5] by using equations:

$$L_{\text{farscluster}}[i,j] = L_{\text{nearscluster}} + L_{\text{add}}[i,j] \quad [dB]$$

$$L_{\text{add}}[i,j] = u_i + (t_{i,j} - t_0) / \mu s \quad [dB]$$

The $L_{\text{farscluster}}[i,j]$ is a value that represents the path loss for the j-th scatterer within the i-th far cluster. The uniformly distributed value $u_i$ that is added to $L_{\text{add}}$ is calculated once for the i-th cluster and does not change for each scatterer within a cluster. The pdf of $u_i$ is given by:

$$f(u_i) = \begin{cases} 0 & \text{for } u_i > 20, u_i < 0 \\ 1/20 & \text{for } 0 < u_i < 20 \end{cases}$$

$t_{i,j}$ is the traveling time of the signal over specific path. We can get traveling time from the corresponding signal distance $s_{i,j}$ by dividing it with the speed of light. The value $t_0$ is the traveling time of the signal to the near cluster (path length BS-MS, because the center of the near cluster is the position of the MS).

### V. Conclusions

This paper presents a directional channel model based on the GSCM. It is outlined where the advantages are, providing directional effects of the impinging signals at the receiver, in comparison to the WSSUS channel model. The directional channel model based on the GSCM focuses on specific scenarios by providing parameter sets and applying ray tracing. The dynamic appearance of the directional effects, like clustered scatterers, provide a realistic channel model especially for applications like beamforming.

The parameter sets and how they are implemented into a channel model in the Java language is described. The computing efficiency is addressed by dividing the parameters into short- and large-scale parameters. In addition by applying the Cholesky decomposition the correlation between the different parameters is considered as well.

### REFERENCES


Opis parametara i njihova implementacija u Javi je detaljno. Problem intenzivnih izračunavanja koje sa sobom donosi geometrijski model kanala je rešen podelom parametara na grupu češće azuriranih (short-scale update) i grupu redje azuriranih (large-scale update). Takođe, primenom Cholesky dekompozicije uzeta je u obzir međusobna korelacija bitnih parametara, što odgovara propagaciji u realnim uslovima.

Poredjenje i implementacija direkcionalnog geometrijsko-stohastičkog modela kanala, Ivan Ćosović i Ronald Raulefs.