Petr IVANIGA[1], Tomáš IVANIGA[2], Ján TURÁN[2], Ľuboš OVSENÍK[2], Michal MÁRTON[2], Dávid SOLUS[2], Jakub ORAVEC[2], Tomáš HUSZANÍK[2]

University of Žilina (1), Košice University of Technology (2), Slovakia

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The Influence of FWM with AWG Multiplexor in DWDM System

***Abstract**. This article focuses on the creation of the sixteen-channel DWDM (Dense Wavelength Division Multiplex) system according to the recommendation ITU-T G.694.1. Currently it is not possible to form a fully optical communication system without testing all non-linear effects possibly influencing its performance. The trend in high-speed transfer communication systems is using the multiplex, so we focused on the AWG (Arrayed Waveguide Grating) multiplexor/demultiplexor. For the purpose of this article we have created a DWDM system with the speed of 10Gbps where we compared two line codes, namely NRZ (Non Return Zero) and BRZ (Bipolar Return Zero) for the channel gaps of 12.5GHz and 100GHz. The individual codes were created in the „Matlab" programme and consequently implemented into the environment generated by „OptSim" by the RSoft company. The resulting signal was evaluated based on BER (Bit Error Rate) and the connected Q-factor for the channel No.3. The created system shows the influence of the system by the non-linear effect FWM (Four Wave Mixing) during the compression between the channels.*

***Streszczenie.** Niniejszy artykuł ma na celu utworzenie szesnastowego kanału DWDM (Dense Wavelength Division Multiplex) zgodnie z normą ITU-T G.694.1. Obecnie nie jest możliwe wdrożenie w pełni optycznego systemu komunikacyjnego bez testowania wszystkich zjawisk nieliniowych, które mogą działać w danym systemie w czasie rzeczywistym. Ponieważ w systemach transmisji danych o dużej szybkości wykorzystuje się multipleks, skupiliśmy się na multiplekserze i demultiplekserze AWG (Arrayed Waveguide Grating). W artykule zbadano system DWDM o szybkości 10Gbps, porównujący dwa kody linii NRZ (Non Return Zero) i BRZ (Bipolar Return Zero) dla kanałów 12.5 GHz i 100 GHz. Poszczególne kody zostały utworzone w programie Matlab, a następnie zostały wdrożone w środowisku OptSim przez firmę RSoft. Powstały system jest obliczany na podstawie szybkości błędu bitowego BER i związanego z tym współczynnika Q dla określonego kanału nr 3. Utworzony system pokazuje wpływ na system poprzez efekt nieliniowy FWM (Four Wave Mixing) podczas kompresji między kanałami. (**Wpływ FWM z multiplekserem AWG w systemie DWDM**).*

Keywords: AWG, BRZ, DWDM, FWM, NRZ
Słowa kluczowe: AWG, BRZ, DWDM, FWM, NRZ

Introduction

It has been a while since the era of the first data transfers. It started a significant development in the area of communication technologies which are currently on a very high level. Despite the advance in the communication systems there remains a problem of the insufficient width of the band. It was partially solved by the optical fibres which gradually replaced the old metal wiring throughout the networks, from the backbone networks to the access networks [1-3]. Offering the most modern services to the final customer (and the exponentially increasing demand on the bandwidth) caused that even the installed optical fibres were not able to offer sufficient due to its exploitation.

This problematic was solved by the multiplexing technique. From the current optoelectronic systems working on the base of multiplexing, the most common are the WDM systems (Wavelength Division Multiplexing) [4, 5]. In practice are used mostly the sub-systems DWDM (Dense WDM) and CWDM (Coarse WDM).

At the beginning were the stated systems utilised only for the backbone networks and they gradually found their way into the transport of metropolitan networks. It is just a question of time when will they be implemented into the final access networks. The transfer reliability of such systems (the transfer by an optical fibre) is influenced by many factors, generally divided into linear and non-linear effects [5-7]. This article deals with the non-linear effect FWM and its possible elimination in the output.

Arrayed Waveguide Grating

WDM multiplexor can be implemented in several ways. These methods can be divided into two categories: the filters based on resonators and the filters based on the interference. AWG multiplexors/demultiplexors are planar devices on the waveguide fields base (Fig. 1) [8]. They create the picture of the field at the input of the waveguide and the waveguide's output at the basic wavelength.

A waveguide arrangement into a grate are frequently called also PHASAR - Phased Arrays, or WGR - Waveguide Grating Routers. The AWG multiplexors/demultiplexors, together with the fibre Bragg grating and the selective filters, are the main parts of the WDM systems [8-10]. The fibre is connected to the waveguide which continues after a short distance as several parallel narrow waveguides.

These waveguides form approximately equally arched centric bends with various length. Then after a short distance they reconnect again into a wide waveguide. The number of such branches equals the amount of the contribution channels of the input signal. The input (single mode) channel waveguide flows into the area of the planar waveguide where it behaves as a point source. The radiation in the planar waveguide converges and creates a circular wave area.

On its opposite side are the rows of channel waveguides receiving this radiation. Each channel accepts radiation with the same phase. The set is constructed in a way that ton the middle multiplexor wavelength the optical lengths of the individual channels differ by an integral multiple of the wavelength.

The optic radiance exiting the channels in the output area of the planar waveguide is of the basically same phase on this wavelength (the phase difference representing an even multiple π is not evident). Rows of the output waveguides create the so-called equiphase area, just as they do at the channel entry. The radiance in the output planar section concentrates into the middle output waveguide [8, 10]. The phase shift between the output of the channels changes at small wavelength changes so that at the output the resulting equiphase area turns by the angle equivalent to the wavelength.

In this case the radiance concentrates into another output channel. This way the wavelengths are separated. The device is also usable in the 'opposite direction', i.e. for joining (multiplexing) of the individual wavelengths from various sources into one output fibre.

The AWG multiplexors also use so-called supervision channel independent of the used data transfer (CWDM or DWDM) [11, 12]. For this purpose it is used a data channel with transfer speed up to 100Mbit.s^{-1} on the reserved wavelength of 1510nm. The most significant technologies utilising AWG are the technology "*Silica-on-Silicon*" (SoS) and the semiconductor technology "*Indium phosphide*" (InP).

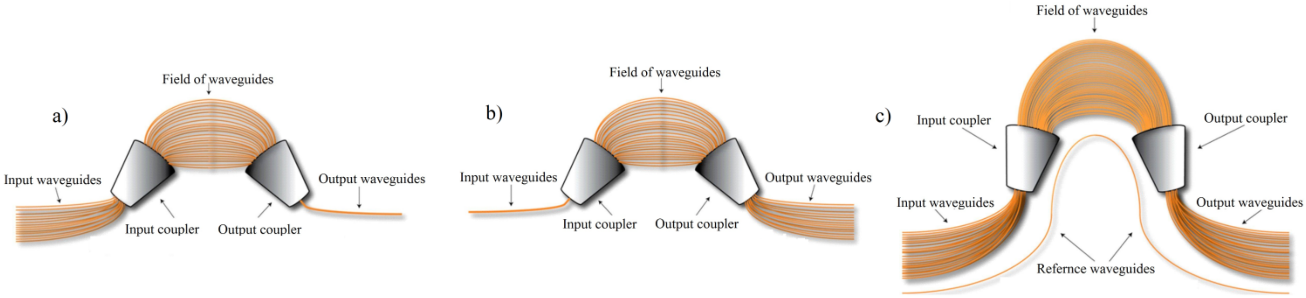

Fig.1. a) AWG multiplexer, b) AWG demultiplexer, and c) AWG configuration.

Mathematical description of AWG

The basic properties of AWG are defined by the equation:

$$(1)\ \theta_{i,IN} = \frac{m}{n_S d}\left\{\lambda_i - \lambda_c\left[1 + \frac{1}{n_{wg}}\frac{dn_{wg}}{d\lambda}\left(\lambda_i - \lambda\right)\right]\right\} - \theta_{i,OUT},$$

in which θ_{IN} and θ_{OUT} represent the angles between the middle axis and the input (the output respectively) waveguides, *m* stands for the order mode of waveguide for the signal wavelength λ_i and λ_c is the central wavelength. The optical grade angle is marked as *d*, n_s and n_{wg} are the effective refractive indexes [10, 13]. This equation also allows chromatic material dispersion.

The extent of the widening fields in AWG can be obtained by the difference of length ΔL between neighbouring waveguides equals an integral number of the wavelengths *m* inside AWG:

$$(2)\qquad \Delta L = m \cdot \frac{\lambda_c}{n_{eff}},$$

where field order mode is defined by the integral number *m*, λ_c is the central wavelength, n_{eff} represents the effective phase index and the fraction λ_c / n_{eff} corresponds with the wavelength inside the waveguide field [14]. When enlarging the field by ΔL, the phase difference can be defined by the relation:

$$(3)\qquad \Delta\phi = \beta \Delta L,$$

while

$$(4)\qquad \beta = 2\pi v n_{eff} / c,$$

where β represents the propagation constant in the waveguide, $v = c / \lambda$ is the frequency of the propagated wave and *c* refers to the speed of light in a vacuum.

A transversal shift *ds* from the axis alongside the image plane for the frequency unit (change of frequency) *dv* is referred to as space dispersion D_{sp} expressed by:

$$(5)\qquad D_{sp} = \frac{ds}{dv} = \frac{1}{v_c} \cdot \frac{n_g}{n_{FPR}} \cdot \frac{\Delta L}{\Delta \alpha},$$

in which the refraction index in the unrestrained propagated area is marked as n_{FPR}, $\Delta\alpha$ represents the variance between waveguides in the input or the output parts of AWG, n_g is the group refraction index of waveguide:

$$(6)\qquad n_g = n_{eff} + v\frac{dn_{eff}}{dv},$$

AWG has a periodic response. The period within the frequency domain is called FSR (Free Spectral Range):

$$(7)\qquad FSR = \frac{v_c}{m}\frac{n_{eff}}{n_g}$$

Four Wave Mixing

FWM is a type of the Kerr effect. This non-linear effect is caused at the light propagation of two or more wavelengths in one optical fibre [15-17]. It results in a new light wave in the optical fibre, called idler, whose wavelength is not identical with as the wavelengths of the input light [18, 20]. When three signals with the frequency f_i, f_j and f_k are propagated in one optical fibre, through the interaction betweeen these signals a new signal will be generated with the frequency of:

$$(8)\qquad f_{ijk} = f_i + f_j + f_k.(i, j \neq k).$$

An example for FWM is on Fig. 2.

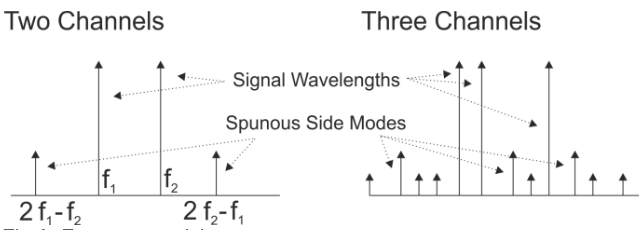

Fig.2. Four wave mixing

The output power, the power of the newly created signal can be expressed as:

$$(9)\quad P_F(L) = \frac{1024\pi^2}{\pi^4 \lambda^2 c^2}(D_x) \cdot \frac{P_i(0)P_j(0)P_k(0)}{A_{ef}^2} e^{-\alpha L} \cdot \frac{(1-e^{\alpha L})^2}{\alpha^2}\eta,$$

where P_i, P_j and P_k are the powers of the input components with the frequency f_i, f_j a f_k, P_F is the power of the signal created by FWM with the frequency f_{ijk}, λ is the wavelength, *n* is the refraction index, *c* is the speed of light in vacuum, α is the loss coefficient, *L* is the length of fibre, A_{eff} is the effective area of the optical fibre core, *D* is the degrading factor and *X* is the non-linear susceptibility. η represents the dependence between the effectivity of FWM and the phase discord:

$$(10)\qquad \eta = \frac{\alpha^2}{\alpha^2 + (\Delta\beta)^2} \cdot \left[1 + \frac{4e^{-\alpha L}\sin^2(\Delta\beta \frac{L}{2})}{(1-(e^{-\alpha L}))^2}\right],$$

where $\Delta\beta$ represents the phase discord. Then $\Delta\beta$ is

(11) $$\Delta\beta = \beta(f_i) + \beta(f_j) - \beta(f_k) - \beta(f_{fi}),$$

where the coefficient β is the propagation constant. Effectivity η is maximal, so its value is 1, when $\Delta\beta = 0$. Effectivity decreases with the increasing frequency . FWM is a non-linear effect with degrading impact on multichannel optical transfer systems [21-23]. Due to this, FWM is the effect to be avoided in DWDM transfer systems. But for some applications this effect is desired, offering technological base for the optical devices. FWM also represents the grounds for measuring non-linearity and chromatic dispersion in optical fibres.

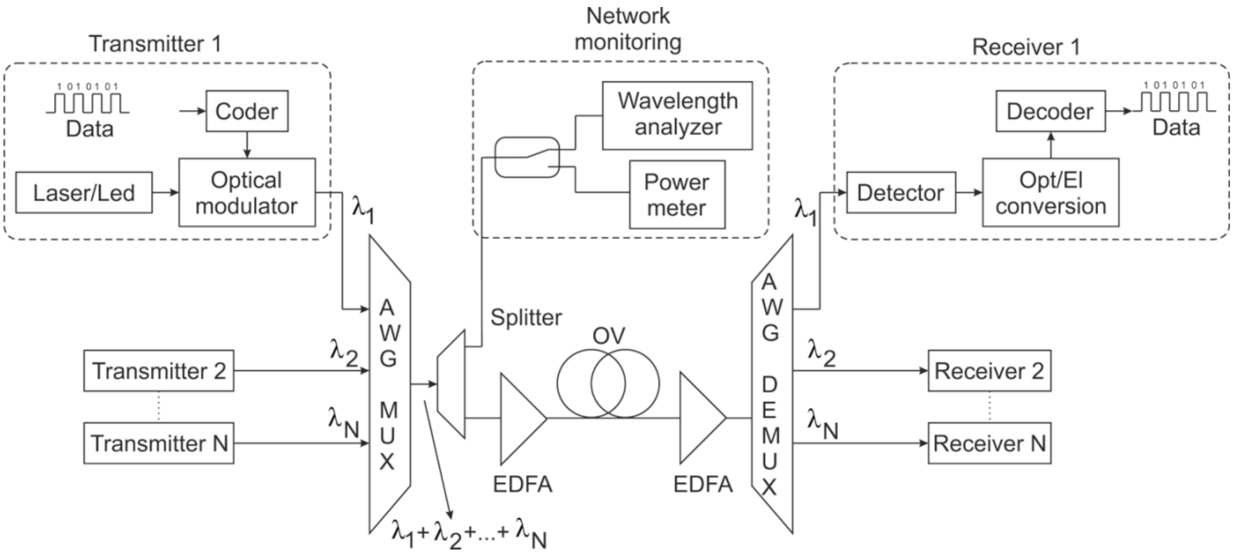

Fig.3. Creation of DWDM system

Creation of DWDM Using AWG to Observe the FWM Effect

A complete scheme of the optical networks was designed in the simulation programme *"OptSim"* [19, 24, 25]. The scheme is illustrated on Fig. 3. The aim of this scheme was the comparison of the optical codes NRZ and BRZ created in the environment *„Matlab"* and consequently implemented into the *„OptSim"* [26, 27].

Creation of a 16 channel DWDM using NRZ and BRZ

The fully optical communication system was created according to the recommendation ITU-T G.694.1. The transmitting part consisted of sixteen basic blocks with each block comprising of a data source, laser, modulator and a coder. The transmitting levels of the laser diode were the same for all simulations: 0V (Low Level) and 5V (High Level). The frequency of this laser diode varied. Frequencies were chosen gradually with the gaps from 100GHz to 12.5GHz, with the special attention given to the middle value at 193.1THz. The FWM effect was not noticeable in the gap setting of 100GHz and 50GHz. Changing to 25GHz with the same amount the FWM started to show and the resulting spectra were projected at 12.5GHz. The reason for changing the gaps was to show the non-linear FWM effect, with the gap of 12.5GHz corresponding to the UDWDM (Ultra DWDM). The width of the transmitted ray was set to 20MHz.

Bit speed of the transmitting channels is 10Gbps and it was constant for every simulation. The modulation utilised was the MachZehnder type. The coding blocks were generated in the environment Matlab. For the first measurement NRZ was chosen - it is the most commonly used code in today's DWDM systems. Its levels are: Low Level = 0V and High Level = 5V. Fig. 4 displays the comparison of the input and the output spectrum using the NRZ coding with the gap between the individual channels of 12.5GHz.

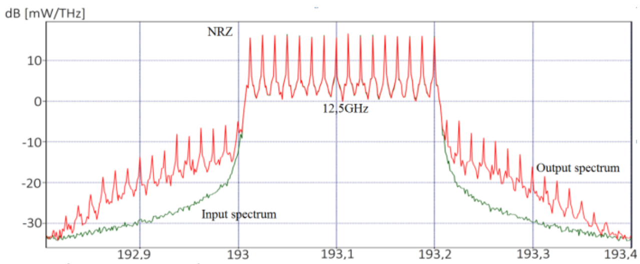

Fig.4. Comparison of the input and output spectre using NRZ and a gap of 12.5GHz.

The second block BRZ operates with the values of -2.5V, 0V and 2.5V. The logical 1 is represented by the value 2.5V, in the middle of each transmitted bit the value returns to zero. Fig. 5 shows the comparison of the input and output spectrum using the BRZ coding with the gaps between the individual channels of 12.5GHz.

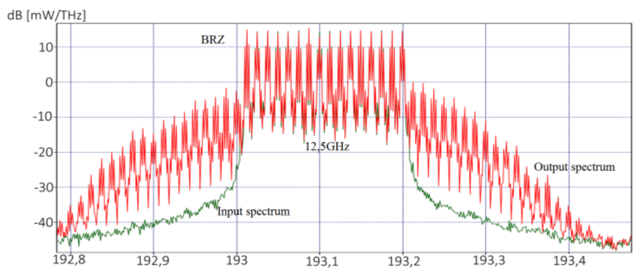

Fig.5. Comparison of the input and output spectre using NRZ and a gap of 12.5GHz.

The frequency spectrum of three channels using the NRZ and BRZ block coding are displayed in Fig. 6. On Fig. 6a) is the transmitting spectre using NRZ and on Fig. 6b) is the transmitting spectrum of three channels using BRZ block coding.

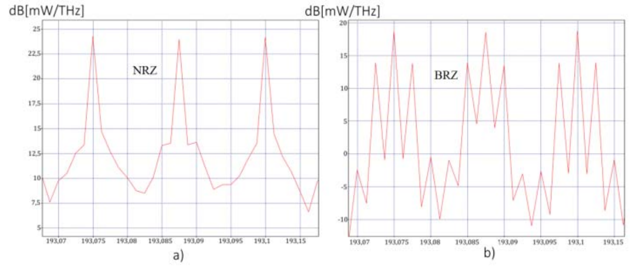

Fig.6. Comparison of the transmitted spectra of NRZ and BRZ signals.

The key component was the AWG multiplexor/ demultiplexor. Its role was to receive the individual optical signals with their different wavelengths and to send them through the optical fibre. After AWG mux was placed the optical amplifier type Booster, to amplify the input signals and which had a constant output power of 3dBm. The other two amplifiers were set to produce a constant amplified signal as their output. This amplification was 20dB. These amplifiers compensated the loss caused by the cable wiring.

Among the optical amplifiers were two blocks of optical fibre 100km long. The losses caused by the fibre attenuation were compensated by the amplifiers. The fibre used had the attenuation of 0.33dB/km during all simulations, according to the standard G-652.D. The dispersion λ_0 was set to the value of 1.322μm and the group index n_1 to the value of 1.4886. The chosen non-linear model had a non-linear refraction index n_2 $2.6{\cdot}10^{-20}$, its diameter was 8.3μm. During the simulations we disregarded SBS (Stimulated Brillouin Scattering), PMD (Polarisation Mode Dispersion) and the Raman effect.

The optical signal enters the AWG demultiplexor after its amplification. Here the total loss was 3dB and the filter type was set to "*Trapezoidal*". Optical receiver is placed at the output of DWDM system. Representation of the simulated values was based on the method "*MonteCarlo*". In the receiver was the Bessel filter with bandwidth 10GHz and the APD photodetector had quantum efficiency 0.9.

The resulting values of BER and Q-factor

All simulations were evaluated based on values of their BER and Q-factor. In fully optical communication systems it is necessary for BER to achieved values below 10^{-12}. All our simulations with the used gaps are in Table I.Fig. 7a) offers the final results of BER for the channel No. 3 with the gap between the channels of 100GHz. BER was $7.86528{\cdot}10^{-31}$ with the corresponding Q-factor of 7.8433. Fig. 7b) records the result values of BER for the channel No. 3 with the gap between the channels of 12.5GHz. BER was $7.74809{\cdot}10^{-13}$ with the corresponding Q-factor of 3.2111.

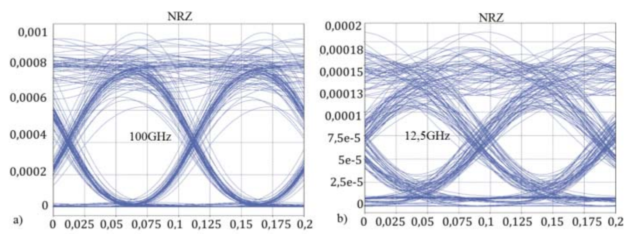

Fig.7. Resulting values of BER for NRZ coding at 100GHz and 12.5GHz.

Fig. 8a) shows the final BER values for the channel No. 3 with the gaps between the channels of 100GHz. BER was $9.4897{\cdot}10^{-29}$ with the corresponding Q-factor of 7.952.

Fig. 8b) displays the result values of BER for the channel No. 3 with the gap between the channels of 12.5GHz. BER was $1.9679{\cdot}10^{-9}$ with the corresponding Q-factor with the value of 4.0256.

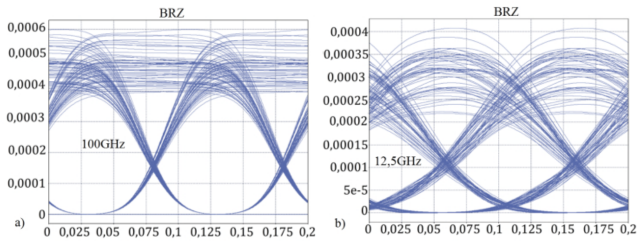

Fig.8. Resulting values of BER for BRZ coding at 100GHz and 12.5GHz.

Table 1. Result values for NRZ and BRZ coding

Type of coding	**Number of channels**	**Gap between the channels [GHz]**	**BER**	**Q-factor**
NRZ	8	100	$5.73{\cdot}10^{-22}$	6.6162
NRZ	8	12.5	$8.34{\cdot}10^{-12}$	3.0215
NRZ	16	100	$7.86{\cdot}10^{-31}$	7.8433
NRZ	16	12.5	$7.74{\cdot}10^{-13}$	3.2111
BRZ	8	100	$9.73{\cdot}10^{-22}$	6.5992
BRZ	8	12.5	$2.11{\cdot}10^{-09}$	3.1564
BRZ	16	100	$9.49{\cdot}10^{-29}$	7.9521
BRZ	16	12.5	$1.97{\cdot}10^{-09}$	4.0256

Conclusion

The aim of this article was to create a fully optical communication system using AWG multiplexor for the purpose of studying the FWM effect. During the system's operation we changed the coding blocks and because of that it was possible to compare the FWM effect on the individual channels in DWDM. The whole system was designed for 8 and 16 channels with the central frequency of 193.1THz. Using NRZ with the gaps of 12.5GHz the FWM effect was not visible in such an extent as when the BRZ was used (Fig. 4 and Fig. 5).

When using the BRZ the new components were displayed in a greater extent which was visible in the resulting values. At stage of system designing it needs to be taken into consideration that the more channels are in the multiplex, the more prominent the FWM effect will be. As BER is acceptable only under the value of 10^{-12}, all our designed schemes are suitable except for the one using BRZ with the gap of 12.5GHz with 8 and 16 channels.

Table I shows that the more dense DWDM system, the worse values of BER and lower Q-factor it will have.

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Authors: *Ing. Petr Ivaniga, PhD University of Žilina, Faculty of Management Science and Informatics, Department of Information Networks, Univerzitná 8215/1, 01026, Žilina, Slovakia, petr.ivaniga@fri.uniza.sk. Ing. Tomáš Ivaniga, Dr.h.c. prof. RNDr. Ing. Ján Turán, DrSc, doc. Ľuboš Ovseník,PhD, Ing. Michal Márton, Ing Dávid Solus, Ing. Jakub Oravec and Ing Tomáš Huszaník., Košice University of Technology, Faculty of Electrical Engineering and Informatics, Department of Electronic and Multimedia Communications, Vysokoškolská 4, 04120, Košice, Slovakia, Emails: {tomas.ivaniga, jan.turan, lubos.ovsenik, michal.marton, david.solus, jakub.oravec, tomas.huszanik}@tuke.sk*

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