Research on Super-PON Communication System with FWM-based Comb Source

Marina Aleksejeva[1], **Ilja Lyashuk**[1], **Ricards Kudojars**[1], **Dmitrijs Prigunovs**[1], **Dilan Ortiz**[1], **Janis Braunfelds**[1, 2], **Toms Salgals**[1, 2], **Sandis Spolitis**[1, 2], **and Vjaceslavs Bobrovs**[2]

[1]Institute of Telecommunications, Riga Technical University
Azenes Street 12, LV-1048, Riga, Latvia
[2]Communication Technologies Research Center, Riga Technical University
Azenes Street 12, LV-1048, Riga, Latvia

Abstract— In this research authors investigated the performance of 16-channel wavelength division multiplexed passive optical network (WDM-PON) by using the Super-PON architecture concept. Super-PON, which is currently going through a standardization process, has been claimed as a promising solution for scaling reach and customer aggregation of PONs. For additional optimization, the authors propose using multi-wavelength four-wave mixing (FWM) based comb source. This paper compares the performance of 16-channel 100 GHz spaced Super-PON transmission system with the data rate of 10 Gbit/s per channel using ITU-T G.652 and ITU-T G.655 recommendation compliant optical fibers: standard single-mode fiber (SSMF), non-zero dispersion-shifted fiber (NZDSF).

1. INTRODUCTION

The demand for transmission capacity and traffic continues to increase rapidly. According to the Global Internet user growth statistics which are introduced in Cisco Annual Internet Report (2018–2023), the total number of Internet users is projected to grow from 4.7 billion in 2018 to 5.3 billion by 2023 operating with 29.3 billion networked devices [1]. High-efficiency dense wavelength-division-multiplexed (DWDM) systems are more and more commonly used to satisfy the increasing demand of end-users, employing passive optical networks (PONs) which have been widely used in access networks. Significant effort has been put for years to increase the speed and transmission distances of passive optical networks. With Super-PON optical layer, each central office (CO) can serve a much larger region and a higher number of customers which thus significantly simplifies the underlying physical infrastructure [2]. Following optical reach and customer coverage improvements will play a significant role in every network operator's choice when new and upgraded infrastructure is going to be built. In this paper, the authors consider using four-wave mixing (FWM) effect-based multiwavelength laser source or so-called optical frequency comb (OFC) for further Super-PON optimization. FWM is one of the well-known nonlinear optical effects (NOE) that affect the quality of fiber optical communication lines [3]. However, it is known that the following nonlinear optical effect can be used productively in fiber optical communication systems for various optical processing functions. The main advantage of using the FWM effect is to minimize high costs since each data transmission channel requires one optical laser source, which can affect installation costs as well as operational expenses. In this paper, the authors suggest the implementation of an FWM-based OFC source, which allows using only two high-power pump lasers instead of sixteen separate lasers (laser array) [4]. The obtained results show that the following transmission system can be a promising solution for the future optimization of fiber optical transmission infrastructures.

2. OFC SOURCE BASED ON THE FWM NOE FOR WDM TRANSMISSION SYSTEM

2.1. Overview of Four-wave Mixing Nonlinear Optical Effect

This part describes four-wave mixing (FWM) as one of the important nonlinear optical effects (NOE). The FWM process has various applications in modern wavelength division multiplexing (WDM) systems. FWM is a scattering process in which three photons are mixed to generate the fourth wave [5]. This happens when the momenta of the four waves satisfy a phase-matching condition, which is, the condition of maximum power transfer. The phase matching can be represented by a relationship between the propagation constant along the z-direction in an SMF as [5]:

$$\beta(\omega_1) + \beta(\omega_2) - \beta(\omega_3) - \beta(\omega_4) = \Delta(\omega) \tag{1}$$

where β is the propagation constant; ω_1, ω_2, ω_3, ω_4 are the frequencies of the first to fourth waves; and Δ is the phase-mismatching parameter [5]. The mixing of two waves at frequencies ω_1 and ω_2 which generate sidebands at new frequencies ($2\times\omega_1$-ω_2) and ($2\times\omega_2$-ω_1) is shown in Fig. 1. These sidebands propagate in the fiber along with the original waves and will grow, causing a decrease in initial signal power [6].

If N waves pass through the fiber, the number of mixed products M generated by FWM is defined as [5]:

$$M = \frac{N^2\,(N-1)}{2} \tag{2}$$

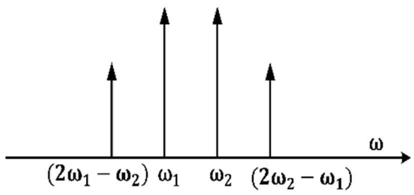


Figure 1: Generation of new frequency components (optical carriers) due to FWM NOE effect [6].

Some of these mixing products occur at certain operating wavelengths. The generated optical waves interfere with the initial signal. Consequently, FWM degrades system performance and leads to crosstalk in optical communication systems such as WDM systems. Thus, FWM is one of the main limiting factors and depends on the power levels in the optical fiber [5]. Nonlinear interactions between the optical signal and the optical fiber transmission medium should be considered as soon as the power of the optical signal is increased [6]. It became necessary to consider the influence of nonlinear effects in areas where WDM and dense WDM (DWDM) systems with channel spacing below 100 GHz are used [7]. However, this NOE as a productive one can be used in fiber optical communication systems for various optical processing functions, like wavelength conversion, high-speed time-division multiplexing (TDM), pulse compression, for fiber optical parametric amplifiers (FOPA) solutions, etc. [3]. Among various applications of FWM in optical communication systems, one is the generation of OFC by using cascaded FWM products, as demonstrated in our study.

2.2. Proposed Super-PON architecture

Super-PON is a PON optical layer able to support an increased optical reach in the distance up to 50 km and increased customer coverage up to 1024 customers per fiber at 10 Gbit/s data rate per lambda (λ) or channel. As it is shown in Fig. 2, extending the reach from 20 to 50 km also enables central office (CO) consolidation, reducing the number of powered sites needed to serve a large area.

In addition, by consolidating the active equipment that requires power and maintenance in fewer COs, Super–PONenables a significant reduction in infrastructure operating costs. Meanwhile, DWDM enables the transport of multiple independent signals over a single SMF fiber by using different wavelengths [2]. In Super-PON, multiple PON instances are mapped to different wavelengths and transmitted over the same feeder fiber, represented in Fig. 2 as section (A). Therefore, for a given information transmission capacity, the total number of required optical fibers can be reduced [2, 8].

3. SIMULATION SETUP OF 16-CHANNEL SUPER-PON TRANSMISSION SYSTEM WITH OFC SOURCE

The simulation setup of a 16-channel 100 GHz spaced Super-PON transmission system with FWM based OFC source for our research was realized in the Synopsys OptSim simulation software environment. Within this research, the obtained bit error rate (BER) values of downstream channels were evaluated. According to IEEE P802.3CS Task Force, the transmission system should support BER better or equal to 1×10^{-12}, so this value was set as a BER threshold. According to ITU-T G.694.1 recommendation for optical C and L bands, the DWDM-PON channel spacing intervals are 100, 50, 25, or 12.5 GHz [9]. Proposed Super-PON architecture uses a 100 GHz nominal channel spacing within L-band downstream, thus the central carrier frequency for our simulation is chosen to be 188.3 THz.

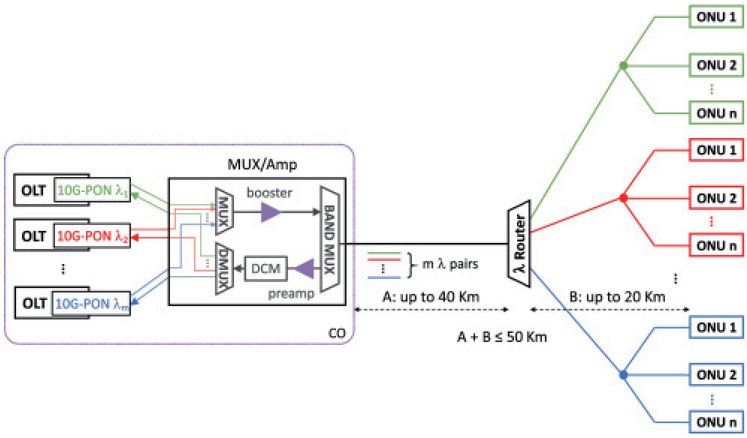


Figure 2: Structural scheme of Super-PON architecture [2].

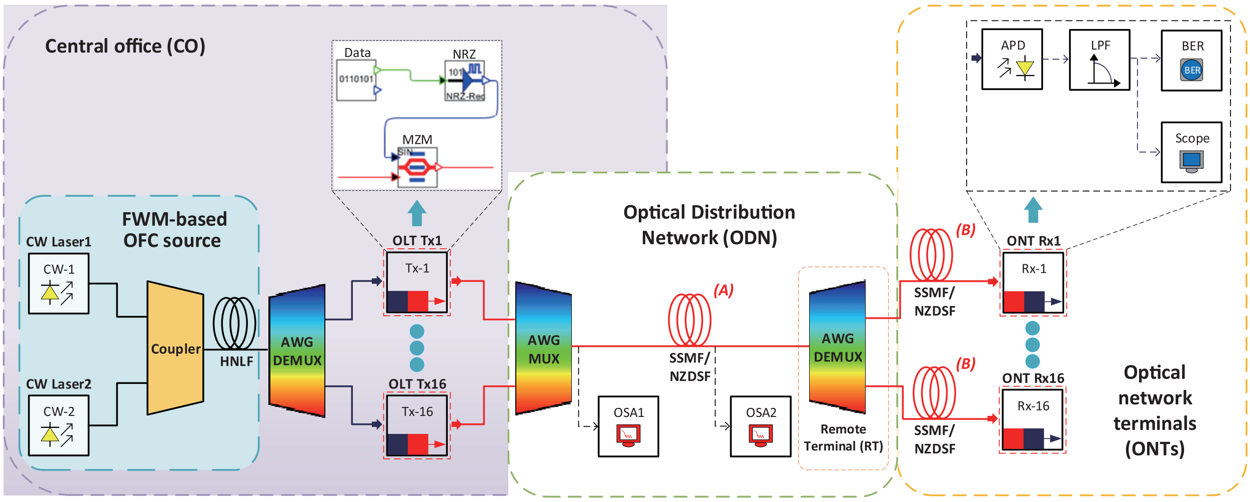


Figure 3: Simulation scheme of 16-channel 100 GHz spaced Super-PON transmission system with FWM based OFC source.

As shown in Fig. 3, The central office (CO) consists of FWM based comb source and optical line terminal (OLT) with sixteen transmitters (OLT_Tx). CO employs an FWM-based OFC source which consists of two continuous wavelength (CW) pump lasers, an optical 2x1 power coupler, and a highly nonlinear optical fiber (HNLF) span. This is a highly efficient technique to generate broadband cascaded FWM optical carriers [10]. The experimentally obtained optimal power of both CW lasers of +23.4 dBm and HNLF length of 0.9 km were chosen to create an OFC applicable for further data transmission. Central frequencies for CW lasers were set at 188.3 THz and 188.4 THz having 100 GHz spacing. As well as following HNLF parameters were applied: zero-dispersion wavelength of 1552.32 nm, the nonlinear coefficient of 11.50 $(\mathrm{W}\times\mathrm{km})^{-1}$, the core effective area of 11.6 $\mu\mathrm{m}^2$ and attenuation coefficient 0.8 dB/km at the reference wavelength of 1550 nm [11]. Carriers (comb source spectral lines) on the output of HNLF fiber are further separated by arrayed waveguide grating (AWG) demultiplexer (AWG DEMUX) and fed to the optical inputs of the Mach-Zehnder modulators (MZM) of each OLT_Tx. Each particular Tx consists of an external MZM and non-return-to-zero (NRZ) driver, which encodes logical data from the pseudorandom bit sequence (PRBS) generator (depicted as Data) and generates an electrical NRZ signal with a bit rate of 10 Gbit/s. Each MZM has a 3 dB insertion loss and a typical 20 dB extinction ratio. The following parameters were set to the employed commercially available arrayed waveguide grating (AWG) multiplexers and de-multiplexers (DEMUX): insertion loss 3.5 dB, channel spacing 100 GHz which corresponds to the recommended Super-PON frequency grid [2], where optical 3-dB bandwidth was 75 GHz and the lowest channel frequency 187.6 THz as the downstream simulation was performed in optical L-band.

As we compare system performance using two different types of transmission media, an ITU-

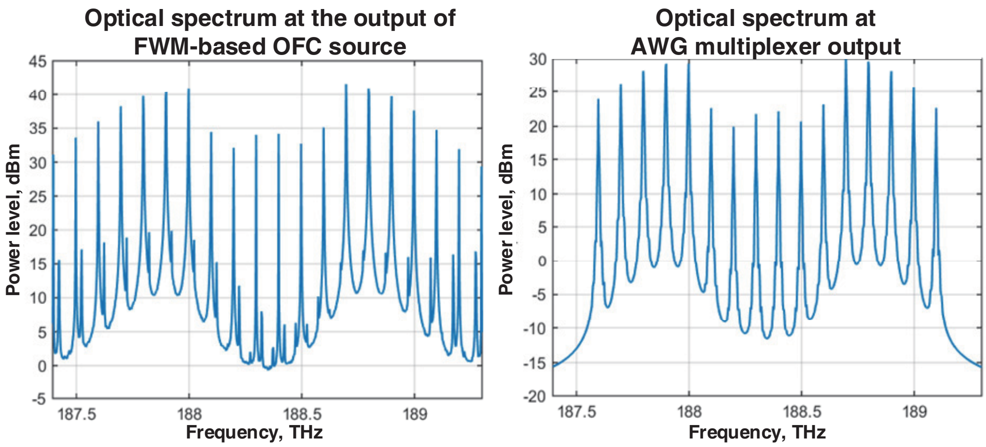
T G.652 standard single-mode fiber (SSMF) and ITU-T G.655 non-zero dispersion-shifted fiber (NZDSF) were employed. The attenuation coefficient was 0.2 dB/km and the dispersion coefficient was 16 ps/nm/km at 1550 nm reference wavelength for SSMF fiber and dispersion coefficient of 4 ps/nm/km and 0.2 dB/km attenuation coefficient for NZDSF fiber, respectively. These types of fibers are one of the best suited and optimized to operate in 1500 to 1600 nm wavelength regions. As it is shown in Fig. 3, the transmission system consists of one fiber span (feeder) from CO to the remote terminal (RT), please see (section A) and fiber spans from RT to the optical receivers of optical network terminals (ONTs), please see (section B). Each receiver (ONT_Rx) consists of an optical receiver based on avalanche photodiode (APD) with the sensitivity level of −24 dBm at 10 Gbit/s bitrate. Afterward, the received modulated signal is filtered by a Bessel low-pass electrical filter (LPF) (−3 dB electrical bandwidth of 7 GHz). The quality of the received signal is then evaluated by the electrical scope (e.g. eye diagrams are captured), and BER BER is estimated.

4. RESULTS AND DISCUSSION

The purpose of this section was to numerically evaluate the performance of the 16-channel 100 GHz spaced Super-PON transmission system with an FWM-based OFC source operating in L-band employing two different types of fibers as a transmission media: standard single-mode fiber (SSMF) and non-zero dispersion-shifted fiber (NZDSF).

The captured optical spectrum at FWM-based comb source output and at AWG multiplexer output before launching into an ODN section are shown in Fig. 4. The optical spectrum observed after transmission through ODN in section A (30 km for SSMF and 38 km for NZDSF) is displayed in Fig. 5. We observed quite high channels' power fluctuations — the difference between the calculated average channel peak power and the measured channel power levels because of the Brillouin scattering effect (SBS).

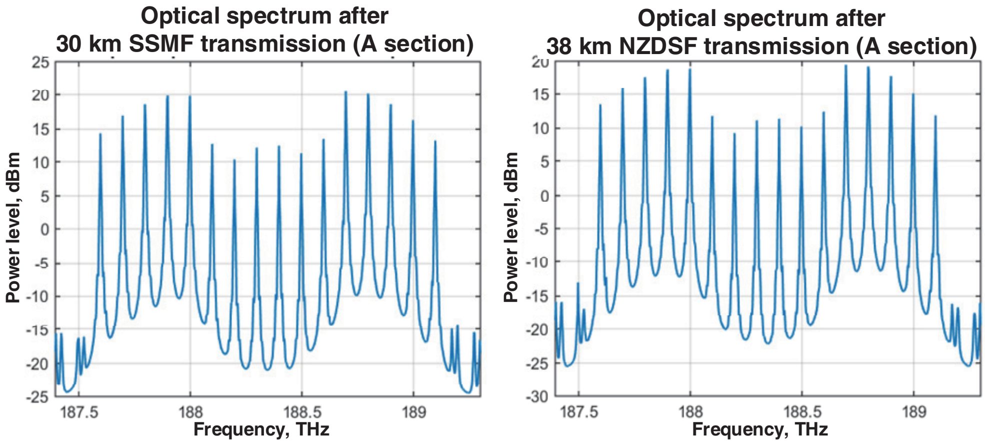
It was found that the lowest BER performance was produced by the 7th channel, where the FWM-based comb source generated a carrier with the lowest optical power level, so further results are shown for this particular channel. Authors consider the maximal transmission distance at the BER threshold of 1×10^{-12} to be the main criteria for the system's evaluation.



(a) (b)

Figure 4: The captured optical spectra of 16-channel 100 GHz spaced Super-PON transmission system: (a) on the output of FWM-based OFC source, (b) on the output of AWG MUX.

According to Super-PON architecture, the total target reach of the transmission system is 50 km, which includes fiber from the central office (CO) to AWG DE-MUX in the remote terminal (section A in Fig. 3) and fiber from AWG DEMUX to ONT_Tx (section B in Fig. 3). The Super-PON concept suggests the distance of section B to be up to 20 km, so the length of fiber span was set at 20 km in our simulation setup [2]. The distance of section A varies depending on the type of employed optical transmission fibers. The obtained values of section A fiber span length before reaching BER threshold 1×10^{-12} were 30 km for SSMF fiber and 38 km for NZDSF, where the BER of the received signal was 7.06×10^{13} and 8.15×10^{-13}. Thus, the total transmission distance for our simulated Super-PON system at 10 Gbit/s is 50 km and 58 km employing SMF and NZDSF fibers, respectively. The results of the experiment are summarized in Table 1.



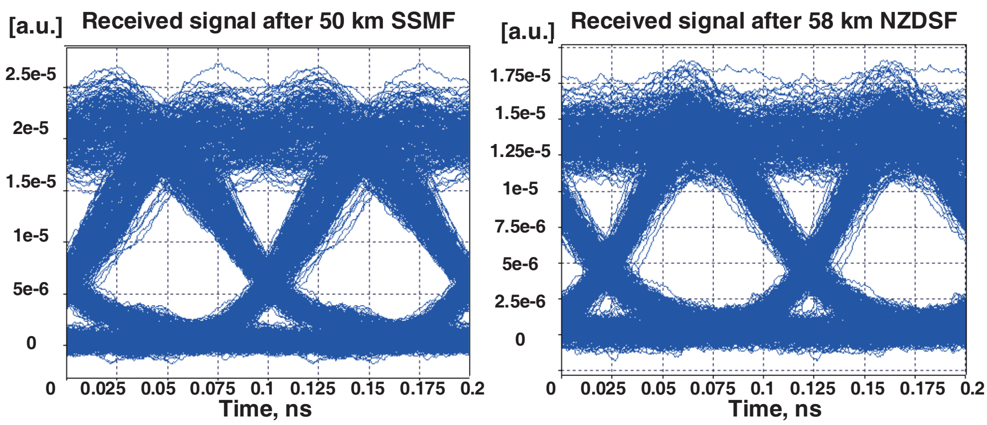
(a) (b)

Figure 5: The captured optical spectra of 16-channel 100 GHz spaced Super-PON transmission system: (a) after transmission over 30 km SSMF ODN link section, (b) after transmission over 38 km NZDSF ODN link section.

Table 1: Comparison of Super-Pon transmission system's performance by fiber type and optical link lenght.

Type of fiber	(A) fiber span length, km	(B) fiber span length, km	Total reach, km	7th channel received signal BER
SSMF	30	20	50	7.06×10^{-13}
NZDSF	38	20	58	8.15×10^{-13}

Figure 6 shows eye diagrams of the received signal after transmission at the 10 Gbit/s data rate over the 50 km of SSMF and 58 km of NZDSF fibers. As it is shown in Figs. 6(a) and 6(b), after 50 and 58 km transmission over SSMF and NZDSF link section, the BER of the received signal was 7.06×10^{-13} and 8.15×10^{-13}.



(a) (b)

Figure 6: Eye diagrams signals received in 7th channel (a) after transmission over 50 km SSMF fiber link, and (b) after transmission over 58 km NZDSF fiber link.

From Table 1 and Fig. 6, it can be seen the BER of the received signal for the 7th channel is below the threshold 1×10^{-12}, as well, the eye-opening of the received signal is high enough to provide an acceptable system performance.

To test the BER performance against the length of A section's optical fiber (SSMF of NZDSF), the following curves were measured as displayed in Fig. 7.

As it is shown in Fig. 7, the BER threshold of 1×10^{-12} has been reached after transmission over 30 km of SSMF span and 38 km of NZDSF span in section (A), while the length of section (B) was

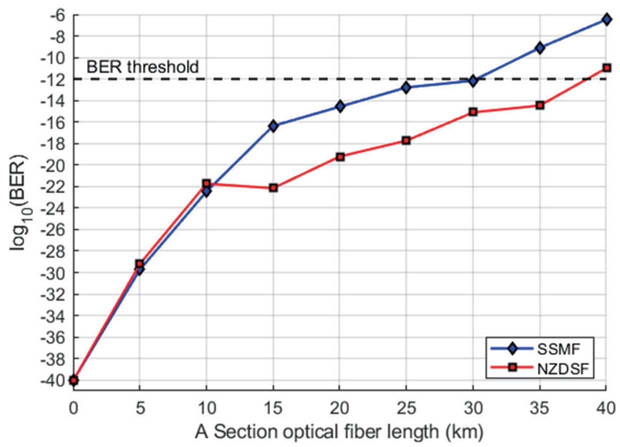


Figure 7: BER versus the length of A section's fiber measured for worst performing 7th channel of the proposed Super-PON system with FWM-based OFC source.

set to a constant value of 20 km in both scenarios, therefore forming the total Super-PON system transmission lengths of 50 and 58 km, respectively.

5. CONCLUSIONS

This research was devoted to the numerical evaluation of the performance of the Super-PON architecture concept. In this paper, the authors compare the performance of a 16-channel 100 GHz spaced Super-PON transmission system with an FWM-based OFC source operating in optical L-band by implementing and comparing SSMF and NZDSF fibers as transmission media. The results of this research showed that employing NZDSF fiber allows gaining an additional 16% or 8 km of total transmission distance before exceeding the defined BER threshold of 1×10^{-12}. As the current Super-PON architecture doesn't include any dispersion compensation module (DCM) for downstream channels, the implementation of NZDSF fiber could be considered as an effective method to overcome dispersion induced transmission length limitations, and thus to improve the total system's reach up to 58 km compared to the 50 km reach by SSMF fiber. The authors also proposed implementing an FWM-based OFC light source for further Super-PON optimization, reduction of operational costs, and increase of energy efficiency as a single OFC source is capable to replace the laser array. It should be noted that our designed system did not require a booster amplifier on the CO side, as the optical power level of the received signal was above -22 dBm for the worst-performing 7th channel, which is above the APD receiver's sensitivity level. The obtained performance indicators as BER and eye diagrams of the received signal verify the feasibility of the simulated transmission system. Therefore, the designed system could be considered as an attractive solution for the reduction of COs and consequently decreasing capital expenditures as well as operating costs.

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