A Novel OFDM/DQPSK Receiver with Adaptive Remodulation Filter

Slavimir STOŠOVIĆ [1], *Zorica NIKOLIĆ* [2], *Bojan DIMITRIJEVIĆ* [2], *Dragan ANTIĆ* [2], *Nenad MILOŠEVIĆ* [2]

[1] The School of Higher Technical Professional Education, Aleksandra Medvedeva 20, 18000 Niš, Serbia
[2] Faculty of Electronic Engineering, University of Niš, Aleksandra Medvedeva 14, 18000 Niš, Serbia

slavimir.stosovic@vtsnis.edu.rs, zorica.nikolic@elfak.ni.ac.rs,
bojan.dimitrijevic@elfak.ni.ac.rs, nenad.milosevic@elfak.ni.ac.rs

Abstract. *The description and performance analysis of a new OFDM/DQPSK signal receiver is considered in this paper. The proposed receiver has performance that is close to the performance for the coherent detection of the OFDM/DQPSK signal, in case of zero carrier frequency offset. In case of non-zero frequency offset, receiver with decision feedback differential detection (DFDD-OFDM) is often used in the literature. The analysis will show that the proposed receiver has better performance in the presence of the frequency offset than DFDD-OFDM receiver, in the sense wider frequency offset range where the error probability is acceptable. The novel proposed OFDM receiver has better performance for all the considered values of the number of OFDM channels.*

Keywords

Detection, estimation, mobile satellite communications, modulation, orthogonal frequency division multiplex, synchronization.

1. Introduction

Modern telecommunication systems often use OFDM since it provides a broadband communication over fading channels. However, the performance of an OFDM system may be significantly deteriorated in case of the frequency offset between the local oscillators at the transmitter and the receiver [1], [2]. The problem with the frequency offset is that it creates the inter-carrier interference since the orthogonality of the OFDM subcarriers is ruined. Since inter-carrier interference may degrade the bit-error rate performance severely, the inter-carrier interference suppression has received considerable attention. Depending on the characteristics of the transmitted signal (pilot-based or not), there are different approaches for solving this problem [3]-[9].

The other approach for the detection of a signal in the presence of carrier frequency offset is to use differential detection (DD), where the phase of the current symbol is compared with the phase of the previous symbol (reference) and a decision is made based on the phase difference [10]. If the phase reference is not stable, due to fading, Doppler effect or poor frequency alignment between the oscillators, the detector performance degrades leading to the irreducible error floors [11]. To deal with this problem a decision-feedback differential detection (DFDD) scheme is proposed and analyzed by Edbauer in [12] for the MDPSK signal transmitted over the additive white Gaussian noise (AWGN) channel, and for Rayleigh and Rician fading environment is analyzed in [13] and [14], respectively. Performance of OFDM receiver with DFDD algorithm (DFDD-OFDM) is presented in [15]. A different solution is to average the phase reference from more than one symbol interval or multiple-symbol differential detection (MSDD-OFDM) can be performed using maximum likelihood sequence estimation [16]-[18].

This paper proposes an OFDM/DQPSK receiver with adaptive remodulation filter (ARF-OFDM), where a new algorithm for the estimator weights adjustment is applied separately in each OFDM channel. Detection performance of the proposed system is close to the coherent detection performance of the differentially encoded signal.

It will be shown that the proposed receiver is able to operate within significantly wider frequency offsets range than the other receivers with similar complexity (MSDD-OFDM and DFDD-OFDM), regardless of the number of OFDM channels.

2. System Model

Analysis and simulations in this paper are performed in the digital complex baseband domain. The i-th sample of the OFDM signal, generated by the Inverse Fast Fourier Transformation (IFFT) at the transmitter is:

$$s(i,k)=\sqrt{\frac{1}{N}}\sum_{n=0}^{N-1}A_n(k)e^{j2\pi\frac{ni}{N}} . \qquad (1)$$

$A_n(k)$ is the amplitude value for n-th subcarrier of the k-th OFDM frame, represented with equation as:

$$A_n(k) = A_n(k-1)e^{j\frac{\pi}{2}d_n(k)}, n = 1,2,\ldots,N - N_{VC} \tag{2}$$

where $d_n(k) \in \{0,1,2,3\}$ represents a DQPSK symbol which is transmitted in the n-th OFDM channel and k-th OFDM frame.

The data is converted in serial sequence, then the cyclic prefix (CP) is added.

The block diagram of the OFDM/DQPSK signal receiver used in this paper is shown in Fig. 1. The received signal is down converted, low-pass filtered, and sampled with the period $T_f = T_{GI} + T_S + T_{CP}$, where T_{GI} is the guard interval duration, T_{CP} is the cyclic prefix duration, T_S is the symbol interval duration. N is the number of data channels and N_{VC} is the virtual channels number (Fig. 1). *S*/*P* represents serial to parallel converter and it requires timing synchronization. After removing the cyclic prefix, a discrete Fourier transform (*DFT*) of length N is performed. In this case we use OFDM demodulator with N subcarriers and discrete Fourier transform.

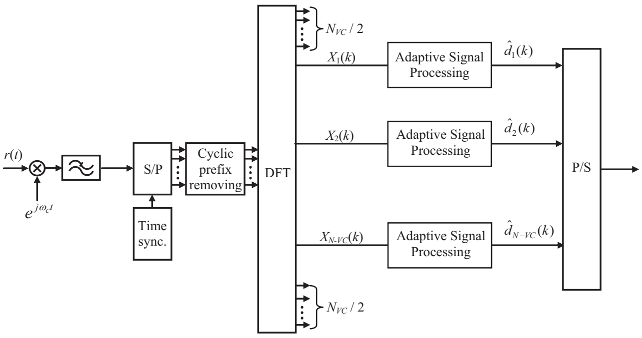

Fig. 1. ARF-OFDM receiver.

If we assume that correct frame and timing synchronization is achieved, then the received sequence in n-th OFDM channel and k-th OFDM frame, after stripping the CP, can be expressed as:

$$X_n(k) = \sqrt{\frac{1}{N}} \sum_{i=kN}^{k(N+1)-1} r(i,k) e^{-j2\pi \frac{\left(n-1+\left\lfloor \frac{N_{VC}}{2} \right\rfloor\right)i}{N}}, \tag{3}$$
$$n = 1,2,\ldots,N - N_{VC}$$

where $r(i,k) = s(i,k) + n(i)$, and $n(i)$ is the AWGN with power spectral density N_0 / 2.

In this paper we propose a signal processing structure whose internal structure is shown in Fig. 2 and the receiver is denoted as ARF-OFDM. The proposed algorithm with DQPSK input signal is equivalent to the LMS algorithm with the CW (Continuous Wave - a signal with constant amplitude and frequency, and a random phase) input signal in terms of adaptation rate and convergence, in case of correctly determined remodulation weights $R_{n,l}(k)$. The remodulation weights are sufficiently correctly determined in the range of error probabilities of practical importance. Transversal filter with remodulation lowers the noise level in the input signal with as little degradation of the useful signal as possible. Therefore, if we put the transversal filter in front of the detector, the detector will work with the estimated input signal which has a smaller noise variance, and it will make better decisions.

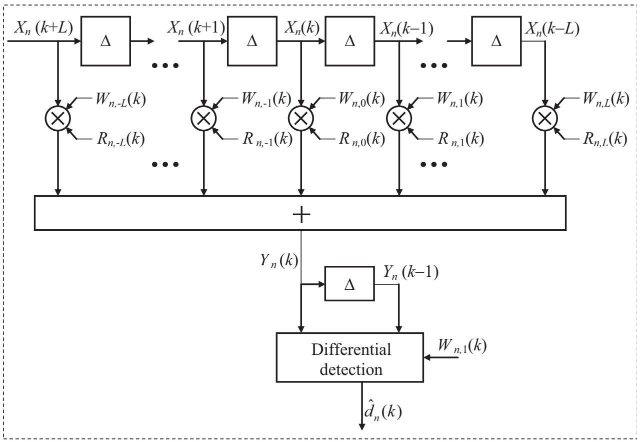

Fig. 2. Adaptive signal processing structure in n-th ARF-OFDM channel.

The signal processing is described with the following equations:

$$Y_n(k) = \frac{1}{2L+1} \sum_{l=-L}^{L} R_{n,l}(k) \cdot X_n(k-l) \cdot W_{n,l}(k) \tag{4}$$

where n = 1, 2, …, (N – N_{VC}) denotes the n-th OFDM channel, 2L is the length of the proposed structure, and $R_{n,l}(k)$ are remodulation weights. The remodulation weights are determined independently for each branch in order to avoid the error propagation. $R_{n,l}(k)$ are deter-mined as:

$$R_{n,l}(k) = \arg\min_{w \in S} \left\{ | X_n(k) - w \cdot X_n(k-l) \cdot W_{n,l}(k) |^2 \right\}$$
$$R_{n,l}(k) \in S \tag{5}$$

where

$$S = \left\{ e^{j\frac{\pi}{2}m}, m \in (0,1,2,3) \right\},$$

$$n = 1,2,\ldots,(N - N_{VC}),$$

$$l = -L,\ldots L, \quad l \neq 0, \text{ and } R_{n,0}(k) = 1.$$

To summarize, weights $R_{n,l}(k)$ are used for the modulation removal, and $W_{n,l}(k)$ are complex weights trying to compensate the phase rotation due to frequency offset. The initial value of the weights is equal to 1 (phase is equal to 0). The convergence and the cost function of the algorithm are discussed in more details in the next subsection.

ARF-OFDM receiver for DQPSK modulation contains a new algorithm, corresponding to the nature of OFDM signals. The adjustment of the adaptive filter weights, $W_{n,l}(k)$, used in all OFDM channels, is performed by the following algorithm:

$$W_{n,l}(k+1) = W_{n,l}(k) + \frac{\mu}{2\cdot L}\sum_{n=1}^{N-N_{VC}} \frac{E_n(k)[X_n(k-l)R_{n,l}(k)]^*}{\overline{|X_n(k)|^2}}, \qquad l=-L,\ldots L,\quad l\neq 0 \tag{6}$$

where $W_{n,0}(k) = 1$ and $E_n(k)$ is a partial (for each OFDM channel) LMS algorithm error signal, given by

$$E_n(k) = X_n(k) - Y_n(k), \tag{7}$$

μ is the adaptation factor, $(\cdot)^*$ represents complex conjugate, and $\overline{|X_n(k)|^2}$ is the average power of the input signal. So, weights $W_{n,l}(k)$ are being used in all OFDM channels, and are being adjusted in each channel, one after another.

In the case of continuous wave (CW) input signal and if the thermal noise is neglected, the filter weight $W_{n,1}(k)$ contains the estimated frequency offset Δf as in [19]

$$W_{n,1}(k) \sim e^{j2\pi\Delta f T_f}. \tag{8}$$

Having the above in mind, we propose a correction for the k-th symbol detection using weight $W_{n,1}(k)$ and the differential detection of k-th symbol is performed in the following way:

$$\hat{d}_n(k) = \arg\min_m \left\{ \left| Y_n(k) - Y_n(k-1)W_{n,1}(k)\exp\left(j\frac{m\pi}{2}\right)\right|^2 \right\}, \qquad m = 0,1,2,3 \tag{9}$$

The proposed structure does not minimize the frequency offset, but has the ability to operate in a wide range of frequency offset. The algorithm has been applied due to its good overall properties, which include satisfactory speed, stability, and not so high complexity.

The difference between previously published DFDD-OFDM and DFDDI-OFDM algorithms [15] on one side and the proposed OFDM-ARF algorithm on the other side is that the proposed algorithm has no feedback loop, and it has the remodulation made for each weight separately. In the absence of feedback, the proposed system is not prone to error propagation.

3. Numerical Results

Performance of the described system is analyzed using Monte-Carlo simulation with one million simulation steps. The carrier frequency is 2.4 GHz, the sampling period before DFT block is T_c = 1 µs. OFDM simulation parameters are N = 16, number of virtual channel N_{VC} = 2, cyclic prefix and guard interval $T_{CP} = T_{GI} = 2T_c$, N = 32 (N_{VC} = 4, $T_{CP} = T_{GI} = 4T_c$), N = 64 (N_{VC} = 8, $T_{CP} = T_{GI} = 8T_c$) for the three simulated cases, which does not limit the generality of the results. T_c represents system sampling interval at the input of the receiver. In most OFDM literature, the cyclic prefix occupies the same interval as the guard interval, but in our simulation the general format of the OFDM signal comprising, separated from the T_{CP} and T_{GI} is considered.

Having in mind that the proposed ARF-OFDM receiver uses a large number ($2L$) of signal samples, their performance will be compared with the performance of the signal processing algorithms with similar complexity. In this paper we considered MSDD-OFDM [18], DFDD-OFDM [15] as the algorithms with similar complexity and DD-OFDM receiver [20] that is often used in literature. Based on analyses shown in [18], we analyzed MSDD-OFDM system with 3 symbols used for detection.

Fig. 3 shows the symbol error probability as a function of the energy per symbol to noise power spectral density ratio (E_s / N_0) if there is no frequency offset in an AWGN channel. The parameters of the proposed ARF-OFDM receiver are: $2L + 1 = 9$ and $\mu = 0.01$. The selected value of the parameter L gives almost optimal error probability performance for a wide range of other system's parameters values. This figure also shows two theoretical cases: differential and coherent detection of the received OFDM signal which is differentially coded at the transmitter. It is known that the differential detection requires larger SNR to reach the performance of the coherent detection.

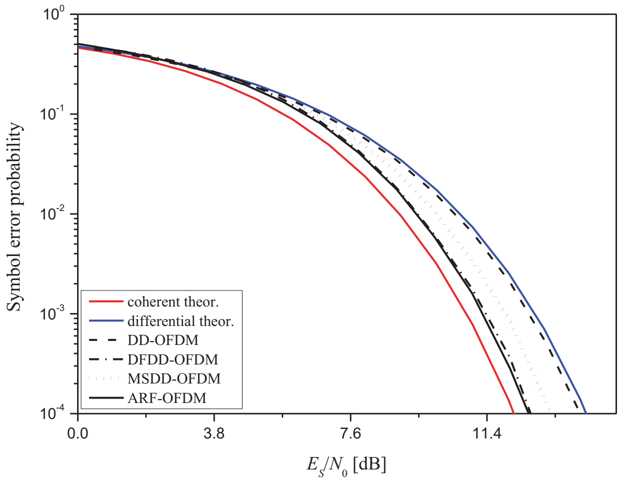

Fig. 3. Symbol error probability as function of signal to noise ratio for Δf = 0 in AWGN channel.

If the signal processing is performed by ARF-OFDM and DFDD-OFDM the performances of the systems are close to the theoretical ones for the coherent detection of DQPSK signal. ARF-OFDM system performances are slightly better than DFDD-OFDM systems performances.

Since OFDM schemes are primarily intended for the mobile and wireless systems where a fading channel is assumed, in the following figures the performance analysis is performed in Rician fading channel with Rician factor $K = 10$ dB. Figs. 4, 5, and 6 show the symbol error rate versus the normalized frequency offset of the receiver if the signal processing is performed by: proposed ARF-OFDM, DFDD-OFDM, MSDD-OFDM with 3 symbols used for detection and DD-OFDM receiver. Three different values of the number of OFDM channels are considered $N = 16$, 32, and 64. In each case, receiver speed is set to $v_{rec} = 150$ km/h, and $E_s / N_0 = 10.5$ dB.

Comparing the corresponding curves in Fig. 4 an improvement may be noticed in system performance in the presence of frequency offset using ARF-OFDM receiver. ARF-OFDM receiver works in a wider frequency offset range compared to the other considered systems. Therefore, the range where there is a satisfying transmission quality is significantly wider for ARF-OFDM receiver. It can be noticed that the error probability for DFDD-OFDM receiver significantly rises after $\Delta f \times T_f = 0.05$. This is because DFDD algorithm is prone to error propagation [14], which becomes significant for higher frequency offset. At ARF-OFDM receiver the remodulation weights are determined independently for each filter branch in order to avoid the error propagation, and the error probability for slightly rises with the frequency offset due to the interchannel interference caused by the frequency offset.

The gain achieved using ARF-OFDM receiver is also noticeable for $N = 32$ and $N = 64$, as can be seen in Figs. 5 and 6. However, in this case DFDD-OFDM has slightly better performance for low frequency offset, but ARF-OFDM is able to operate for much higher values of the carrier frequency offset.

4. Conclusions

In this paper we proposed the ARF-OFDM DQPSK receiver. In the absence of the carrier frequency offset, the detection performance of the proposed system is close to the coherent detection performance of the differentially encoded signal.

The ARF-OFDM DQPSK receiver is compared with the receiver using the signal processing block of similar complexity (MSDD-OFDM and DFDD-OFDM), i.e. with the algorithms using a large number of samples for the operation. After the comparison, we can draw a conclusion that the ARF-OFDM DQPSK receiver is able to operate within significantly wider frequency offsets range than the other two (MSDD-OFDM and DFDD-OFDM) receivers, regardless of the number of OFDM channels.

Hence the proposed technique is highly suitable for applications where bandwidth efficiency is utmost concern, such as mobile communications and low bit-rate transmissions between ground transceivers and LEO (low earth orbit) satellites.

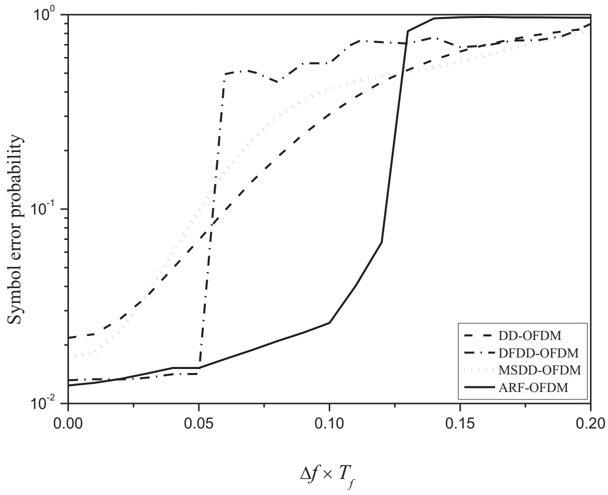

Fig. 4. Symbol error probability versus normalized frequency offset for $N = 16$, $N_{VC} = 2$ and $T_{GI} = T_{CP} = 2T_c$.

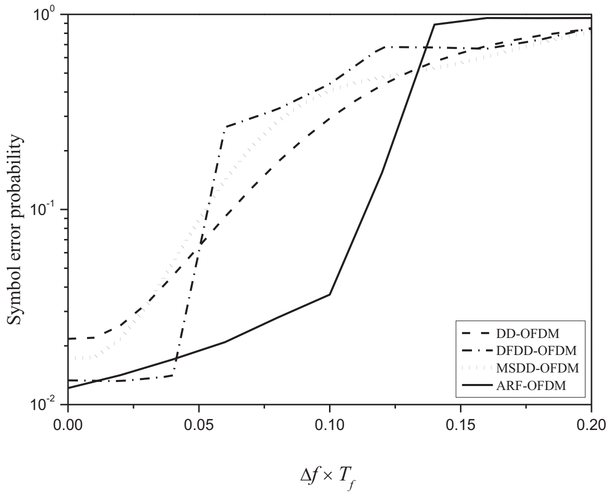

Fig. 5. Symbol error probability versus normalized frequency offset for $N = 32$, $N_{VC} = 4$ and $T_{GI} = T_{CP} = 4T_c$.

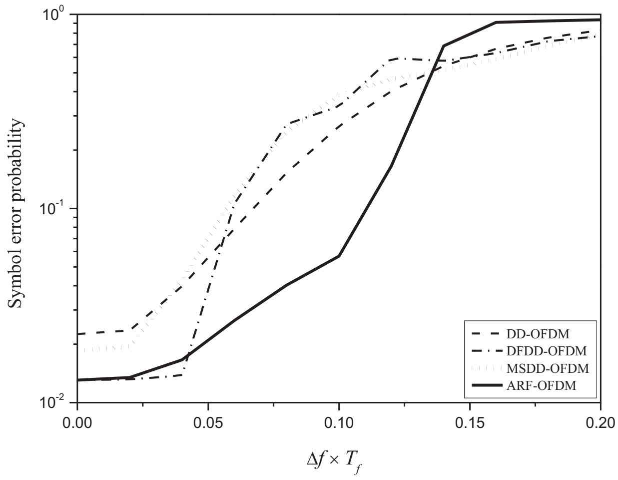

Fig. 6. Symbol error probability versus normalized frequency offset for $N = 64$, $N_{VC} = 8$ and $T_{GI} = T_{CP} = 8T_c$.

References

[1] POLLET, T., VAN BLADEL, M., MOENECLAEY, M. BER sensitivity of OFDM systems to carrier frequency offset and Wiener phase noise. *IEEE Transactions on Communications,* 1995, vol. 43, no. 2, p. 191 - 193.

[2] NARASIMHAN, R. Performance of diversity schemes for OFDM systems with frequency offset, phase noise and channel estimation errors. In *IEEE International Conference on Communications, ICC.* New York City (USA), 2002, vol. 3, p. 1551 - 1557.

[3] MASSEY, J. Optimum frame synchronization. *IEEE Transactions on Communications*, 1972, vol. 20, no. 2, p. 115 - 119.

[4] MOOSE, P. H. A technique for orthogonal frequency division multiplexing frequency offset correction. *IEEE Transactions on Communications*, 1994, vol. 42, no, 10, p. 2908 - 2914.

[5] SCHMIDL, T. M., COX, D. C. Robust frequency and timing synchronization for OFDM. *IEEE Transactions on Communications*, 1997, vol. 45, no. 12, p. 1613 - 1621.

[6] ZHANG, W., XIA, X.-G., CHING, P. C. Clustered pilot tones for carrier frequency offset estimation in OFDM systems. *IEEE Transactions on Wireless Communications*, 2007, vol. 6, no. 1, p. 101 - 109.

[7] DAFFARA, F., CHOULY, A. Maximum likelihood frequency detectors for orthogonal multi-carrier systems. In *IEEE International Conference on Communications, ICC*. Geneva (Switzerland), 1993, p. 766 - 771.

[8] DAFFARA, F, ADAMI, O. A new frequency detector for orthogonal multicarrier transmission techniques. In *IEEE 45th Vehicular Technology Conference*. Chicago (USA), 1995, p. 804 - 809.

[9] HSIEH, M. H., WEI C. H. A low complexity frame synchronization and frequency offset compensation scheme for OFDM systems over fading channels. *IEEE Transactions on Vehicular Technology*, 1999, vol. 48, no. 5, p. 1596 - 1609.

[10] SIMON, M. K., ALOUINI, M.-S. *Digital Communication over Fading Channels: A Unified Approach to Performance Analysis*. New York (USA): Wiley, 2000.

[11] KORN, I. Error floors in satellite and land mobile channels. *IEEE Transactions on Communications*, 1991, vol. 39, no. 6, p. 833-837.

[12] EDBAUER, F. Bit error rate of binary and quaternary DPSK signals with multiple differential feedback detection. *IEEE Transactions on Communications*, 1992, vol. 40, no. 3, p. 457 - 460.

[13] SCHOBER, W., GERSTACKER, H., HUBER, J. B. Decision-feedback differential detection of MDPSK for flat Rayleigh fading channels. *IEEE Transactions on Communications*, 1999, vol. 47, no, 7, p. 1025 - 1035.

[14] SCHOBER, R., GERSTACKER, W. H., Decision-feedback differential detection based on linear prediction for MDPSK signals transmitted over Ricean fading channels. *IEEE Journal On Selected Areas In Communications*, 2000, vol. 18, no. 3, p. 391 - 402.

[15] STOŠOVIĆ, S., DIMITRIJEVIĆ, B., FEDRA, Z. Application of improved decision feedback differential detection algorithm at OFDM/MDPSK system. In *Proceedings of the 22nd International Conference Radioelektronika 2012*. Brno (Czech Republic), 2012, p. 123 - 126.

[16] DIVSALAR, D., SIMON, M. K. Multiple-symbol differential detection of MPSK. *IEEE Transactions on Communications*, 1990, vol. 38, no. 3, p. 300 - 308.

[17] GAO, C., HAIMOVICH, A. M., LAO, D. Multiple-symbol differential detection for MPSK space-time block codes: decision metric and performance analysis. *IEEE Transactions on Communications*, 2006, vol. 54, no. 8, p. 1502 - 1510.

[18] DIMITRIJEVIĆ, B., STOŠOVIĆ, S., MILOŠEVIĆ, N., NIKOLIĆ, Z. Performances of the OFDM/DQPSK system with MBDD in the presence of frequency offset. In *Proceedings of TELFOR 2010*. Belgrade (Serbia), 2010, p. 475 - 478.

[19] HASAN, M. A., LEE, J. C., BHARGAVA, V. K. A narrowband interference canceller with an adjustable center weight. *IEEE Transactions on Communications*, 1994., vol. 42, no. 2/3/4, p. 877 - 880.

[20] STOŠOVIĆ, S., DIMITRIJEVIĆ, B., MILOŠEVIĆ, N., NIKOLIĆ, Z. Frequency offset influence on OFDM/MDPSK system performance. *In Proceedings of ICEST 2010*. Ohrid (Macedonia), 2010, p. 81 - 84.

About Authors ...

Slavimir STOŠOVIĆ was born in Prokuplje, Serbia, in 1981. He received the B.E.E. degree at the Faculty of Electrical Engineering, University of Niš in 2007. At present, he is an assistant professor at the School of Higher Technical Professional Education in Niš, and he is working on his Ph.D. thesis. His research interests include mobile and wireless communications and radio signal processing.

Zorica NIKOLIĆ was born in 1955 in Niš. She received the B.E.E., M.S., and Ph.D. degrees at the University of Niš in 1979, 1985, and 1989, respectively. She is now a professor at the Faculty of Electronic Engineering, University of Niš, where she teaches basics of telecommunications, telecommunication networks, mobile communications, spread spectrum systems, and wireless communications. Her main fields of interest include mobile and wireless communications.

Bojan DIMITRIJEVIĆ was born in Leskovac, Serbia, in 1972. He received the B.E.E., M.Sc., and Ph.D. degrees from the University of Niš in 1998, 2002, and 2006, respectively. His research interests include interference suppression in mobile and wireless communications.

Dragan ANTIĆ was born in Vranje, Serbia, in 1963. He received the B.E.E., M.Sc., and Ph.D. degrees from the University of Niš in 1987, 1991, and 1994, respectively. His research interests include simulation and modeling, automatic control systems, electromotor drive control, and power system control.

Nenad MILOŠEVIĆ was born in Knjaževac, Serbia, in 1973. He received the B.E.E., M.Sc., and Ph.D. degrees from the University of Niš, Serbia, in 1997, 2000, and 2007, respectively. He is teaching Basics of Telecommunications, Telecommunication Networks, Mobile Telecommunications, and Powerline Communications. His interests include mobile and wireless communications with special emphasis on cooperative communications.