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Short-term fading simulation using artificial neural networks

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ABSTRACT

A novel method for short-term fading simulation is presented in this paper. Proposed solution is based on artificial neural network principles. In order to obtain an adequate training data set, extensive measurements of the received electric field strength were carried out in an indoor environment, in a nonline-of-sight scenario. As quality assessment of the proposed method, performance comparisons were made with existing Rayleigh fading simulation methods. The statistical analysis of the short-term fading sequence obtained by the proposed method has shown better correspondence with measurement results as compared to other analyzed methods.

1. Introduction

In a wireless system, the characteristic that transmitted signal loses its deterministic properties and becomes incidental in time and space domain is described with the notion of fading. Essentially, the received signal is affected by both long-term (slow) fading and short-term (fast) fading [1]. The long-term fading corresponds to the locally averaged electric field strength and is mainly caused by the environment profile between the transmitter and the receiver. On the other hand, the short-term fading is mainly caused by multipath reflections. In practice, it is impossible to anticipate short-term signal fluctuations only on the basis of physical rules of signal propagation. Actually, it is only possible to talk about statistical characteristics of received electric field strength.

The short-term fading simulators are of great importance due to their key role in performance assessment of wireless communication systems. The simulation of short-term fading process has been of theoretical and practical interest for many years. In order to simulate the wireless radio channel of mobile communication systems, it is usually assumed that the short-term fading underlies the Rayleigh statistical distribution. For generating the Rayleigh fading process a number of simulation methods have been proposed based on either a sum-of-sinusoids (SoS) method [2–9], on the inverse discrete Fourier transform (IDFT) algorithm [10,11], or on a white Gaussian noise (WGN) filtering [12–20]. If infinite computing resources were available, two of these mentioned methods could produce the "ideal" Rayleigh fading process. This is the case with the SoS method with infinite number of oscillators and filtering of WGN with infinite order autoregressive (AR) filter. It is important to stress that all of mentioned methods have been developed and tested against theoretical short-term fading characteristics [21, pp. 70–82], but not directly against data obtained by field measurements.

In this paper a novel artificial neural network (ANN) based simulation method of the short-term fading is proposed. Contrary to the existing simulators which were developed solely over theoretical characteristics of the short-term fading, the main idea of the new method was to create a short-term fading simulator trained upon measurement data which could be obtained in an actual communication system. The goal was simulation of the short-term fading process, more precisely fading envelope extracted from a received signal. The underlying concept of the proposed method is estimating the following short-term fading value by processing several successive preceding fading values through the ANN. In order to obtain short-term fading values, extensive electric field strength measurements were carried out in an indoor environment, in a nonline-of-sight (NLOS) scenario. Short-term fading values extracted from the received electric field strength values were used for ANN both training and validation processes. The basic concept of the ANN simulator was initially proposed in [22]. Based on the initial experiences gained in that work, the simulator is improved significantly. Using more sophisticated measuring equipment has caused some changes not only in the structure of the simulator but also in the way the simulator is optimized. Additionally, comparing to [22], a number of simulation methods already proposed in literature [2,6,11,18] was implemented in order to properly validate the proposed simulation method. Comparing the characteristics of the

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new ANN method and the existing methods with short-term fading characteristics observed by measurements, the advantages and disadvantages of each method are highlighted. For the sake of completeness, all simulation methods are compared with theoretical Rayleigh fading characteristics [21, pp. 70–82] as well. According to the results, it seems that the proposed ANN method has certain advantages over other simulation methods.

The remainder of this paper is organized as follows. Existing Rayleigh fading simulators are briefly presented in Section 2. Measurement procedure and processing of the gathered data are described in Section 3. Section 4 introduces the model of the proposed ANN fading simulator. ANN training and validation processes are described in Section 5. Verification of the ANN fading simulator in terms of performance comparisons with existing Rayleigh fading simulators is given in Section 6.

2. Existing Rayleigh fading simulation methods

Several existing Rayleigh fading simulation methods that can be taken as the most popular are briefly described in this section:

(1) *SoS based methods*. One way to model the Rayleigh fading process, leveraged on Clarke's two-dimensional isotropic scattering model [23], is to superimpose the outputs from several sinusoidal generators. According to the so-called classical Jakes' method [2], if the number of oscillators N is of the form $4M+2$, and M is a natural number, Rayleigh fading waveform over time t can be modeled as:

$$x(t) = \frac{2}{\sqrt{N}}\left[2\sum_{k=1}^{M} e^{j\beta k}\cos 2\pi f_k t + \sqrt{2}e^{j\alpha}\cos 2\pi f_d t\right], \tag{1}$$

where $f_k = f_d \cos((2\pi k)/N)$, f_d is the maximum Doppler frequency, and α and β_k are arbitrary parameters. However, it can be seen that there are no random variables involved once the parameters are chosen, which means that the described model is deterministic. Also, it was found in [3] that classical Jakes' simulator is not wide-sense stationary (WSS) when averaged across the physical ensemble of fading channels.

Another widely accepted SoS based method is the WSS-improved Jakes' model [6]. According to this method, the normalized low-pass discrete short-term fading process is generated by:

$$x(t)=\sqrt{\frac{2}{N}}\sum_{k=1}^{N}(\cos(2\pi f_d t\cos\alpha_k+\phi_k)+j\cos(2\pi f_d t\sin\alpha_k+\varphi_k)), \tag{2}$$

with $\alpha_k = (2\pi k - \pi + \theta)/(4N)$, $k = 1, 2, \ldots, N$, where θ and phase offsets φ_k, ϕ_k are statistically independent and uniformly distributed on the interval $[-\pi, \pi)$ for all t. Despite very good approximation of theoretical Rayleigh fading process has been reported when N is not less than 8 [6], for finite N the WSS fading simulator is not autocorrelation ergodic [24].

(2) *IDFT based method*. IDFT method is well known to be a high-quality and efficient short-term fading generator [11]. Following this method, it is necessary to generate complex zero-mean Gaussian noise $A(k)+jB(k)$, with the real and complex parts independent and identically distributed [25, p. 140]. This complex vector is then multiplied with a real valued vector which actually represents a vector with filter coefficients $F(k)$. Finally, the IDFT of the resultant vector gives the desired discrete short-term fading process $x(n)$, $n = 0, 1, \ldots, N-1$,

$$x(n) = \frac{1}{N}\sum_{k=0}^{N-1} F(k)(A(k)+jB(k))e^{j(2\pi kn/N)}. \tag{3}$$

Actually, the values of the filter coefficients $F(k)$ determine the properties of the generated process. For the required Rayleigh distributed process, the filter sequence is given by [11, Eq. (21)]. Unfortunately, as all required fading values are generated within one single IDFT operation, this method can be unattractive for generation of very long short-term fading sequences.

(3) *Filtered WGN based methods*. The correlated Rayleigh fading values can be generated also by filtering complex WGN. The first of two popular filtered WGN methods is based on infinite-impulse response (IIR) low-pass filter utilized to approximate the desired autocorrelation function (ACF) [26]. Many possibilities for the choice of filter design exist. However, it was found that third-order Butterworth filter provide good approximation to the desired autocorrelation characteristics [12,14]:

$$H(s) = \frac{\omega_0^3}{(s+\omega_0)(s^2+2\xi\omega_0 s+\omega_0^2)}, \tag{4}$$

where selection of parameters ω_0 and ξ has great impact on generated short-term fading process. It should be kept in mind, when using filtered WGN methods in practice, it is needed to run the filter a little bit due to entering the stationarity [27].

The second commonly used filtered WGN method is based on passing the complex WGN through an AR filter [18]. Basically, this technique employs all-pole IIR filtering to shape the spectrum of uncorrelated Gaussian values. Unlike previous WGN filtering method, precise matching of theoretical statistics is possible by increasing the order of the filter, what on other hand makes it more complex for implementation. In fact, AR filters of order p can be designed to produce any ACF up to p points. The relationship between desired autocorrelation $R_{XX}[k]$ and $AR(p)$ parameters is given by [28]:

$$R_{XX}[k] = \begin{cases} -\sum_{m=1}^{p} a_m R_{XX}[k-m], & k = 1, 2, \ldots, p \\ -\sum_{m=1}^{p} a_m R_{XX}[-m] + \sigma_p^2, & k = 0, \end{cases} \tag{5}$$

with WGN variance:

$$\sigma_p^2 = R_{XX}[0] + \sum_{k=1}^{p} a_k R_{XX}[-k]. \tag{6}$$

For higher order AR models, the above equation tends to have the poles outside the unit circle, making the filter unstable. This problem can be alleviated by using diagonal loading ϵ to the autocorrelation matrix [18, Eq. (14)] and it is chosen in such a way that it is the least value that makes the filter stable.

3. Gathering and processing of measurement data

In order to obtain the information regarding the electric field strength at the receiver input, extensive NLOS measurements were carried out in an indoor environment. More precisely, building of the School of Electrical Engineering in Belgrade was chosen as measurement environment due to its complex infrastructure characterized by high electric field strength dynamics (over than 80 dB). Stationary transceiver Motorola MC Micro transmitted CW RF carrier at the frequency of $f_c = 457$ MHz with output power of 25 W. On the other side, the receiving equipment was mounted on an industrial cart which was being moved through the chosen indoor environment with constant speed of $v = 0.2$ m/s. Calibrated half-wave dipole antenna Anritsu MP663A, having a vertical polarization, was connected to the Rohde&Schwarz ESPI test receiver (9 kHz to 7 GHz). ESPI was recording electric field strength values with sampling time of $t_s = 25$ ms. Total distance of 720 m has