5G Mobile Wireless Access and Digital Channeling with RF Over Fiber for Long-Haul 64-QAM Communication

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ABSTRACT
This paper presents the experimental results of a novel radio over fiber (RFoF) architecture that is capable of transmitting data at 20 Gb/s over a 600 km fiber. Such high bit rates are required by 5G systems for long-haul communication. This is accomplished by overcoming the limitation of single mode fibers (SMF) of power attenuation and chromatic dispersion. This is achieved by interspersing sections of the SMF with dispersion compensating filter (DCF) and embedding midway of the fiber length with chirped fiber Bragg grating (CFBG). Moreover, the proposed approach is shown to enhance the total bandwidth over a long-haul gigabit passive optical network (GPON) using integrated channel CWDM. In the experiment, a 64-quadrature amplitude modulation (64-QAM) signal was modulated onto coarse wavelength division multiplexing (CWDM) signal. With the proposed RFoF architecture the signal power received over a 600 km fiber is greater than a conventional optical architecture by 19 dB for identical applied input optical power of 20 dBm. This translates to significant power saving can be achieved with the proposed architecture over existing architectures that should reduce the carbon footprint of long-haul optical communications systems. The optical receiver is shown to have a sensitivity of -28.3 dBm for a bit-error-rate (BER) of 10^{-9}. These results demonstrate the viability of the proposed RFoF architecture in providing significant improvement in the bit rate over a transmission distance.

Keywords:
5th Generation (5G); Gigabit Passive Optical Networks (GPON); Coarse Wavelength-Division Multiplexing (CWDM); Radio Frequency over Fiber (RFoF); Dispersion Compensation Fiber (DCF); Chirped Fiber Bragg Grating (CFBG)

1. INTRODUCTION

Radio frequency over fiber (RFoF) technology offers an optimal solution for the exponentially expanding market in mobile communication systems of the 5th generation (5G) and of the Internet-of-Things (IoT). The benefits of RFoF includes high-bandwidth capacity at economical cost, where the demand for virtually unlimited bandwidth is a requirement. With the current global deployment of 5G system RFoF offers a solution for delivering broadband access to the last mile, i.e., the network connection between the carrier's Central Office (CO) and the subscriber's location. One of the major developments in fiber optic technology has been point-to-multipoint fiber-to-the-premises (FTTP) networks that use a single optical fiber to provide service to different premises. Such networks enable reduction of capital expenditure and comprise an optical line terminal (OLT) at the CO, a splitter and optical network units (ONUs). In [1] it is shown that by properly configuring fiber and CO equipment it is possible to streamline the system operation. In [2] it is shown how optical splitters can allow a single optical fiber to serve between 32–128 ONU [2].

High bandwidth devices, like HDTV, require transmission rates of up to 20 Mb/s, and to stream an average standard definition television (SDTV) requires 6 Mb/s [3-4]. To use broadband services such as HDTV, HD video streaming, and interactive online gaming over fiber-to-the-home (FTTH) access network typically requires bandwidth more than 60 Mb/s [2]. The transmission impairments of the wireless medium however pose significant challenges [3],[4] such as massive power consumption in the base-stations, non-line-of-sight (NLOS) conditions, limited bandwidth, and lower data bit rate. RF over fiber is ideal for overcoming these challenges in wireless systems, as it utilizes a wide bandwidth, in the order of terahertz (THz), and offers relatively low power loss (~0.2 dB/km). The strength of a RF signal is its ability to provide tether less connection to users. In this study we demonstrate the feasibility of using RFoF to integrate 5G technology with existing fiber communications infrastructure for transmitting signals with bit rates of 20 Gb/s (downlink) and 10 Gb/s (uplink).

5G is the latest mobile technology that brings greater speed, capacity, and functionality to mobile services, opening new opportunities for consumers, businesses, and public services. Currently, 5G is reusing spectrum that has previously been used to deliver services such as TV broadcasting and wireless broadband. The physical layer of 5G uses orthogonal frequency-division multiplexing (OFDM) with a typical cell radius of up to 5 miles [5]. 5G like its predecessor, i.e., 4G-LTE, offers wireless and fixed access services and can expand broadband services with mobility to areas, where today no fixed broadband access is feasible because of excessive cost [6]. Moreover, it includes attributes of frequency reuse, flexible bandwidth scalability. Both 5G and 4G-LTE base-stations require a lot of energy to transmit signals over 5 km. The path-loss of 5G at 3.5 GHz between a base station (BS) antenna of height 30 m and subscriber's handset height of 2 m is ~165 dB for transmission range of 4,900 m; in 4G-LTE systems this figure is ~158 dB [7]. This means a cost-effective solution is needed to overcome transmission cost and signal impairment. RFoF precludes the deficiencies inherent in 5G with the potential to increase the bandwidth and data rate, and to improve the spectral efficiency; thus, raising the broadband, speed between users and between users and BS.

Extremely high bit rates are achievable with gigabit passive optical network (GPON) systems; hence such systems have been shown to be instrumental in the development of high-speed passive optical networks with upstream bit rates reaching 2.5 Gb/s and downstream of 1.25 Gb/s [7]. GPON supports transmission formats such as internet protocol (IP), time-division multiplexing (TDM), wavelength-division multiplexing (WDM) and coarse-WDM (CWDM) at high-levels of performance. The heart of a GPON system is the OLT, performing key functions such as traffic scheduling, buffer control and bandwidth allocation. Data received by the power-splitter from the OLT via several kilometers of fiber can support 32 optical network units where each ONU can support multiple wavelengths. In fact, the ONU can support multiple users over a remote antenna unit (RAU) by sending RF signal directly connected it. Media access control (MAC) is used to regulate communication between the OLT, ONU and all optical network terminals (ONTs). MAC controls the transfer of data upstream to the OLT when permission has been given.

In [8], a hybrid OFDM is proposed where tracking technology is employed to converge wire line and wireless transmissions for optical millimeter wave transmission over fiber. The authors have demonstrated transmission of 40 Gb/s OFDM data stream over a 50 km single mode fiber. The authors in [9] have demonstrated application of hybrid OFDM based wireless over fiber using reflective semiconductor optical amplifier and polarization multiplexing technique that supports bidirectional wireless network. Here the downlink signal is modulated by 10 Gb/s and 6.25 Gb/s OFDM data stream mixed with 200 MHz radio frequency and communicated over 50 km SMF plus 10 m wireless link with the assistance of horn antenna. Presented in [10] is an integrated SMF and free-space optics (FSO) network with multiband radio-over-fiber system. This system can transmit 10 Gb/s at 60 GHz, 10 Gb/s at 15 GHz and 10 Gb/s over 40 km with enhanced fault protection through SMF and FSO. The authors in [11] have demonstrated four-level pulse amplitude modulation for 448 Gb/s free-space optical communication over 600 m. With the proposed technique significant 3 dB modulation bandwidth improvement is acquired using injection-locked vertical-cavity surface-emitting lasers.

To meet the evolving needs of wireless communications technology this paper demonstrates that it's possible to significantly enhance data rates with GPON–CWDM network. Coarse wavelength division multiplexing technology is used to combine several signals of different wavelengths on laser beams for transmission along fiber optic cables with channel spacing of 20 nm. Although compared to dense-WDM (DWDM) this spacing is quite wide however it allows the use of inexpensive lasers and there is no need to strictly control the drift encountered in lasers. The fact, that the laser can operate uncooled, gives the CWDM the virtue of being a low energy consumption technology [12].

This paper describes the experimental results of a novel CWDM radio frequency over fiber architecture for 5G backhaul networks. We have demonstrated the feasibility of transmitting data at 20 Gb/s over a distance of 600 km using the proposed GPON-CWDM network architecture. The results show that the proposed system can significantly enhance the system bandwidth to: (1) extend the coverage area, (2) increase the data bit rate, (3) decrease the power consumption, and (4) improve the signal quality (SNR) of the wireless system. The proposed GPON-CWDM network topology utilizes RFoF to integrate 5G; the investigation proves the RFoF system's ability to transmit a mixed signal (analog and digital) via fiber optic cable. With the proposed technique the capacity of the optical communication network is increased. It is shown that the deployment of optical fiber links to distribute RF signals from a central station (CS) to remote antenna units (RAU) results in extremely low signal loss, i.e., 0.2 dB/km for the wavelength of 1550 nm. Also shown is the viability of transmitting 5G signals over CWDM channels in GPON via an RFoF system. In this study we have limited the number of 5G signals to 18 different wavelengths; however, in practice this would be far greater. 5G transmissions to the RAU need to be converted to fiber optic signals. WDM is used to multiplex the optical CWDM and the RF signals for transmission via fiber; first, to a fiber of length of 160 km and then to 210 km. Chromatic dispersion in the single mode fiber is controlled using triple symmetrical compensator scheme and a mix of SMF, dispersion-compensating fiber and chirped fiber Bragg grating for transmission over 600 km. The transmission distance we have used in the study is representative of a long-haul optical fiber network that is used to cover a large geographical area. The compensator scheme is used to equalize the dispersion slope in a fiber, which is demonstrated using DCF and CFBG. Dispersion-compensating fiber is proven to be effective in overcoming chromatic dispersion in high velocity light. This is achieved using a negative dispersion slope to compensate the positive dispersion in SMF.

The rest of the paper is organized as follows: Section 2 presents related work, and Section 3 describes the design of the GPON-CWDM network architecture via RFoF system for transmission of 5G signals over a fiber of 210 km and 600 km. The results of this study are discussed in Section 4, and the work is concluded in Section 5.

2. RELATED WORK AND BACKGROUND

Integration of PON in optical system architectures to enhance capacity and services for next-generation networks has been investigated in references [13]–[24]. The research presented in this paper uses wireless systems (5G-OFDM) and passive optical system (OLT, EPON and GPON) for signal transmission. We have demonstrated the feasibility of significantly extending the transmission over a 600 km fiber. Moreover, we have used symmetrical compensation technique to enable transmission of 5G with a very low power budget.

Y. Shi. et al [14] have demonstrated transmission of LTE, WiMAX and UWB using a SMF of 25 km. In their experimental work, the various wireless system signals are combined prior to modulation using a Mach Zehnder Modulator (MZM). In our research work, we utilize WDM for each wireless system after each MZM. This arrangement has the advantage of preventing signal impairment resulting from any interference. Shen et al [25] propose a different architecture for the integration of EPON and WiMAX to realize bandwidth enhancement in fiber communications. The integrated architecture takes advantage of the mobile and non-line-of-sight features of wireless communications. EPON is used as a backhaul connecting different WiMAX base-stations. Such integration can lead fixed mobile convergence and provide additional positive features better capacity utilization and support of improved quality-of-service (QoS) provisioning; simplification of network operations and providing wired and wireless broadband access services through a single passive optical network. A novel architecture for next-generation OFDMA-based PONs is proposed by D. Qian et al in [17]. They have experimentally demonstrated a heterogeneous 10 Gb/s OFDMA-PON architecture by transmission of standard WiMAX over 20 km fiber, together with two PON channels.

Milosavljevic et al, [22] demonstrate the interoperability of standard WiMAX and GPON using overlapping radio cells. They show the feasibility of transmitting multiple un-coded IEEE802.16d channels through a single RF subcarrier at rates of 50 Mb/s downstream and 15 Mb/s upstream via GPON and WiMAX microcell link of 21 km.

In [26] Ng et al demonstrated the integration of a radio over fiber communication system composed of three modulation formats, i.e., quadrature phase-shift keying (QPSK), 16-quadrature amplitude modulation (16-QAM) and 64-QAM, which are modulated onto orthogonal frequency division multiplexing (OFDM) signal. The bit rate for 16-QAM and 64-QAM achieved were 22 Mb/s and 50 Mb/s, respectively. In [27] the authors report a network architecture where 5G multiple-input multiple-output (MIMO) radio over fiber signals is transmitted over a standard PON. The architecture can be applied when using an OFDM-PON where efficient convergence of wired and wireless networks can be achieved. In addition, single-sideband frequency translation technique is used to produce a high spectrally efficient approach involving two MIMO-RFoF. Radio over fiber technique of 10 GB/s giga-PON network architecture reported in [28] uses single mode fiber of length 50 km to propagate the radio signals. Radio-over-fiber system architecture proposed in [29] employs three hybrid photonic millimeter-wave generation techniques in WDM-PON network. Demonstrate in [30] is the convergence of a NOMA-CAP wireless waveform with a single carrier wired signal in a PON scenario using radio-over-fiber (RoF) technology. Specifically, fifteen NOMA-CAP bands, with two NOMA power levels to double the capacity, transmit 15 Gb/s multiplexed with a digital 10 Gb/s four-level pulse amplitude modulation (PAM-4) signal for downlink application.

In this paper, we utilize a GPON-CWDM architecture in the deployment of 5G wireless system using CWDM and RFoF technologies to accomplish high bit rates of 20 Gb/s (downlink) and 10 Gb/s (uplink). 5G signals are applied to the bidirectional splitter-32 at different wavelengths over a SMF of length 160 km, and from the splitter to the WDM-DEMUX over SMF of 50 km. We have demonstrated that by utilizing CDF and CFBG we can substantially increase the transmission length of the fiber to 600 km.

3. DESIGN OF GPON-CWDM VIA RFOF SYSTEM

3.1 GPON-CWDM via RFoF over 210 km FIBER

The architecture of the proposed system, shown in Fig. 1, was modelled using OptiSystem simulation package. It starts with downstream direction beginning with GPON headend and optical line terminal (OLT). As stated earlier, the OLT is the major component of GPON as it needs to support downstream data rates of 20 Gb/s to the splitter. The OLT is constituted using CWDM, WDM-MUX, WDM-DEMUX 5G-TX and 5G-RX. In the proposed CWDM the channel wavelengths are spaced at 20 nm apart in contrast to 0.4 nm spacing in DWDM. Laser emissions corresponding to the 18 channels have specific wavelengths from 1611 nm down to 1271 nm. The wavelength variability of the CWDM laser is ± 3 nm, whereas, in a DWDM laser, the tolerance is much narrower.

5G can maintain multiple transmission bandwidths from 1.4 up to 20 MHz. Peak data rate target using RFoF system in this study is 10 Gb/s (uplink) and 20 Gb/s (downlink). The maximum data uplink bit rate for 5G is 1000 Mb/s. QPSK modulation scheme employed ranging from 16-QAM to 64-QAM can be easily modified to accommodate different subcarriers and their reception conditions. The system is set up for 5G due to its transmission scheme (OFDMA) and the increased scalability of the actual physical layer parameters.

Successful transmission is demonstrated for 5G 64-QAM OFDM channels via combined GPON and RFoF architecture. Here the 5G 64-QAM channels are fed into the OLT's Mach-Zehnder modulator. Continuous wave (CW) laser-diode used delivers an output-power of 3 dBm at a frequency of 193.1 THz, with linewidth of 10 MHz, relative noise-dynamic range of 3 dB, and noise-threshold of -100 dB. Laser-diode CW radiates light-wave of frequency 193.1 THz into MZM to modulate with 5G. The resulting optical wave is launched into the fiber and fed into WDM-MUX. WDM assures signal integrity for various RF signal formats and prevents interference with the GPON-CWDM spectrum. Emission wavelengths from the laser were set with a 20 nm pitch CWDM grid to operate with the base-station. The 18-channel CWDM wavelength is launched into WDM-MUX, which combines it with 5G signal into a single bidirectional SMF of length 160 km connected at the end to a bidirectional splitter. The splitter separates the optical signal to multiple fibers and distributes the downstream data (20 Gb/s) from/to the OLT and WDM-DEMUX. The signal is then combined with the upstream data (10 Gb/s) from ONUs and WDM-DEMUX to a single OLT.

Each ONU can support 24 end-users. WDM-DEMUX is connected to the splitter via one bidirectional SMF of length 50 km. WDM systems are attractive for the first mile as no signal division is required, and it enables individual users to use their own channel. Quadrature demodulator is used at the 5G receiver to demodulate the RF signal.

Upstream data from the user is transmitted to ONU at a rate of 10 Gb/s, which is then transferred via a splitter to OLT. WDM-MUX is used to deploy 5G of wavelength

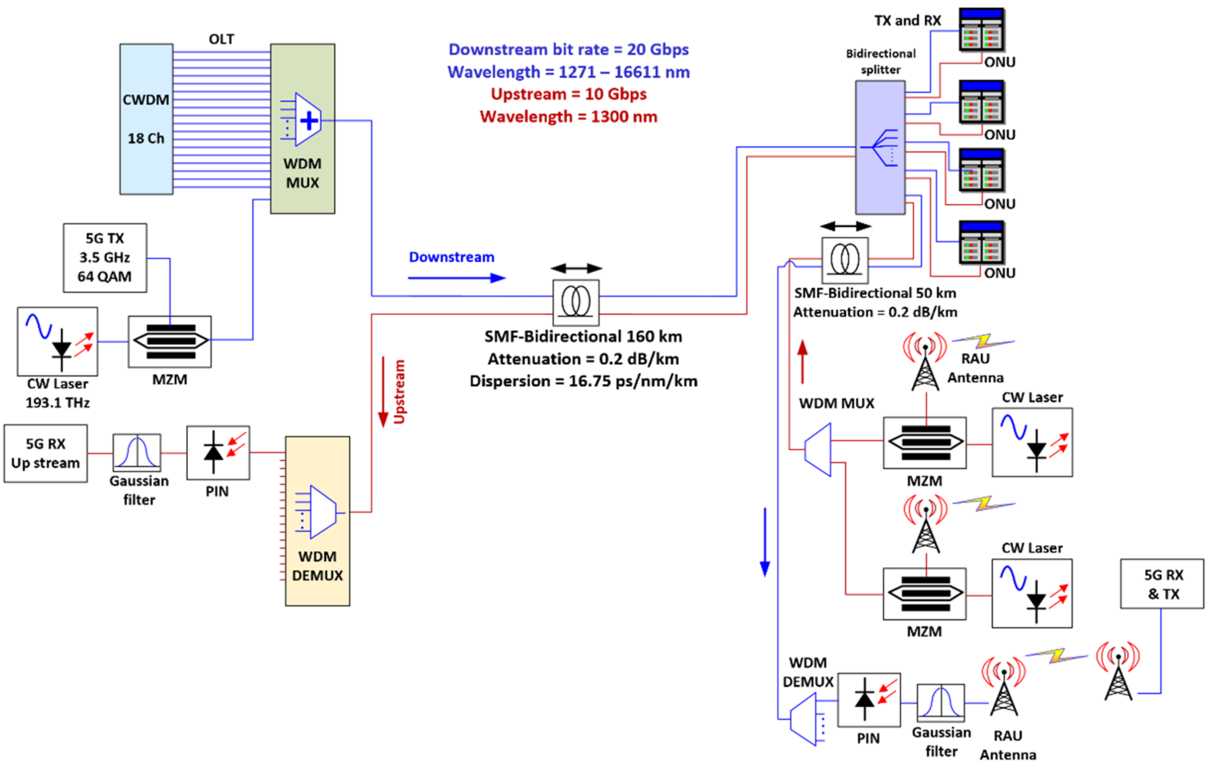

Figure 1. 5G combined with baseband and transmitted via GPON-CWDM RFoF system.

1300-1320 nm over SMF of 50 km length to the splitter and subsequently to OLT via bidirectional fiber of length 160 km. WDM-DEMUX in the OLT filters out the optical signal which is then converted into electrical signal by the PIN diode and transmitted via RAU to the 5G receiver.

3.2. SMF, DCF and CFBG Extended GPON-CWDM over Fiber Length 600 km

The following section describes the setup of the GPON network used to increase the transmission distance of the fiber link. The system is extended by the deployment of dispersion compensation techniques of dispersion compensation filter (DCF) and chirped fiber Bragg grating (CFBG).

Architecture for 5G via RFoF is shown in Fig. 2 and photograph of the experimental setup is shown in Fig. 3. The 64-QAM 5G OFDMA downstream is transmitted as RF signals to the fiber. The 5G RF spectrum at 3.5 GHz comprises of 128 subcarriers of 20 MHz bandwidth. Included in the downstream path are dispersion compensation by DCF and CFBG. The 5G data at the base-station is applied to the fiber as RF signal at 3.5 GHz. The RF signal is converted into a fiber optic signal by modulating the laser beam with the RF signal. The optical signal from the laser diode is injected into the MZM and subsequently into the WDM. This is followed by multiplexing the optical signal with CWDM wavelength, which is fed to the RFoF system. The RFoF system, comprising a DCF of length 25 km, two SMF of lengths 125 km, and DCF of length 25 km connected to the CFBG. The 25 km DCF is an optimal length needed to fully compensate for the dispersion slope and accumulated dispersion in the 125 km SMF. By increasing the DCF length the power of the optical signal is attenuated. Therefore, it was necessary to use an Erbium-doped fiber amplifier (EDFA) of 12.8 dB after CDF, and EDFA of 20 dB after each SMF. The noise figure of EDFA between 1622 to 1271 nm is 4 dB.

CFBG is used because of the high-power attenuations in DCF and the noise in EDFA. It is also used to minimize the energy loss in the fiber optic system and to control the chromatic dispersions in conjunction with the DCF. The chirped bandwidth of the CFBG is $\Delta\lambda$ = 2 nm with n = 0.0006 on a 125 mm grating. The proposed setup allows modification of the positive dispersion signal in SMF; hence, transmission of the signal can be achieved over a fiber of length 600 km. The dispersion of SMF used is 16 ps/nm.km with signal attenuation of 0.2 dB/km. Therefore, the full accumulated dispersion is 9600 ps/nm. To neutralize the positive signal dispersion in SMF, it was necessary to configure the DCF to cancel dispersion. The dispersion factor (DDCF) required to compensate the positive dispersion signal in SMF can be determined using the expression $(D_{smf} \times L_{smf}) + (D_{DCF} \times L_{DCF}) = 0$, where D_{smf} is the dispersion factor in the SMF, L_{smf} is the fibre length of the SMF, and D_{DCF} is the length of the DCF.

Bidirectional splitter can accommodate multiple wavelengths, and ONU can support 24 users and WDM. In the above scenario this allows the user to support 16 channels. Data at 10 Gb/s is transmitted upstream from the user to the ONU and via a splitter to the OLT at wavelengths of 1300 nm and 1320 nm. Data is then forwarded to OLT 5G via the splitter and a bidirectional fiber. The optical power is then converted into the electrical signal using a photo detector diode in the ONU. Bandpass Gaussian filter is used to reduce electrical signal noise to a minimum.

4. RESULTS AND DISCUSSION

The following section presents the measured results for a fiber link of 210 km. The link is then increased to 600 km.

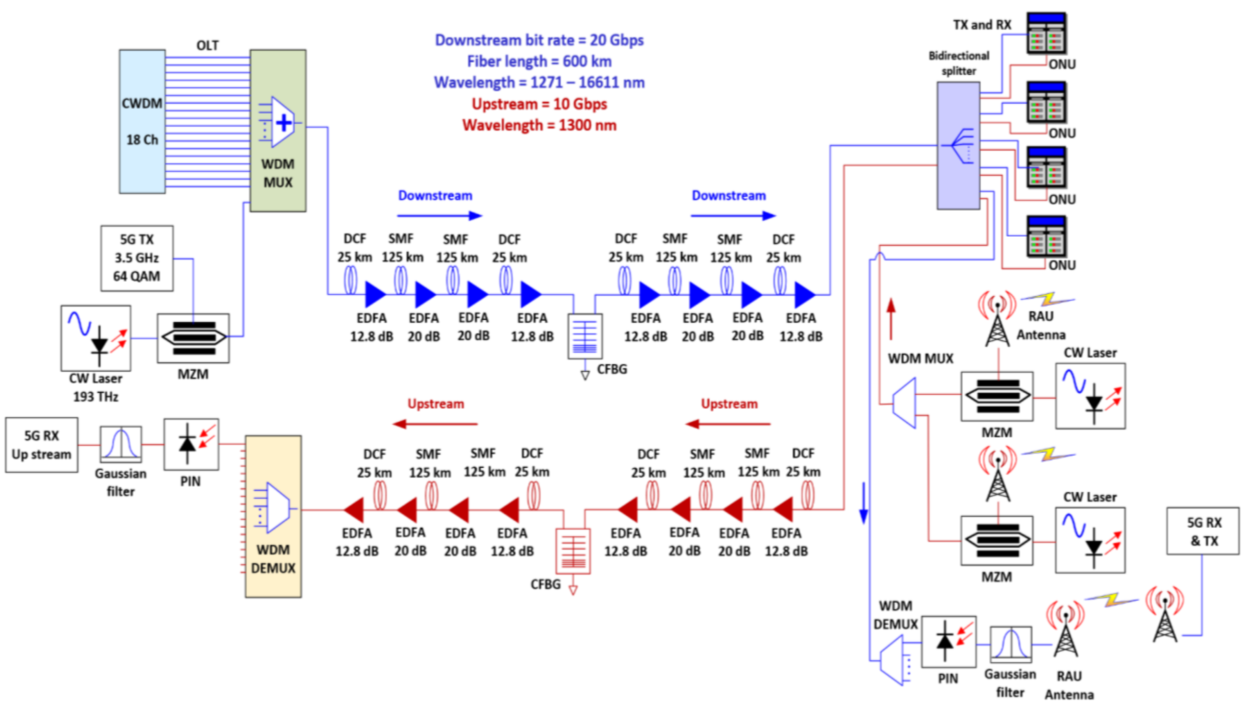

Figure 2. Downstream and upstream of GPON-CWDM network via RFoF using SMF, DCF and CFBG for a 600 km fiber.

4.1. GPON-CWDM Based RFoF over SMF of 210 km

In this section, 5G and 18-CWDM channels are modulated and converted to the optical channels, and subsequently multiplexed in WDM-multiplexer before transmission over the GPON-RFoF system using a bidirectional SMF of 160 km length. At the receiver the bidirectional splitter forwards the optical signal to the ONUs via bidirectional SMF of length of 50 km, and subsequently to the WDM-DEMUX. The system's total fiber length is 210 km.

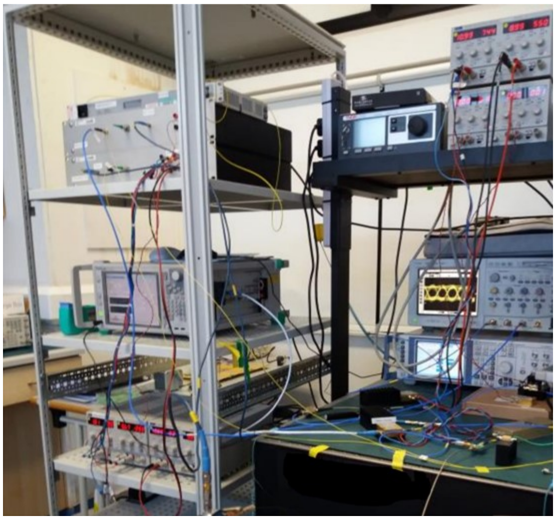

Figure 3. Photograph of the experimental setup.

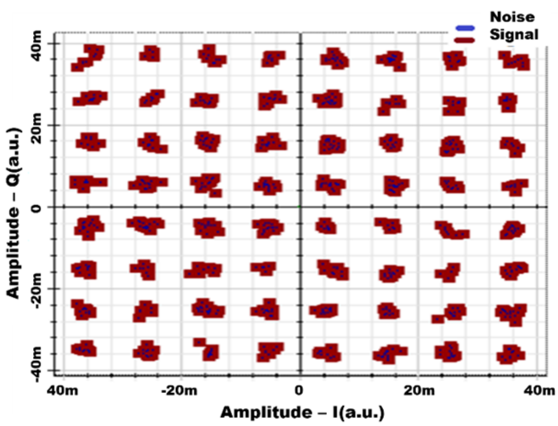

Figure 4. 64-QAM signal constellation diagram of the 5G signal over a 20 km fiber length.

The transmission distance of the signal is limited due to positive chromatic dispersion in the SMF. In the WDM-DEMUX, the wavelengths carrying the 5G signal are separated and subsequently transmitted to the 5G-RX. Fig. 4 shows the 64-QAM electrical constellation diagram of the 3.5 GHz 5G-RX signal at the receiver via RFoF over bidirectional SMF of 20 km. At every 20 km, the optical signal is monitored to improve the quality of the signal, reduce power attenuation, and improve the OSNR and SNR parameters. Fig. 4 shows the noise in the system is due to the laser diode, power attenuation and signal dispersion in SMF. Also, the baseband signal picks up some white noise. In the bidirectional SMF, the optical signal becomes weak after 20 km, due to power attenuation and signal scattering as well as chromatic dispersion, thus affecting the quality of the signal.

The 64-QAM constellation diagram of the 3.5 GHz 5G-RX signal at the receiver 210 km is shown in Fig. 5. The high level of noise results from high power loss in the SMF. Hence the signal constellation is distorted, as shown in Fig. 5, which limits the transmission distance of the signal because of the positive dispersion (16 ps/nm.km). Spreading or broadening of the light pulse also leads to signal distortion and loss per km. It was therefore necessary to use EDFA to amplify the optic signal. The DCF and CFBG are used here to increase the signal transmission, by controlling the signal spreading in SMF.

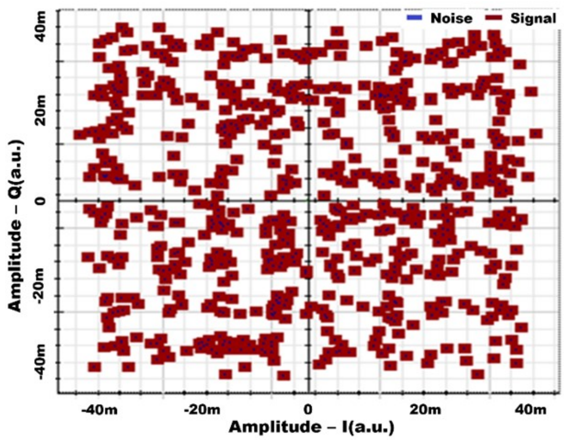

Figure 5. 64-QAM signal constellation diagram of 5G for 210 km fiber length.

Fig. 6 shows the constellation of 64-QAM 5G-Rx over a 210 km fiber using a standard link. It is evident the distortions in the signal at the receiver has significantly increased due to attenuation in the signal power, contamination by noise, signal delay and the resulting shift in phase, and chromatic dispersion effects the noise.

The optical emission spectrum of the combined 18 channel CWDM signal is shown in Fig. 7 for 5G signal transmitted at a data rate of 20 Gb/s. The CWDM offers a favorable approach of delivering 20 Gb/s to the access network. The WDM-MUX is powered into the bidirectional SMF link of 210 km. WDM multiplies fiber capacity by multiplexing optical light signals of different wavelengths onto the SMF; the wavelength range of the fiber from 1271 to 1611 nm carries the baseband (digital signal) and analogue signal (5G RF). The power level at the wavelength of 1271 nm to 1382 nm is in the region of -33 dB, and from 1550 nm to 1622 nm is in the region of -12 dB. The wavelength of the 5G-RF signal is 1552.5. The green shaded area in the spectrum displayed in Fig. 7 represents noise, which is due to the wireless RF signal and the laser diode. The spectrum confirms the dependency of the energy level to the wavelength.

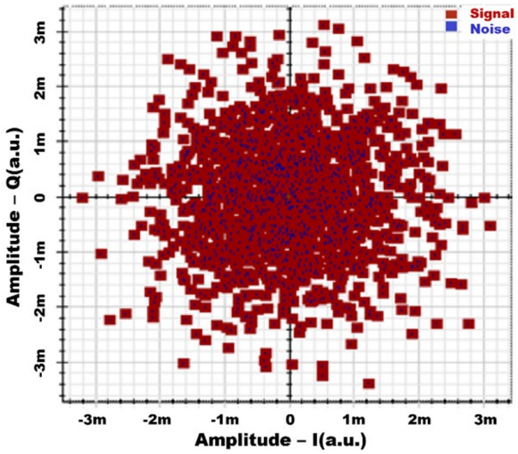

Figure 6. 64-QAM signal constellation diagram of the 5G signal over 210 km fiber length using a conventional RFoF setup.

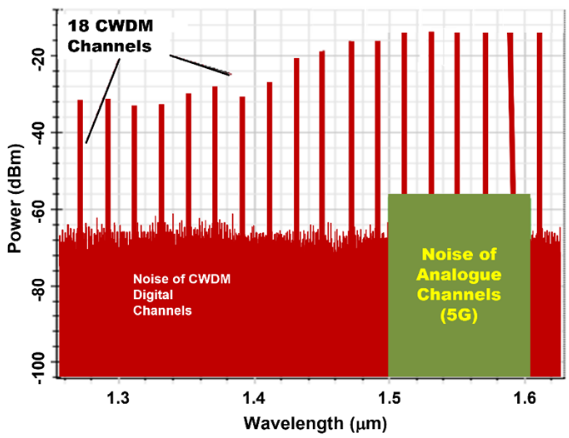

Figure 7. Optical emission spectrum for 20 Gb/s for combined 18 channel 5G TX CWDM signal for SMF length of 210 km.

At the splitter various wavelengths are applied into the SMF of 50 km. The length over which the signal is transmitted from GPON to WDM-DEMUX via the splitter is 210 km. Fig. 8 shows a down-converted 20 Gb/s eye diagram for the ONU after WDM-DEMUX. The wide-open eye diagram indicates minimal signal distortion. From Fig. 8 the magnitude of BER at ~25 ps is $3.16e^{-6}$.

The optical signal-to-noise ratio (OSNR) specifying the quality of the signal in an optical network is defined by the ratio of the signal power to the signal noise power. The OSNR depends on the bit rate, which means, the higher the bit rate, the higher the required OSNR. It is defined by the expression $\text{OSNR(dB)} = 10log(P_{signal}/P_{noise})+10log(B_m/B_{ref})$, where P_{signal} is the average signal power; P_{noise} is the optical noise power; B_m is the noise equivalent bandwidth of an optical spectrum analyzer; and B_{ref} is an optical reference bandwidth normally 0.1 nm at 1550 nm. Noise occurs at the transmitter laser diode from an erbium-doped fiber amplifier.

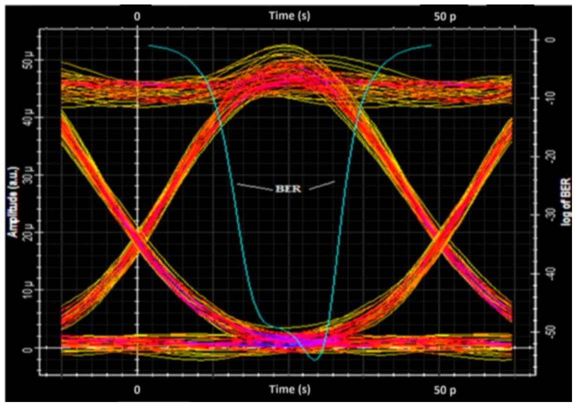

Figure 8. Eye Diagram and BER for WDM-ONU signal through SMF length of 210 km.

Fig. 9 shows the downstream RF spectrum of 64-QAM 5G-RX at a carrier frequency of 3.5 GHz with bandwidth of 200 MHz. Signal and noise are represented by the blue colored spectrum, the green represents the noise, and the red represents the signal without noise. The signal is transmitted through bidirectional SMF of length 160 km to the splitter, then to a SMF of length 50 km and finally to the WDM-DEMUX. The optical signal is separated to the 5G wavelength of 1552.5 nm. The optical signal is subsequently converted to an electrical signal in the photodiode and transmitted to the 5G receiver. The power amplitude of the signal is approximately -40 dBm and the OSNR 24 dB.

Table I shows the optical RF frequency to the splitter after SMF of 160 km. OSNR at the input and output of the SMF link as well as the power of the output signal in dBm is shown for each discrete frequency. The highest OSNR occurs at the wavelength of 1591 nm (188.43 THz). The lowest OSNR is at the wavelength 1531 nm (195.81 THz). The difference between the OSNR at the input and the end of the SMF after 160 km is 73.92 dB.

Table II shows the OSNR at WDM-DEMUX after SMF of 210 km. Frequencies from 188.43 THz to 198.41 THz correspond to the wavelengths from 1591 nm to 1511 nm. The average power loss at the splitter is 73.43 dBm. A further power loss of 0.11 dB results for the span from the splitter to the WDM-DEMUX. As a result, from Table II the highest OSNR occurs at the wavelength of 1591 nm (188.43 THz), the low-power loss at the wavelengths 1550 nm to 1590 nm; high-power loss arises at the wavelengths from 1371 nm to 1391 nm.

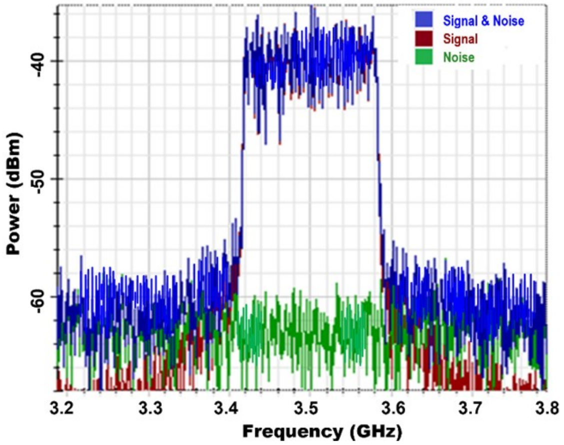

Figure 9. Eye Downstream RF spectrum of 5G-RX after SMF of 210 km.

TABLE I: OSNR AFTER 160 KM OF FIBER

Freq. (THz)	Input OSNR (dB)	Output Signal (dBm)	Output OSNR (dB)
188.43	95.99	-11.01	22.07
190.83	95.86	-11.14	21.88
193.29	95.99	-11.01	21.96
195.81	95.86	-11.14	21.77
198.41	95.99	-11.01	21.85

TABLE II: OSNR AFTER 210 KM OF FIBER

Freq. (THz)	Signal Power (dBm)	Noise Power (dBm)	OSNR (dB)
188.43	-10.04	-32.00	21.96
190.83	-10.17	-31.95	21.78
193.29	-10.04	-31.89	21.85
195.81	-10.17	-31.84	21.66
198.41	-10.04	-31.78	21.74

4.2. RFoF Based GPON-CWDM System for Transmission of 5G over 600 km

Signal dispersion imposes a limit on the transmission range of the optical system. With a shorter wavelength the channel loss increases thereby restricting the communication distance and the light separation ratio. To operate with a low energy budget, it was necessary to employ CWDM with spacing of 20 nm between the channels. This spacing is much greater than for DWDM, which is typically 3.2 nm. Compensating the chromatic dispersion in the system is also essential to increase the transmission distance of the fiber link to 600 km; in practice this distance is typical for covering a large geographical area to distribute to multiple clients. It was also necessary to adjust the signal to reduce the power attenuations encountered in the SMF. Thus, the proposed system combines SMF, DCF and CFBG to fulfill these requirements.

In Fig. 2 the DCF is set up for -80 ps/nm.km due to SMF dispersion of 17 ps/nm.km at 1552 nm, which shortens the path of the transmitted signal. DCF is used to achieve zero signal dispersion and to limit chromatic dispersion. As a result, DCF can extend the signal transmission. Chirped fiber Bragg grating is used here because of the high-power attenuation (0.6 dB/km) of the DCF. CFBG behaves like a tunable signal transmitter and reduces the power attenuations in the SMF and DCF. It also works like an optical filter.

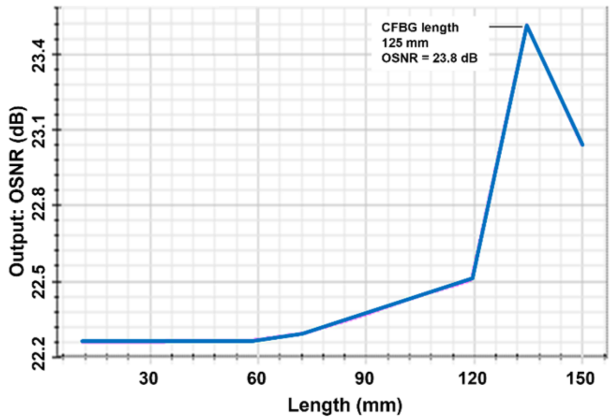

Figure 10. OSNR for CFBG chirp length in millimeters.

Finally, the CFBG chirp is setup to 125 mm to achieve a high OSNR. Fig. 10 shows the OSNR after signal transmission over 600 km. With a CFBG chirp length of 20-30 mm the lowest OSNR realized is 22.2 dB, and with a chirp length of 125 mm the OSNR peaks at 23.8 dB. A high OSNR means low BER; hence satisfying the quality of the transmitted signals.

Transmittivity and reflectivity of the wavelength period in CFBG for the chirp length of 125 mm is shown in Fig. 11. The CFBG is used as a filter in the SMF and DCF setup for wavelengths from 1271-1611 nm. The red line represents the signal transmission and the blue the reflected wavelength. Wavelengths of 1271nm and 1550nm are the reflected wavelength reduced by -92.67 dB and -57.62 dB, respectively. The chirp period function (Λ) is 0.533766 µm for chirped bandwidth ($\Delta\lambda$) of 2 nm. The chirp period is specified as a variance of the grating period along the distance. The total chirp represents the difference between the first and the last grating period.

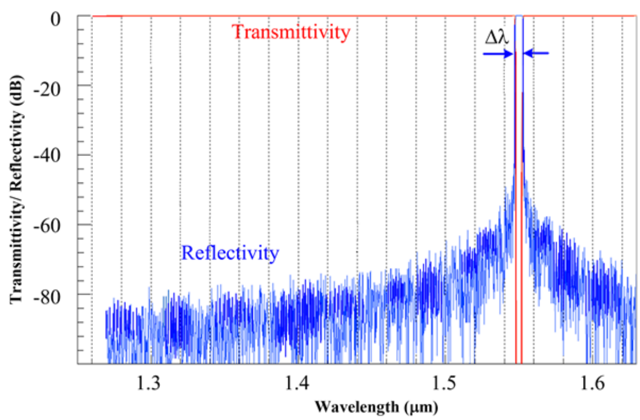

Figure 11. Measured transmittivity and reflectivity of wavelengths from 1.2 to 1.6 microns.

The grating period chirp depends on the grating length, as expressed by $\Lambda(z)=\Lambda(0)-((z-L/2))/L\Delta$, where $\Lambda(z)$ is the period chirp function; $\Lambda(0)$ is the center of chirp; L is the grating length, and Δ is the total chirp. It is possible to reconstruct an unknown grating with the knowledge of the reflection coefficient only.

Fig. 12 shows the downlink of optical modulation of multiple transmission channels over a splitter based GPON fiber network, using CWDM technology. The channel spacing is 20 nm, which guarantees low-power consumption by the system and allows transmission of 5G-RF at a wavelength of 1551.7 nm over 600 km. Fig. 12 demonstrates the proposed GPON systems can employ CWDM technology via RFoF to provide, in this example, of up to 18 baseband wavelengths and 2 wireless systems using the same fiber infrastructure. However, the performance of the 20 Gb/s CWDM module incurs slight degradation after 600 km.

Fig. 13 shows an eye diagram to illustrate the calculation of the signal-to-noise (SNR) ratio and the Q-factor. SNR is the ratio of the signal amplitude to the noise at either the top or the base of the signal given by Eqn. (1), and the Q-factor can be calculated using Eqn. (2) [31].

$$\mathrm{SNR} = \frac{\mu_{PTop} - \mu_{PBase}}{\sigma_{PTop} - \sigma_{PBase}} \quad (1)$$

$$\text{Quality factor} = \frac{\mu_{PTop} - \mu_{PBase}}{\sigma_{PTop} + \sigma_{PBase}} \quad (2)$$

Where μ_{PTop} is mean value of the eye top, σ_{PTop} is standard deviation of the eye top, μ_{PBase} is mean value of the eye base, and σ_{PBase} is standard deviation of the eye base.

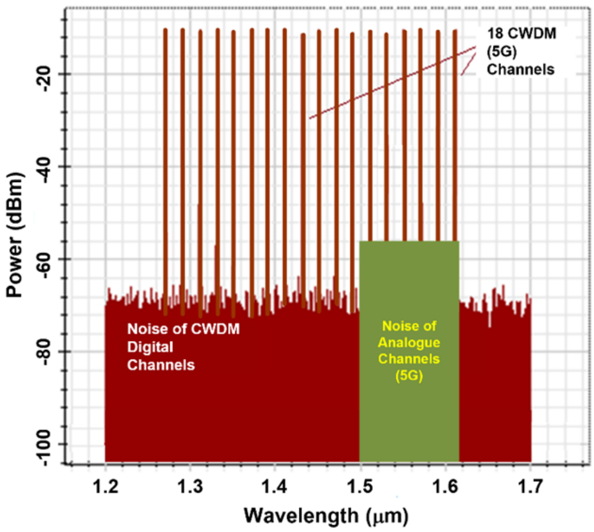

Figure 12. Optical spectrum of 18 channel 5G-RF using CWDM in GPON over 600 km.

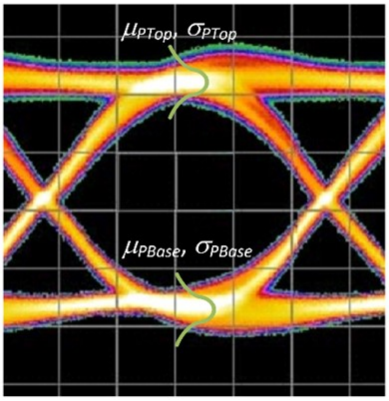

Figure 13. Example of a typical eye diagram.

Fig. 14 shows a clear open eye diagram of the downstream 20 Gb/s CWDM channels after transmission over 600 km via the proposed triple compensation system (SMF-DCF and CFBG) to the bidirectional splitter, and from there to the ONU. In the ONU, the photodiodes convert the optical signal to an electrical signal, which is subsequently transmitted to the users. This result indicates a satisfactory performance without overlaps in the diagram. The Q-factor measured in Fig. 13 is 25.17, which can be read directly from the right-hand y-axis.

Fig. 15 represents a clear open eye diagram of the downstream 20 Gb/s GPON-CWDM channels via the proposed RFoF system. The optical signal is transmitted via the triple compensation system (SMF, DCF and CFBG) to the bidirectional splitter over a fiber length of 600 km. From the splitter, the optical signal is transmitted to the ONU, where the photodiode is located, which converts the optical signal to an electrical signal and then transmitted to the users. The BER scale is in logs, shown on the right-hand axis in Fig. 15. The magnitude of the minimum BER is 1.58e^{-4}. The Q-factor in Fig. 15 is calculated to be 12.93.

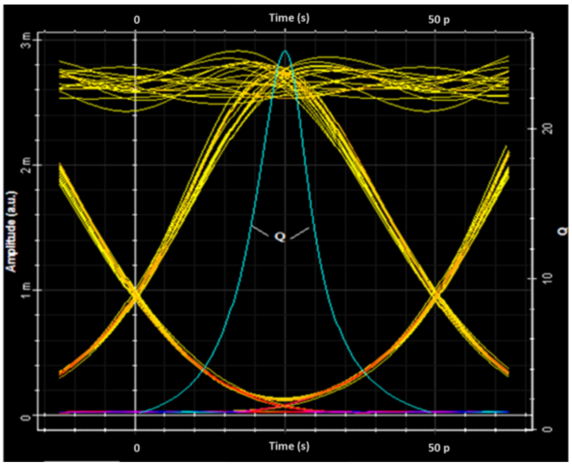

Figure 14. Downstream eye diagram showing the Q-factor after BER after transmission of the optical signal over 600 km.

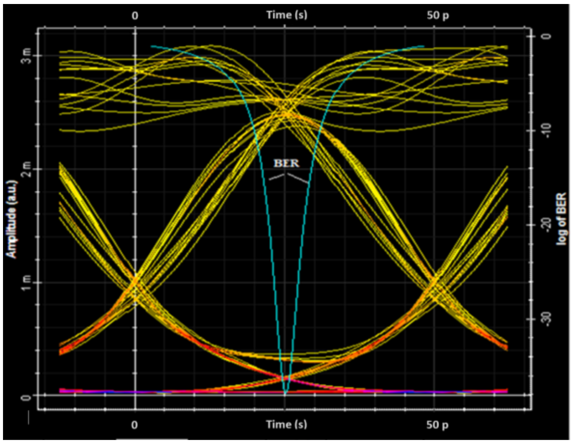

Figure 15. Downstream eye diagram showing BER after transmission of the optical signal over 600 km.

Fig. 16 shows the measured downstream RF spectrum of the 64-QAM 5G-RX using the proposed RFoF setup at a carrier frequency of 3.5 GHz after transmission over a fiber of 600 km long. Also, shown is the spectrum of the signal using a conventional RFoF setup. The bandwidth of the signal is 160 MHz. The signal is transmitted via bidirectional SMF, DCF and CFBG fiber to a bidirectional splitter, and from the bidirectional splitter to the WDM-DEMUX. In the WDM-DEMUX the separated optical signal 5G wavelength of 1552.5 nm is converted to an electrical signal using a photodiode. The blue color indicates the signal with noise. The green spectrum represents the noise, and the red spectrum the signal without noise. The RF power level of the pulse is approximately -33 dBm after travelling 600 km. The figure shows using the conventional optical link setup the RF power measured is approximately -52 dBm. This is 19 dB below that with the proposed link.

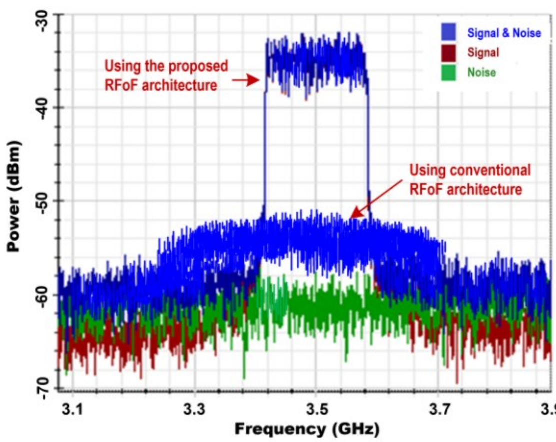

Figure 16. Downstream RF spectrum of the 5G-RF signal after transmission over a fiber of 600 km.

With the proposed architecture the noise begins to have a significant impact on the performance of the system for lengths above 600 km. Error vector magnitude (EVM) variation over the 600 km is shown in Fig. 17. The figure shows how the EVM deteriorates with increasing fiber length. This is because by increasing the fiber length there is a corresponding increase in the delay spread caused by the fiber chromatic dispersion.

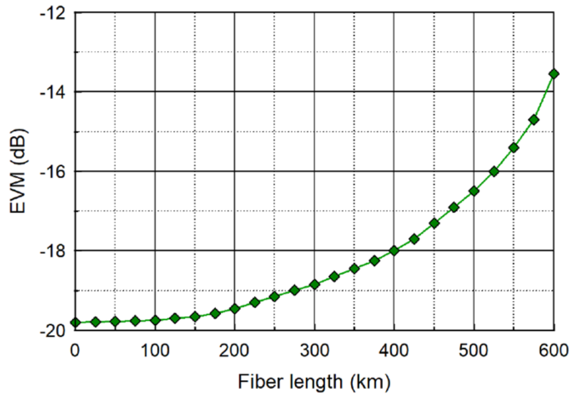

Figure 17. EVM degradation with fiber length for 64-QAM modulation.

The sensitivity of the receiver is defined as the optical power required for achieving a BER of 10^{-9}. The BER was calculated using statistical methods, where the signal received is compared to the transmitted signal. Fig. 18 shows the sensitivity of the channels using the proposed RFoF setup. For clarity BER performance of only six channels from 1 to 18 are shown. The difference observed in BER is because of the different wavelengths used for the various channels.

Table III provides a comparison of the parameters of the proposed RF over optical fiber architecture with recent works reported in literature. Although the performance of the proposed system cannot be directly benchmarked against other optical systems because they are designed for different specifications; however, the table provides useful information. The transmission rate of reference [8] is double that of the proposed fiber optical system; however, this is over a significantly shorter fiber length. Compared to references [9] and [10] the transmission rate of proposed system is double, and this is over a significantly larger fiber optic length without compromising the BER.

TABLE III: PARAMETER COMPARISON WITH OTHER WORKS

Parameters	This work	[8]	[9]	[10]	[32]
QAM	64	16	32	16	64
Fiber length (km)	600	50	50	70	10
Transmission rate (Gb/s)	20	40	10	10	-
Input power (dBm)	20	-	-	-	33
Receiver sensitivity (dBm)	-28.3	-	-19	-	-
BER	10^{-9}	1.6×10^{-9}	10^{-9}	10^{-9}	-

5. CONCLUSION

Experimental results presented here demonstrate the viability of the proposed RF over optical fiber architecture for transmission of bit rates up to 20 Gb/s over a long-haul fiber of 600 km. This was achieved by strategically interweaving sections of SMF with DCF and utilizing a CFBG midway to overcome the chromatic dispersion and power attenuation associated with SMF fibers. The experiment was done by using a 64-QAM signal that was modulated onto CWDM signal. With the proposed RFoF architecture the signal power received over a 600 km fiber was 19 dB greater than conventional optical architecture with the same input optical power. This means that significant power saving can be achieved over a conventional long-haul optical network. With the proposed RFoF architecture the receiver sensitivity is -28.3 dBm for BER of 10^{-9}, optical signal-to-noise ratio is 22.2 dB, and the eye diagram is open wide.

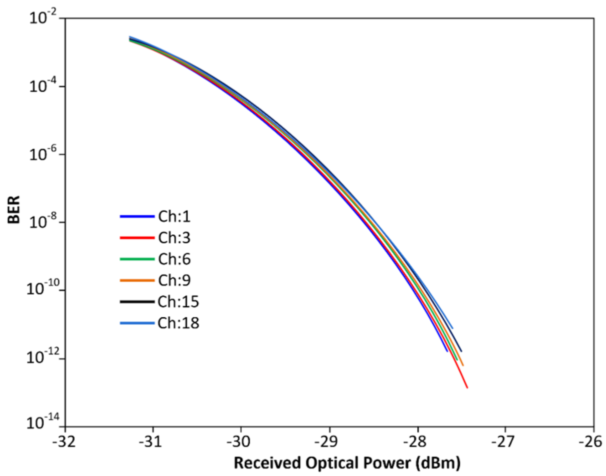

Figure 18. BER performance for the baseband channels 1 to 18.

AUTHOR CONTRIBUTION

Authors Mazin Al Noor, Bal S. Virdee, and Karim Ouazzane were instrumental in the design, development of the proposed architecture. They also conducted the experimental work. Authors Dion Mariyanayagam, Harry Benetatos, and Svetla Hubenova conducted the modelling and simulation work. All authors contributed to the writing of the paper.

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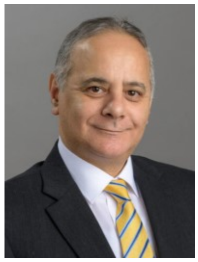

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