Wireless Systems

An efficient technique to estimate the realisation bit error rate of multiband OFDM based UWB systems

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SUMMARY

In this paper, we present a simple method to estimate the realisation bit error rate (RBER) of a multiband orthogonal frequency division multiplexing (OFDM)-based ultra-wide band (UWB) system. Under time-varying channels, error event based BER estimation of convolutionally encoded systems requires the knowledge of error events in the Viterbi decoding. In this work, we show that the upper-bound of instantaneous outage capacity is a function of the percentage of subcarriers, whose signal-to-noise (SNR) ratio is less than a predefined outage threshold which we call as realisation outage ratio (ROR). Simulation results reveal that the RBER of the channel realisations and their corresponding ROR are highly correlated at an optimally selected outage threshold. Using this correlation, we form a simple mathematical model between ROR and RBER and obtain quite accurate and consistent RBER estimates with respect to the error event based RBER estimates and the empirical RBER simulation results. Copyright © 2009 John Wiley & Sons, Ltd.

1. INTRODUCTION

The development of several entertainment technologies and applications such as High Definition TV and personnel computing devices has increased the demand for wireless home networking [1]. These applications, however, require large bandwidth to operate, which cannot be achieved by the existing wireless LAN technologies, such as 802.11b/a/g. To support such high-bandwidth applications, ultra-wide band (UWB) has gained great interest since it has the ability to provide data rates up to 500 Mbps over short distances [2, 3] and consequently becomes a good physical (PHY) layer alternative for wireless personal area networks.

One way of generating UWB signals is to use orthogonal frequency multiplexing (OFDM) which has been widely used in many wireless applications such as IEEE 802.11g WLAN standard. In this paper, we consider the multiband OFDM (MB-OFDM) technique as the PHY layer of the UWB system proposed by Texas Instruments [4].

The UWB systems are regulated to operate between 3.1 and 10.6 GHz unlicensed spectrum, using a low power signal with at least 528 MHz bandwidth [5]. The MB-OFDM proposal divides the 7.5 GHz UWB spectrum into equal 14 sub-bands where each has a bandwidth of 528 MHz. The building blocks of the considered MB-OFDM system are shown in Figure 1. In this system, the information bits are first encoded using a convolutional code with a rate of 1/3, constraint length (K) of 7 and generator polynomials \( g_0 = [133]_8, g_1 = [145]_8 \) and \( g_2 = [175]_8 \). Following that, the puncturing is employed to achieve the desired data rate. The encoded and punctured data stream is passed through a two-stage block interleaver, where the coded bits are first interleaved over the sub-bands in time, and then it is also interleaved over the OFDM subcarriers within each sub-
band. The interleaved bit stream is mapped into QPSK symbols which are converted into parallel streams subsequently. After obtaining the time domain signal via IFFT, the signal is reconverted to serial and guard periods are added. Following the digital-to-analogue (DAC) conversion, analogue baseband OFDM symbols are up-converted to the associated sub-bands according to a predefined time–frequency interleaving pattern (TFI). Since current form of the TFI utilises the first three sub-bands with 100 sub-carriers for each, there are totally \( N = 300 \) different sub-carriers to carry the information bits. The signal at the output of the transmitter is sent over the noisy UWB channel [6]. The MB-OFDM UWB receiver performs the reverse operations of the transmitter.

As in all wireless systems, the performance of MB-OFDM system is degraded by severe distortions such as multipath fading, shadowing, multi-user interference, etc. In addition to the performance degradation, these distortions make the channel time varying and thereby instantaneous characteristics and quality of the channel changes in time. To quantify the performance of such time-varying channels, the average bit error rate (ABER) based on knowledge of the channel statistics can be used as a metric. In literature, Wessman et al. [7] derived ABER performance results of convolutionally coded OFDM systems using the channel statistics. Although ABER shows the channel performance on the average, it does not provide any information about the instantaneous performance of the system. Therefore, to quantify the instantaneous channel performance, bit error rate (BER) associated with a particular realisation of the MB-OFDM channel can be a useful measure, which will be referred as realisation bit error rate (RBER) throughout the paper.

Knowing the RBER rather than the ABER allows us to design higher layer protocols and perform cross-layer optimisation such as optimising the frame or packet size dynamically and performing opportunistic scheduling [8–12] according to the instantaneous channel condition. Hence, the estimation of the RBER with knowledge of the channel state information has utmost importance to increase the capacity and performance of the system.

In literature, Malkamaki et al. [13] and Zummo et al. [14] have derived the union bounds for ABER and RBER of the convolutionally coded OFDM system over fading channels assuming CSI is known to the receiver. Sandell et al. [15] have derived a bound for RBER of the coded-OFDM system by truncating the union bound. However, Schlegel et al. have showed in Reference [16] that the union bound can deviate significantly from the empirical RBER values, and have concluded that the truncation of union bound may sometimes yield inaccurate RBER estimates. In the MB-OFDM context, recently, Snow et al. [17] have proposed a truncated union bound technique to obtain the RBER estimate of the MB-OFDM system. This RBER estimation method requires knowing all the error events in the Viterbi algorithm [18] which may become computationally expensive and may require the use of a large memory unit to store the dominant error events. We refer to this scheme as an error event based RBER estimation method in the rest of the paper.

To reduce the complexity and the need for large memory of the error event based RBER estimation technique, in this paper, we propose a simple RBER estimation method which is derived upon the instantaneous outage capacity of the channel. For this purpose, we first derive an upper-bound for the instantaneous outage capacity of the MB-OFDM channel and then show that this bound is a function of a metric called realisation outage rate (ROR). Basically ROR is the percentage of subcarriers whose signal-to-noise (SNR) ratio is less than a fixed outage threshold (OT). By minimising the correlation coefficient between the reciprocal of the ROR and the RBER, we obtain the optimal OT and using
this optimal OT, we develop a simple RBER model which is basically a function of the ROR of the channel realisation. We refer to this scheme as realisation outage capacity (ROC) based RBER estimation. Simulation results show that ROC-based RBER estimation gives satisfactory RBER estimates that are quite consistent both with the error event based RBER estimation and empirical RBER simulation results.

Rest of the manuscript is organised as follows, in Section 2, we review the error event-based RBER estimation technique. In Section 3, we describe the ROC-based RBER estimation method. Section 4 presents the simulation results. Finally, Section 5 is devoted to our conclusions.

2. ERROR EVENT-BASED RBER ESTIMATION METHOD

In this section, we will briefly introduce error event based RBER estimation method [17] for the MB-OFDM UWB channel described earlier. We refer this scheme as error event-based RBER estimation method in the rest of the paper.

The MB-OFDM system in Figure 1 can be modelled as flat-fading channel after the IFFT block. The received in-phase or quadrature component of the QPSK modulated signal is a noisy BPSK signal that can be expressed mathematically as

\[ r_j = \sqrt{E_c} h_j (2c_j - 1) + z_j \quad 1 \leq j \leq L_c \] (1)

where \( L_c \) is the length of the received codeword sequence, \( E_c \) the energy of a coded bit, \( c_j \in \{0, 1\} \) the \( j \)th bit of the transmitted code sequence, \( h_j \) the in-phase or quadrature channel gain over which the BPSK symbol, \( 2c_j - 1 \), is transmitted, \( z_j \) the additive Gaussian noise with mean of zero and variance of \( \sigma^2 = N_0/2 \).

To calculate the error event-based RBER estimate, it is first assumed that all-zero codeword is transmitted over a particular channel realisation. Second, only \( L \) input error code sequences that cause deviations from the all-zero path and have Hamming weight less than \( w_{\text{max}} \) have been considered. Correspondingly, we have \( L \) codeword error sequences, \( e_l \), for \( 1 \leq l \leq L \) and each of which has length of \( I_l \).

Under a particular channel realisation (channel state information-CSI), \( h = [h_1 h_2 \ldots h_{L_c}]^T \), the pairwise error probability for the error event caused by the \( l \)th error sequence, \( e_l \), starting at the \( i \)th position of the codeword can be written as [13]

\[
\text{PEP}_{l,i}(h) = Q \left( \sqrt{\frac{2E_c}{N_0} \sum_{j=1}^{I_l} |h_{i+j-1}|^2 \left( c_{v,i+j-1}^{(l)} - c_{v,i+j-1}^{(0)} \right)^2} \right)
\] (2)

where \( e_l \) is the \( v \)th component of the error sequence \( e_l \) and \( c_v^{(l)} \) and \( c_v^{(0)} \) denote the \( v \)th component of the correct codeword and the detected codeword due to the error event, respectively. Then the approximate RBER due to this error sequence becomes

\[
\text{RBER}_{l,i}(h) = a_l \text{PEP}_{l,i}(h) \] (3)

where \( a_l \) is the number information bit errors after Viterbi decoding as result of the error sequence \( e_l \).

Due to the all error sequences starting at the \( i \)th bit position, the union bound approximation of the RBER can be obtained as

\[
\text{RBER}_i(h) = \sum_{l=1}^{L} \text{RBER}_{l,i}(h) \] (4)

Assuming all \( L_c \) starting positions of the error sequences are equally likely and the maximum value Equation (4) can be tightened to 0.5 and the error event-based RBER estimate can be obtained as [17]

\[
\text{RBER}(h) = \frac{1}{L_c} \sum_{i=0}^{L_c} \min \left( \frac{1}{2}, \text{RBER}_i(h) \right) \] (5)

3. PROPOSED RBER ESTIMATION METHOD

Error event-based RBER estimation requires the storage of the dominant error events in the Viterbi Trellis and the computation of Equation (5). To reduce the computational complexity and the memory need of the error event-based RBER estimation method, in this section, we propose a simple method that is based on the outage capacity of the channel realisation \( h \).
The capacity of the a multicarrier system with $N$ subcarriers is given as [19]

$$C(h) = \sum_{i=1}^{N} \frac{B}{N} \log_2 \left( 1 + \frac{|h_i|^2}{\sigma^2} \right)$$  \hspace{1cm} (6)$$

where $B/N$ is the bandwidth allocation for each subcarrier and $|h_i|^2/\sigma^2$ denotes the SNR of the $i$th subcarrier.

For a single carrier system, data are correctly received if the instantaneous SNR of the channel is greater than some minimum required value. Otherwise, the receiver declares outage, i.e. the received bits are decoded incorrectly [19]. Therefore, we define this minimum required SNR to decode bits correctly as the OT. Then, the instantaneous outage capacity of a single carrier has the form

$$C_i = \left( 1 - I \left( \frac{|h_i|^2}{\sigma^2}, \gamma \right) \right) \frac{B}{N} \log_2 \left( 1 + \frac{|h_i|^2}{\sigma^2} \right)$$  \hspace{1cm} (7)$$

where $I(.)$ is an indicator function that is one if the carrier SNR is below the OT, $\gamma$, and zero otherwise, which is mathematically expressed as

$$I \left( \frac{|h_i|^2}{\sigma^2}, \gamma \right) = \begin{cases} 1 & \text{if } \frac{|h_i|^2}{\sigma^2} < \gamma \\ 0 & \text{otherwise} \end{cases}$$  \hspace{1cm} (8)$$

By putting Equation (7) into Equation (6), the instantaneous outage capacity $C_{out}$ of an OFDM system is written as

$$C_{out}(h) = \sum_{i=1}^{N} \left( 1 - I \left( \frac{|h_i|^2}{\sigma^2}, \gamma \right) \right) \frac{B}{N} \log_2 \left( 1 + \frac{|h_i|^2}{\sigma^2} \right)$$  \hspace{1cm} (9)$$

Note that Equation (9) can be written as an inner product of two vectors $x$ and $y$ of length $1 \times N$, whose elements can be respectively written as

$$x_i = \frac{1}{N} \left( 1 - I \left( \frac{|h_i|^2}{\sigma^2}, \gamma \right) \right)$$

$$y_i = B \log_2 \left( 1 + \frac{|h_i|^2}{\sigma^2} \right)$$  \hspace{1cm} (10)$$

Since all vector elements are non-negative and using Cauchy–Schwartz inequality

$$<x, y> = x^T y \leq \|x\|_2 \|y\|_2$$  \hspace{1cm} (11)$$

and using also the fact that $L_2$ norm of a vector is less than or equal to $L_1$ norm, i.e. $\|x\|_2 \leq \|x\|_1 \leq \|x\|_1 [20]$. $C_{out}(h)$ is bounded as

$$\sum_{i=1}^{N} \left( 1 - I \left( \frac{|h_i|^2}{\sigma^2}, \gamma \right) \right) \frac{B}{N} \log_2 \left( 1 + \frac{|h_i|^2}{\sigma^2} \right) \leq$$

$$\sum_{i=1}^{N} \left( 1 - \frac{1}{N} \right) \left( 1 - I \left( \frac{|h_i|^2}{\sigma^2}, \gamma \right) \right) \times \sum_{i=1}^{N} B \log_2 \left( 1 + \frac{|h_i|^2}{\sigma^2} \right)$$  \hspace{1cm} (12)$$

$$C_{out}(h) \leq c \left[ 1 - \frac{1}{N} \sum_{i=1}^{N} I \left( \frac{|h_i|^2}{\sigma^2}, \gamma \right) \right]$$  \hspace{1cm} (13)$$

where $c = \sum_{i=1}^{N} B \log_2 \left( 1 + \frac{|h_i|^2}{\sigma^2} \right)$ is a constant for a given channel realisation. Therefore, the upper-bound of $C_{out}(h)$ becomes a function of the instantaneous channel realisation, $h$, and the OT, $\gamma$. We define the ROR as the percentage of the subcarriers whose SNR is below the OT as

$$F_{\gamma}(h) = \frac{1}{N} \sum_{i=1}^{N} I \left( \frac{|h_i|^2}{\sigma^2}, \gamma \right)$$  \hspace{1cm} (14)$$

Hence, the upperbound of the $C_{out}(h)$ can be written in terms of ROR as

$$C_{out}(h) \leq c [1 - F_{\gamma}(h)]$$  \hspace{1cm} (15)$$

If the ROR of a channel realisation is small, it is expected that the channel has relatively high capacity and causes less number of bit errors. Therefore, we expect a minimum correlation between RBER and the reciprocal of ROR, $1/F_{\gamma}(h)$, for a given channel realisation and OT. Hence, the optimal value for the OT $\gamma^*$ can be found by minimising the average correlation coefficient, $\rho(\gamma)$, between the reciprocal of ROR and the RBER as

$$\gamma^* = \arg \min_{\gamma} \rho(\gamma)$$  \hspace{1cm} (16)$$

Assuming the statistics of the random vector $h$ is available, the average correlation coefficient, $\rho(\gamma)$, can be calculated as

$$\rho(\gamma) = \frac{\text{COV}_h \left[ \text{RBER}(h), 1/F_{\gamma}(h) \right]}{\sqrt{\text{VAR}_h \left[ \text{RBER}(h) \right] \times \text{VAR}_h \left[ 1/F_{\gamma}(h) \right]}}$$  \hspace{1cm} (17)$$

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where the notations $\text{COV}_h$ and $\text{VAR}_h$ are used to stress that the statistical averaging is performed over the random vector $h$ in the calculations of the covariance and variance, respectively.

Since the statistics of the channel realisation $h$ may not be available or be hard to obtain in practice, an estimate of the average correlation coefficient, $\rho(\gamma)$ is needed to determine the optimal OT. For this purpose, we first select $M = 100$ independent UWB channel realisations [6] for which the distance between the transmitter and the receiver is kept fixed at 3 m. We take the same average noise power per information and the link budget parameter values as specified in the TI’s proposal [4]. After that, we obtain RBER and $F_\gamma$ values for all realisations considered to estimate the average correlation coefficient as

$$\rho(\gamma) = \frac{\left( \frac{1}{M} \sum_{m=1}^{M} \text{RBER}(h_m) \right)^2 - \left( \frac{1}{M} \sum_{m=1}^{M} F_\gamma(h_m) \right)^2}{\sqrt{\left( \frac{1}{M} \sum_{m=1}^{M} \text{RBER}(h_m) - \frac{1}{M} \sum_{m=1}^{M} \text{RBER}(h_n) \right)^2} \left( \frac{1}{M} \sum_{m=1}^{M} F_\gamma(h_m) - \frac{1}{M} \sum_{m=1}^{M} F_\gamma(h_n) \right)^2}}$$

(18)

where $\text{RBER}(h_m)$ and $F_\gamma(h_m)$ denote the RBER and the ROR of the particular channel realisation $h_m$, respectively.

After estimating the average correlation coefficient using Equation (18), we perform a simple line search to determine the optimal value of the OT $\gamma^*$ using Equation (16).

Figure 2 shows the correlation coefficient versus OT graph for both the code rate of $r = \frac{1}{2}$ (320 Mbps) and $r = \frac{3}{4}$ (480 Mbps). At $r = \frac{1}{2}$, the optimum OT is obtained around $\gamma^* = 2$. Recall that the number of subcarriers whose SNR is greater than the OT should have negligible influence on the bit errors. Under certain CSI, as the code rate of the system increases, error-correction capability and therefore the RBER performance of the MB-OFDM system get worse. As a consequence some number of subcarriers whose SNR is slightly greater than $\gamma = 2$ would more likely introduce more errors. For this reason, the OT will be expected to increase. Simulation results in Figure 2 show that for the code rate of $r = \frac{3}{4}$, the optimal OT is observed to be around $\gamma^* = 3$, which agrees well with our initial expectation.

After determining the optimal OTs, we next plot $\log_{10}(\text{RBER})$ as a function of $1/F_\gamma(H)$ over many channel realisations in the Figure 3 for $r = \frac{1}{2}$ and Figure 4 for $r = \frac{3}{4}$, respectively. In both figures, each marker corresponds to an RBER of a particular channel realisation.

$$\text{RBER}(H) = \min(0.5, 10^{a(1/F_\gamma(H)) + b(1/F_\gamma(H)) + c})$$

(19)

where the model parameters $a$, $b$ and $c$ are obtained by minimising the mean square error for the quadratic-curve fitting.

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**Fig. 2.** Outage threshold versus correlation coefficient.

**Fig. 3.** RBER as a function of $1/F_\gamma(H)$ for various channel realisations and code rate $r = 1/2$ at $\gamma^* = 2$. 

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Fig. 4. RBER as a function of $1/F_\gamma(H)$ for various channel realisations and code rate $r = 3/4$ at $\gamma^* = 3$.

Table 1. Fitted quadratic curve parameters.

<table>
<thead>
<tr>
<th></th>
<th>$r = 1/2$</th>
<th>$r = 3/4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>0.62</td>
<td>0.0734</td>
</tr>
<tr>
<td>$b$</td>
<td>-5.0501</td>
<td>-1.462</td>
</tr>
<tr>
<td>$c$</td>
<td>4.58</td>
<td>1.643</td>
</tr>
</tbody>
</table>

fitting. The proposed RBER estimation model is upper-bounded by 0.5 since the fitted curve may yield a value near one for $F_\gamma^{-1}$ values around 0 The optimal values of these parameters are summarised in Table 1.

Our proposed RBER estimation method, which is expressed in Eq. 19, will be referred as ROC-based RBER estimation subsequently.

In order to obtain ROC based RBER estimation, we only need to store the optimal OT value and the curve-fitting parameters and perform two summation and two multiplication operations as can be seen from Eq. 19. Contrary to our method, the error event-based RBER estimation requires to store $L \times L_C$ bits in a memory unit and to perform $L \times L_C$ summation and $L + 1$ multiplication operations according to Equation (5) where $L$ is the number of considered error events and $L_C$ is the codeword length [17]. Hence, the ROC-based method is computationally simpler and requires less number of memory units. Please note that in the above analysis, we have assumed that the optimal threshold and the dominant error events are determined off-line before performing the ROC-based estimation technique and error event-based RBER estimation method, respectively.

In the next section, through the simulation, we analyse the performances of the ROC-based RBER estimation and error event based RBER estimation methods under various SNR.

4. SIMULATION RESULTS

In this section, we compare the performances of the ROC-based RBER estimate and the error event-based RBER estimates. The SNR of the MB-OFDM system is defined according to Reference [7] as

$$\text{SNR} = \frac{E_b}{N_0} = \frac{E[|x_k h_k|^2]}{N_0 \times r \times \log_2 M} \quad (20)$$

where $x_k$ represents the modulated symbol sent over one MB-OFDM sub-carrier, $M$ is modulation constellation size (e.g. $M = 4$ for QPSK) and $r$ is the rate of the convolutional coding. In the simulation, we use QPSK symbols with average unit energy (i.e. $E[|x_k|^2] = 1$) and UWB Channel Model 1, which models a line of sight channel valid for distances between 0 and 4 m [6]. Also, for the error event-based RBER estimation method, we consider error sequences with maximum Hamming weight $w_c = 23$ that corresponds to $L = 511$ dominant error events.

For the simulations, we first randomly select two independent UWB channel realisations. The empirical RBER values and the error event- and ROC-based RBER estimates for each of these realisations are obtained and plotted in Figure 5, for the code rate of $r = 1/2$. We also repeated the same experiment using the same realisations for the

Fig. 5. Empirical, error event-based and proposed RBER estimation performances for two independent channel realisations and code rate $r = 1/2$. 

\[
\]

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code rate of \( r = \frac{3}{4} \) in Figure 6. From Figures 5 and 6, one can deduce that for a given channel realisation, error event-based RBER estimation works well especially for high SNR values whereas the proposed RBER estimation method satisfactorily estimates the RBER for a wide range of SNRs.

As a second experiment, by taking the empirical RBER values as reference, we calculate the root mean square error (RMSE) for both estimation techniques in order to quantify and compare their accuracy. For a particular channel realisation \( m \) and certain SNR, let \( \rho_m(SNR) \), \( \hat{\rho}_{m,1}(SNR) \) and \( \hat{\rho}_{m,2}(SNR) \) denote the empirical RBER value, error event-based RBER estimation and ROC-based RBER estimation, respectively. The RMSE for error event-based RBER estimation, \( \text{RMSE}_1 \) and the RMSE for ROC based RBER estimation, \( \text{RMSE}_2 \), can be determined as

\[
\text{RMSE}_p(SNR) = \sqrt{\frac{1}{M} \sum_{m=1}^{M} (\rho_m(SNR) - \hat{\rho}_{m,p}(SNR))^2} \quad p \in \{1, 2\}
\]

We next obtain RMSE for both estimation techniques over various channel realisations under the same SNR and plot them in Figure 7. As seen from this figure, for both code rates, the RMSE of ROC based RBER estimation is smaller than that of error event-based RBER estimation.

Hence, the ROC-based RBER estimation is not only computationally simpler and requires less amount of storage but it is also more accurate with respect to the error event-based RBER estimation method.

5. CONCLUSIONS

In this paper, in order to estimate the instantaneous RBER of a convolutionally encoded MB-OFDM UWB system, we have proposed a method that relies on the instantaneous outage capacity of a multicarrier system. We showed that by selecting an optimal OT, the percentage of subcarriers whose signal to noise ratio is lower than this threshold is highly correlated with the actual BER of the channel. Using this, we have devised an efficient RBER estimation technique which is simple to implement, requires small amount of storage and models the RBER performance of the channel accurately for a wide range of SNR values.

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Mehmet Keskinöz got his M.S and PhD degrees from Electrical and Computer Engineering, Carnegie Mellon University, Pittsburgh (USA), in 1997 and 2001, respectively. In 2001, he joined the Electronics Engineering Programme of Sabanci University Istanbul, Turkey where he is now an Associate Professor. He is the director of the Communication Theory and Technologies (CTT) group. His research interests include signal processing for wired and wireless communications, UWB communications, multiband OFDM UWB systems, wireless mesh networks, magnetic and optical data storage systems, distributed detection and data fusion for wireless sensor networks, turbo and LDPC coding, synchronisation, digital watermarking. He is a recipient of Turkish NSF research grant on distributed detection in wireless sensor networks and Career Award on wireless mesh networks in August 2005. He is the co-guest editor of IEEE Communications Magazine January 2009 Special Issue on Advances in Signal Processing for Wireless and Wired Communications. He has been on the programme/organisational committees of several national and international conferences and he has served as a TPC member in many conferences including IEEE SIU, IEEE ICC, Globecom and Internmag etc. He is a reviewer of IEEE Transaction on Wireless Communications, Transaction Signal Processing and Transaction on Magnetics. He is a member of IEEE Communication Society, IEEE Signal Processing Society and Optical Society of America. For further details please check URL http://people.sabanciuniv.edu/keskinoz/.