OFDM-BASED RELAY SYSTEM FOR NEXT GENERATION WIRELESS NETWORKS

Enis Kočan, Milica Pejanović-Đurišić[1]

ABSTRACT

Relay systems implementing Orthogonal Frequency-Division Multiplexing (OFDM) on a physical layer are subject of a great research interest in recent years since they are recognized as a potential solution for the implementation in the next generation WWAN (Wireless Wide Area Network) and WLAN (Wireless Local Area Network) systems, due to their possibility to increase the capacity and coverage of these systems. It is proven that the OFDM-based relay system may improve performance in terms of capacity and error rate if the subcarrier permutation (SCP), according to average signal-to-noise ratios on the first hop and the second hop, is performed at the relay station. In this paper, error rate performance of OFDM-based amplify-and-forward (AF) relay system with SCP is examined, in order to identify the scheme which achieves optimal performance.

1. INTRODUCTION

The next generation wireless communications systems are facing a great challenge to fulfill demands in terms of capacity, quality of service and reliability, due to the great number of new emerging services and multimedia applications. By increasing the employed center frequency and the occupied bandwidth, the capacity problem could be solved. For example, it is envisaged that the future mobile radio communication systems (4G) will operate in spectrum around 5GHz, and will occupy bandwidth of 100MHz [1]. However, this logical solution is leading towards the constraints with the range as the major problem that will appear in future wireless communication systems. Namely, the path-loss will be significantly increased in the high working frequencies, and the noise power will also be increased as a consequence of a larger bandwidth. The range problem could be coped by implementing a greater number of base stations, which is impractical and expensive solution, especially in dense populated urban

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areas. Therefore, relaying is proposed for extending the base station coverage area, as well as for increasing the achievable capacity.

In the simplest relay system the communication between the source (S) terminal and destination (D) terminal is realized through the relay (R), which receives the signal from the S, then performs appropriate signal processing and forwards the signal to the D. This kind of relay system is named dual-hop relaying system (Fig. 1). The signal processing at the R usually assumes amplifying-and-forwarding or decoding-and-forwarding of the received signal, thus having two corresponding kinds of relaying, denoted as AF and DF, respectively. In the AF relaying method, fixed gain relaying, or variable gain relaying may be implemented, depending on the possibility of R to estimate S-R channel. As R terminal it may be used any terminal which, at a given moment, may share its resources with another communication pair, or it may be infrastructure based R station, placed by an operator. These infrastructure based R stations would be much simpler and cheaper than the base stations (BS). As it is shown in the figure, there can still exist direct link between S and D terminals, and D terminal may combine signals from S and R in order to improve the reliability or capacity.

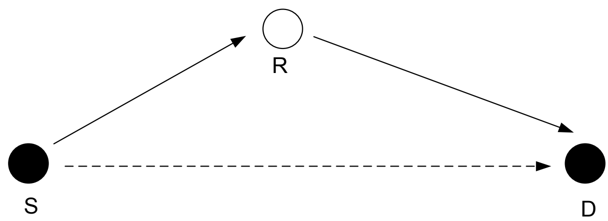

Figure 1. Dual-hop relaying system

The relaying concept is not a new idea. It appeared for the first time in 1971 in the work of van der Maulen, where he analyzed the communication system with three terminals. Later, in 1979 T.M.Cover and A.A.El Gamal have published a paper on the capacity of a relay channel. However, up to a recent time, there was an inconsiderable interest for the relaying systems. Nowadays, the intensive research work on relaying systems is ongoing, as they are recognized as a potential solution for the next generation WWAN (Wireless Wide Area Network) and WLAN (Wireless Local Area Network) systems. The performance of single carrier relaying systems in different channel conditions, as well as for different relaying strategies, is widely examined in the literature [2]-[5]. Lately, multicarrier relaying systems, using Orthogonal Frequency Division Multiplexing (OFDM) as transmission technique, have attracted extensive attention [1], [6]-[11].

2. OFDM-based relay systems

Using parallel data transmission by orthogonal subcarriers, OFDM enables high-data rate communication through wireless channel and it has been proven to be robust to destructive effects of multipath fading. Thus, OFDM is already accepted in many standardized wireless communication systems, like DAB (Digital Audio Broadcasting), DVB (Digital Audio Broadcasting) and WLAN standards (IEEE 802.11a/g), [12]. Used as a transmission technology in wireless relay systems, OFDM presents a candidate for the next generation of WLAN and WWAN systems [1], [7].

By implementing relaying methods in OFDM-based WWAN and WLAN systems, radio coverage can be improved in scenarios with high shadowing (e.g. bad urban or indoor scenarios). This allows to significantly increase the Quality of Service (QoS) for the users in areas heavily shadowed from a base station (BS)/access point (AP). The extension of the radio range of a BS/AP by means of fixed relay stations (FRSs) allows broadband radio coverage of much larger cells comparing with a case when conventional one-hop system is implemented. The FRS concept provides the possibility of installing temporary coverage in areas where permanent coverage is not needed (e.g. construction sites, conference-meeting rooms) or where a fast initial network roll-out has to he performed. The wireless connection of the FRS to the fixed network substantially reduces infrastructure costs, which in most cases are the dominant part of the roll-out and operations costs. FRS only needs mains supply. In cases where no main is available, relays could rely on solar power supply. Apart from the scenario with FRS in the WLAN networks, there is ongoing work on the standardization of WLAN mesh networks (IEEE 802.11 Task Group s), where the relays are user terminals [13].

Beside WWANs and WLANs, there is also an interest for the implementation of OFDM-based relaying in other wireless systems. Thus, for example, AF relays have been used recently in OFDM systems as a mean to increase network coverage in DAB systems [14]. Further, 802.16 Task Group *j* [Mobile Multihop Relay (MMR)] is currently standardizing relay scheme for 802.16-based network with centralized or semidistributed resource allocation [15]. Some sensor networks deploying OFDM as transmission technology and relaying concept, have also been tested.

3. Performance improvement of OFMD-based relay systems through subcarrier permutation

Implemented as a transmission technique in relay systems, OFDM brings about additional freedom of making decisions on a subcarrier basis at the relay station, according to the channel conditions in the first and the second hop. It means that the performance of OFDM-based relay system can be improved if R performs appropriate subcarrier permutation (SCP), depending on the average signal-to-noise ratio (SNR) on the subcarriers in S-R and R-D links.

The idea of subcarrier permutation in OFDM AF relaying was first introduced in [6], and a little bit later was independently discussed in [7] and [1]. The author of [1] proves that, in special cases, when the signal received by a relay is noise-free, the system achieves maximum capacity if the subcarrier with the highest SNR from the first hop is mapped to the subcarrier with the highest SNR on the second hop, second best – to second best, etc. As the subcarrier-based permutation significantly increases necessary signaling overhead, the author in [1] proposed to group adjacent subcarriers in chunks, and then the relay should perform chunk permutation according to the average chunk's SNRs. General proof that this kind of SCP maximizes received SNR and achievable capacity in OFDM AF relaying systems was first presented in [8]. The capacity analysis, for the case of fixed gain AF relaying, is performed in [9] numerically, using the derived SNR probability density function (PDF). However, when the BER performance is taken into account, it is proven in [10] that the described SCP presents the best solution for OFDM AF relay system only in the low SNR region. By employing majorization theory the authors in [10] proved that the BER performance of the dual-hop OFDM variable gain AF relay system in the medium and high SNR regions can be improved by using the opposite SCP scheme, where the subcarrier with the highest SNR from the first hop is mapped to the subcarrier with the lowest SNR on the second hop, etc. The analytical BER performance analysis for OFDM relay system employing SCP was for the first time reported in [11].

In this paper some of the results we have obtained through the research on error rate performance of OFDM-based relay system implementing best-to-best (BTB) SCP and best-to-worst (BTW) SCP will be shown, in order to present the possibility to further enhance BER performance of OFDM relay systems through appropriate choice of SCP scheme. The given results prove that the analyzed system may be considered as a promising solution for the next generation of WLAN and WWAN systems.

4. System model

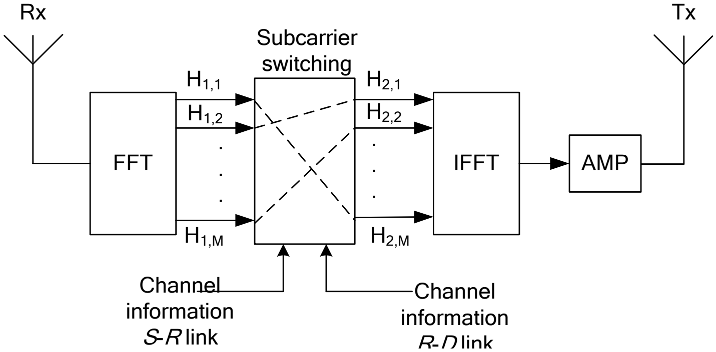

Figure 2. Block scheme of the OFDM-based fixed gain relay terminal with SCP

Figure 2 gives the block scheme of the analyzed relay terminal implementing fixed gain relaying. We consider an OFDM dual-hop relaying system with a source terminal S, a half-duplex relay terminal R, and a destination one D, all equipped with a single antenna. The relay terminal has FFT (Fast Fourier Transformation) and IFFT (Inverse Fast Fourier Transformation) blocks for OFDM demodulation and OFDM modulation, respectively. Furthermore, R has a block that performs subcarrier permutation, mapping the subcarriers from the first hop to subcarriers on the second hop according to their transfer functions. It is assumed that R has perfect channel knowledge of both S-R and R-D links, and D knows the permutation function performed at R. The post-FFT signal on the i-th subcarrier, received at the relay station, is given by

$$Y_{R,i} = X_{1,i}H_{1,i} + N_{1,i}, \quad 1 \le i \le M \tag{1}$$

where M is total number of subcarriers, $H_{1,i}$ is i-th subcarrier transfer function, and X_i is data symbol sent by source on the i-th subcarrier. $N_{1,i}$ represents additive white Gaussian noise for the i-th subcarrier with variance $\mathbf{E}(|N_{1,i}|^2)=N_{01}$, where $\mathbf{E}(\cdot)$ denotes the expectation operator. The relay operates in the fixed-gain AF mode, where the signal that reaches the relay is amplified by a fixed gain, G. Assuming that the SCP function $v(i)$ at the relay station maps the i-th subcarrier from the first hop to the k-th subcarrier of the second hop, the signal at the destination can be presented in the frequency domain as

$$\begin{aligned} Y_{D,k} &= GH_{2,k}Y_{R,v(i)} + N_{2,k} \\ &= GH_{2,k}H_{1,i}X_i + GH_{2,k}N_{1,i} + N_{2,k}, \quad 1 \le k \le M \end{aligned} \tag{2}$$

where $H_{2,k}$ denotes the k-th subcarrier transfer function on the second hop. $N_{2,k}$ is the additive white Gaussian noise at the destination on the k-th subcarrier, with variance $\mathbf{E}(|N_{2,k}|^2)= N_{02}$.

Fadings in the S-R and R-D channels are assumed to be independent and identically distributed (i.i.d.) among the subcarriers. Moreover, we assume Rayleigh fading in each subcarrier, so that the PDF and the cumulative distribution function (CDF) of the SNR in each of the S-R subchannels are given by $f_{SR}(x)=\lambda_{SR}\exp(-\lambda_{SR}x)$ and $F_{SR}(x)=1-\exp(-\lambda_{SR}x)$, while the corresponding PDF and CDF of the SNR in each of the R-D subchannels are given by $f_{RD}(x)=\lambda_{RD}\exp(-\lambda_{RD}x)$ and $F_{RD}(x)=1-\exp(-\lambda_{RD}x)$, respectively. $\lambda_{SR}=1/\bar{\gamma}_{SR}$ and $\lambda_{RD}=1/\bar{\gamma}_{RD}$ denote the inverse of the average SNR on the S-R and R-D link. From (2) the end-to-end SNR on the k-th subcarrier can be written as in [11]

$$\gamma_{k,end}=\frac{\dfrac{\dot{o}_S\,|H_{1,i}|^2}{N_{01}}\,\dfrac{|H_{2,k}|^2}{N_{02}}}{\dfrac{|H_{2,k}|^2}{N_{02}}+\dfrac{1}{G^2N_{01}}}=\frac{\gamma_{k,SR}\gamma_{k,RD}}{\gamma_{k,RD}+\rho} \tag{3}$$

where ρ denotes the constant that depends on the gain G through $\rho=\dot{o}_R/(G^2N_{01})$. $\dot{o}_S$ and $\dot{o}_R$ represent average symbol power per subcarrier transmitted by S and R, respectively.

5. Performance analysis

Using the results for order statistics of the exponentially distributed random variables, given in [16], as well as integrals given in [17], and implementing some mathematical transformations, we derived the PDF of SNR for the BTB SCP as

$$f^{BTB}_{\gamma_k,end}(x)=\frac{2}{\bar{\gamma}_{SR}}\sum_{j=0}^{k-1}\sum_{i=0}^{k-1}\alpha_j\alpha_i e^{-\beta_j\frac{x}{\bar{\gamma}_{SR}}}\left[\sqrt{\frac{\rho\beta_j x}{\beta_i\bar{\gamma}_{SR}\bar{\gamma}_{RD}}}K_1\left(2\sqrt{\frac{\rho\beta_j\beta_i x}{\bar{\gamma}_{SR}\bar{\gamma}_{RD}}}\right)+\frac{\rho}{\bar{\gamma}_{RD}}K_0\left(2\sqrt{\frac{\rho\beta_j\beta_i x}{\bar{\gamma}_{SR}\bar{\gamma}_{RD}}}\right)\right] \tag{4}$$

where $K_0(\cdot)$ and $K_1(\cdot)$ are zero and first order modified Bessel functions of the second kind defined in [18]. Coefficients α_i, β_i are given as:

$$\alpha_i=(-1)^i M\binom{M-1}{k-1}\binom{k-1}{i}\ \text{and}\ \beta_i=i+M-k+1 \tag{5}$$

The PDF of SNR for the BTW SCP is obtained with the similar approach as the one implemented for the BTB SCP. The final form can be written as

$$f_{\gamma_k,end}^{BTW}(x)=\frac{2}{\overline{\gamma}_{SR}}\sum_{j=0}^{k-1}\sum_{i=0}^{M-k}\alpha_j\delta_i e^{-\beta_j\frac{x}{\overline{\gamma}_{SR}}}\left[\sqrt{\frac{\rho\beta_j x}{\varepsilon_i\overline{\gamma}_{SR}\overline{\gamma}_{RD}}}K_1\left(2\sqrt{\frac{\rho\beta_j\varepsilon_i x}{\overline{\gamma}_{SR}\overline{\gamma}_{RD}}}\right)+\frac{\rho}{\overline{\gamma}_{RD}}K_0\left(2\sqrt{\frac{\rho\beta_j\varepsilon_i x}{\overline{\gamma}_{SR}\overline{\gamma}_{RD}}}\right)\right] \quad (6)$$

where

$$\delta_i=(-1)^i M\binom{M-1}{k-1}\binom{M-k}{i} \text{ and } \varepsilon_i=i+k \quad (7)$$

Using the obtained PDF functions, MGF functions of SNR for both SCP schemes are derived as

$$\mathcal{M}_{\gamma_k,end}(s)=\frac{1}{\overline{\gamma}_{SR}}\sum_{j=0}^{k-1}\sum_{i=0}^{k-1}\frac{\alpha_j\alpha_i}{B_j(s)}\left[\frac{1}{\beta_i}+e^{\frac{A_{j,i}}{B_j(s)}}E_1\left(\frac{A_{j,i}}{B_j(s)}\right)\left(\frac{\rho}{\overline{\gamma}_{RD}}-\frac{A_{j,i}}{\beta_i B_j(s)}\right)\right] \quad (8)$$

for the BTB SCP, and

$$\mathcal{M}_{\gamma_k,end}(s)=\frac{1}{\overline{\gamma}_{SR}}\sum_{j=0}^{k-1}\sum_{i=0}^{M-k}\frac{\alpha_j\delta_i}{B_j(s)}\left[\frac{1}{\varepsilon_i}+e^{\frac{T_{j,i}}{B_j(s)}}E_1\left(\frac{T_{j,i}}{B_j(s)}\right)\left(\frac{\rho}{\overline{\gamma}_{RD}}-\frac{T_{j,i}}{\varepsilon_i B_j(s)}\right)\right] \quad (9)$$

for the BTW SCP. $E_1(\cdot)$ is the exponential integral function defined in [18]. The corresponding coefficients are given through:

$$A_{j,i}=\rho\beta_j\beta_i/\overline{\gamma}_{SR}\overline{\gamma}_{RD},\ \ B_j(s)=s+\beta_j/\overline{\gamma}_{SR} \text{ and } T_{j,i}=\rho\beta_j\varepsilon_i/\overline{\gamma}_{SR}\overline{\gamma}_{RD} \quad (10)$$

Closed form bit error rate (BER) expression for k-th subcarrier pair of differentially phase shift keying (DPSK) modulated OFDM-based relay system with SCP permutation is derived through MFG based approach as

$$P_{b,k}=0,5\mathcal{M}_{\gamma_k,end}(1) \quad (11)$$

while the average BER for the whole system is calculated as

$$P_b=(1/M)\sum_{k=1}^{M}P_{b,k}\,. \quad (12)$$

In case of binary phase shift keying (BPSK) modulation, a tight approximation of exact BER results are obtained through PDF-based approach, and using the Chianni's approximation of complementary error function given in [19]. The obtained k-th subcarrier pair BER expression in case of BTB SCP can be written as

$$P_{b,k}=\frac{1}{2\overline{\gamma}_{SR}}\sum_{j=0}^{k-1}\sum_{i=0}^{k-1}\alpha_j\beta_i\left[\frac{1}{2\beta_i}\left(\frac{1}{3B_j(1)}+\frac{1}{B_j(4/3)}\right)+\frac{e^{\frac{\rho A_{j,i}}{B_j(1)}}}{6B_j(1)}E_1\left(\frac{\rho A_{j,i}}{B_j(1)}\right)\left(\frac{\rho}{\overline{\gamma}_{RD}}-\frac{\rho A_{j,i}}{\beta_i B_j(1)}\right)\right.$$
$$\left.+\frac{e^{\frac{\rho A_{j,i}}{B_j(4/3)}}}{2B_j(4/3)}E_1\left(\frac{\rho A_{j,i}}{B_j(4/3)}\right)\left(\frac{\rho}{\overline{\gamma}_{RD}}-\frac{\rho A_{j,i}}{\beta_i B_j(4/3)}\right)\right], \quad (13)$$

while for the BTW SCP scheme, the obtained expression is

$$P_{b,k}=\frac{1}{2\overline{\gamma}_{SR}}\sum_{j=0}^{k-1}\sum_{i=0}^{M-k}\alpha_j\delta_i\left[\frac{1}{2\varepsilon_i}\left(\frac{1}{3B_j(1)}+\frac{1}{B_j(4/3)}\right)+\frac{e^{\frac{\rho T_{j,i}}{B_j(1)}}}{6B_j(1)}E_1\left(\frac{\rho T_{j,i}}{B_j(1)}\right)\left(\frac{\rho}{\overline{\gamma}_{RD}}-\frac{\rho T_{j,i}}{\beta_i B_j(1)}\right)\right.$$
$$\left.+\frac{e^{\frac{\rho T_{j,i}}{B_j(4/3)}}}{2B_j(4/3)}E_1\left(\frac{\rho T_{j,i}}{B_j(4/3)}\right)\left(\frac{\rho}{\overline{\gamma}_{RD}}-\frac{\rho T_{j,i}}{\varepsilon_i B_j(4/3)}\right)\right] \quad (14)$$

The average BER for BTB SCP and BTW SCP schemes are obtained after substituting relations (13) and (14) in (12), respectively.

It is worht mentioning that the same approach implemented for BPSK modulation can be used for deriving BER expressions for M-QAM modulations.

6. Results

The subsequent presented analytical and simulation results assume perfectly synchronized OFDM AF relaying system with implemented SCP. The OFDM system has M=16 subcarriers, which in a real scenario can be considered as 16 chunks with uncorrelated transfer functions from chunk to chunk. It is also assumed that $\dot{O}_S=\dot{O}_R$ and $N_{01}=N_{02}$, so that $\overline{\gamma}_{SR}=\overline{\gamma}_{RD}$. The relay gain G is calculated assuming that the average subcarrier symbol power transmitted by the relay is $\dot{O}_R$ and using the relay's knowledge of the average fading power on the S-R link

$$\rho=\frac{\overline{\gamma}_{SR}}{e^{1/\overline{\gamma}_{SR}}E_1\left(1/\overline{\gamma}_{SR}\right)} \quad (15)$$

Simulation results are obtained through Monte Carlo simulations, where only the frequency domain part of the analyzed system is taken into consideration, as it is assumed to be perfectly synchronized. The subcarrier transfer functions on the first and second hop are generated as independent complex Gaussian random variables with zero mean and variance 1/2, meaning that the average subcarrier power is equal to 1. Ten OFDM symbols are transmitted through each channel realization.

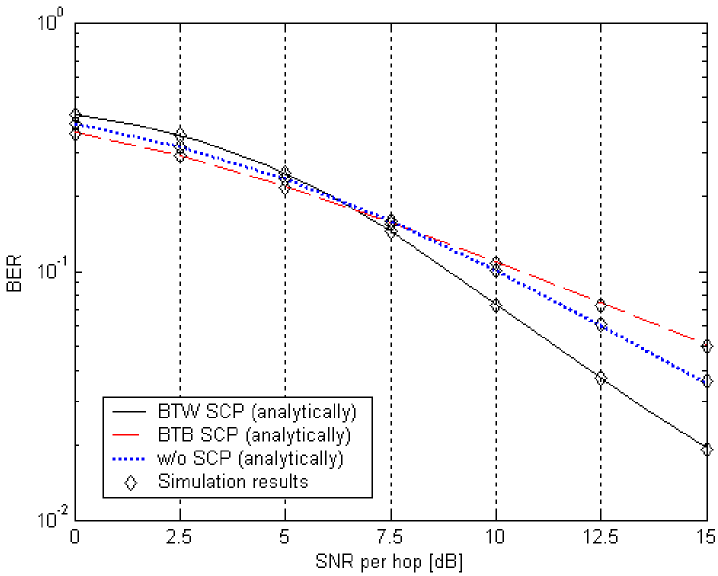

Figure 3. BER of DPSK modulated OFDM AF relay system with SCP

Fig. 3 presents the BER performance of DPSK modulated OFDM AF relay system for the BTW SCP and the BTB SCP. For the sake of comparison, the BER performance of the OFDM AF relay system without (w/o) SCP is presented. The BER for the AF system w/o SCP is analytically obtained using the MGF derived in [3]. The obtained analytical results are completely verified by simulations. As expected, for the low SNR values BTB SCP achieves the best BER performance. It outperforms BTW SCP system up to the SNR value of 6.5dB approximately, and the system w/o SCP up to the SNR value of 7.5dB. For SNR values above 6.5 dB, the BTW SCP scheme has the lowest BER and its advantage in BER performance increases very fast as the SNR values increase. It already achieves more than 1dB SNR gain over the system w/o SCP and almost 2dB SNR gain over the BTB SCP scheme, for the BER value of 10^{-1}.

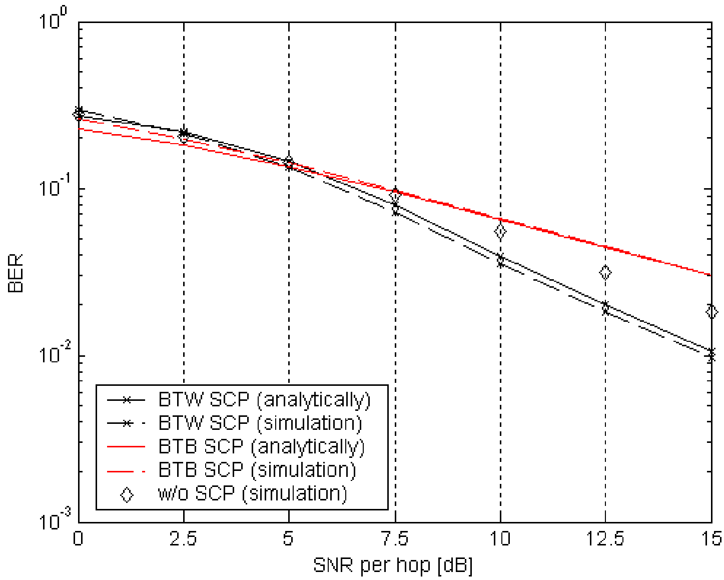

Figure 4. BER of BPSK modulated OFDM AF relay system with SCP

BER results for the BPSK modulated OFDM AF system with BTW SCP, BTB SCP and w/o SCP schemes are given in Fig. 4. The analytically obtained BER results for both SCP schemes present a tight approximation of the exact BER values. The small difference compared to the exact results is expected, as the approximation of erfc(·) is used in averaging the BER over the region of all SNR values. Considering that simulation results are the exact ones, it can be seen that the intersection point for the BER graphs of BTW SCP and BTB SCP is now approximately 4dB, meaning that after that point the BTW SCP scheme achieves significantly lower BER. For example, the SNR gain is more than 1dB for a BER of 10^{-1}. Note that for SNR=15dB, the BTB SCP scheme attains a BER of $3{\cdot}10^{-2}$, whereas the BER for the BTW SCP scheme is 10^{-2}, i.e., three times lower.

Having the presented BER results in mind, it is obvious that OFDM AF relaying systems may switch from the BTB SCP to BTW SCP scheme depending on the average SNR in S-R and R-D links. Apparently, this hybrid SCP scheme is expected to achieve optimum BER performance.

7. Conclusions

OFDM-based relay systems are recognized as a promising solution for next generation wireless communication systems. In the future WWAN and WLAN systems, the scenario with infrastructure relay station will probably be used. It is proven that the capacity of OFDM-based relay systems is maximized if the subcarrier permutation (SCP), namely best-to-best SCP (BTB SCP), is implemented at the R station. However, if the error rate performance is considered, it appears that BTB SCP scheme is not optimal solution for all SNR values. In this paper we presented the analytically obtained results for BER performance of the OFDM-based relay system implementing BTB SCP, as well as BER performance of the assumed system implementing BTW SCP. Closed form BER expressions are obtained for the DPSK modulated system for both SCP schemes, while for the BPSK modulation tight approximations of the exact BER results are derived. It has been shown that the BTB SCP scheme outperforms BTW SCP in the low SNR regime, while in the medium and high SNR region, the relative performance of BTB SCP and BTW SCP are reversed, in the sense that BTW SCP yields lower BER. So, it has been pointed out that, in order to optimize the BER performance, the OFDM AF relaying system may switch from one SCP scheme to another, depending on the average S-R and R-D channel conditions.

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