Applying COST 259 Channel Models to UMTS Uplink System-Level Simulations with Smart Antennas

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Abstract – In this paper we investigate the impact of spatio-temporal channel models on the system-level capacity in the UMTS FDD uplink. We study the performance of space-time processing for flat fading and COST 259 channel models. The results are expressed in terms of multiple-access noise rise, which is derived by a stationary system simulator. Smart-antennas provide a clear advantage in mixed rate traffic services in comparison to non-adaptive antenna systems. In urban environments, the flat fading assumption is found to be a lower bound for the capacity estimation of both conventional and smart-antenna systems, respectively.

1. Introduction

The European 3rd generation mobile communication system is known as the Universal Mobile Telecommunications System (UMTS). It will enable tomorrow’s wireless Information Society, delivering high-value broadband information, commercial and entertainment services to mobile users. UMTS will play a key role in creating the future mass market for high-quality multimedia communications that will approach 2 billion users worldwide by the year 2010 [1]. The main advantage of 3G mobile systems will be mixed services with variable data rates. The customer profile of a 3G system will consist of a large number of low-data-rate and voice users with the concurrent service to a high-data-rate user population.

The frequency division duplex (FDD) mode of UMTS is based on a Wideband Code Division Multiple Access (W-CDMA) technique. CDMA systems are interference limited in nature and severely suffer from the near-far effects because all users operate in the same frequency band simultaneously. This is essentially more critical in the uplink of UMTS where all users are potential interferers. The problems due to the near-far effect are reduced in the downlink because of the better orthogonality of the individual signal [2].

2. Data Model

In the following we present the used Channel Model, the System model and the Signal model.

A) CHANNEL MODEL

An important part of the evaluation process of a system employing smart-antenna arrays is the channel modeling. For system capacity investigations, flat fading channel models are widely used [4],[5]. This is a gross simplification of the nature of mobile radio propagation channels and does not capture the detailed information of state of the art channel modeling [7]. Hence, we study the impact of a channel model that includes both the spatial and the temporal distribution of the energy reaching the receiver. Moreover we compare this with the results obtained under the flat fading assumptions.

SPATIO-TEMPORAL CHANNEL MODEL

Within the European research initiative COST 259 [7] several channel models have been developed. They are aimed at UMTS and HIPERLAN², with particular emphasis on smart-antennas and directional channels. They have been introduced in the 3rd generation standardization process by 3GPP [6]³.

The path loss is modeled based on the proposed models for UMTS system simulations presented in [2] for pre-defined environments. Path loss correlation between two up-link connections from a single user equipment (UE) to different BSSs is considered by a correlation coefficient of 0.5 [13]. The log-normal large-scale fading is modeled with a mean of $\mu_L=0$ and a standard deviation of $\sigma_L=6\text{dB}$.

In order to test advanced antenna array systems, the main focus of the channel model has to be on the azimuthal and temporal properties. Especially the statistics of the delay and azimuth of the impinging waves as well as their expected power are of great interest. According to [7] and [8] we define a Laplacian shape for the Azimuth Power Spectrum (APS) seen at the BS antenna. For the Delay Power Spectrum (DPS) we assume the widely used one-sided exponential decaying function [8]. Both can be written as

$$APS(\phi) \propto \exp\left(-\sqrt{\frac{|\phi|}{\sigma_\phi}}\right)$$ (1)

$$DPS(\tau) \propto \exp(-\tau / \sigma_\tau), \text{ for } \tau > 0$$ (2)

where $\phi$, $\sigma_\phi$, $\tau$ and $\sigma_\tau$ denote the azimuth towards the UE seen at the BS, the azimuth spread, the delay and the delay spread, respectively. For typical urban environments the azimuth power delay spectrum can be written as

$$P(\phi, \tau) \propto APS(\phi) \times DPS(\tau)$$ (3)

In our model we assume a tapped delay line model for a typical urban scenario. We consider a single scattering cluster and $L$ impinging multipath-components. The delay spread is $\sigma_\tau = 0.5\mu s$ and the start of the cluster is at $\tau_{cl}=0\mu s$.

¹High PERformance Local Area Networks
²Within 3GPP [6] only the temporal domain is considered till now.
³Results have shown, that enlarging the standard deviation to $\sigma_L=10\text{dB}$ has negligible impact on the results.
where the azimuth domain we assume we spread of \( \sigma_z=8^\circ \) around \( \theta_0 \), where \( \theta_0 \) corresponds to the azimuth toward the UE.

B) SYSTEM MODEL

Following the results of [3], 19 sites for single cell investigations have to be considered in the system model. For each site we assume 3 sectored cells. Hence, a total of 57 cells altogether has been taken into account. The main investigations have to be considered in the system model.

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Table 1: Main simulation parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of cells</td>
<td>57</td>
</tr>
<tr>
<td>Inter-BS distance</td>
<td>1000m</td>
</tr>
<tr>
<td>Background noise floor</td>
<td>-105dBm</td>
</tr>
<tr>
<td>Path loss model</td>
<td>Macro cell [2]</td>
</tr>
<tr>
<td>Log-normal large-scale fading</td>
<td>( \mu_z=0, \sigma_z=6dB )</td>
</tr>
<tr>
<td>Path loss correlation</td>
<td>0.5 [13]</td>
</tr>
<tr>
<td>Max. UE TX power</td>
<td>21dBm</td>
</tr>
<tr>
<td>TPC dynamic range</td>
<td>80dB</td>
</tr>
<tr>
<td>Power control error</td>
<td>( \mu_\epsilon=0, \sigma_\epsilon=0.5dB )</td>
</tr>
<tr>
<td>No. of antenna elements</td>
<td>1 and 4</td>
</tr>
<tr>
<td>Inter-element spacing</td>
<td>d=( \lambda/2 )</td>
</tr>
<tr>
<td>Number of impinging rays</td>
<td>10</td>
</tr>
<tr>
<td>Delay Spread</td>
<td>( \sigma_\tau=0.5\mu s )</td>
</tr>
<tr>
<td>Azimuth spread</td>
<td>( \sigma_\theta=8^\circ )</td>
</tr>
</tbody>
</table>

C) SIGNAL MODEL

Following the notation of Bello [10], the azimuth-delay spread function of the channel for each path \( l \) from UE \( k \) to BS \( \zeta \) is given by

\[
h_{l,k,\zeta}(\phi,\tau) = \sqrt{p_{l,k,\zeta}} e^{i\theta_{l,k,\zeta}} e^{j\delta(\phi - \phi_{l,k,\zeta}, \tau - \tau_{l,k,\zeta})}.
\]

where \( \sqrt{p_{l,k,\zeta}} \) and \( \theta_{l,k,\zeta} \) denote the amplitude and the phase of the \( l^{th} \) signal path at a single antenna element impinging at delay \( \tau_{l,k,\zeta} \) and azimuth \( \phi_{l,k,\zeta} \). The array response vector for a single UE \( k \) at BS \( \zeta \) for the delay \( \tau \) is thus given as

\[
a_{l,k,\zeta}(\tau) = \sum_{l=1}^{N} \left\{ c_{l,k,\zeta}(\phi) h_{l,k,\zeta}(\phi,\tau) d\phi \right\}
\]

where \( c_{l,k,\zeta} \) is the array steering vector of a wave impinging from an azimuth direction \( \phi_{l,k,\zeta} \) at an \( M \)-element uniform linear array with an inter-element spacing \( d \).

In the FDD mode of UMTS, the time a wavefront takes to pass through the array is much smaller than the chip interval \( T_c \). Therefore, the narrowband assumption for antenna arrays is valid. This makes it possible to model the time delays as phase shifts. The array steering vector can thus be written as

\[
c_{l,k,\zeta}(\phi) = [1, e^{-2\pi l \sin \theta_{l,k,\zeta}}, \ldots, e^{-2\pi (M-1) \sin \theta_{l,k,\zeta}}]^{T}.
\]

We assume that we perfectly know the channel, so the spatial covariance matrix of the \( k \)-th user in the cell \( \zeta \) at a certain delay \( \tau \) becomes:

\[
R_{l,k,\zeta}^{(S)}(\tau) = a(\theta_{l,k,\zeta}) a^H(\theta_{l,k,\zeta})
\]

In the same way we define the spatial interference and noise covariance matrix \( Q_{l,k,\zeta}^{(I)}(\tau) \) as

\[
Q_{l,k,\zeta}^{(I)}(\tau) = \sum_{k=1}^{K} R_{l,k,\zeta}^{(S)}(\tau) + \sigma_N^2 I
\]

where \( \sigma_N^2 \) and \( I \) denote the noise variance and the \( M \times M \) identity matrix, respectively.

3. Space Time Processing

Space-time processing in 3G Generation systems can be seen as an evolution of more “traditional” receiver structures. Space-time processing combines time-only and space-only processing. Time-only processing corresponds to equalizers that use a weighted sum of signal samples (RAKE receiver), and space-only processing corresponds to simple beamforming that uses a weighted sum of antenna outputs.

Examples for literature available on space-time processing are [15], [16], [20], [22], [23] and [25]. A block diagram of our space-time base station receiver structure is shown in Figure 1.

A) SPATIAL PROCESSING

For the implementation of combining algorithms of the multiple antenna signals, it is important to know whether the spatial interference and noise covariance matrix is diagonal or not [17], [14], meaning the interference is white. In case of a large number of users in the system, spatial whiteness can be generally expected [11], [12]. The UMTS network controller will reduce the transmit power level of each individual UE to a minimum, even in the case of a few high-data-rate users. Hence, singular interferers with high power levels, which would be represented by high off-diagonal correlation, do not occur.

We investigated whether interferer whiteness is fulfilled or not. An example for a long-term interference and noise covariance matrix with only few high-data-rate users is given in Figure 2. We observe that the covariance matrix has a diagonal shape. But we also see that the spatial covariance matrix is not stringently diagonally dominant [26] and hence spatial whiteness is not given per se in a multi-service environment. This corroborates the intuition that single “very” high data users contradict the assumption of a spatially white covariance matrix.
Without any assumption about the spatial covariance matrix behavior, we compute the complex antenna weights for the \( k \)-th user as the dominant generalized eigenvalue of \([R^{(S)}_{k,\zeta}, Q^{(S)}_{k,\zeta}]\) [18]. This well known beamforming concept corresponds to maximizing the signal-to-noise-plus-interference ratio SNIR in the uplink [17] and the estimated ratio of signal to interference power for the \( k \)-th UE. From

\[
\mathbf{w}^{\text{opt},S}_{k,\zeta}(\tau) = \arg \max_{\mathbf{w}_{k,\zeta}} \mathbf{w}_{k,\zeta}^{H} \mathbf{R}^{(S)}_{k,\zeta}(\tau) \mathbf{w}_{k,\zeta}^{S}
\]  

we obtain the optimum spatial weights for the \( k \)-th UE in cell \( \zeta \) as a function of the delay \( \tau \). The output signal of the spatial processing for the \( n \)-th delay tap is thus given by

\[
z_{k,\zeta}(\tau,n) = (\mathbf{w}^{\text{opt},S}_{k,\zeta}(\tau,n))^{H} \mathbf{R}^{(S)}_{k,\zeta}(\tau,n) \mathbf{w}^{\text{opt},S}_{k,\zeta}(\tau,n)
\]  

**B) TEMPORAL PROCESSING**

Applying the optimal spatial weights to the receiver structure shown in Figure 1, we obtain optimum SNIRs for each delay tap at the rake receiver input for each individual user. For the temporal consideration we assume a wide-sense-stationary (WSS) channel with uncorrelated scattering (US) only. The complete short-term channel estimate in time can be obtained by correlation with the pilot sequence, which is part of the control channel in the UMTS FDD mode. The consequence of the US condition is that the contributions of the temporal taps selected for further processing steps are uncorrelated.

An example for a temporal signal covariance matrix is given in Figure 3.

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4 Two adjacent taps are usually not completely uncorrelated due to filtering and oversampling. Analysis in [19, chapter 29.3,"The selective rake receiver"] has shown that the correlation is in the range of 0.02 for raised cosine pulse shapes. Thus, we assume two adjacent taps to be uncorrelated.
Since we only have a limited number \( N \) of rake fingers, the taps with the highest signal power are selected. As mentioned above, we can assume temporal whiteness of the interfering signals. Thus, the optimum output of the rake receiver can be achieved by maximum ratio combining (MRC) of the selected fingers [17]. The weights for the rake fingers are thus given by

\[
w_n = (h_n^{(T)})^\dagger
\]

where \( h_n^{(T)} \) and \( (\cdot)^\dagger \) denote the temporal channel impulse response and complex conjugate, respectively.

4. Simulations

For the investigations on the system behavior, we now have to consider a number of cells. As already mentioned, we consider 19 3-sector sites, leading to a total of 57 cells. In doing so, we correctly estimate the inter-cell interference at the inner site and thus we are able to come up with trustworthy conclusions at the end [3].

Taking the whole network into account, we calculate the interference seen at the BS antenna for each user. Since we now have a total number of \( K \) users in the entire network, we easily find from (8)

\[
G_{\zeta k}^{(S)}(\tau) = \sum_{\ell=1}^{K} R_{\ell\zeta}^{(S)}(\tau) + \sigma_N^2 I
\]

the spatial covariance matrix including the total network interference for the \( k \)-th user belonging to cell \( \zeta \). Following the description above and repeating the procedure for \( \zeta = \ldots Z \) (\( Z = 57 \) cells), we can finally calculate the quality requirement at the BS antenna connector for each user in the network.

Introducing the processing gain \( GP \) as a function of the service of the \( k \)-th user

\[
GP_{k\zeta} = \frac{W}{R_{k\zeta}}
\]

with the modulation bandwidth \( W \) and the user data rate \( R_{k\zeta} \), we obtain the ratio of combined received energy per information bit to the effective noise power spectral density, \( N_{eff} \) at a single point in time

\[
\frac{E_{\zeta}}{N_{eff}} = \frac{\text{RSCP}_{k\zeta}}{\text{ISCP}_{k\zeta}} GP_{k\zeta}
\]

\( \text{RSCP}_{k\zeta} \) and \( \text{ISCP}_{k\zeta} \) are the Received Signal Code Power and the interference Signal Code Power (including noise) of the \( k \)-th user in cell \( \zeta \) after beamforming and rake combining.

For the computer simulation of the above model, we use a stationary Monte-Carlo approach [3]. The main simulation parameters are given in Table 1.

5. Results and Discussion

This section is structured as follows: First we give the definition of the system capacity bound and the system load in the uplink of a CDMA system. Then we discuss the results of space-time processing and compare them with the space-only (flat fading) results.

SYSTEM LOAD DEFINITION

The maximum load, i.e., the maximum capacity of a single cell in the UMTS FDD uplink, is defined as the number of users corresponding to a certain rise in multiple-access interference MAI over the thermal background noise [2]. This “noise rise” is the increase in the uplink noise at the BS antenna connector due to the uplink interference. It is expressed as a dB figure relative to the thermal noise floor (more precisely, the thermal noise including the man made noise). The 95% confidence value of this noise rise is taken over all Monte Carlo runs and all monitored cells. Our chosen design target value for this figure will be 6dB. This is equivalent to 75% of the pole-capacity loading of a CDMA system [2], [21].

SPACE-TIME RESULTS

For the investigations on space-time performance on system-level we take the spatial-temporal channel model proposed in Section 2. Moreover we assume ideal channel estimation for the weight calculations.

![Figure 4: Noise rise vs. the number of users per cell for a flat fading and the proposed spatial-temporal channel model.](image)

We investigated a service mix of 40% speech users and 60% 64kbit/s data users. Figure 4 shows the results, comparing a single antenna and the four element antenna array case in a flat fading channel and the COST259 environment. For the temporal combiner we assumed a maximum of four selective rake fingers. Our investigation reveals a diversity gain due to rake finger assignment. Thus the noise rise in the COST259 channel is consistently smaller than in the flat fading environment.

We also investigated 1, 4 and 6 antenna element uniform linear arrays with 2 and 4 rake fingers for the temporal combining as schematically shown in Figure 1. The results for a service mix of 40% speech users and 60% 64kbit/s data users are presented in Figure 5. We assumed a delay spread of 0.5μs [6] (about 2Tc) and a number of 10 impinging multipath components. In case of 2 rake fingers only, the results are worse than in the flat fading environment, which
corroborates the intuition that we sum up only a portion of the received power [19], [24].

In general, the performance of rake receivers and the number of necessary rake fingers depend on the environment. In narrowband channels a low number of rake fingers is sufficient to sum up the signal energy. If we consider a urban channel with a high delay spread, more rake fingers are required [24]. This can be observed from Figure 5, where four rake fingers perform better than two in any antenna case.

Future UMTS base stations will provide at least four rake fingers per receiver branch. Thus, in the investigated urban environment the flat fading assumption turns out to be a lower bound for the capacity estimation for both conventional and smart-antenna systems, respectively.

Figure 5: Noise rise in the central cells. The BSs are equipped with 1, 4 or 6 antenna elements and the temporal rake receiver combines 2 or 4 taps.

6. Conclusions

The main focus of this study is the benefit of smart-antennas in the uplink of a multi-service UMTS FDD system. We demonstrated the importance of a realistic channel model accounting for spatial-temporal characteristics of mobile radio channels for a fair assessment of smart-antenna benefits.

We applied the capability of antenna array processing to our stationary Monte-Carlo UMTS system simulation approach. Based on this we investigated the mixed service capacity in the uplink. We compared and evaluated the performance of space-time processing under both flat fading and spatial-temporal channel conditions. We investigated systems with single-element antennas, four- and six-element antenna arrays at all base stations within the network. Also we looked at the effect of a limited number of rake fingers in an urban environment. Building on the results in Section 5 we conclude:

- There can be a substantial increase in system capacity by incorporating antenna arrays at the base-station. The capacity gain depends on the business-case realization.
- Spatial whiteness is not necessary given in a multi-service UMTS scenario.
- The flat fading assumption is a lower bound for the capacity estimation in urban scenarios.

Overall, we have shown a significant increase of mixed service capacity of UMTS uplink by space-time processing and thus we strongly recommend their use at the base station.

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8. References