The optical E-band use in the NG-RAN/O-RAN radio signals transmission over ODN path

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Abstract—The paper presents the results of the analysis of the occupancy of optical bands in the ODN by systems from the xPON family. The analysis results show that the free NG Option 2 range, located in the optical E-band, can be successfully used to transport the NG-RAN/O-RAN radio signals over the ODN path. Calculations showing the maximum range of optical fronthaul links for CPRI/eCPRI interfaces were performed. Analyzes supported by calculations and computer simulations were performed, which offer the possibility of using optical E-band to transport the A-RoF (RFoF) radio signals over ODN using high radio frequencies approved by 3GPP for use in the NR interface of 5G Rel-17 mobile systems.

Optical distribution networks (ODN) are currently recognized as the so-called last mile in access to fixed broadband services. Various telecommunications and ICT systems, including mobile systems, can be launched based on this fiber-optic infrastructure. The primary medium used by xPON systems is the single-mode optical fiber of the G.652D [1] or G.657A1 [2] standard, the single-modality ranges of which are equally wide and are in the 1260–1675 nm waveband, see Fig. 1. Operating bands of xPON systems are adapted to the single-modality band of these fibers. Chromatic dispersion and attenuation are the main parameters that limit the range of a passive fiber-optic link operating without amplification and dispersion compensation. Figure 2 shows the results of the analysis of the occupancy of optical bands by the so-called passive optical systems and networks. It is evident that not all systems run simultaneously on the same ODN, so the approach to resource planning should be different in each case. Currently, the most common systems are GPON (ITU-T G.984) or GEPON (802.3ah or 802.3bk), which occupy the same or similar resources (US: 1260-1360nm, DS: 1480-1500 nm - with one optical fiber and US/DS: 1260-1360 nm – with two optical fibers). Currently, commonly implemented networks with 10 Gbps interfaces operate only on one fiber (DS/US) and occupy other resources, guaranteeing coexistence with optical GPON/GEPON signals. In the case of XG-PON, XGS-PON, or 10G-EPON, this is the range of 1260–1280 nm (US) and 1575–1580 nm (DS).

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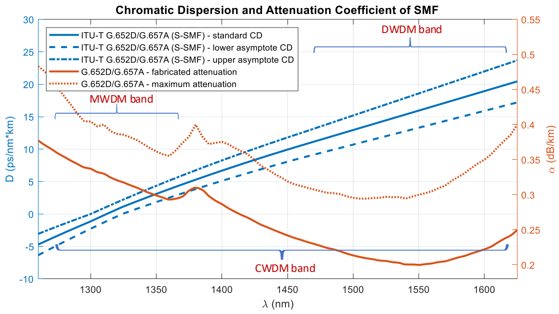

Fig. 1. Basic parameters of the ITU-T G.652D and ITU-T G.657A SMFs [1–2].

Regulation [3] defines two bands intended for the operation of the Next Generation systems, i.e. NGA Option 1-2 and NGA Option 2, see Fig. 2. The first one is already reserved by basic and high-speed systems. The Option 2 band (most of the optical E-band) is still free and is surrounded by wide guard spacing on the short and long wave sides, which should only be observed when low-stable GPON/GEPON interface lasers are used. Therefore, it is worth taking an interest in this still free range. The use of the optical E-band is possible when optical fibers without OH ions are used in the ODN, see Fig. 1. To check the quality of the passive network, it is enough to perform an OTDR measurement at a wavelength around 1400 nm. After obtaining a successful measurement result, it can be assumed that the optical fiber of the G.652D or G.657A standard is used in the network. The possibility of using optical E-band in active fiber-optic systems has been investigated in several research projects [4–6].

In this paper, the key issue is the analysis of the possibility of connecting NG-RAN/O-RAN network components using ODN and optical E-band resources.

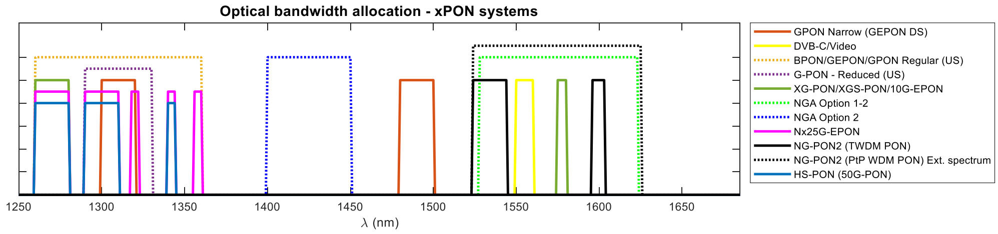

Fig. 2. Optical bands occupied by xPON family systems and New Generation Access bands.

This can be done using the methods presented in [7] or connecting O-RAN components by any part of the ODN. This is possible because we assume that the fronthaul (FH) or mid-haul (MH) link will operate using an independent optical E-band.

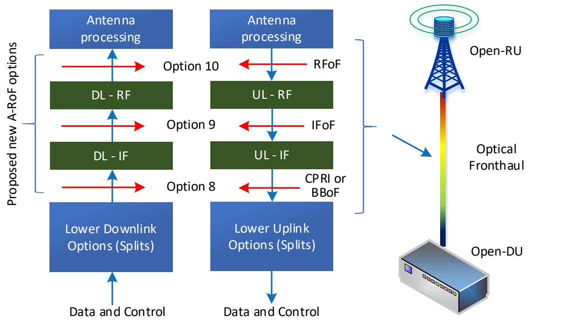

Fig. 3. Proposed new A-RoF splits (options) enabling the transport of radio signals in an all-optical fiber-optic fronthaul network [8, 9].

The 5G/6G radio signals can be transported over the ODN network in 2 formats, i.e., D-RoF or A-RoF [9]. In the case of the D-RoF format, we have CRPI interfaces (Fig. 3) or eCPRI (new solutions for FH/MH links of 5G/6G mobile systems). These interfaces rely on predetermined digital streams to transport digitized baseband (BB) radio signals. In the next step, we will check the permissible range of the FH link of the O-RAN network, which will be limited by the chromatic dispersion occurring in the optical E-band of the ODN path based on the G.652D/G.657A optical fiber. In the basic and, at the same time, cheap, which is crucial, optical interface, the NRZ-OOK format is used, for which the pulse duty factor can be calculated based on the permissible reduction in the receiver sensitivity for a specific inter-symbol interference PP_{ISI} [10]:

$$\varepsilon = \sqrt{\left(10^{\frac{PP_{ISI}}{5}} - 1\right)} \Big/ 2\pi \, . \qquad (1)$$

The permissible range of the optical link with a specific bit-rate can be determined using the relationship [10, 11]:

$$L_{\max} = \frac{\varepsilon c}{D \lambda_0^2 B \sqrt{\left(B/\pi f\right)^2 + \sigma_v^2}} \, , \qquad (2)$$

where, respectively, D – chromatic dispersion coefficient, λ_0 – optical carrier wavelength, B – bit-rate of the optical link, f – time slot filling, σ_v – 20-dB frequency bandwidth of the laser spectrum. Based on equations (1) and (2), we will determine the maximum range of the D-RoF fronthaul link. The results of these calculations are presented in Fig. 4.

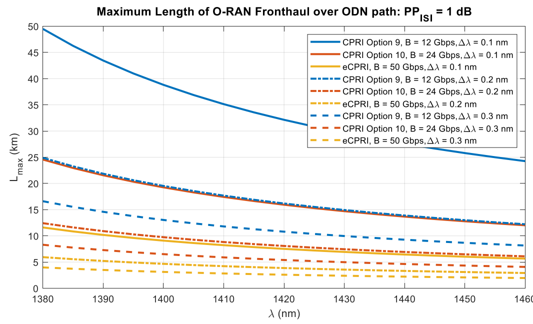

Fig. 4. Maximum range of a D-RoF (CPRI/eCPRI) fronthaul link operating in optical E-band in the NRZ-OOK format.

To use solutions from the A-RoF family, it was proposed to extend the function of Option 8 and introduce two new Options (Splits) numbered 9 and 10 [8, 9], see Fig. 3. Option 10 is particularly demanding due to the need to transport the signal in the RFoF format. The primary phenomenon limiting the transport of the RFoF signal in the optical path is the Dispersion Induced Power Penalty (DIPP), which can be described by a specific transformed relationship [12]:

$$\text{DIPP-CIR}_{IM} = 20\log\cos\left(\pi D(\lambda_0) L \frac{\lambda_0^2}{c} f_{RF}^2\right) \qquad (3)$$

where f_{RF} – radio carrier frequency, L – length of optical FH path, λ_0 – optical carrier wavelength.

Figure 5 shows the results of DIPP-CIR calculations, assuming that the maximum radio carrier frequency is 71 GHz. This is the limiting upper frequency in the mmWave band (FR2-2) that 3GPP approved in Rel-17 of the 5G mobile system. The white spaces visible in Fig. 5 show places where optical channels can be successfully created, allowing for the effective transmission of RFoF signals using a simple and cheap direct detection (DD) technique. The radio signal in the DL direction in the 5G NR interface is of the CP-OFDM format. This creates a radio channel of a fixed width, which will affect the width of the sideband in the modulated optical signal.

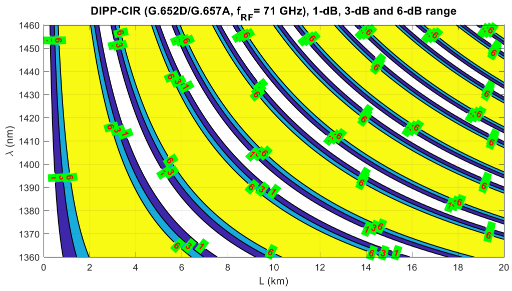

Fig. 5. Results of the DIPP-CIR calculations, taking into account the 1-dB and 3-dB thresholds, obtained in the range of the optical E-band for the fronthaul path based on the G.652D/G.657A optical fiber.

The uneven impact of DIPP on individual CP-OFDM components can be expressed as [13]:

$$\Delta\text{DIPP-CIR}_{(\text{dB})}\left(f_0,\Delta f_{RF}\right)=\left|\text{DIPP-CIR}_{(\text{dBc})}\left(f_0-\frac{\Delta f_{RF}}{2}\right)-\text{DIPP-CIR}_{(\text{dBc})}\left(f_0+\frac{\Delta f_{RF}}{2}\right)\right| \quad (4)$$

where Δf_{RF} - frequency bandwidth of CP-OFDM signal. Figure 6 shows the results of exemplary calculations of differential DIPP-CIR values performed using Eqs. (3) and (4). Analyses were performed for the 1-dB threshold, the extreme carrier frequencies of the FR1 and FR2 ranges, and two example bandwidths of CP-OFDM radio signals. The length of the fronthaul optical path, in this case, is 20 km. In Figure 6, the characteristics of f_{RF} = 24 GHz are not plotted because no subrange falls within the 1-dB threshold.

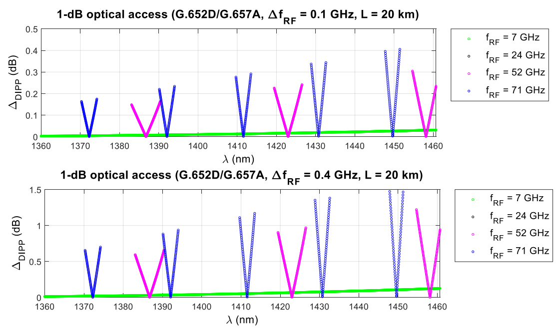

Fig. 6. Differential DIPP-CIR as a function of the optical wavelength in the optical E-band: a) 100 MHz RF channel, b) 400 MHz RF channel.

To check the correctness of determining the wavelength ranges helpful in transmitting the RFoF signal over the ODN path, the simulation was performed using the G.652D optical fiber in the VPIphotonics Design Suite 11.4 simulator. A DFB laser and MZI modulator (MZM) are used on the optical transmitter side. The receiver was a PIN-type photodetector. The CP-OFDM modulation technique was used to create the radio signal with two numerological μ values, where each subcarrier was modulated in the 256-QAM format. Figure 7 shows the simulation results confirming the predictions regarding the impact of the DIPP phenomenon on the extreme optical carriers from the optical E-band.

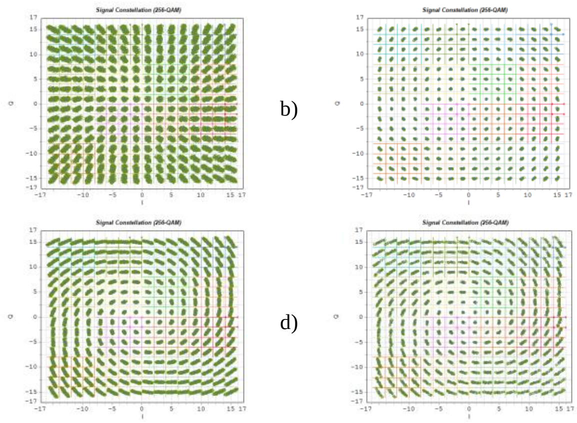

Fig. 7. Simulation results of transmitting the RFoF signal over the optical path based on the G.652D optical fiber (f_{RF} = 71 GHz): a) N_{OFDM} = 2048, μ = 2, L = 20 km, λ_0 = 1360 nm; b) N_{OFDM} = 2048, μ = 3, L = 16 km, λ_0 = 1360 nm; c) N_{OFDM} = 4096, μ = 2, L = 16 km, λ_0 = 1460 nm; d) N_{OFDM} = 2048, μ = 3, L = 16 km, λ_0 = 1460 nm.

In the simulations, no additional redundant FEC techniques were used, which resulted in an increased SER of 6×10^{-3} (Fig. 7a), 3×10^{-8} (Fig. 7b), 1×10^{-2} (Fig. 7c), and 2×10^{-2} (Fig. 7d), respectively. It should be noted that the transmission of RFoF signals took place in challenging conditions due to the radio carrier's high frequency and the BB modulation's high order. When lowering these parameters (RF, n-QAM), SER will improve significantly, especially when the selected optical channel is within the 1-dB threshold. It should also be noted that the simulation was carried out without the presence of signals from xPON systems in the optical path. The presence of such signals may cause the SRS phenomenon to deteriorate the transmission because the Stokes shift frequency limit will be exceeded. This will be the next stage of research.

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