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Multiuser wireless channel simulation for communication systems with nonparametric reception

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Abstract. When combined with error-correction codes reception techniques based on nonparametric hypothesis testing and order statistics provide strong immunity to different types of interference including multiuser interference. That makes communication systems using such reception techniques most appealing candidates for various applications such as Machine-to-Machine (M2M) communications and Internet Of Things (IOT). Unfortunately analytical treatment of communication systems with nonparametric reception remains a cumbersome task. Therefore simulation remains the main tool for the development of such systems. For multiuser systems supporting hundreds of active users and operating in fading channels (e.g. IOT) time spending grows drastically hampering the design process. Thus the development of simplified multiuser channel models is of great interest. In this paper two simplified mathematical models of multiuser interference for the case of a single user nonparametric reception are proposed. The effectiveness of the proposed models is compared by means of modulation. Special attention is paid to the problem of software implementation of the models proposed.

1. Introduction

Reception techniques that are used in modern communication systems rely on the assumption that channel state information (CSI) and thus decision statistics distributions at the receiver side are known to the receiver or at least can be estimated with desired accuracy. In many real life applications that is not true. This is particularly true for M2M and IOT systems in which hundreds of devices send short packets simultaneously and thus it is difficult to estimate the CSI with desired accuracy. Thus reception techniques based on nonparametric statistical tests and the use of order statistics not requiring CSI and able to withstand severe interference are of great interest.

Unfortunately very little is known of the analytical description of systems making use of such reception techniques. Thus simulation remains the primary method for effective design and investigation of various communication systems with nonparametric reception. However in case of multiuser systems (which is probably the most interesting case) straightforward simulation of hundreds of users each having a different channel due to the difference in their location is both a very computational- and time-consuming operation. Consequently simplified channel models need to be proposed and investigated in order to reduce the computation burden and speed up the development process. In what follows two simplified channel models for the simulation of the coded DHA FH OFDMA systems [1] with nonparametric reception are considered.

2. A coded DHA FH OFDMA system description

Let us consider the coded DHA FH OFDMA in more detail. First and foremost let us consider the transmission procedure. The information to be transmitted is first encoded with a $C_q(n,k)$ code. Each symbol of the resulting (say i th) codeword $\overline{v}^i = [v_0^i, v_1^i, \ldots, v_{n-1}^i]$ is mapped into a weight 1 column vector of length q . Thus the codeword is represented by a binary n by q matrix B^i with exactly one nonzero entry in each column. An all zero n by $Q-q$ ($Q >> q$) matrix Z is appended to the matrix B^i forming the matrix $X^i = \begin{bmatrix} B^i \\ Z \end{bmatrix} = \left[\overline{x}_0^i, \overline{x}_1^i, \ldots, \overline{x}_{n-1}^i \right]$.

Each column of the matrix X^i is then permuted independently (permutations $\pi_0, \pi_1, \ldots, \pi_{n-1}$ are chosen equiprobably from the set of all possible permutations.) The columns of the resulting matrix $\Omega^i = \left[\pi_0(\overline{x}_0^i), \pi_1(\overline{x}_1^i), \ldots, \pi_{n-1}(\overline{x}_{n-1}^i) \right]$ are then fed into the OFDM modulator. In what follows we shall assume that apart from the signal from the user under consideration K interfering signals are transmitted via the same channel.

Let us now consider the reception process. Within the scope of this process n OFDM symbols are to be received. Thus a matrix $F^i = \left[\overline{f}_0^i, \overline{f}_1^i, \ldots, \overline{f}_{n-1}^i \right]$ corresponds to each transmitted codeword $\overline{v}^i$ (here $\overline{f}_j^i$ is the column vector corresponding to the j th OFDM symbol (and thus the j th symbol of this codeword)). The receiver applies inverse permutations to each column of the matrix F^i the obtained matrix being given by $\Xi^i = \left[\overline{\chi}_0^i, \overline{\chi}_1^i, \ldots, \overline{\chi}_{n-1}^i \right]$ where $\overline{\chi}_j^i = \pi_j^{-1}(\overline{f}_j^i)$ and $\pi_j^{-1}()$ stands for the inverse permutation for the permutation $\pi_j()$. Each element of the first q rows of the matrix Ξ^i is then squared. The elements of the resulting matrix Y^i are given by the following equation

$$\begin{gathered} \forall\ j \in \{1,\ldots,q\} \ \ \kappa \in \{0,\ldots,n-1\} \\ Y^i(j,\kappa) = (\chi_j^i(\kappa))^2 \end{gathered} \qquad (1)$$

where $\chi_j^i(k)$ is the k th element of the column vector $\overline{\chi}_j^i$. Please note that the column-wise permutation at the transmitter side corresponds to the hopping procedure whereas the inverse permutations correspond to dehopping. Since inverse permutations are applied at the receiver side the first q rows of the matrix Ξ^i (and thus corresponding rows of the matrix Y^i) correspond to the first q rows of the transmitted matrix X^i (and thus corresponding rows of the matrix B^i.) The matrix Y^i is then used for detection i.e. decsion making on the codeword transmitted.

In what follows two nonparametric detectors will be considered: the RANKSUM detector [2] and the α detector [3]

3. Wireless channel simulation

A common approach to simulation of a wireless radio channel is to distinguish between the three different types of factors that influence the signal while its propagation:

- path loss (which is treated as a deterministic process depending on the distance between the receiver and the transmitter)
- slow fading (a relatively slow varying random process due to shadowing)
- fast fading (a faster random process due to scattering, reflections etc.)

Probably one of the most general models that can describe the first two factors is the log-normal model. Within the scope of this model the power loss (in dB) is given by

$$PL(d) = 10\log_{10} P_t - 10\log_{10} P_r = PL_{fs}\left(d_0\right) - 10\gamma\log_{10}\left(\frac{d}{d_0}\right) + X_N\left(0,\sigma_F\right) \qquad (2)$$

where P_t is the transmitted power, P_r is the power at the receiver, $PL_{fs}\left(\ \right)$ is the path loss (in dB) in free space, d is the distance between the receiver , d_0 is the reference distance, γ is the path loss exponent, that depends on the scenario under consideration, $X_N\left(0,\sigma_F\right)$ is the Gaussian random variable with mean 0 and standard deviation σ_F (in dB) which depends on the scenario under consideration.

The log-normal model possesses several advantages. It is more realistic than deterministic path loss models such as free space or two-ray model. On the other hand, unlike path loss models based on experimental data such as Longley-Rice, Hata (or Okumura-Hata), Walfisch-Bertoni et al. [4] it holds for a wide range of scenarios and parameters and thus needs not to be restricted to any specific kind of a scenario.

Several methods have been proposed in order to incorporate the power degradation due to fast fading into the mathematical model of the path loss presented above. The simplest way to do so is to introduce additional term with exponential distribution into the equation (2). However it is difficult to derive the parameters corresponding to real life channels for that approach. Thus in what follows we shall be using another approach that is based on the assumption made by Suzuki [5]: the signal undergoes lognormal shadowing when traveling to the zone where it experiences fading due to multiple scattering. Assume a FH OFDMA (or a DHA FH OFDMA) system where K users transmit in the uplink . The amplitude of the received signal from the j th user transmitting a signal on the k th subcarrier is then given by

$$\tilde{A}_k^j = \Lambda^j \left|H_k^j\right| A^j \qquad (3)$$

where $\Lambda^j = 10^{-\frac{PL\left(d_j\right)}{20}}$ is the signal amplitude decrease due to shadow fading (here d_j is the distance between the transmitter of the j th user and the receiver and PL is given by (2)),

$H_k^j = \sum\limits_{m=0}^{Q-1} h^j\left(m\right) e^{-i\frac{2\pi km}{Q}}$ is the gain factor corresponding to k th subcarrier of the channel.

A^j is the amplitude of the signal transmitted by the j th on the k th subcarrier

4. Models development

Let us consider the main assumptions to be used hereinafter. First and foremost we are interested in simulation of the single user reception of the signal transmitted in a multi-user coded DHA FH OFDMA using one of the detectors described above. Uplink transmission is considered and although we assume that all the K active users have the same transmitted power we also assume that no power control is used in the system under consideration. Thus the received power of each user (including the user under consideration) depends solely on the power degradation due to propagation and the transmitted power.

Since the goal of the communication system design is to guarantee reliable communication to be available within the certain zone (commonly referred to as transmission zone i.e. the zone within which communication with Word Error Probability (WER) less or equal to certain predefined threshold values is guaranteed) we are interested in the worst case scenario. Thus our main assumption is “pessimistic” i.e. we assume that the user under consideration is at the edge of the zone i.e. the distance between the receiver and the transmitter of the other users (hereinafter they will be referred to as "interfering users") is either the same or smaller than that between the receiver and the transmitter of the user under consideration and the same holds for the average power of the respective signals.

4.1. The Pessimistic Path Loss Model (PPLM) and the Pessimistic Shadowed Fading Model (PSFM)

The first model to be considered is the Pessimistic Path Loss Model. Within the scope of this model it is assumed that path loss plays predominant part in signal power degradation and thus if we are interested in the worst case scenario it is sufficient to model the path loss by assuming that the power of the signal received form each of the interfering users is κ ($\kappa \gg 1$) times greater than that of the user under consideration while the power degradation due to fading is negligible.

The Pessimistic Shadowed Fading Model is more realistic. In this model it is assumed that the signal from each user undergoes power degradation due to both path loss and shadowing and fading as explained in Section 3. Thus both lognormal path loss and gain factors need to be calculated for each user for each OFDM symbol.

4.2. Implementation issues

One of the most challenging problems commonly associated with wireless channel simulation for multiuser communication systems is the need for multiple convolutions calculation. In fact the propagation of every single OFDM symbol sent by every active user can be described as linear convolution in time domain. Thus for straightforward simulation of the communication system with hundreds of active users in time domain both the computation burden and time spending are very high. That is why in what follows we choose to carry up channel simulation in frequency domain only. Although this approach has some drawbacks since some of the effect at the receiver end cannot be addressed directly for OFDM-based systems it reduces the time spending drastically since each codeword can now be represented as a sparse matrix and numerous convolutions can be omitted as well as multiple calculations of Fast Fourier Transform and Inverse Fast Fourier Transform. However for the PSFM channel impulse responses or frequency transfer functions are to be generated which is also a time consuming process. Thus the following approach was used: multiple channel impulse responses for both the user under consideration and the interfering users were generated in advance and pre-sorted in files. Please note that since we were interested in a DHA FH OFDMA simulation the only interfering signals that can affect the system performance and thus are of interest to us are those transmitting in the hopset of the user under consideration at the moment under consideration. So even for hundreds of users there is no need to generate signals and channel gains for each user, but rather for a small fraction of them transmitting via the subcarriers that are in the hopset. Thus fading channel simulation for the interfering users is done in the following way: for each user a random subcarrier number is chosen, then for those u active users that transmit via one of the subcarriers currently in the hopset of the user under consideration a random file with pre-stored channel impulse responses is chosen. For each of the u active users a random channel response is then chosen and the gains corresponding to the subcarrier chosen by the respective user is calculated. Thus although used fixed set of pre-stored impulse channel responses is used the choice is randomized by the three random steps discussed above. Please note that we choose to store impulse responses rather than transfer functions in order to minimize both disc space consumption and computational burden due to multiple reads from the disc. This approach turns out to be very beneficial for the software that is optimized for the FFT and sparse matrix storage implementation.

5. Simulation

To validate the potential of the PPLM model simulation has been carried out. The total number of subcarriers has been fixed to $Q = 4096$, while the instantaneous hopset cardinality was set to $q = 16$. As an example in what follows we present results for a rate 1/6 MDS code obtained from RS code (15,2,14) by puncturing. Channel impulse responses were generated using 3GPP Typical Urban model for various rates (5 km/h, 20 km/h, 40 km/h, 60 km/h, 100 km/h, 200 km/h), carrier frequency $f_c = 2.4\,\text{GHz}$ and bandwidth 20 MHz. For interfering users 1000 files each containing 150 channel impulse responses were written, while for the user under consideration 200 files each containing 1000 channel impulse responses were written. For lognormal path loss simulation the following parameters were used: it was assumed that the distance between the user under consideration and the receiver is equal to d, whereas the distance between each of the interfering users and the receiver is equiprobably chosen from the set $S_d = \{d, 0.99d, 0.98d, \dots, 0.01d\}$, the path loss exponent was fixed to $\gamma = 3.5$ (this value correspond to urban radio) and the standard deviation is given by $\sigma_F = 10\,dB$. Within the scope of this model an assumption was made that apart form the multi-user interference the received signal is affected by the background noise which can be described by the SNR ratio (in dB) given by

$$SNR = 10\log_{10}\left(\frac{E_s}{\log_2(q)E_N}\right) \tag{4}$$

were E_s is the transmitted energy (per symbol) and E_N is the noise energy (in the entire band available to the users). In the next section simulation results for this scenario are presented.

5.1. Simulation results

In Figure 1 dependencies of the Word Error Rate (WER) provided by the α detector (for α=4) on the number of interfering users for different values of the SNR are presented

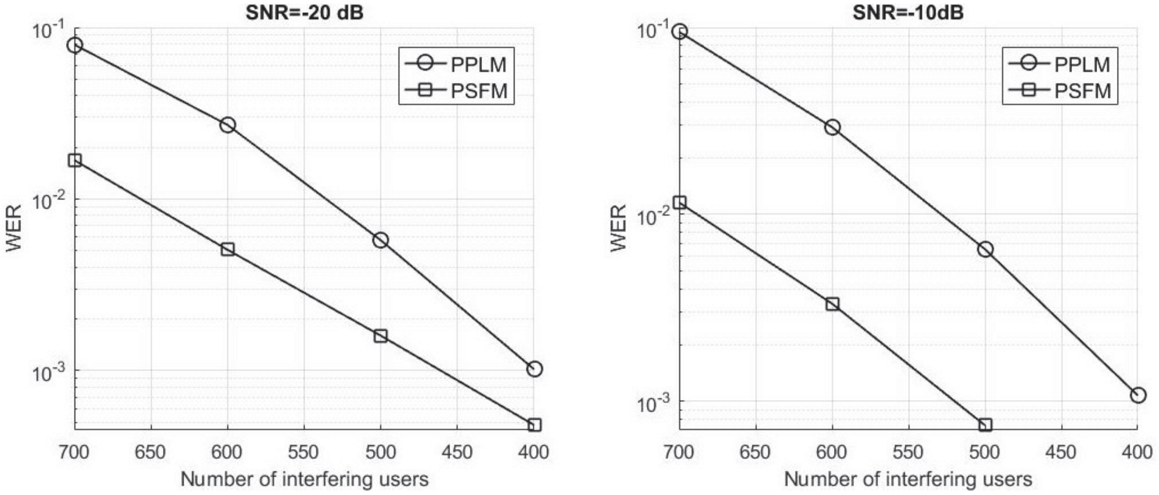

Figure 1 WER vs. number of interfering users for the α detector ($\alpha = 4$).

As can bee seen the PPLM model indeed gives a very pessimistic estimation of the WER (although for higher SNR values the gap is less substantial.) Moreover the curves presented show that for the PPLM the detector demonstrates almost no sensitivity to SNR value, whereas the more realistic PSFM shows greater sensitivity (although the difference in WER for different SNR values is moderate due to the robustness of the detector itself.)

In Figure 2 dependencies of the Word Error Rate (WER) provided by the RANKSUM detector on the number of interfering users for different values of the SNR are presented. Similarly to the previous case one might note that for SNR=-10 dB the PPLM model provides a pessimistic (i.e. upper) estimate on the value of WER. However the case where SNR=-20 dB is different since for relatively low values of the number of active users the value of the WER for PSFM is greater than that for the PPLM. This effect shows that for a relatively low number of interfering users and low SNR the influence of the background noise is dominant. Again similarly to the previous case the RANKSUM detector shows greater sensitivity if the PSFM is used. Thus not only PSFM is more realistic it is also better suited to demonstrate the background noise effect. Although PPLM is less time consuming it provides less accurate estimates.

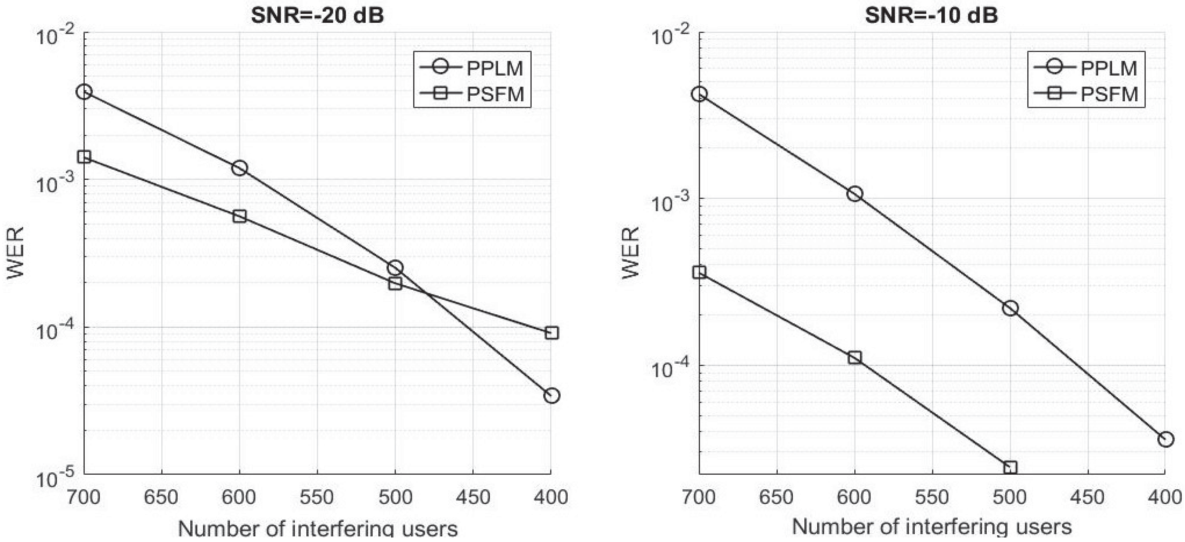

Figure 2 **WER vs. number of interfering users for the RANKSUM detector.**

6. Conclusion

Hereinabove two simplified models of the multi-user system employing DHA FH OFDMA were considered. It has been shown that although the PPLM is less computationally expensive it is less accurate and thus in most scenarios it is preferable to use PSFM. It has been shown that for the DHA FH OFDMA systems the computational burden of the PSFM implementation can be reduced drastically thus making the use of the PSFM practical.

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