Simulation of Wireless Digital Communication Systems

Ronnie LANDQVIST, Abbas MOHAMMED

Blekinge Institute of Technology, School of Engineering, 372 25 Ronneby, Sweden
ronnie.landqvist@bth.se, abbas.mohammed@bth.se

Abstract. *Due to the explosive demands for high speed wireless services, such as wireless Internet, email and cellular video conferencing, digital wireless communications has become one of the most exciting research topics in electrical and electronic engineering field. The never-ending demand for such personal and multimedia services, however, demands technologies operating at higher data rates and broader bandwidths. In addition, the complexity of wireless communication and signal processing systems has grown considerably during the past decade. Therefore, powerful computer-aided techniques are required for the process of modeling, designing, analyzing and evaluating the performance of digital wireless communication systems. In this paper we discuss the basic propagation mechanisms affecting the performance of wireless communication systems, and present a simple, powerful and efficient way to simulate digital wireless communication systems using Matlab. The simulated results are compared with the theoretical analysis to validate the simulator. The simulator is useful in evaluating the performance of wireless multimedia services and the associated signal processing structures and algorithms for current and next generation wireless mobile communication systems.*

Keywords

Wireless communications, Rayleigh fading channels, multi-media applications and services, simulation and modeling, signal processing.

1. Introduction

Over the last decade the world has witnessed explosive growth in the use of wireless mobile communications. Looking around we find users with mo- bile phones, wireless PDAs, pagers, MP3 players, and wireless headphones to connect to these devices - a small testament of the impact of wireless communications on our daily lives. In addition the burst of new technologies such as Bluetooth and ultra wideband (UWB) short-range wireless communication systems are encouraging the further development of a wide variety of distributed wireless devices.

Second generation wireless mobile communication systems (e.g., GSM) are mature technologies now. Radio communications are in the process of a qualitative leap due to the technological revolution and new services that have emerged recently. The technical revolution and continuing growth of mobile radio communication systems has been made possible by extraordinary advances in the related fields of digital computing, high-speed circuit technology, the Internet and, of course, digital signal processing [1].

Third generation (3G) and next generation wireless mobile communication systems should support a substantially wider and enhanced range of services with respect to those supported by second generation systems. These services include data, images and video, electronic mail, and interactive multimedia communications. The never-ending quest for such personal and multimedia services, however, demands technologies operating at higher data rates and broader bandwidths [2]. This combined with the unpredictability and randomness of the mobile propagation channel has created many new technically challenging problems for which innovative, adaptive and advanced signal processing algorithms may offer new and better solutions! In addition, modified and improved modeling of fading channels is needed for the proper performance evaluation of these emerging wireless communication systems.

There have been many papers on the modeling of mobile fading channels [3]-[15]. However, in most papers the emphasis is either on showing the statistical properties of the simulator or the evaluation of the receiver's equalization and beamforming structures without giving great information or detailed implementation of the simulators themselves. This is particularly a difficult task for new research students needing to simulate the complicated digital communication systems in order to evaluate the performance of the different blocks in the system. In this paper we present a simple, powerful and efficient way for the simulation of digital wireless systems. The paper also discusses the basic propagation mechanisms affecting the performance of wireless communication channels. We will also show how to implement these mechanisms in a simulator and also provide theoretical analysis for comparing with the simulated results. We are using Matlab, one of the most popular simulation packages (especially in academia) for the design of communication systems. The simulator is highly configurable; that is it is easy to change the modulation technique or the rate to suit a particular service in multimedia communication systems or by adding other structures (e.g. equalization, beamforming, etc.) for the proper evaluation of the system's performance [16], [17]. An extended version of the simulator to support space-time applications or multiple-input multiple-output (MIMO) systems is also available [16] but not presented here due to length consideration.

The paper is organized as follows. In Section 2, the basic propagation mechanisms and parameters affecting the operation and performance of wireless communication systems are discussed. The Rayleigh fading channel and processes and their statistical properties are also presented in Section 2. Section 3 presents the simulator that we have implemented in Matlab and discusses its different functional blocks. The practical implementation of a channel impulse response with Rayleigh fading taps is discussed in Section 4. In Section 5 the implemented simulator is verified by comparing the results from Monte Carlo simulations to those results available in already published work in the field. Finally the paper is concluded in Section 6.

2. The Wireless Channel

2.1 Physical Description

The propagation factors that affect the quality of the received signals in wireless communication systems are the path loss, large-scale fading and small-scale fading [4].

The path loss is basically a drop in signal power as a function of distance. When a mobile receiver moves away from the base station, i.e. when the distance increases, the signal will become weaker because of power loss in the transmission medium. For free-space propagation, the signal strength is inversely proportional to the distance squared (i.e. $1/d^2$, where d is the distance between the transmitter and receiver). Measurement of wireless channels have found out that, in practice, the signal strength decreases more rapidly than $1/d^2$; a typical value often used in predicting propagation of wireless channels is $1/d^4$. The path loss has the lowest rate of change of the three above-mentioned propagation factors and the attenuation normally reaches 100-120 dB in the coverage area.

The large-scale fading varies faster than the path loss and is normally described as a log-normal distributed stochastic process around the mean of path loss. This type of fading is introduced because of the shadowing from buildings and other structures in the environment. The large-scale fading introduces attenuation of about 6-10 dB.

The small-scale fading is, as the name implies, the fastest varying mechanism amongst the three mentioned propagation factors. It is introduced as a consequence of the multipath propagation together with the time-varying nature of the channel. The multipath propagation arises from the fact that the transmitted signal is reflected from objects such as buildings or mountains, scattered from smaller objects such as lamp posts and diffracted at edges of houses and roof-tops, etc. Hence, the signal will reach the receiver from different directions. Each path may have different delay, introducing a spread in time (Delay Spread) of the received signals, indicating that the channel may be characterized by an impulse response, where each impulse represents a signal path with a certain delay. Depending on the maximum difference in time between the first and last received signals, the maximum excess delay T_m, and the inverse of the rate at which the symbols are transmitted, the symbol duration T_s, the channel may be classified as frequency selective or flat. The channel is said to be frequency selective when $T_m > T_s$, because different frequencies of the transmitted signal will experience different amount of attenuation. On the other hand, if $T_m < T_s$, then the channel is said to be flat since all frequencies of the transmitted signal would experience essentially the same amount of attenuation.

The time-varying property of the small-scale fading is due to the Doppler effect. Consider a fixed transmitter and a moving receiver. A transmitted sinusoid in a single-path case will experience a frequency shift because of the Doppler effect. Thus, in a multipath environment, the total effect on the received signal will be seen as a Doppler spreading or spectral broadening of the transmitted signal.

An important issue in the design of wireless communication systems is the channel equalizer. The task of the equalizer is to estimate the impulse response of the wireless channel and compensate for it by performing inverse filtering. The objective is to retrieve the signal that was transmitted over the channel by equalizing or reversing (inverse filtering) the effect of the channel. The major impediment to efficient equalization is the small-scale fading. The focus of this paper is the implementation of a simulator to be used in the development and simulation of equalizers (see [16], [17] for example). Therefore the focus will be on the implementation of a simulator for small-scale fading, i.e. multipath propagation with Doppler effect. The other factors will not be discussed further.

Extensive measurements (see [5], [20]–[22] e.g.) have been performed in order to identify a suitable stochastic process to model a signal that is affected by small-scale fading. Based on these measurement campaigns the Rayleigh process was suggested as a suitable model for non-line-of-sight propagation. The Rayleigh process is implemented in the channel model in the simulator in order to simulate the effects of the small-scale fading. The relevant definitions and statistical properties of the Rayleigh process are given in the next section, and its practical implementation in the simulator is discussed in Section 4.

2.2 Mathematical Description

A continuous time complex Gaussian process is defined as

$$\mu(t) = \mu_1(t) + \sqrt{-1}\mu_2(t) \tag{1}$$

with

$$\mu_1(t), \mu_2(t) \in N(0, \sigma_0^2) \ , \tag{2}$$

where $\mu_1(t)$ and $\mu_2(t)$ are independent real Gaussian processes with variance σ_0^2. The Power Spectral Density (PSD) for the complex Gaussian process $\mu(t)$ was originally derived by Clarke [6] under the assumption of an idealized model for omnidirectional antennas where the wave propagation occurs in the two-dimensional plane. The angle of arrival is assumed to be uniformly distributed from 0 to 2π. The PSD is

$$S_{\mu\mu}(f) = S_{\mu_1\mu_1}(f) + S_{\mu_2\mu_2}(f) \tag{3}$$

with

$$S_{\mu_i\mu_i}(f) = \begin{cases} \dfrac{\sigma_0^2}{\pi f_{max}\sqrt{1-\left(\dfrac{f}{f_{max}}\right)^2}} & , |f| \le f_{max} \\ 0 & , \text{otherwise} \end{cases} \tag{4}$$

for i = 1, 2. Here $f_{max} = \nu/\lambda$ denotes the maximum Doppler frequency. The parameter ν is the velocity of the mobile receiver. The wavelength λ of the carrier is defined as $\lambda = \nu_{light} / f_c$, where ν_{light} is speed of light and f_c is the carrier frequency. Equation (4) is often referred to as Jakes PSD, even though Clarke was the first to derive it.

A continuous-time real valued Rayleigh process is obtained by taking the absolute value of the complex Gaussian process, i.e.

$$\zeta(t) = |\mu(t)| = \sqrt{\mu_1^2(t) + \mu_2^2(t)} \cdot \tag{5}$$

Important statistical properties for the Rayleigh process are the Level Crossing Rate (LCR), the Average Fade Duration (AFD) the Probability Density Function (PDF) and the Auto-Correlation (ACR).

The LCR of the Rayleigh process $\zeta(t)$ is denoted by $N_\zeta(x)$ and describes how often the process crosses a level x in the positive direction within one second. It is defined as

$$N_\zeta(x) = \sqrt{2\pi}\, f_{max} \frac{x}{\sqrt{2}\sigma_0} \exp\left[-\left(\frac{x}{\sqrt{2}\sigma_0}\right)^2\right], \quad x \ge 0. \tag{6}$$

The AFD of the Rayleigh process $\zeta(t)$ denoted as $T_\zeta(x)$ is the expected length of the time intervals in which $\zeta(t)$ is below the level x. ACF is defined as [7]

$$T_\zeta(x) = \frac{\exp\left[2x/\left(\sqrt{2}\sigma_0\right)\right] - 1}{\sqrt{2\pi}\, f_{max} x/\left(\sqrt{2}\sigma_0\right)}, \quad x \ge 0 \cdot \tag{7}$$

Finally, the PDF equals

$$p_\zeta(x) = \begin{cases} \dfrac{x}{\sigma_0^2}\exp\left[-x^2/\left(2\sigma_0^2\right)\right] & , \quad x \ge 0 \\ 0 & \quad x < 0 \end{cases} \tag{8}$$

and the ACR

$$r_{\mu\mu}(\tau) = J_0\left(2\pi f_{max}|\tau|\right), \tag{9}$$

where $J_0(\cdot)$ is zero-order Bessel function of the first kind.

In the next section an overview for the complete simulator is presented. The Rayleigh process is part of the fading channel model in the simulator, and is implemented using Jakes method, which will be described in detail in Section 4.

3. Overview of the Simulator

A simulator for wireless communication systems has been implemented in Matlab. The simulator is shown in Figure 1 and consists of nine processing blocks that implements the various aspects of a typical wireless communication system.

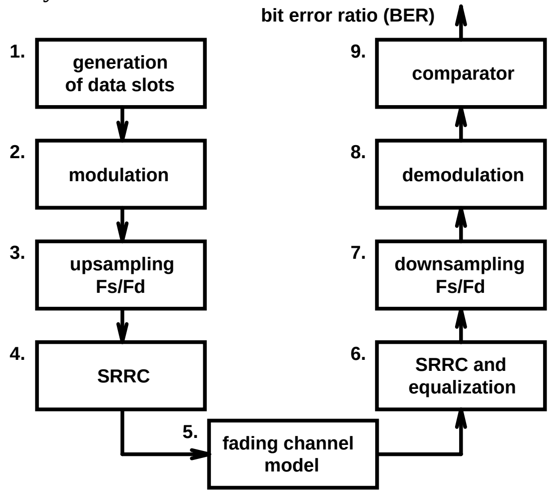

Fig. 1. The functional blocks of the simulator.

The first block (block 1) generates the binary data that will be transmitted over the channel. The data can consist of continuous symbols or it can be formatted slots which contains for example training sequences.

The modulator (block 2) is responsible of modulating the binary data with the chosen modulation technique. The output is, in general, a sequence of symbols (i.e. complex numbers) at the symbol rate F_d symbols/second.

The interpolator (block 3) increases the sampling frequency to the frequency used in the system, F_s samples/second, by inserting $F_s / F_d - 1$ zeros between each input sample. The output is a sequence of "zero-padded" symbols. The fraction F_s / F_d is denoted as the over sampling factor.

In order to limit the bandwidth used by the transmitter, the pulse train from the interpolator is filtered or shaped (pulse shaping) by filters (block 4 and 6) in a way that does not introduce intersymbol interference. In the simulator we use Square Root Raised Cosine (SRRC) filters at both the transmitter and receiver sides, in order to fulfil the Nyquist criteria. We have also implemented an equalizer in the receiver (block 6) for testing different equalizing techniques [16], [17].

The channel model block in the simulator (block 5) implements both time-invariant and time-variant channel impulse responses. Both frequency selective fading and flat fading may be generated for different velocities. The Rayleigh fading signals are generated using Jakes method [7], [6], [8], described in Section 4. Additive White Gaussian Noise (AWGN) is also implemented in the model.

The optimal sampling point is found and used by the sampler (block 7) to produce a signal at the symbol rate. The symbol rate signal is then demodulated (block 8) and the received data is compared to the transmitted data in the comparator (block 9) in order to calculate the Bit Error Rate (BER) of the system.

One may add any other processing blocks that are needed in the particular case that is under investigation. E.g., if one is interested in the BER for a particular coding scheme, one may add a source encoder and a channel encoder between block 1 and 2. At the receiver side, the corresponding source decoder and channel decoder are added between block 8 and 9. In this paper, the focus is on the raw BER where no coding schemes are used.

We will now continue the discussion of the channel model block in Section 4. Then, in Section 5, we will show BER-curves for different simulator configurations and propagation scenarios.

4. Simulation of Wireless Fading Channels

4.1 Jakes Method

A mobile fading channel without a line-of-sight path may be modelled as a Rayleigh process as discussed in Section 2. On the other hand, if a line-of-sight path is present a Rice process should be used instead. In this paper only Rayleigh processes are considered which are generated using Equation (5). When $\mu_1(t)$ and $\mu_2(t)$ are white, i.e. non-colored, the resulting signals $\mu(t)$ and $\zeta(t) = |\mu(t)|$ will contain samples that are totally uncorrelated. However, it is well known that this is not the case for mobile channels [6]. In fact $\mu(t)$ should have the PSD as given in (3). One way to accomplish this is to filter the signals $\mu_1(t)$ and $\mu_2(t)$ so that (4) is fulfilled. Another way is to use the theory of deterministic processes. More specifically, the Rice method [10, 11] may be used to create a fading signal by summing an infinite number of weighted harmonic functions with equidistant frequencies and random phases:

$$\mu_i(t) = \lim_{N_i \to \infty} \sum_{n=1}^{N_i} c_{i,n} \cos\left(2\pi f_{i,n} t + \theta_{i,n}\right), \tag{10}$$

$$c_{i,n} = 2\sqrt{\Delta f_i S_{\mu_i \mu_i}(f_{i,n})}, \tag{11}$$

$$f_{i,n} = n \Delta f_i . \tag{12}$$

The expression (10) represents a zero-mean Gaussian process with the desired PSD, $S_{\mu i\, \mu i}(f)$. The phases $\theta_{i,n}$ are random variables, uniformly distributed in $[0, 2\pi)$, and Δf_i is chosen in such a way that (12) covers the relevant frequency range.

Jakes method [8] is a practical solution where the Rice method is applied with a finite number of harmonic functions N_i to create a signal $\mu_i(t)$ with the PSD given in (4). The Jakes method in its classical form can only be used when one Rayleigh realization is desired. Therefore, Jakes method has to be adjusted by including extra phase shifts in the oscillators in order to generate several uncorrelated realizations [7], [12].

In the modified Jakes method the $j^{th} = 1, 2, ..., j_{tot}$ Rayleigh process in discrete time is generated by

$$\zeta^{(j)}(n) = |\mu^{(j)}(n)| , \tag{13}$$

where

$$\mu^{(j)}(n)) = \mu_1^{(j)}(n) + \sqrt{-1}\mu_2^{(j)}(n) . \tag{14}$$

The in-phase and quadrature components $\mu_1^{(j)}(n)$, $\mu_2^{(j)}(n)$ are given by

$$\begin{aligned} \mu_1^{(j)}(n) = & \\ & 2\sum_{k=1}^{K_0} \cos(\beta_k)\cos\left[\omega_d n \cos\left(2\pi k / K + \xi_{kj}\right) + \gamma_{kj}\right] \\ & + \sqrt{2}\cos\left(\omega_d n + \gamma_{(K_0+1)j}\right), \end{aligned} \tag{15}$$

$$\begin{aligned} \mu_2^{(j)}(n) = & \\ & 2\sum_{k=1}^{K_0} \sin(\beta_k)\cos\left[\omega_d n \cos\left(2\pi k / K + \xi_{kj}\right) + \gamma_{kj}\right]. \end{aligned} \tag{16}$$

The variables β_k and γ_{kj} are stochastic variables uniformly distributed in $[0, 2\pi)$, $K = 4K_0 + 2$ and ξ_{kj} is defined as

$$\xi_{kj} = \frac{2\pi(j-1)}{j_{tot} K} . \tag{17}$$

The parameter $\omega_d = 2\pi f_{max} / F_s$ is the maximum Doppler frequency in rad/s normalized with the sampling frequency F_s. The number of oscillators K_0 has to be assigned a suitable value, see [7].

In order to ensure that the simulated fading channel is implemented properly, it is recommended to estimate the statistical properties (LCR, AFD, PDF and ACR) of the Rayleigh process which had been generated using the Jakes method or the modified Jakes method. A comparison between the estimated statistics and the analytically derived statistics should show good agreement [7] as will be confirmed in Section 5.2.

4.2 Generating the Discrete-Time Impulse Response

An impulse response of a baseband wireless channel consists in general of a number of impulses; each impulse has its own phase, amplitude and delay because of different travel distances and attenuation of the path it represents. Thus, the continuous-time baseband impulse response can be represented as the sum of impulses defined by

$$g(t)=\sum_{j=1}^{j_{tot}}\mu^{(j)}(t)\delta(t-\tau_j)\ , \tag{18}$$

where $\mu^{(j)}(t)$ is a time-variant complex Gaussian coefficient with PSD given by (3), τ_j is the delay of the jth path and $\delta(t)$ is Dirac delta function.

The impulse response in (18) may have infinite bandwidth. However, as we have mentioned earlier, filtering is used in the transmitter and receiver for bandwidth limitations, to satisfy the Nyquist criteria for (theoretically) zero intersymbol interference and for the reduction of out-of-band noise. Taking this into account, and considering ideal brick wall Nyquist filter with cut-off frequency $F_c < F_s/2$, the joint or total response becomes

$$g'(t)=\sum_{j=1}^{j_{tot}}\mu^{(j)}(t)\frac{\sin\left[2\pi F_c(t-\tau_j)\right]}{\pi(t-\tau_j)}\ . \tag{19}$$

A discrete-time filter to be used in the simulator is obtained by sampling the impulse response in (19), i.e. by setting $t = n / F_s$. It is worth mentioning that in the simulator we have implemented Square Root Raised Cosine filtering at both the transmitter and receiver sides, in order to fulfill the Nyquist criteria, see Figure 1.

As an example, consider the continuous-time impulse response

$$\begin{aligned} h(t) &= (-0.3+0.8i)\delta(t-1/F_s) \\ &+ (0.2+0.3i)\delta(t-2.3/F_s)\ . \end{aligned} \tag{20}$$

In Figure 2 we show the amplitude, phase and group delay for the continuous-time and the discrete-time impulse response, resp. The sampling frequency is F_s = 315 900 Hz, cut-off frequency for the brick-wall filter is $F_c = 0.5\ F_s$ Hz. The number of filter coefficients (the designed filter length) is 16 coefficients which are also shown in Figure 2. It is evident from this figure that the correspondence between the continuous-time filter and the discrete-time filter is excellent. We conclude that the designed impulse response is in good agreement with desired characteristics of the original continuous-time response.

5. Computer Simulations

Implementing a simulator for wireless communications is a demanding task, and if not implemented carefully many sources of errors that can cause the simulator to give false results. Therefore, it is crucial that the simulator is properly verified so that it gives the expected results. Consequently, it is recommended to define a set of test cases that can be used to assure the reliability of the simulator. The simulations were carried out on an IS-136 Cellular system, with the carrier frequency set to 850 MHz and the sampling frequency of the simulator was 24300 Hz.

In this section the simulator is verified by means of Monte Carlo (MC) simulations. Three configurations are defined. In the first π/4-DQPSK modulated symbols are transmitted over a time-invariant AWGN channel. The resulting BER is compared with the results available in the open literature [18, 19]. In the second case one realization of a Rayleigh fading process is generated. The statistics of the resulting process is estimated and compared with the analytical expected statistics. Finally, the last test case verifies that MC simulation gives the expected BER for transmission of π/4-DQPSK modulated symbols over two-tap Rayleigh fading channel.

Note that no equalizer is needed in these test cases since π/4-DQPSK modulation is used, where the information lies in the phase changes (relative phase) and not in the phase itself (absolute phase).

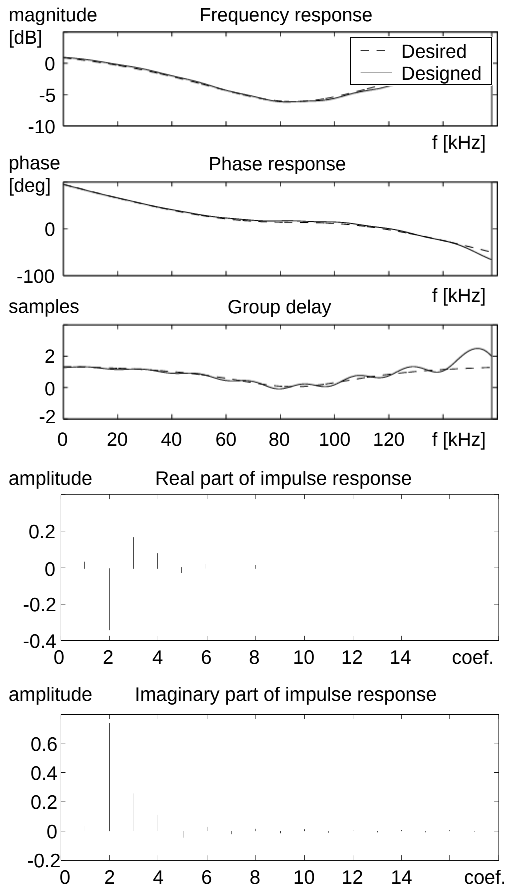

Fig. 2. Example of design of a discrete-time impulse response. The used parameters are: Sampling frequency F_s = 315 900 Hz, the cut-off frequency for the brick-wall filter $F_c = 0.5\ F_s$ Hz, length of filter 16 coefficients, impulses positioned at $\tau_1 = 1/F_s$ and $\tau_2 = 2.3/F_s$ seconds, and complex amplitudes 0.8 i – 0.3 and 0.3 i + 0.2.

5.1 Case 1 - Simulation of an AWGN Channel

In the first test case we consider a system with a channel that is subject to AWGN only, and verify the simulation results by comparing them with the theoretical results of the chosen modulation scheme.

We use a setting to transmit 10 000 π/4-DQPSK modulated symbols in each of the 10 Monte Carlo simulation runs at the rate of 24 300 symbols/second. In Fig. 3 we show the BER curves for an over sampling factor of 13 employing SRRC filtering with roll-off factor 0.2. It is evident that the simulated and analytical BER are in good agreement. Consequently, we conclude the simulator, with a high-degree of confidence, is correctly implemented.

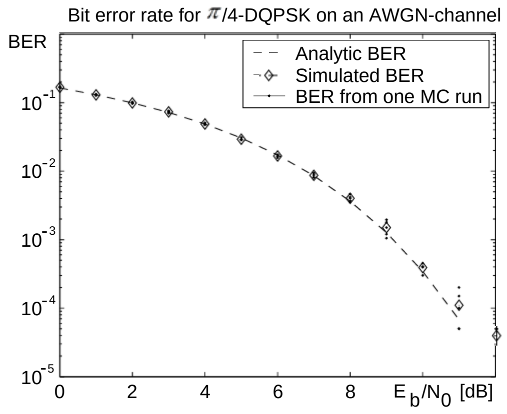

Fig. 3. BER as a function of E_b/N_0: AWGN channel, over sampling factor = 13 samples/symbol and SRRC-filter is used.

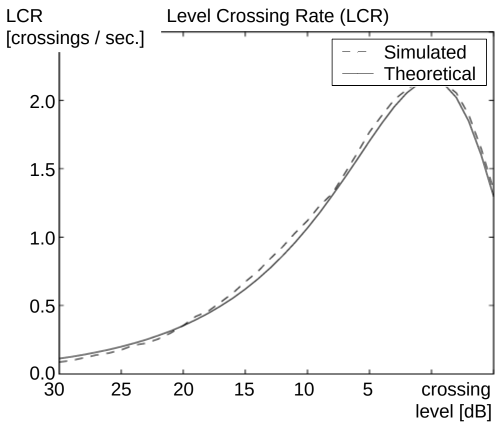

Fig. 4. Estimated and analytical LCR for Rayleigh fading channel with a normalized Doppler frequency of f_n = 0.01.

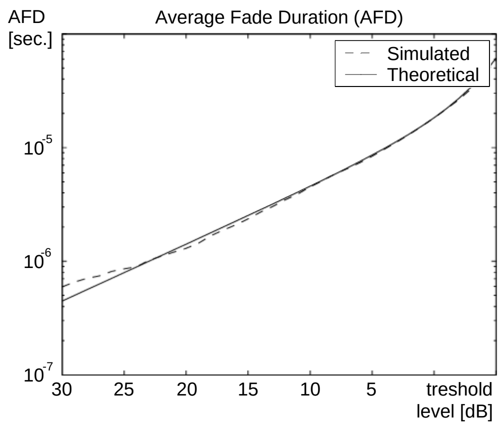

Fig. 5. Estimated and analytical AFD for Rayleigh fading channel with a normalized Doppler frequency of f_n = 0.01.

5.2 Case 2 - Generation of a Rayleigh Fading Channel Response

In the second test case the implementation of Jakes method is verified. The test is performed in the same way as in [7]. First, one realization of a Rayleigh fading channel is generated using Jakes method. Then, the resulting realization is used to estimate the relevant statistics (i.e. the LCR, AFD, PDF and ACR). In Fig. 4–6, the estimated LCR, AFD and PDF are shown together with the expected analytical curves for a normalized Doppler frequency f_n = = ω_d / (2π) = 0.01. From these figures, we can see good agreement between the results of the simulated and analytical statistics. The ACR show the same good agreement but is not shown here.

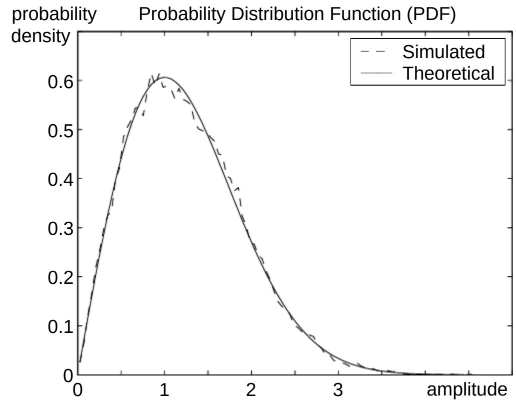

Fig. 6. Estimated and analytical PDF for Rayleigh fading channel with a normalized Doppler frequency of f_n = 0.01.

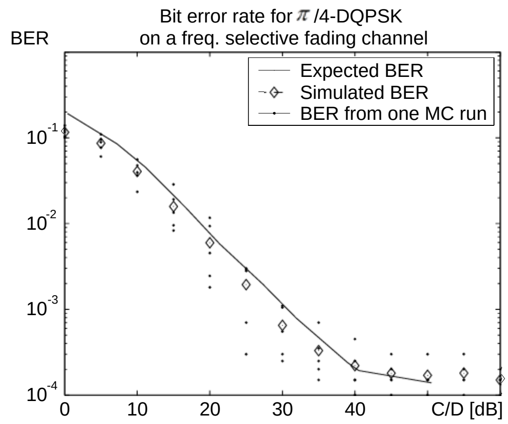

Fig. 7. BER versus C/D for π/4-DQPSK in a frequency-selective two-path Rayleigh fading channel for a seven sample signal delay. E_b/N_0 = 100 dB, 850 MHz, 24 300 symbols per second, velocity 120 km/h, SRRC filter with roll-off factor 0.2, 10000 symbols, over sampling factor = 13 samples per symbol.

5.3 Case 3 - Simulation of a Two-Tap Rayleigh Fading Channel

In the last test case Jakes method is verified in terms of BER results. The configuration of the test case is the same as described in [13]: A two-tap (two-path) time-variant impulse response is constructed using the methods discussed in this paper. Both taps are modeled as Rayleigh fading processes using Jakes method and they have an average power C and D, respectively. The second tap is placed 7 samples after the first one. It is assumed that no noise is present. Figure 7 shows the BER versus C / D, i.e. the average power ratio of the first path to the second path, in the two-path Rayleigh fading channel. Again, the simulated and analytical results are in good agreement.

6. Conclusions

The performance of wireless communications systems depends greatly on the propagation environment and the radio channel condition. An understanding of the wireless channel characteristics and the associated parameters is, therefore, an essential step in the simulation, analysis and design of wireless communication systems. This consequently allows the successful testing and evaluation of the performance of present and future wireless communication systems where the multimedia services and the advanced signal processing algorithms are expected to play a major role. This article presented physical, mathematical and statistical analysis of these systems. In addition, we have also presented an efficient and simple approach using Matlab for the simulation of digital wireless systems and compared its results with the theoretical analysis. The simulator can be easily adapted for the proper analysis and evaluation of the performance of emerging wireless technologies and services.

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About Authors...

Ronnie LANDQVIST was born in June 1974 in Sweden. He is a Ph.D. student at Blekinge Institute of Technology (Sweden) and received his Master of Science Degree in 1999 at the same university. His current focus is signal processing algorithms for mobile communication applications.

Abbas MOHAMMED received his PhD degree from the University of Liverpool, UK, in 1992. He is currently an Associate Professor and heading the research activities in Mobile Communications and Radio Navigation at Blekinge Institute of Technology. He is a Fellow of IEE, life-member of the International Loran Association, an Associate Fellow of the UK's Royal Institute of Navigation and a member of IEEE and IEICE. He is also a board member of IEEE Signal Processing Swedish Chapter. He has published many papers on telecommunications and navigation systems. He has also developed techniques for measuring skywave delays in Loran-C receivers. He was the Editor of a special issue "Advances in Signal Processing for Mobile Communication Systems" of Wiley's International Journal of Adaptive Control and Signal Processing. He received the 1994 Best Paper Award from the International Loran Association, USA.