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# Bidirectional MDRZ Downstream and NRZ OOK Upstream SS-WDM RoFSO Communication System

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**Abstract:** A cost-effective spectrum sliced wavelength division multiplexing radio over free space (SS-WDM RoFSO) full duplex communication system architecture has been proposed and analyzed. For the downlink, a 10 Gbits/s high spectrally efficient and amplitude maintaining modified duobinary return to zero (MDRZ) modulated the filtered slices from the light source. The free space optical (FSO) channel was modeled by the well-known Gamma-Gamma model and was further subjected to moderate rain attenuation conditions. Four FSO transceivers were used to mitigate against laser beam scintillation, geometrical losses and rain attenuation. For uplink, a reflective semiconductor optical amplifier (RSOA) was used both as a modulator and an amplifier. Its amplitude squeezing effect was used to erase the information in the MDRZ modulated downstream seeding wavelength for uplink transmission of 10 Gbits/s NRZ OOK signals. At a bit error rate (BER) of $1.262 \times 10^{-9}$, our proposed architecture revealed that 10 Gbits/s symmetric SS-WDM RoFSO can achieve 4.167 km of free space transmission. Power penalty of approximately 0.2 and 3 dB was achieved for downstream and upstream, respectively, which assures the feasibility of the proposed architecture. Such a system is meant to co-exist with the forthcoming fifth generation long-term evolution urban systems.

**Keywords:** MDRZ, NRZ OOK, radio over free space, spectrum slicing, wavelength reuse

## 1 Introduction

The emergence of bandwidth hungry applications such as high definition TV, online transactions and gaming, cloud computing, among others, has been the drivers for high data rate wireless connectivity. At the same time, the wireless spectrum is already congested. Thus, radio over free space optical (RoFSO) communication has emerged as a potential candidate for radio signal transmission over free space. Central station (CS) generated radio-frequency optical signals are delivered to the remote antenna via free space, thus shifting complex expensive components to the CS [1]. High data rates, large scalable bandwidth and mobility are some of the virtues that the next generation of access networks aims to meet [2].

Free space optics (FSO) is a line of sight technology in which data is transmitted through air, water or vacuum. FSO has had a remarkable impact in the research domain worldwide due to its prominent features such as low cost, huge bandwidth (comparable to that of optic fiber), license free full duplex operation, high security and immunity to electromagnetic interference when compared to its radio-frequency counterpart [2]. To enhance mobility inherent on the wireless scheme on the huge bandwidth of optical communication system, Radio over free space (RoFSO), system have been the research direction [3]. The idea is to convey RF sub-carriers on the optical signal at the optical line terminal (OLT) in the central office (CO), so that the baseband data streams and the data modulated RF signals can be simultaneously delivered to the wireline and wireless users [4]. However, FSO performance is adversely limited to short span length due to atmospheric turbulence and prevailing weather conditions [5]. Aerosols, haze, fog among other particles cause exponential extinction of the information carrying laser beam by phenomenon of scattering and absorption [5].

To mitigate against the short comings of FSO, different techniques have been proposed in the literature. Spectrum slicing wavelength division multiplexing (SS-WDM) technique has been proposed in the distribution links to support multiple users at high data rates. In such a scheme, a broadband light source is sliced and the slices are used to modulate data signals. Further such a technology reduces the overall system cost since a single light source is required compared to expensive tunable lasers and associated components typically used in ordinary WDM. Meanwhile in [6], SS-WDM has been shown to improve the FSO communication compared to

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ordinary WDM. Similar results have been demonstrated in [7] for Vellore weather conditions.

Modulation schemes plays an important role in data transmission over free space. Differential shift keying (DPSK) is the current modulation techniques to achieve appreciable performance in cost-effective high-speed networks [8]. However, the requirement of the Mach-Zehnder interferometric demodulator as well as balanced detector for DPSK signals may not be a cost-effective solution. Modified duobinary return to zero (MDRZ) provide advantage of smaller timing jitter and amplitude distortion. When compared to OOK, it provides smooth operation even at relatively higher average channel powers. Moreover, a simple direct detection receiver is used. To create a bidirectional SS-WDM RoFSO system, a cost-effective solution is wavelength reuse in which both the downstream and upstream channels use the same wavelength for improving wavelength utilization efficiency [9]. There is no optical source in ONU. The reflective semiconductor optical amplifier (RSOA) has been proposed as an uplink colorless transmitter and modulator in the ONU due to its high optical gain, wide optical bandwidth and good integration capabilities [10].

Experimental evaluations of multiple transmitters and multiple receivers have been demonstrated [11]. It has been inferred that using more than one beam at the transmitter and receiver is an option. Such an architecture reduces beam scintillation since each beam traverse a different and independent path so that light signals are affected differently by the channel conditions. Moreover, effects of physical obstructions such as birds, insects, rain and low visibility are brought to minimum. As suggested in [11], authors in [12], implemented a MIMO technique involving four links at the same wavelength. A MIMO system having four links is an optimum multi beam solution than a single, two or three beam systems. Consequently, there is no performance improvement in WDM FSO system using more than four beams [11]. This has been found to be a good mitigation strategy especially in rain conditions.

Therefore, in this paper, we extend the previous works by exploring modified duobinary return to zero (MDRZ) modulation for a bidirectional SS-WDM RoFSO communication system under moderate rain weather conditions. Such a modulation scheme has been motivated due to small timing jitter and amplitude distortion [13], potentially making it ideal for use as a seeding wavelength for upstream transmission. NRZ OOK was used for ONU uplink data transmission because of its simplicity. A set of four FSO transceivers was used to create a MIMO architecture as a way of mitigating against the effects of atmospheric scintillation and weather degradation. This proposed architecture takes full cognizant of the fact that already bidirectional full duplex FSO transceivers are in the market [14]. To the best of our knowledge, such architectures are rare in literature.

The rest of the paper is organized as follows: in Section 2, a review of the atmospheric and turbulence models is given. In Section 3, system design is discussed. Results are in Section 4 followed by comparison with state of the art work in Section 5. Finally, the paper is concluded in Section 6.

## 2 Atmospheric and turbulence models

Adverse weather results in exponential extinction $h_L$ of the information carrying laser beam, described by Beer–Lambert law as [15]:

$$h_L = e^{-\sigma L}, \tag{1}$$

where $L$ is the link length and $\sigma$ is the atmospheric attenuation coefficient given by [15]:

$$\sigma = \frac{3.91}{V}\left(\frac{\lambda}{550}\right)^{-q}, \tag{2}$$

where $\lambda$ is the wavelength in mm, $V$ is the visibility in (km), and $q$ is the distribution size of particles obtained from Kim-Kruse model. The value of $q$ is 1.6 for $V \geq 50$ km, 1.3 for 6 km $\leq V \leq 50$ km and $0.585V^{\frac{1}{3}}$ for $V \leq 6$ km [5].

Gamma-Gamma modeling partitions the normalized light intensity into small scale and large-scale eddies, with both small scale and large-scale eddies following the Gamma distribution, Mathematically, the PDF of the Gamma-Gamma fading model is expressed as [16]:

$$p(I) = \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\gamma(\alpha)\gamma(\beta)} I^{\frac{\alpha+\beta}{2}-1} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta I}\right), I > 0, \tag{3}$$

$\alpha$ and $\beta$ denote the effective numbers of large-scale and small-scale eddies respectively, $K_n(\cdot)$ is the modified Bessel function of second kind of order $(\alpha - \beta)$ and $\gamma(\cdot)$ is the Gamma function. The effective numbers $\alpha$ and $\beta$ are given as:

$$\alpha = \left(exp\left[\frac{0.49\sigma_R^2}{\left(1 + 1.1\sigma_R^{12/5}\right)^{7/6}}\right] - 1\right)^{-1} \tag{4}$$

$$\beta = \left( exp\left[ \frac{0.51\sigma_R^2}{\left(1 + 0.69\sigma_R^{12/5}\right)^{5/6}} \right] - 1 \right)^{-1} \quad (5)$$

The Royton variance is defined as $\sigma_R^2 = 1.23 C_n^2 k^{\frac{7}{6}} L^{\frac{11}{6}}$ and $k = 2\pi/\lambda$ is the wavelength. $C_n^2$ is the refractive index structure, which determines the strength of the atmospheric turbulence. The refractive index structure has the values: $5 \times 10^{-17} m^{-\frac{2}{3}}, 5 \times 10^{-15} m^{-\frac{2}{3}}$ and $5 \times 10^{-13} m^{-\frac{2}{3}}$ for weak, moderate and strong turbulence regimes, respectively.

## 3 System design

The proposed light wave set up for a five-channel bi-directional SS-WDM RoFSO multi-beam system employing MDRZ modulation in the downstream and NRZ OOK in the upstream is shown in Figure 1. The system consists of a transmitter, multi-beam FSO link and the receiver. At the CO, a single CW laser source centered at 193.1 THz with a linewidth of 10 MHz is sliced into five slices using an arrayed waveguide grating (AWG) demultiplexer. A second-order Gaussian optical filter was used to filter the optical signals. For downlink, each of these slices is modulated by a Mach-Zehnder modulator using $2^{15} - 1$ PRBS data sequence to generate MDRZ modulated signals. The PRBS signifies or represents a random source of data, which may be speech, video, data, picture or music. The MDRZ spectrum sliced signals were multiplexed by a second AWG and the aggregate signal sent over multipath free space with variable link length.

The design of an MDRZ transmitter involves generating an NRZ signal first, which is modified by a delay and subtract circuit to give an output used to pulsate the first MZM modulator. The first MZM is concatenated to the second MZM which is being driven by a sinusoidal electrical signal with a 40 GHz frequency and −90° phase. In this scheme, the phase of all zeroes is kept constant, but a 180° phase is introduced between all consecutive ones, leading to suppression of the carrier signal [13] . The outputs from 5 transmitters is a multiplexed using a second AWG multiplexer resulting in a composite signal with wavelength ($\lambda_1 - \lambda_5$). An optical power splitter

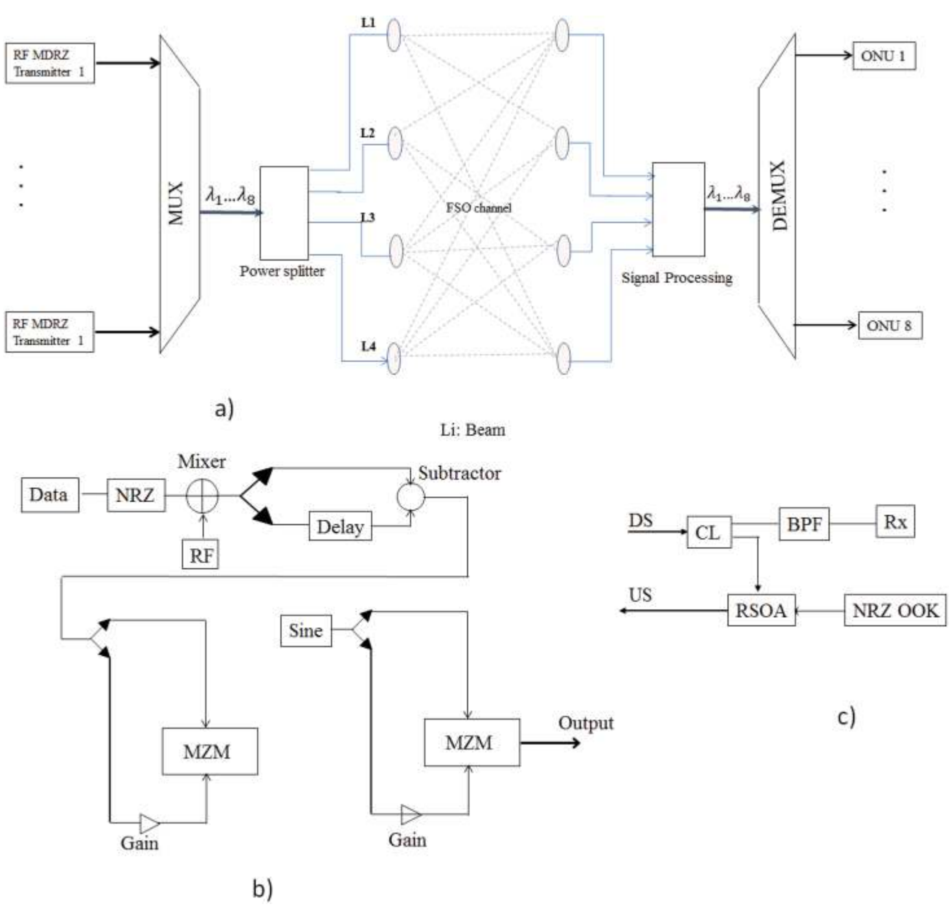


**Figure 1:** Proposed SS-WDM RoSFO architecture: (a) system, (b) RF MDRZ transmitter and (c) ONU.

is used to split the multiplexed signal into four beams, ($L_1, L_2, L_3$ and $L_4$). This has been done as a way of mitigating turbulence and weather degradation effects. In other words, each of these beams is send to a transmitting telescope, which determines the size as well as the direction of the beam before it is launched in free space. Thus, each transmitted beam will be received by four receiving telescopes, thus a sixteen channel MIMO link has been created. The output optical signals from the four-receiving telescope were processed using the MATLAB component in co-simulation with Optisystems. Simple selection combining algorithm was applied for signal processing at the remote node (RN).

In the remote node (RN), the SS-WDM signals transmitted over free space are de-multiplexed by another AWG so that signals with various wavelength are routed to different optical network units (ONUs). At each ONU, a 3 dB optical splitter is used to so that half of the MDRZ modulated signal is fed to the optical filter and then is direct detected using an APD photodetector. This is followed by a low pass Bessel filter of order 2, a 3R regenerator and finally a BER analyzer. For uplink, the other half of the modulated downstream signal is directly re-modulated by the reflective semiconductor optical amplifier (RSOA) to generate the 10 Gbps NRZ OOK upstream signal. The RSOA used here has reflectivity values at input and output facets of $5 \times 10^{-5}$ and 0.99, respectively. Since the seeding power of the RSOA has a significant effect on its modulation characteristics, a variable optical attenuator was used to keep an adequate optical power at the input of the RSOA to operate in the gain saturation regime. Thanks to the amplitude squeezing effect of the RSOA which erased the downstream information for wavelength reuse. The re-modulated NRZ OOK signals were multiplexed using an AWG at RN and launched into the FSO channel to the OLT where it is demultiplexed by another AWG and finally received by an APD receiver in the CO. OptiSystems 14 was used for simulation.

## 4 Results and discussion

In this study, the simulation was carried out using OptiSystem 14 commercial simulation software. BER analyzer and optical power meters were used for measurements. Weather attenuation of 4 dB/km was applied. Figure 2(a) shows the output spectrum of the CW laser centered at 193.1 THz with a line width of 10 MHz. Figure 2(b) is the spectrum of the filtered optical signal slices modulated by 10 Gbps MDRZ electrical signal. The spectrum of the aggregated signal prior to transmission over free space channel is shown in Figure 2(c). The amplified modulated NRZ OOK upstream signal is shown in Figure 2(d).

The proposed architecture has also been characterized by the $Q$ factor, which can be expressed mathematically as:

$$Q(x) = \int_x^{\infty} \frac{1}{\sqrt{2\pi}} e^{-\frac{y^2}{2}} dy. \tag{6}$$

The relationship between the BER and the $Q$ factor is [3];

$$Q = 20 \log \left[ \sqrt{2} erfc^{-1} 2BER \right], \tag{7}$$

where *erfc* is the complimentary error function.

The BER in simple terms is defined as the percentage of bits received with errors divided by the total number of bits that have been transmitted, received or processed over a given time period. It relates to the probability of incorrect identification of bits by the decision circuit in the receiver. For meaningful optical communication, its value should be less than or equal to $1 \times 10^{-9}$. Generally, as the distance increases, the $Q$ factor decreases, but the decrease is more in the uplink direction that the downlink direction, implying that MDRZ is much more tolerant to the atmospheric turbulence and weather conditions compared to NRZ OOK.

From Figure 3, an acceptable $Q$ factor of 6, in the downstream direction, of the proposed SS-WDM MDRZ radio over free space system is able to achieve a distance of 4.167 km, without a repeater, when subjected to a weak atmospheric turbulence channel and moderate rain attenuation conditions. For the uplink, the NRZ OOK over a MIMO FSO channel can achieve a link range of 3.685 km at an acceptable $Q$ factor without a repeater.

Alternatively, the same information can be portrayed by means of BER as a function of distance as shown in Figure 4 . It can also be noted that for the same distance of 4.167 km in the downlink, the SS-WDM MDRZ have a BER of $1.262 \times 10^{-9}$, while for the uplink direction a BER of $1.27 \times 10^{-9}$ is achieved by the NRZ OOK over a MIMO FSO system for a distance of 3.685 km.

The power performance has also been analyzed as shown in Figure 5. It is noted that generally, in the downlink direction, the SS-WDM MDRZ RoFSO communication system requires −25.54 dBm to achieve a BER of $1.262 \times 10^{-9}$, while a power of −20.98 dBm is required by the re-modulated NZR OOK to achieve a BER of $1.27 \times 10^{-9}$. Hence NRZ OOK requires more power to achieve an acceptable BER as compared to MDRZ. This maybe explained due to the fact that for the NRZ OOK, the

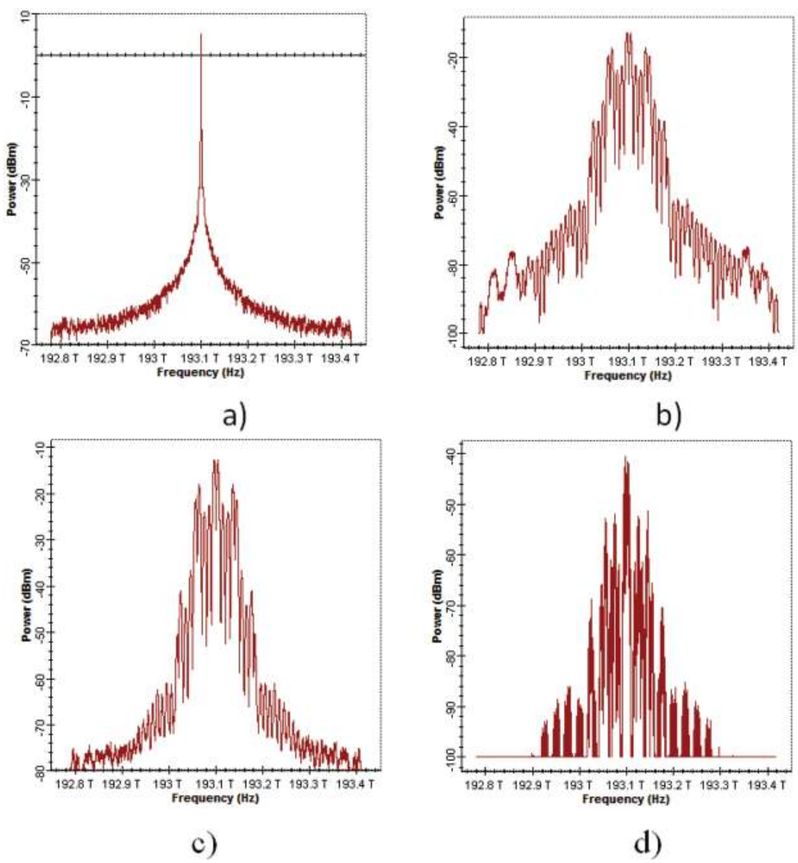


**Figure 2:** (a) CW laser output spectrum centered at 193.1 THz, (b) transmitter output, (c) modulated downstream signal and (d) modulated upstream signal.

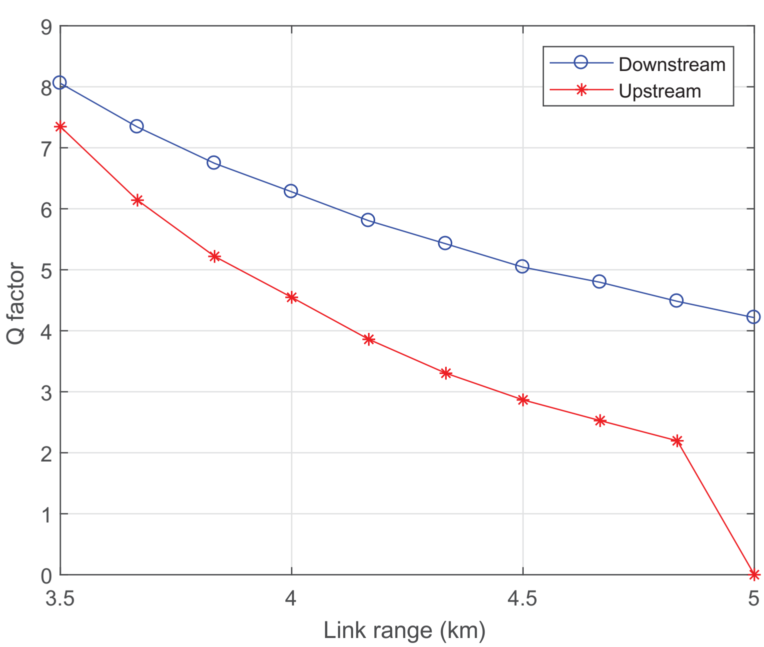


**Figure 3:** Maximum *Q* factor vs range.

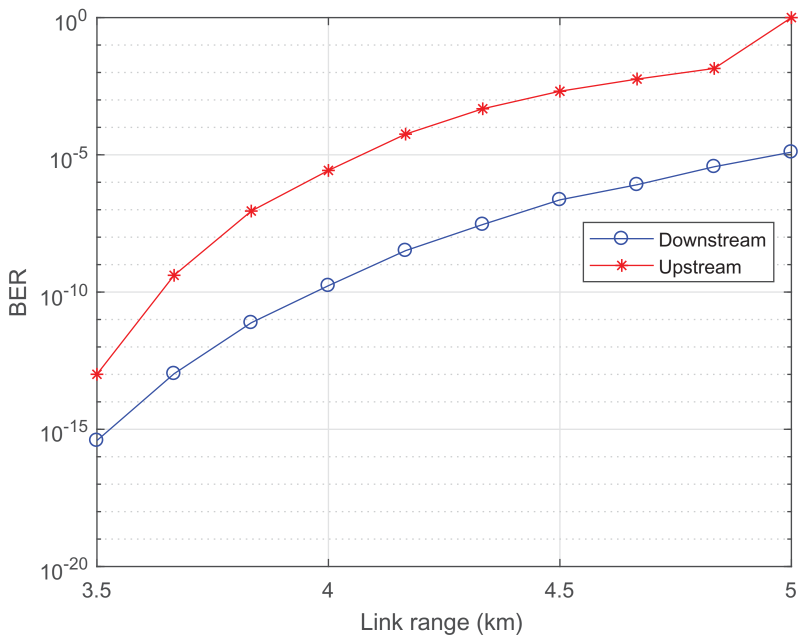


**Figure 4:** BER versus link range.

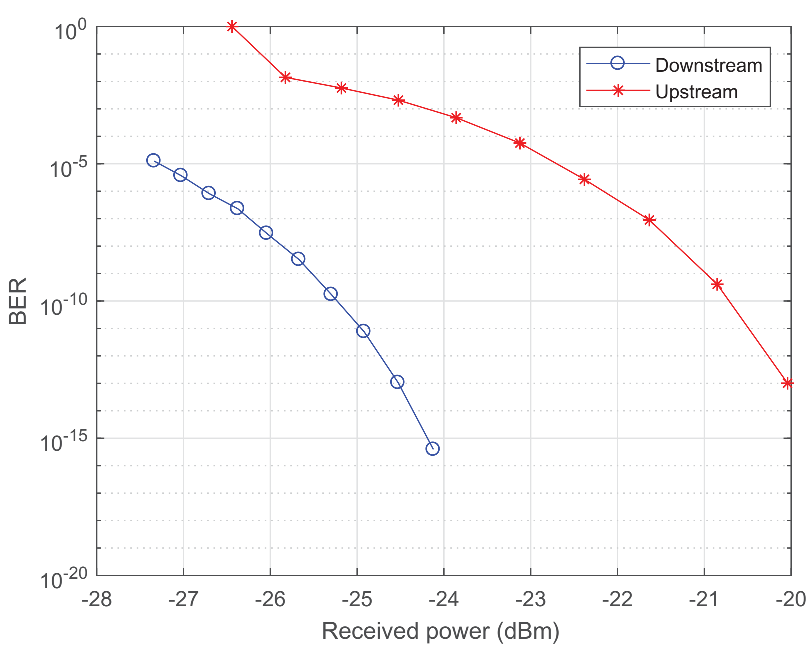


**Figure 5:** Power performance.

information is carried in the amplitude, which is heavily affected by scintillation as the laser beam propagates through free space channel. Contrariwise, for the MDRZ in the downlink, the information is carried in the phase. Furthermore, MDZR has been known to be resilient to chromatic dispersion in fiber optic communication [13], and the same characteristics is evident.

From Figure 6, we can see that the required optical signal at BER of approximately $1 \times 10^{-9}$ in Back to Back (B2B) case is approximately 25.7 dB. After 4.167 km of MIMO free space transmission, the power penalty is approximately 0.2 dB. Thus, a very low power penalty is achieved for the downlink direction. Also, a good eye opening is observed after a distance of 4.167 km, which is almost the same as the B2B case. For the uplink, shown in Figure 7, the required optical signal at BER of approximately $1 \times 10^{-9}$ in B2B is approximately 24.5 dB. After 4.167 km of MIMO free space transmission in the

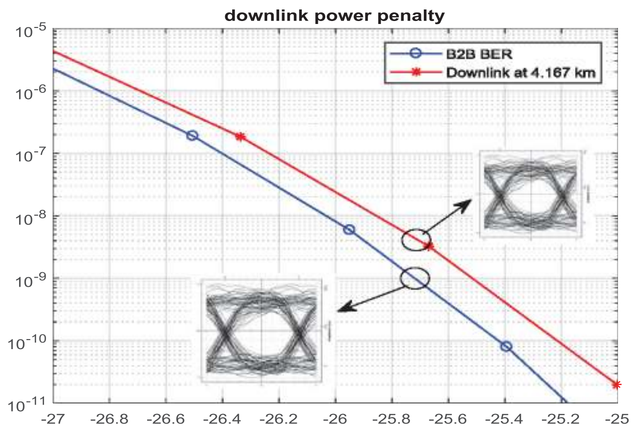


**Figure 6:** Downlink power penalty.

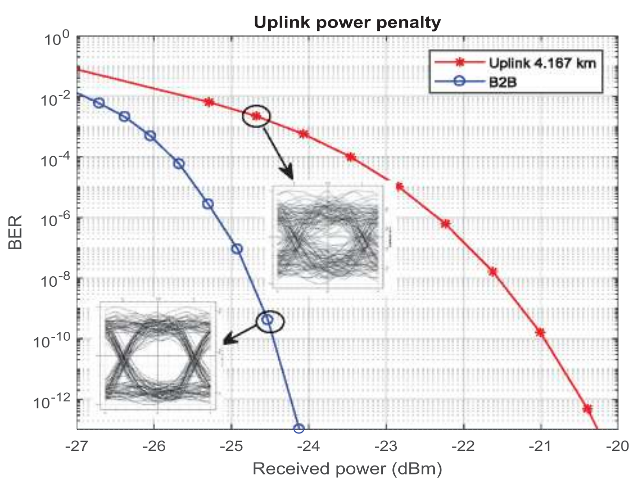


**Figure 7:** Uplink power penalty.

uplink direction, the remodulated NRZ OOK power penalty is approximately 3 dB. All these results assure of the feasibility of the proposed cost-effective spectrum sliced MDRZ WDM RoFSO using four FSO transceivers. Thus, this architecture is promising for the forthcoming 5G networks.

## 5 Comparison of proposed architecture with other works

In this section, we compare the performance and characteristics of the proposed cost-effective SS-WDM RoFSO system using four FSO transceivers as a way of mitigating against the effects of atmospheric turbulence and adverse weather conditions. The comparison has been drawn from the research works conveying data over free space, which might or might not have RF subcarriers mixed with baseband signal. This comparison has been done to determine the novelty of the current proposed architecture.

From Table 1, it is clear that most research works were limited to less data rate; 1.56 Gbps in [6, 7], 1.25 Gbps in [12], and 2.5 Gbps [17]. The geometric losses were not considered in [18], hence a much longer span of 190 km was observed in [18]. But geometrical losses are gives as $P_t/(4\pi L^2)$, where $P_t$ is the transmitted power. This then imply that it has serious degradation impact in terrestrial FSO systems. Furthermore, Refs [12], [17] and [18] are not cost-effective architectures since they require tunable laser sources or independent CW laser trans-

**Table 1:** Comparison of the present architecture with current state of art.

| **Parameter** | **Ref [6]** | **Ref [7]** | **Ref [12]** | **Ref [17]** | **Ref [18]** | **Current investigation** |
|---|---|---|---|---|---|---|
| Transmission mode | Single directional downlink | Single directional | Single directional | Single directional | Single directional | Bi directional |
| Transmitter modulation | SS-WDM | SS-WDM | WDM NRZ OOK | WDM NRZ OOK Power | WDM NRZ DPSK | SS-WDM MDRZ in downlink, |
| formats | NRZ OOK | NRZ OOK | | (10 dBm) was too high | | NRZ OOK in uplink |
| Data rate | 1.56 Gbps | 1.56 Gbps | 1.25 Gbps | 2.5 Gbps | 2.5 Gbps | 10 Gbps |
| Channel conditions | 4 dB/km SISO | 4 dB/km SISO | MIMO | MIMO 4 dB/km, Geometric loses neglected | SISO 0.2208 dB/km, Geometrical losses neglected | MIMO with 4 dB/km, Geometric losses |
| Maximum distance | 2.5 km | 3.3 km | 1.1 km | 4.75 km | 190 km | 4.167 km |

mitters. Hence, the current proposed architecture show improvement over current state of the art architectures because of the following advantages: (1) when geometric losses and atmospheric turbulence are considered, we achieved 4.167 km bidirectional transmission of RoFSO; (2) it uses spectrum slicing with a power efficient advanced modulation format (MDRZ) in the transmitter. Such an architecture greatly reduces the transmitter cost, since a single CW laser source is used instead of costly tunable multiwavelength source. (3) The ONU is made colorless through wavelength reuse, thus the overall cost of the ONU is greatly reduced; moreover, colorless ONU manufacturing cost is greatly reduced. (4) The use of four links to mitigate atmospheric turbulence and weather degradation is a clear cost-effective option. This is motivated due to low cost and power efficient FSO transceivers. Thus, we have reduced the overall cost of the FSO communication system. (5) Finally, our proposed architecture can transmit RoFSO data at 10 Gbps, thus enhancing mobility.

## 6 Conclusion

A novel cost-effective full duplex spectrum slicing wavelength division multiplexing radio over free space communication system has been proposed and investigated in terms of the $Q$ factor, BER power penalty and eye opening. The BER and $Q$ factor of $1.262 \times 10^{-9}$ and 6, respectively, have been achieved over a distance of 4.167 km in the downlink direction after suffering from channel induced beam scintillation and moderate rain degradation. Furthermore, for that distance, the power penalty was relatively low and the eye opening was good, proving the feasibility of the proposed architecture. Such an architecture find useful applications in the forthcoming 5G cellular networks to connect base stations in cities, where the installation of optic fiber is virtually impossible.

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