Performance Assessment of Mobile OFDM-based Systems: Variability within Given Wideband Channel Categories

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Abstract: An ongoing challenge in communications is to provide ever faster, broadband multi-media access to mobile terminals. In the mobile multipath environment, performance is affected by both frequency-selectivity and Doppler spread. Realistic channel simulators are required to compare competing systems on a fair basis. The RACE code-division testbed (CODIT) provides a realistic model based on extensive wideband measurements, ideal for OFDM (Orthogonal Frequency Division Multiplexing) testing, which defines a range of indoor and outdoor environment categories. However, there remains considerable variability within any given category. To enable fair and reliable comparison, the variability within a given channel type must be quantified, since this determines the length of simulation time and the number of independent instances of a channel type to be averaged before stable and repeatable results can be inferred. This paper explains how the channel model was implemented, providing the important environment parameters. Variability is then quantified in terms of statistics of BER (Bit Error Ratio) from simulation runs of differing lengths for many different instances of nominally the same environment. An accurate estimate (~5%) of mean BER for a given CODIT environment typically requires averages over simulations of around 90-150 instances of the channel, with runs of at least 700 OFDM symbols.

Key words: OFDM (Orthogonal Frequency Division Multiplexing), CODIT (code-division testbed), wideband, channel-model, variability, doppler spread, BER (Bit Error Ratio), WiMax, MCM (multi-carrier modulation).

1. Introduction

Mobile telecommunications systems must now compete to provide access to a wide range of multi-media services. This requires the flexibility simultaneously to carry not only conventional digital voice signals and text but also broadband data, audio and video streams etc., and heralds a convergence of mobile telecommunications, broadcast and broadband wireless access systems [1, 2]. The required flexibility (e.g., bandwidth, quality of service) can be provided by an air interface based on Orthogonal Frequency Division Multiplexing (OFDM) [3-7], as we see for example in the long-term evolution programme in 3G Partnership Project (3GPP) [8] and in Worldwide Interoperability for Microwave Access (WiMax) [9]. A well-designed OFDM system exhibits resilience to frequency selective fading, reducing multi-path distortion and provides high spectral efficiency whilst enabling efficient hardware implementation.

To evaluate OFDM system performance correctly for the wideband mobile channel a simulation must
Table 1  Channels’ parameters included in the CODIT channel model.

<table>
<thead>
<tr>
<th>Channel Type</th>
<th>Scatterer</th>
<th>$\Omega$</th>
<th>$m_i$</th>
<th>$\tau_{\text{max}}$ (\mu s)</th>
<th>$\alpha_{i0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban</td>
<td>1-20</td>
<td>[0.5-1.5]</td>
<td>1</td>
<td>2.4</td>
<td>$[0, \pi]$</td>
</tr>
<tr>
<td>Suburban</td>
<td>1</td>
<td>1</td>
<td>15</td>
<td>0</td>
<td>$[0, \pi]$</td>
</tr>
<tr>
<td></td>
<td>2-6</td>
<td>[0.1-0.4]</td>
<td></td>
<td>15.8</td>
<td>$[0, \pi]$</td>
</tr>
<tr>
<td>Rural</td>
<td>1</td>
<td>1</td>
<td>25</td>
<td>0</td>
<td>$[0, \pi]$</td>
</tr>
<tr>
<td>Town Squares</td>
<td>1</td>
<td>1</td>
<td>25</td>
<td>0</td>
<td>$[0, \pi]$</td>
</tr>
<tr>
<td></td>
<td>2-5</td>
<td>[0.05-0.8]</td>
<td></td>
<td>0.2</td>
<td>$[0, \pi]$</td>
</tr>
<tr>
<td></td>
<td>6-10</td>
<td>[0.01-0.05]</td>
<td>1</td>
<td>0.2</td>
<td>$[0, \pi]$</td>
</tr>
<tr>
<td>Corridor</td>
<td>1</td>
<td>1</td>
<td>25</td>
<td>0</td>
<td>$\alpha_{n} = [0, \pi]$</td>
</tr>
<tr>
<td></td>
<td>2-5</td>
<td>[0.05-0.2]</td>
<td></td>
<td>5</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>6-10</td>
<td>[0.01-0.05]</td>
<td>1</td>
<td>0.16</td>
<td>$[0, \pi]$</td>
</tr>
</tbody>
</table>

Table 2  Key parameters of the 3G and 4G systems.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency band</td>
<td>2 - 8 GHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>5 - 20 MHz</td>
</tr>
<tr>
<td>Data rate</td>
<td>Up to 20 Mbps</td>
</tr>
<tr>
<td>Access</td>
<td>MC-CDMA or OFDM</td>
</tr>
<tr>
<td>Forward error correction</td>
<td>Concatenated coding scheme</td>
</tr>
<tr>
<td>Switching</td>
<td>Packet</td>
</tr>
<tr>
<td>Mobile top speeds</td>
<td>200 km/h</td>
</tr>
</tbody>
</table>

model both delay spread and Doppler characteristics realistically. However, difficulty arises when evaluating performance over the wide range of radio channel environments that there can be considerable variability of performance within any particular channel category.

A channel simulator [10], based on the RACE-CODIT (RACE: Research and Development in Advanced Communications Technologies in Europe; CODIT: Code Division Testbed) model [11] was constructed in MATLAB-Simulink. The simulator provided for evaluation of OFDM performance for the range of channel environments listed in Table 1 for system parameters typical of an OFDM system dimensioned for the mobile channel and listed in Table 2. Typical outputs were Bit Error Ratio (BER) curves versus Signal-to-Noise Ratio (SNR) at each mobile velocity. Obviously, since the simulation generates random examples of noise, it is necessary to repeat the simulation a sufficient number of times to have confidence in the estimated error rate at a given SNR. However, it was found that each different randomly-generated instance of the channel would nevertheless generate a significantly different BER curve due to variability in the random channel parameters and the long-term fluctuations built into the model.

This paper describes work that was undertaken to evaluate the variability of performance that can arise amongst different instances of the same channel type, as defined for the CODIT wideband channel model.

The Fourth Generation Wireless Forum (4GWF) suggested a preferred mobile broadband system that can operate in as little as 5 MHz of spectrum with a total of 20 Mbps of throughput [5, 12]. 4G does not have a solid specification as of yet, so the parameters rely on general proposals where the targeted bit rate is 20 Mbps in a frequency spectrum of 5–20 MHz [7, 13].

In order to study the performance of the next generation cellular mobile systems, it is essential that the transmission multipath propagation channels be characterized. Many propagation channel models have been specified in [14-16]. Furthermore, to establish some assessment scenarios, the channels proposed in the European RACE programmer [17-19] are considered for different environments and channel types that can be distinguished as follows:

(1) Macrocell sizes have a radius of 1 km to 35 km, thus, they are suited for the support of mobile systems with high velocities. The urban, suburban, rural and hilly environments are the basic channels in the macro-
cell sizes.

(2) Microcell sizes typically have a radius less than 1 km, which are found in dense urban areas and city centers. Thus, the mobile speeds are limited to city traffic.

(3) Picocell sizes have a radius up to 100 m. These channels are typically applicable to indoor like environments, where the mobile speed is in the order of few m/s.

The following sections provide, firstly, a very brief overview of OFDM followed by a description of the CODIT channel model as implemented in this work. This is followed by a discussion of the parameters used in the simulations and of example results from the simulations. Finally, an “error analysis” is applied to the variability found in the simulation results, reflecting that amongst the wideband channels modeled. We conclude with recommendations on obtaining suitably accurate estimates of average BER for a given channel environment type.

2. OFDM System

OFDM applies the principle of multi-carrier modulation (MCM) by dividing the communication channel into narrow frequency bands and splitting the high data rate stream into a number of parallel, lower bit rate streams each of which modulates one sub-carrier transmitting in one of these frequency bands [20-23].

OFDM signals are typically generated digitally due to the difficulty of generating the signal by using a large number of analogue oscillators. The OFDM technique transforms a frequency selective wideband channel into group of non-selective narrowband channels, which makes it robust against large delay spreads. OFDM obtains high spectral efficiency by preserving orthogonality in the frequency domain between sub-carriers [24].

The OFDM scheme is implemented using the Discrete Fourier Transform (DFT) [25-27]. The composite OFDM signal is usually assembled as the in-phase and quadrature components of an equivalent baseband signal by taking the Inverse Discrete Fourier Transform (IDFT) of a complex vector that describes the constellation point for each of the parallel data symbols [28]. The general formula for the transmitted OFDM base-band signal is shown in the following expression.

\[
s_j(t) = \sum_{k=-N/2}^{N/2-1} S_k e^{j2\pi f_s t} p(t - lT_u)
\]

where \( k f_s \) is the \( k \)th sub-carrier of the \( l \)th OFDM symbol having the frequency spacing \( f_s \) between the sub-carriers, \( T_u \) is the time duration of the useful OFDM symbol and \( p(t - lT_u) \) is the rectangular pulse shaping filter applied to each sub-carrier. In the equivalent baseband representation, the sub-carriers each have an integer number of cycles within one symbol duration. This means that the frequency spacing between sub-carriers is the reciprocal of the OFDM symbol duration \( ( f_s = 1/T_u ) \) and thus the sub-carrier signals are orthogonal over the symbol period even though their sidebands overlap [29-32].

To prevent aliasing caused by the D/A converter, zero padding is introduced to the input of the IDFT block so that the number of total sub-carriers (IDFT size) is given by \( N = N_d + N_z \), where \( N_d \) is the input complex data sub-carriers and \( N_z \) is the number of zeros that are added. A basic block diagram of OFDM transmitter and receiver is shown in Fig. 1.

Transmission over wireless multipath channels is in general subject to both frequency dispersion caused by Doppler spread, and time dispersion caused by multipath fading. Frequency dispersion causes loss of orthogonality between sub-carriers and results in an error, which depends critically on the design of the transmitter pulse shaping filters. These filters could be used to reduce the power in the side lobes of the OFDM sub-carriers and thus, reducing the interference between the adjacent sub-carriers, which is called the inter-carrier interference (ICI). Some studies on the design of OFDM pulse shaping filters to reduce the effect of ICI have been presented in [33-36].
Classical OFDM offers robustness to time dispersion by employing a cyclic prefix (CP) insertion, which is introduced by copying the last portion of the OFDM symbol time series to the beginning of the symbol. CP, at the cost of reduction of the symbol rate of the OFDM signal, provides protection against inter-symbol interference (ISI) caused by time dispersion of the channel [37-40]. The OFDM signal is converted from digital to analogue, producing the equivalent baseband complex time domain signal that is up-converted, by mixing it with the operating (carrier) frequency, to the bandpass channel.

The receiver, as illustrated in Fig. 1, performs the reverse operation by down converting the received bandpass signal to its equivalent baseband complex signal, which is then converted from analogue to digital. The CP is removed and the received time domain OFDM signal is applied to the DFT process to demodulate the complex sub-carriers. Zeros are then removed to extract the desired complex data sub-carriers. A parallel to serial conversion is applied on the received parallel complex data sub-carriers. The data sub-carriers then input to the coherent demodulator (De-Mapper), to reconstruct the serial data bits.

3. The CODIT Channel Model

This model is based on the CODIT research project described in [17-19] and named as the CODIT channel model, which represents a way of approximating the behavior of the propagation channel by introducing parameters of a large number of outdoor and indoor channel types. This ubiquity of channel modeling representation identifies the CODIT channel as one of the most promising channel models in the assessment of the mobile communication systems.

The approach of the CODIT channel model assumes that the signal strength produced by one path is caused by the sum of one fixed (potentially dominant) component and a sufficiently large number of waves received in the same resolvable delay. The CODIT channel model assumes there are 100 such waves [19].

The CODIT channel model creates a realistic impulse response with a number of independent paths.
at various delays. The different path amplitudes, phases and delays vary in a manner that closely resemble the available measurements for that type of environment, i.e., realistically simulating the delay profile, the angle of arrival (AoA) distribution, and hence the Doppler spectrum, and time variation of the profile. The CODIT channel model provides a time-variant channel impulse response given by,

\[ h(t, \tau) = \sum_{i=1}^{L} E_i(t) a_i e^{j(2\pi f_{d} \tau + \phi)} \delta(t - \tau_i(t)) \]  

(2)

Where \( L \) is the number of paths, \( E_i(t) \) describes the long-term variations, \( a_i \) describes the attenuation due to the short-term variations, \( f_{d} \) is the Doppler frequency shift, \( \phi \) is the initial phase while \( \tau_i(t) \) describes the delay spread associated with each path.

The number of paths in the CODIT channel model is fixed and its maximum value considered for this model is 20, depending on the environment simulated. Each path simulates one scatterer object that is characterized by the following parameters:

- The scatterer mean power (\( \Omega_i \));
- The scatterer coherence coefficient (\( m_i \));
- The scatterer mean incident angle (\( \alpha_i \));
- The scatterer time delay (\( \tau_i \)).

The scatterer mean power (\( \Omega_i \)) is the mean of the total receiving signal amplitude, from the direct or dominant rays and their diffused waves. In other words, it is the power collected from the \( i^{th} \) path at the receiver front end. The parameters of (\( \Omega_i \)) must be normalized such that the channel impulse response (CIR) has a total average power equal to one, that is,

\[ \sum_{i=1}^{L} \Omega_i = 1 \]

The scatterer coherence (\( m_i \)) is related to the parameter of the Rice distribution. In general the value of (\( m_i \)) is related to the wall surface roughness and building structure irregularity [36].

For a Rayleigh type environment (\( m = 1 \)), the amplitude of the fixed path is (\( a_{i0} = 0 \)) where the fading characteristics are due to the diffuse paths of similar amplitudes. For a Rician type, strong contribution of (\( a_{i0} \)) is expected. The higher value of (\( m_i \)) will give slower fluctuations, the spectrum being more concentrated around the frequency shift of the fixed path. Thus, when nLoS environment is simulated, (\( m_i \)) will assume values between (1 & 5), whereas for a LoS environment (\( m_i > 10 \)) will be required. The initial phases of the coherent and diffused paths, (\( \phi_{i0} \)) and (\( \phi \)), form a uniform distribution over the interval \([-\pi, \pi]\) [19].

The amplitude of the coherent path, (\( a_{i0} \)), is considered constant and fixed according to the following equation,

\[ a_{i0} = \sqrt{\Omega_i (1-m_i)} \]  

(4)

The amplitude of the remaining paths, (\( a_y \)), is assigned according to a Rayleigh distribution with \( \Omega_i \), mean, \( m_i \), coherence coefficient and standard deviation given according to the following equation,

\[ a_y - \text{dev} = \frac{\Omega_i}{N_{waves}} (1-\sqrt{1-m_i}) \]  

(5)

The Doppler shift and the Doppler spectrum of the coherent and diffuse parts respectively are indirectly specified by introducing the angle scattering function of the proposed scatterer as follows,

\[ f_{D0} = \frac{\nu}{\lambda} \cos \alpha_{i0} , \quad f_{Dy} = \frac{\nu}{\lambda} \cos \alpha_y \]  

(6)

where \( f_{D0} \) is the Doppler shift and \( f_{Dy} \) is the Doppler spectrum. (\( \alpha_{i0} \)) is randomly selected according to a uniform distribution over the range of [\( 0, \pi \)]. While (\( \alpha_y \)) are assumed to follow a Gaussian distribution over the range of [\( 0, 2\pi \)] with mean value \( \alpha_{i0} \) and standard deviation \( \sigma = 0.15 \) rad.

The values of these parameters are randomly generated and given in Table 1. All the values of the variables have been measured by a group of researchers in different areas related to [20].

4. Simulation Parameters

The CODIT channel model can be used in the frequency range of 1.7-2.2 GHz, with a bandwidth of 5 MHz. However, simulation and validation results should hold for up to 20 MHz as mentioned in Ref.
Table 3 summarizes the OFDM system parameters that are used in this paper to investigate the suitability of OFDM as an air interface for the next generation mobile systems under the conditions of time varying channel model (the CODIT channel model). These parameters are based on the worst case between the CODIT channels that are given in Table 1. The worst case is using the suburban channels with maximum delay spread of 15.8 $\mu$s. Thus, to protect the OFDM signal from the inter-symbol interference, the cyclic prefix length should be greater than the maximum delay spread.

5. Simulation Results

BER performance evaluation is performed for an OFDM-based mobile communication system incorporating QPSK modulation under the CODIT channel conditions of path loss, time delay and Doppler frequency shift. This performance evaluation takes place using Matlab/Simulink simulation model that is illustrated in Fig. 2 showing the OFDM transmitter and receiver blocks and the CODIT channel model, which is illustrated in Fig. 3 showing the short-term and long-term variation blocks as well as the delay profile block.

The Bit Error Rate/Ratio (BER), which is the ratio of the number of bits received in error to the total number of bits transmitted is given by,

$$BER = \frac{\text{Bits in Error}}{\text{Total Number of Bits}}$$

For estimating an accurate BER value, the simulation must be run for an enough time. This simulation run time should be related to the length of the OFDM symbol, which determines the number of transmitted bits, in addition to the desired BER. At high signal to noise ratio (SNR), the BER becomes very low, thus, the simulation must be run for very long time to estimate the BER value. From this point, if a simulation generates no errors, it does not mean that the BER is zero, but that the simulation did not have enough transmitted bits.

Clearly, confidence in the BER estimate reduces as BER reduces. For a simulation run over 350 OFDM symbols each of which consists of 2048 QPSK mapped sub-carriers, the number of errors counted for a BER of
$10^{-5}$ is 1434, while for a BER of $10^{-5}$ it is only 14. We restrict the analysis to BER of 18 dB and 28 dB where the accuracy of the BER estimate (determined by the added white noise rather than the variations in the channel) is highly reliable.

Fig. 4 illustrates the OFDM BER performance at different mobile speeds under the conditions of the urban channel type. For higher mobile speeds, i.e. $v = 30 \text{ m/s}$, the Doppler affects the BER performance at $SNR = 28 \text{ dB}$. This indicates that the increase of the signal to noise ratio above this value does not affect the BER performance of the OFDM system since the interference due to the Doppler Effect starts to dominate the BER performance.

The BER performance at lower speeds at the suburban channel type is worst than other channels in this paper. This is due to the higher delay spread

![Urban Channel Type](image)

![Suburban Channel Type](image)

Fig. 4 BER performance for OFDM system under the urban channel type conditions.

Fig. 5 BER performance for OFDM system under the suburban channel type conditions.

![Rural Channel Type](image)

![Town Squares Channel Type](image)

![Corridor Channel Type](image)

Fig. 6 BER performance for OFDM system under the rural channel type conditions.

Fig. 7 BER performance for OFDM system under the town squares channel type conditions.

Fig. 8 BER performance for OFDM system under the corridor channel type conditions.

($\tau_{\text{max}} = 15.8 \mu s$) that introduces more multipath attenuation as illustrated in Fig. 5.

Figs. 6, 7 and 8 illustrate the OFDM BER performance under the conditions of the rural, the town squares and the corridor channel types, respectively. Its
solitary line-of-sight path characterizes the rural channel type, where the town squares and the corridor channel types are characterized by the short delay spread as given in Table 1.

The physical distribution of the channel scatterers determines the angle of arrival, thus, determining the Doppler Effect on the OFDM signal. In the last three channels, the effect of Doppler is less than the urban and the suburban channel type due to this distribution and due to the limited speed for the corridor channel type.

6. Simulation Error Analysis

Although the RACE CODIT project was able to develop a range of useful categories for environment types and a means of comparing wideband channel measurements [19], the propagation channel within any one category can still be highly variable, and this is reflected in the behavior of the model when it is initialized with different random seeds.

The simulations take quite a long time to run, and to explore the variability we need to run them many times, so to reduce the run time, we focus on BER results at just two SNR levels, 18 dB and 28 dB.

This simulation is first run for different values of initial seeds (corresponding to different instances of the same channel type) where each run lasts for a specific time. We see that the behavior is highly correlated at each SNR value, but highly variable from one instance of initial seed value to another as illustrated in Fig. 9. The standard deviation of these BER estimations gives the expected error in the mean, i.e., it quantifies the statistical variation of individual BER vs. SNR curves over a large number of instances of the same channel type as shown in Fig. 10 and Fig. 11.

Running the simulation using two different signal to noise ratio (SNR) values, i.e., $SNR = 18 \& 28 \, dB$, results in the following ratio of the standard deviation to the mean of the BER for different number of seeds,

$$\frac{\sigma}{E} = \frac{0.0032811}{0.0053273} = 62\% \quad (8)$$

$$\frac{\sigma}{E} = \frac{0.00029125}{0.00061396} = 47\%$$

The standard deviation represents the expected error in using any one observation (simulation run) to estimate...
the mean value. To obtain an estimate of the mean BER to within any given tolerance, the simulation must therefore be run for a number of repetitions, each with a different seed, that reduces this ratio according to the well-known relationship:

$$\sigma_m = \frac{\sigma}{\sqrt{n}}$$

where $\sigma_m$ is the standard error in the mean of $n$ observations and $\sigma$ is the standard deviation of each observation.

Next, we ran the simulation with given initial seeds for a very much longer time. The aim was to explore the variability within each instance of the channel.

The results of running the simulation for three different initial seeds are illustrated in Fig. 12 for $\text{SNR} = 28\, \text{dB}$, which show BER results comparable to the mean value in the previous case.

The probability density formed from the running average BER in terms of the number of simulated OFDM symbols is given in Fig. 13. We observe a much narrower distribution, where the ratio of the standard deviation to the mean of the BER for the first seeds in this case is given in the following equation,

$$\frac{\sigma}{E[\text{BER}]} = \frac{0.00011462}{0.00054697} = 20\%$$

The ratio is much lower than the results in Eq. (8), indicating that there is a smaller variability within any given instance of the channel than amongst many separate instances. There is clearly little benefit in obtaining a highly accurate estimate of the BER for a given instance of the channel, if the behavior of different instances is subject to much larger variability.

In order to obtain a stable estimate of the BER performance, the advice must therefore be to average over many instances of the channel, using relatively short simulation runs for each instance.

From the values of estimated BER at two example SNR values in our case, it is apparent that the BER estimate for a given channel instance stabilizes after around 700 OFDM symbols. There is then a high degree of variability in the estimates derived from many instances of the same channel type. To reduce the error in the estimate of the mean BER to something of the order of 5% would require an average over around 90 - 150 instances of the channel for SNR of 18 dB and 28 dB respectively.

7. Conclusions

This paper described a propagation simulation tool for OFDM developed using Matlab/Simulink. Example results are given for conventional, micro- and indoor pico-cells for various types of environment showing the impact of Doppler spread due to the velocity of the mobile on the OFDM performance.

Within any given channel type, significant variability in results for BER performance were observed dependent on the length of the simulation run and amongst different instances of the same channel type.
An analysis of that variability allows optimization of the simulation time required to obtain the average BER for a given channel type to within the required accuracy.

References


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