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EXTENDING TRANSCEIVER CAPACITY WITH A SCALABLE SPECTRUM SLICING TECHNIQUE FOR OPTICAL ACCESS NETWORKS

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The paper demonstrates a spectrum slicing technique applied to PAM-4 modulated signal spectrum at 40 Gbaud baudrate for optical access networks. The spectrum slicing is shown in VPIphotonics simulation environment, where characteristics of key components are measured in the laboratory and loaded into the corresponding elements of the simulation setup. The spectrum of electrical baseband signal is sliced in four slices introducing an additional degree of freedom – higher data rate signals can be transmitted by re-using already-existing lower bandwidth transceiver components in an optical access network. This tackles the electronic bottleneck enabling the on-demand variable bandwidth allocation and extends the life span of opto-electrical components during network upgrades. Furthermore, the use of the proposed spectrum slicing technique has a positive side-effect when it comes to security concerns, as the signal spectrum is divided into slices. All slices are necessary to obtain the reconstructed signal and even if an eavesdropper gets most of the slices it is still not enough. The simulation results show that the proposed spectrum slicing and stitching approach is a viable solution to overcome the problem of limited frequency bandwidth of electrical components.

Keywords: *Fast Fourier Transform (FFT), optical access network, pulse amplitude modulation 4 (PAM-4), spectrum slicing, transceiver.*

1. INTRODUCTION

The bandwidth of electrical and opto-electrical components of a transceiver is a major limiting factor causing a bottleneck in fiber optic networks [1]–[3]. Spectrum slicing aims to reuse the existing transceiver's low bandwidth equipment (such as Mach-Zehnder modulator (MZM) and PIN photodiode) to satisfy high bandwidth demands in optical access networks. This technique uses digital signal processing (DSP) to slice the electrical baseband data signal into parts (i.e., spectrum slices). These sliced parts are transmitted through the wavelength-division multiplexed passive optical network (WDM-PON), and then the reconstructed signal is assembled at the receiver [4]–[6].

Next-generation optical access networks, for example, Super-PONs standardized by IEEE 802.3 Working Group [7], must be adaptive when it comes to the ensured data transmission frequency bandwidth. The bandwidth must change dynamically depending on the user demand. In this regard, spectrum-slicing solutions with DSP have a potential to overcome the restrictions of the limited frequency bandwidth of electrical components. Spectrum slicing also introduces another level of security in optical access networks. The signal spectrum is divided into slices and all slices are necessary to obtain the reconstructed signal. Even if an eavesdropper gets most of the slices, it is still not enough to get the reconstructed signal. M-PAM allows transmitting $\log_2(M)$ more data bits over the same bandwidth as non-return-to-zero (NRZ). Therefore, we can slice M-PAM optical signal bandwidth in a smaller number of slices to transmit higher bit rate signals (e.g., doubled or quadrupled) compared to previous research, where NRZ is used [1], [2], [4]–[6]. The authors in [2] achieved maximum transmission rate of 56 Gbit/s and in [5] the maximal reach of 40 km for 10 Gbit/s. In addition, [8] shows that potential energy consumption reduction is measured in hundreds of wats if spectrum slicing using DSP is applied. Even though DSP block adds to energy consumption that depends on the number of operations to perform and specific ASIC implementation, the overall energy consumption is lowered. Effective modulation formats in sense of bits per symbol, for instance, M-PAM, can further reduce power by minimising the required energy to process one bit. This fact can significantly reduce operational expenditure (OPEX) [9]. However, M-PAM implementation is challenging since it has more signal levels and is more sensitive to signal distortions.

The next consideration is the multiplexing scheme for transmitting slices over the network. It depends on the application type – non-real-time and real-time [5]. Non-real-time applications can be supported by time-division-multiplexing (TDM). However, additional synchronization and scheduling techniques are required. In contrast, for real-time applications, wavelength division multiplexing (WDM) allows transmitting each slice on a separate wavelength. WDM also boosts network upgrade to achieve an increase in capacity and reach. Furthermore, no additional inverse Fast-Fourier transform (IFFT) is needed before the WDM multiplexer [8]. It is important to mention that sliceable transceivers have also been studied for metro networks [10], where a high-capacity flow of 100 Gbit/s is established by slicing the signal into two 50 Gbit/s slices [11]. However, metro networks are out of scope of this research as they use different modulation format –

DP-16QAM at 32 Gbaud.

This paper aims at studying a configuration of spectrum-sliced optical access network that requires a lower number of slices to transmit a higher bit rate signal, and simultaneous transmission of these slices over the network. As a result, we have built a 40 Gbaud PAM-4 system with a spectrum slicing technique in VPIphotonics Design Suite [12] supported by MATLAB [13] software. The component characteristics are measured in laboratory and loaded into simulation setup. The bandwidth of 40 Gbaud PAM-4 modulated optical signal is sliced in four slices, each having 10 GHz bandwidth, and transmitted simultaneously over WDM channels. This study demonstrates that telecommunications service providers can ensure the transmission of at least four times broader bandwidth signals than the already-existing equipment allows. The number of slices is determined by the bandwidth of a 10 Gbit/s transceiver and the data signal. 10 Gbit/s electronic equipment is currently the most widely used in the telecommunications industry. We use a transceiver with -3 dB bandwidth of 12 GHz and 40 Gbaud PAM-4 data signal. A higher baudrate would result in the necessity to upgrade electronic components such as digital-to-analogue converter (DAC) and analogue-to-digital converter (ADC) to support 40 GHz frequency bandwidth. That, in turn, means capital investments for substituting the already existing optical access network equipment. Four slices are chosen since they occupy the whole bandwidth of a transceiver and allow using 10 Gbit/s equipment. Additionally, the spectrum slicing technique can be helpful for WDM-PON networks used to deploy 5G communications, where each wavelength should have at least 25 Gbit/s or higher data rates [14]–[16].

The rest of the paper is structured as follows. Section 2 explains how the spectrum slicing technique is implemented using a DSP block. The simulation setup of the optical access network in the downlink to analyse the spectrum slicing technique is shown in Section 3. Section 4 presents the obtained results as spectra and waveform of each slice, eye diagram, and bit error rate (BER) correlation diagrams of the reconstructed signal. This section also provides a discussion of the obtained results. Finally, Section 5 concludes with the usefulness of the proposed technique in avoiding the limited bandwidth problem.

2. SPECTRUM SLICING USING DSP BLOCK

Signal slicing divides a high bandwidth electrical signal spectrum into several lower bandwidth signals. Signal slicing and stitching at the transmitter's and receiver's sides require DSP, as shown for the downlink scenario in optical access networks in Fig. 1. The figure demonstrates signal slicing in four slices used in this research.

Spectrum slicing is implemented with a DSP block in the optical line terminal (OLT), but the stitching of a signal is implemented with another DSP block in the optical network terminal (ONT). The process of spectrum slicing starts when the DSP block receives PAM-4 signal in the time domain. The first operation is to transfer the electrical signal from the time domain to the frequency domain using Fast Fourier Transform (FFT). Then N mathematical rectangular filters with no attenuation and latency divide the spectrum of a signal into slices. After that, slices in the passband (except the first slice) are down-converted to the baseband. Finally, each slice is converted back to the time domain using inverse Fast Fourier Transform (IFFT) to be sent to electro-optic modulators. The proposed spectrum slicing method is scalable in bandwidth.

The process of signal stitching is similar at the receiver's side but in reverse order as spectrum slicing. The received electrical signals representing slices are converted to the frequency domain using FFT. Next, all slices except the first one are up-converted to the initial passband position. The reconstructed signal is obtained by combining all slices into one spectrum. Finally, the signal is converted back to the time domain using iFFT and sent to the signal analyser for quality measurements.

The electrical signal with N GHz frequency bandwidth can be sliced into multiple slices. The number of slices depends on the electrical signal data rate and the signal is sliced in the exact number of slices for each slice to match the transceiver bandwidth [5], [6].

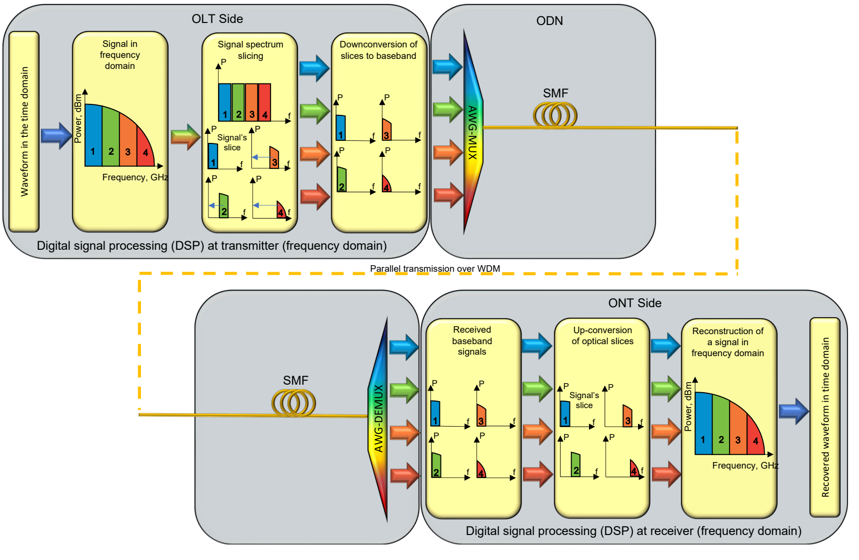

Fig. 1. The proposed principle of slicing an input electrical baseband signal into equal bandwidth slices at the OLT, and a reconstruction of the original signal waveform at the ONT.

Signal slices are transmitted simultaneously over different WDM channels in an optical distribution network (ODN). The used bandwidth of the electro-optical and electrical components of the transceiver is scalable and the necessary electrical bandwidth of the high-frequency network hardware is at least two times smaller than in the case of the initial electrical signal before slicing.

3. STRUCTURE OF THE SETUP

The simulation setup of a WDM-PON system employing spectrum slicing in an OLT to divide 40 Gbaud PAM-4 signals into four 10 GHz slices is shown in Fig. 2. Each slice is transmitted in parallel on a separate wavelength in ODN over ITU-T G.652.D single-mode fiber (SMF) span. Each slice is received, returned to the initial passband position, and the original signal is reconstructed in an ONT. Channel spacing is chosen to be 100 GHz according to the ITU-T G.694.1 recommendation. The 100 GHz channel spacing is chosen over 50 GHz to reduce the crosstalk between adjacent 40 Gbaud PAM-4 channels and improve the BER performance. The parameters of various simulation blocks are set according to equipment available in our lab for further experimental validation purposes.

OLT starts with 40 Gbaud PAM-4 signal generation, which is shown as a PAM-4 block. In a simulation, two pseudo-random bit sequences (PRBS15) with a length of 2^{15} -1 are fed to separate NRZ encoders. The outputs of NRZ coders are combined with a power coupler to form a 40 Gbaud PAM-4 signal. Generated PAM-4 data signal is sent to the DSP block (explained in detail in the previous section). DSP block is implemented in MATLAB and performs spectrum slicing in the simulation environment. The sampling rate of 16 samples per symbol and a data rate of 40 Gbaud are the main parameters considered. We obtain N number of slices as separate waveforms at the output of the DSP block (after the digital-to-analogue converter (DAC)). The signal slices (waveforms) are then sent to MZMs in OLT transmitters. Individual waveforms or slices (N = 1…4) that are separately sent to MZMs are shown in Fig. 2 as dashed lines for simplicity (otherwise slices are sent over individual electrical lanes).

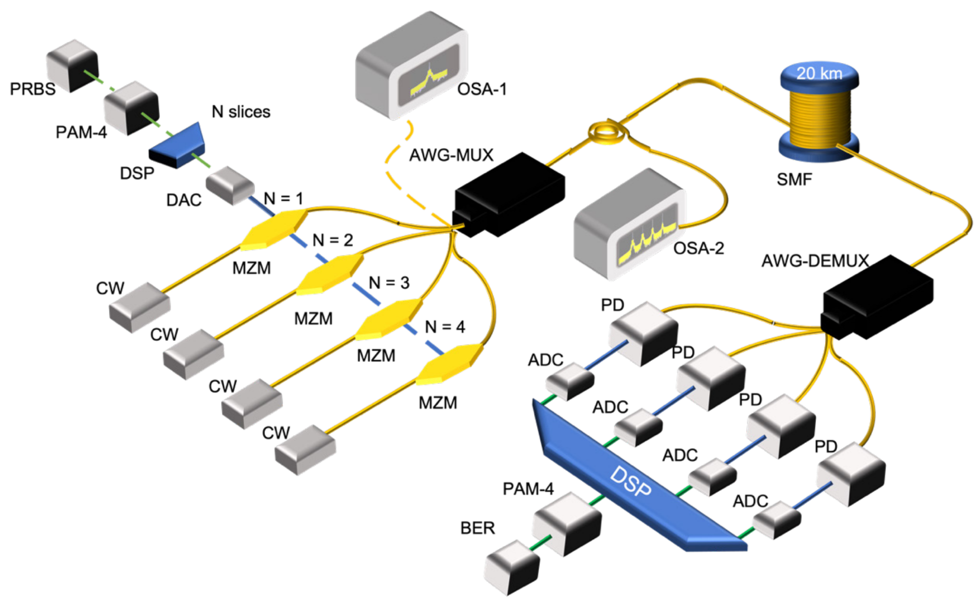

Fig. 2. The WDM-PON setup to analyse PAM-4 signal transmission using a spectrum slicing technique.

OLT transmitter consists of a continuous wave (CW) laser, MZM modulator, DC block for MZM biasing. CW lasers provide optical carriers with an output power of +15 dBm and central frequencies of 193.1, 193.2, 193.3, and 193.4 THz – one for each slice. Channel spacing of 100 GHz ensures negligible optical crosstalk. The laser linewidth is set to 100 kHz, and the side mode suppression ratio to 30 dB. MZM modulator with an extinction ratio of 20 dB modulates the waveform onto an optical carrier. We have measured the 12 GHz MZM amplitude response in a laboratory and loaded it into the simulation to ensure modulator operation as close to the laboratory as possible. Arrayed waveguide grating multiplexer (AWG-MUX) combines modulated optical carriers from all OLT transmitters for further transmission over ODN. AWG-MUX has 3-dB bandwidth of 75 GHz. ODN is implemented as variable-length ITU-T G.652 single-mode fiber (SMF) span with 0.02 dB/km attenuation and 16 ps/nm/km dispersion coefficient at 1550 nm reference wavelength. An optical spectrum analyser (OSA-1) is used before an AWG-MUX to measure the spectra and waveform of each slice, but OSA-2 measures all combined slices before the SMF transmission.

An AWG-DEMUX, with a 3-dB channel bandwidth of 75 GHz, demultiplexes the signal into four separate slices after the signal transmission over ODN. Then each slice is sent to the corresponding PIN photodiode in the ONT receiver. PIN photodiode has 0.7 A/W responsivity and BER 10^{-12} at a sensitivity level of -20 dBm. PIN receives a slice and converts it to an electrical signal to be sent to the DSP block for the reconstruction of the original signal. We have also measured the amplitude response of a 3-dB bandwidth of a 12 GHz PIN photodiode in a laboratory and loaded it into the simulation to ensure photodiode operation as close to the laboratory as possible. After analogue-to-digital converter (ADC) converts electrical signal into a digital signal, the DSP block reconstructs the original signal, and we obtain the original electrical signal in the time domain (waveform) at the output of this block. BER estimation of the reconstructed signal is performed in the VPI simulation setup.

4. RESULTS AND DISCUSSION

We use an eye diagram (Fig. 3a) to qualitatively assess the signal before the fiber transmission. Eye diagrams of the reconstructed 40 Gbaud PAM-4 signal after the B2B transmission are shown in Figs. 3b and 3c.

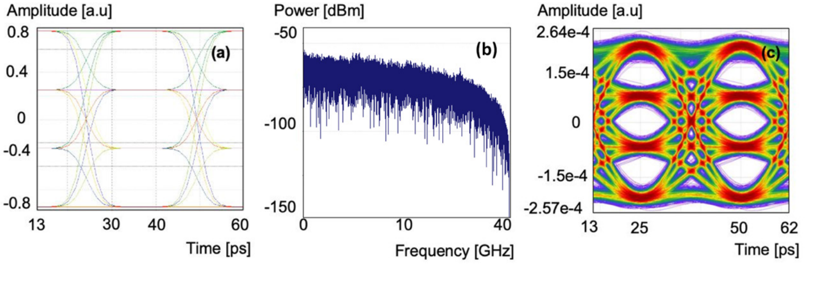

Fig. 3. Diagram of the signal before the fiber transmission, where (a) the eye diagram of the original electrical signal, (b) the electrical spectrum of the reconstructed PAM-4 signal, and (c) the eye diagram of the reconstructed 40 Gbaud PAM-4 signal after B2B transmission.

As shown in Fig. 3b, the spectrum of the reconstructed signal after B2B transmission is relatively smooth. No amplitude fluctuations can be seen in the transition areas of each slice. The eye diagram of the received signal is well open, and all four levels are distinguishable as no time skew or amplitude compression is observed in Fig. 3. The BER value after the B2B transmission is 1.1×10^{-7}, and the obtained BER value is well below the FEC threshold (e.g., 1×10^{-3}) [17]. Spectrum slicing and the original signal reconstruction process reduces the BER value from ideal to 1.1×10^{-7}. This aspect must be considered before the signal transmission over the SMF fiber span.

Next, we show the optical spectra and the waveform of each slice. Observing if the shape of optical spectra and waveform of each slice does not change during signal transmission is critical. The change means that the reconstruction of the original signal is impossible. That, in turn, means that spectrum slicing cannot be used to transmit higher bandwidth signals over a lower bandwidth transceiver. Figure 4 summarises the optical spectra of each slice at the output of the OLT transmitter. Figure 5 shows optical spectra of all four slices at the output of AWG-MUX and after the transmission over SMF fiber. The central frequency in Figs. 4 and 5 is set to 193.25 THz for representation purposes. Accordingly, the central frequencies of the carriers are 193.1, 193.2, 193.3, and 193.4 THz.

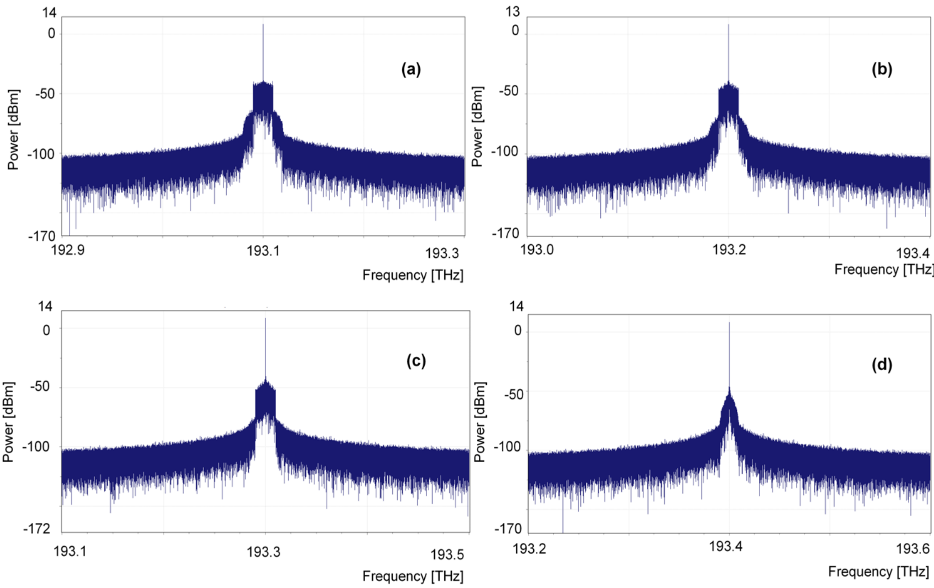

Fig. 4. Optical spectra of each slice on the output of OLT transmitters (a, b, c, d).

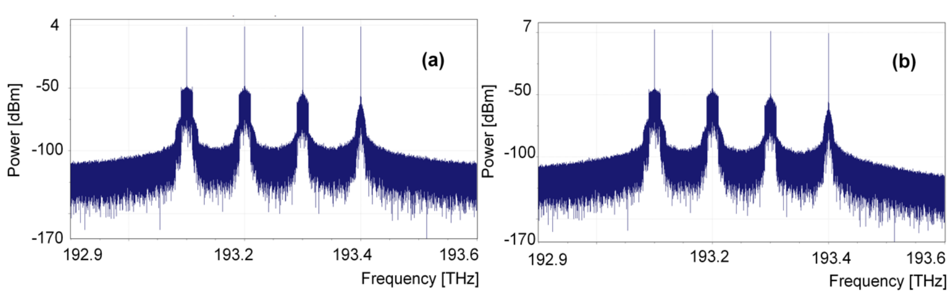

Fig. 5. Optical spectra of four slices – (a) at the output of AWG-MUX and (b) at the output of transmission fiber.

The spectrum of each slice retains the shape after the AWG-MUX combines signals coming from the OLT transmitters if comparing Figs. 4a–d. The shape of the spectrum also does not change after signal transmission over ODN as seen by comparing Figs. 5a and 5b. The only difference here is the attenuation, but all spectral components are attenuated evenly, which will not affect signal reconstruction. We can already state that signal reconstruction is possible as the spectra does not change, and spectrum slicing is viable to fulfill its purpose.

We perform BER counting for the received PAM-4 signal after reconstructing the original signal to assess the transmission quality quantitively. Figure 6 illustrates eye diagrams of the reconstructed PAM-4 signal after 10 km and 20 km transmission distances, respectively. As one can see from Figs. 6a and 6b, the eye stays relatively open despite the increasing transmission distance. The obtained BER values for 40 Gbaud PAM-4 signal sliced in four slices are 1.1×10^{-6} and 2.6×10^{-4} for 10 km and 20 km transmission distances, respectively. These BER values are below the FEC threshold of 1×10^{-3}.

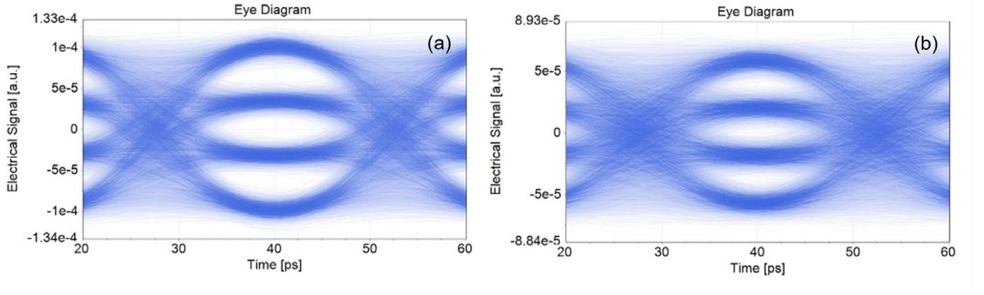

Fig. 6. Eye diagrams for the reconstructed 40 Gbaud PAM-4 signal after (a) 10 km and (b) 20 km transmission distance.

We use the BER correlation diagram to assess how transmission distance changes the BER value. Figure 7a shows BER changes for the worst-performing data channel for 40 Gbaud PAM-4 signal sliced in four slices. The diagram indicates the maximal transmission distance without the dispersion compensation of 22 km, where the BER value stays below the FEC threshold. Maximal transmission distance corresponds to a standard optical access network length.

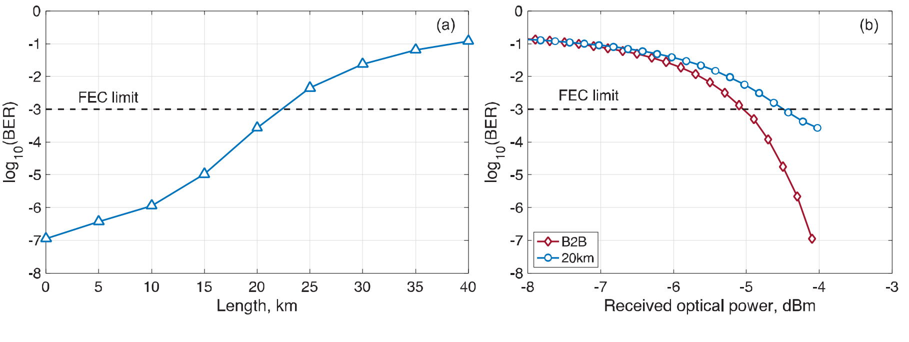

Fig. 7. BER correlation diagrams for 40 Gbaud/s PAM-4 signal sliced in four slices – (a) BER versus fiber length and (b) BER versus average received signal power for B2B and 20 km transmission.

Further, the BER versus average received signal power for B2B and 20 km transmission is investigated. As shown in Fig. 7b, a slight decrease in the received signal power yields a considerable increase in BER. A drop of 2 dB (at the pre-FEC BER level) of the received signal power in both B2B and 20 km fiber span results in the BER value above the FEC threshold. It is difficult to ensure proper signal transmission at such received optical power. Figure 7b also shows that in the case of B2B transmission, the minimal received signal power level on the PIN photoreceiver should be about -5 dBm. However, for 20 km of SMF span, the minimal received power should be about -4.5 dBm to ensure the FEC threshold of 1×10^{-3}. Considering optical power at the input of optical fiber (8 dBm), the power budget to ensure the FEC threshold for B2B transmission is 13 dB, and for 20 km of SMF fiber span is 12.5 dB. These results indicate that power budget is one of the most important considerations when choosing spectrum-slicing for extending the capacity of the transceiver of an optical access network. The inaccurate planning of the power budget can drastically reduce the performance and viability of the proposed solution.

5. CONCLUSIONS

We have successfully demonstrated the proposed spectrum slicing based on DSP. 10 GHz transceiver is capable of transmitting the whole 40 Gbaud PAM-4 waveform over up to 22 km SMF span by slicing it into four slices each occupying 10 GHz bandwidth. Slices are transmitted in parallel using the WDM approach, where each electrical slice is modulated on a separate optical carrier. It is not necessary to buy new equipment for each network upgrade migrating to higher speeds (e.g., from 10 Gbit/s NRZ to 80 Gbit/s PAM-4) by using this technology. The already existing opto-electrical equipment (e.g., 10 GHz transceivers) can be upgraded by using the proposed spectrum slicing technique.

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