

Performance Comparison of WDM MIMO RoFSO Links for 5G Applications

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Abstract

The ubiquitous deployment of 5G systems is expected shortly. The 5th generation systems are envisioned to deliver a comprehensive selection of services with revolutionary data rates through a single network. Optical fiber networks are going to be the backbone of such 5G systems endowing huge data transfers. Radio over Fiber (RoF) is a promising network architecture that can provide all the provisions envisaged in the development of 5G systems. However, in certain scenarios, these fiber optic networks may encounter empirical problems in deployment. Radio over Free Space Optical (RoFSO) links can be used as an alternate in such environments. To increase the data carrying capacity of the link, Wavelength Division Multiplexing (WDM) communication equipping multiple wavelengths can be used. The free space link may suffer from atmospheric disturbances like rain, fog, and haze. In such adverse conditions, Multiple Input Multiple Output (MIMO) transceivers can be used to increase the link performance. In this work, the performance analysis of such WDM MIMO RoFSO links carrying 5G frequencies is carried out. The work also presents a comparison of single path and MIMO RoFSO links, single channel and WDM RoFSO links, and a combination of these. It is found that, transporting data over WDM channels can increase the capacity of the RoFSO system tremendously while the MIMO link setup can maintain the transmission range and link performance even when high data rates are used.

Keywords: 5G, Free space optics, Radio over fiber, Optical wireless communication, Wavelength division multiplexing

Introduction

The ever-growing demand for high data rates compels the communication networks to augment their information carrying capacity. Diverse services are in demand and the data rates they impose are also gigantic. There are wired networks in operation which can fulfil such requirements. However, people require this high data transfer capacity over wireless medium. The existing 4G communication networks are about to be saturated and will no longer be able to provide additional bandwidth or new services. This is majorly due to the growth in mobile usage, growth in spectrum resources, and the intensity of spectrum reuse [1]. The huge number of mobile devices, abundance of sensors for IoT applications, high bandwidth demanding services like high-definition video streaming, AR and VR technologies, cloud applications etc. suffocates the existing wireless networks [2,3]. In this conjuncture, a shift to the next generation, the 5th generation wireless communications has become inevitable. The soon to be deployed 5G networks are expected to deliver enormous data rates and multitudinous services over the same network [4]. The major challenges of low latency, high data rate, high capacity, massive connectivity, unwavering Quality of Service (QoS), and low cost are supposed to be addressed by 5G networks [5,6]. But for such an upgrade to a whole new network, the communication standards and infrastructure must be upgraded. Additional high frequency wireless bands are proposed to be used along with the traditional bands. While the traditional Radio Frequency (RF) bands are required to provide wide coverage for services like telephony, upper frequency bands also are to be used to provide higher data rates though to shorter distances [7,8]. So, in effect the new network will be an amalgamation of multiple frequency bands which has big as well as small cell sizes. When the cell size reduces due to the use of high frequencies, a large number of antenna units or Radio Access Points (RAP) have to be deployed. This will tremendously increase the

cost of the system [9]. To implement such a complex network, Radio over Fiber (RoF) is a promising technology.

Radio over Fiber is a hybrid technology which uses both the traditional optical communication network and wireless network for its operation [10]. The existing systems transport the baseband data over optical fiber and impose it on to radio frequency signals to transport it further over the wireless channel. The baseband to radio frequency conversion at each base station required dedicated circuitry which made the system complex and costly. It is impractical to use such an architecture to deploy huge number of base stations for the 5G networks. It is in this scenario, the RoF systems play its pivotal role. In RoF systems, instead of the baseband data, the RF signal to be transmitted over the air is directly modulated on to the light. This completely avoids the necessity of baseband to RF conversion at each base station. Thus, by using the RoF architecture, the base stations can be made functionally simple. Only minimal circuitry will be required at the base stations to convert the light signals to RF signals and transmit them using an antenna [11]. Using such RoF architecture, the huge number of base stations can be deployed cost effectively. The RoF systems jointly takes all the advantages of optical communication and wireless communication. The networks are highly transparent and can be used to transport any signals, analog or digital, any modulation scheme for any service, irrespective of their bands.

Optical fiber will be the backbone of RoF systems transporting all the signals till the last mile to the base station/RAP. But in certain scenarios, due to physical limitations, deploying fibers may be difficult or not be practical at all. In such scenarios, a modified version of the RoF systems, Radio over Free Space Optics (RoFSO) can be helpful [12]. The system uses free space to communicate instead of optical fiber cables. This saves the time and effort that is required to deploy the cables. Only a pair of transmitter and receiver is required at Line of Sight (LoS) to accomplish the communication [13]. The free space link can be used to replace the fiber link or a combination of both also can be used according to the requirement. However, since the system uses free space between the transmitter and receiver to transmit light signals, the performance of the link is highly dependent on the atmospheric channel. The climatic variations like fog and rain may affect the link performance adversely.

To overcome the adverse effects of weather conditions, the link can be modified with multiple transmitter and receiver devices which operates parallelly. Such a Multiple Input Multiple Output (MIMO) architecture can increase the link performance significantly. The introduction of MIMO helps to increase the link performance of not only the RoFSO communication links but also of conventional free space optical links [14].

Wavelength Division Multiplexing (WDM) is a traditional technology used in fiber optic communication to increase the capacity of the channel [15]. Multiple wavelengths carrying different information can be transmitted over the same fiber without them being mixed up. Each wavelength acts as a separate channel and can be used to transport any type of data without inter channel interferences. At the receiving end, the wavelengths can be separated using a WDM demultiplexer. The same property is applicable in the case of FSO as well. This technique is used to increase the capacity of the RoFSO system further [13].

The advantages of such RoFSO system include fast deployment, long distances up to 8 km, high bit rates with WDM, no licensing, high data carrying capacity, immunity to electromagnetic interference, data security, invisible and eye safe, low costs compared to fiber cabling, low maintenance etc. [16]. The limiting factors are beam dispersion, rain, fog, atmospheric absorption, shadowing, and pollution. However, the high bandwidth and signal transparency make it an apt solution for last mile 5G network deployment. The basic architecture of a RoFSO system is shown in **Figure 1**.



Figure 1 General block diagram of a radio over FSO link.

RoFSO systems finds its major application in situations where trenching and laying of optical fibers is difficult. The link distances can be up to kilometers depending on the weather conditions and data rates. The link can also be helpful in events and disaster management situations where fast and temporary deployment is necessary. The network has its additional applications in metropolitan area networks, other local area and backhaul networks, and for backup links [17]. The links are highly efficient and can provide high speed data transfer on par with fiber systems. The major bottle necks occur from climatic conditions which can be alleviated using MIMO transceivers.

Large amount of research is carried out in FSO communications and several schemes and topologies were proposed by researchers. Different techniques to combat the weather conditions, and techniques to increase the data rates and to reduce the cost etc. were discussed in connection with traditional fiber networks [18-20]. The feasibility of RoF along with FSO for 5G applications incorporating the 26 GHz band high frequency band is not yet explored. The addition of more wavelengths to incorporate more data and thereby increased data carrying capacity also were not fully explored. This work focusses on analysis and comparison of multiple RoFSO links with and without using MIMO and WDM techniques.

The rest of the paper is organized as: Section 2 discusses the system design, network and link parameters chosen for study. Section 3 analyzes and compares the results, and section 4 concludes the paper.

System design methods

A Radio over Free Space Optical communication system having a data rate of 10 Gbps per channel is considered for this study. A Pseudo Random Bit Sequence (PRBS) generator is used to generate the 10 Gbps pseudo random data. A total of 65536 samples were generated from a sequence of length 1024 bits with 64 samples per bit. The generated bits are then Non-Return to Zero (NRZ) coded. The line coded data is then amplitude modulated on a 26 GHz radio signal. The RF frequency 26 GHz is selected from the 5G pioneer band than the middle 6 GHz band to assess the system performance at high data rates with smaller cells [21]. The baseband to RF modulation is kept simple with On-Off Keying (OOK) to keep the analysis simple and free from effects of modulation format. The reference optical wavelength selected is 1550 nm. The above-mentioned parameters are selected globally for all the systems in this study and are kept common for all simulations for conducting a proper performance comparison. The basic simulation setup of a Single-Input Single-Output (SISO) Radio over Free Space Optical communication system is shown in **Figure 2**.

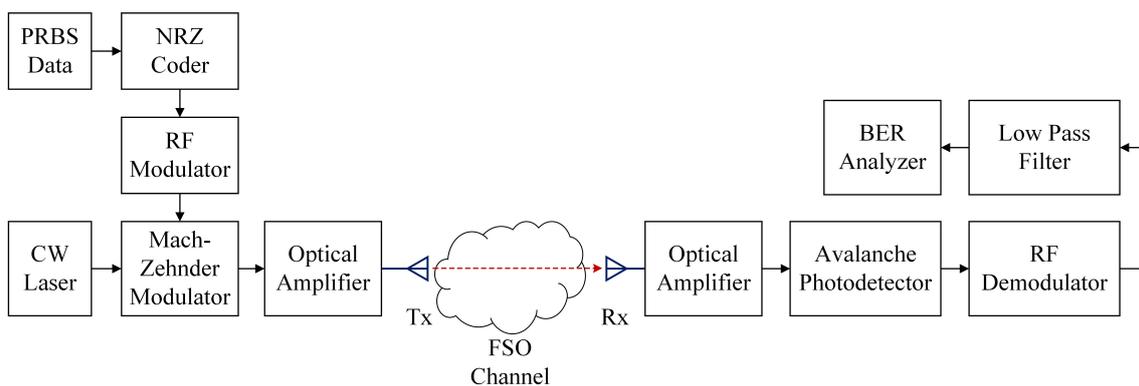


Figure 2 Simulation setup of a SISO RoFSO communication link.

A laser generating 1550 nm continuous wave with 0 dBm (1 mW) optical power is selected as the light source. The 1550 nm light is then modulated with the baseband modulated 26 GHz RF signal. A single drive Mach-Zehnder Modulator (MZM) is used for the external optical modulation. External modulation is selected over direct laser modulation for better operation at high data rates. The RF modulated light is then amplified using an ideal optical amplifier which boosts the optical power by 20 dB. To compare the system performances properly, amplifier noises are not considered in this study. The amplified light signals are then transmitted using the transmitter lens arrangement (Tx).

For performance analysis, the range of the free space channel is varied for different configurations. To accommodate the geometrical loss of the link, aperture diameters of the transmitter and receiver selected are 10 and 45 cm, respectively. The transmitter and receiver are assumed to have losses of 1 dB each, and 2 mrad beam divergence. Among the log-normal and gamma-gamma models available for intensity scintillation calculation, the gamma-gamma model is chosen in this work. The optical power P_r received at the receiver can be calculated as,

$$P_r = P_t \frac{d_r^2}{(d_t + \theta L_p)^2} 10^{-\alpha L_p / 10} \quad (1)$$

where P_t is the transmitted power, d_r is the receiver aperture diameter in meters, d_t is the transmitter aperture diameter in meters, θ is the beam divergence in mrad, L_p is the path length, and α is the free space attenuation [22]. The attenuation α of the free space channel is primarily dependent on the weather conditions and the wavelength used for transmission. The attenuation α is calculated as,

$$\alpha = \frac{3.91}{v} \left(\frac{\lambda}{\lambda_0} \right)^q \quad (2)$$

where v indicates the visibility in kilometers, λ points out the transmitted wavelength in nanometers, and q denotes the atmospheric particle size distribution which basically causes the scattering which in turn creates the attenuation. λ_0 is the reference wavelength of 550 nanometers used for attenuation calculation [23].

According to the Kruze model adopted in this work for free space channel modelling, the value of q is 1.6 for visibility greater than 50 km, q is 1.3 for visibility in the range 50 to 6 km, and q is $0.58v^{1/3}+0.34$ for visibility less than 6 km. Eq. (2) can be used to calculate the attenuation factors for various weather conditions. The attenuation in decibels, is given as,

$$\tau = 4.3429 \times \alpha \times L \quad (3)$$

where L is transmission distance [23]. The climatic condition for this performance comparison study is assumed to be clear sky where the attenuation is minimum. According to the Kruze model, the visibility in clear sky is assumed as 23 km and with a transmission wavelength of 1550 nm, the attenuation is calculated using Eqs. (2) and (3) as 0.2 dB/km. This attenuation amount is similar to that of a typical optical fiber and the same is used for all free space models demonstrated in this work. The visibility and attenuation values calculated for various other weather conditions according to the Kruze model is given in **Table 1** for further reference.

Table 1 Attenuation during various climate conditions for $\lambda = 1550$ nm using Kruze model [23].

Condition	Visibility [km]	Attenuation [dB/km]
Clear air	23	0.2
Haze	2	2.8
Rain	1	6.5
Light fog	0.8	8.5
Moderate fog	0.6	11.9
Dust fog	0.5	14.7
Dense fog	0.1	90
Heavy dust	0.07	132.8
Heavy fog	0.05	190.9

At the receiving end, the optical signals received using the receiver lens arrangement (Rx) is amplified using an optical amplifier to increase the signal power. The ideal optical amplifier provides a gain of 20 dB. The amplified signal is then detected and converted to electrical signal using an Avalanche Photo Diode (APD). The responsivity of the APD chosen is 1 A/W, gain is 3, and the dark current is 10 nA. The RF demodulator then amplitude demodulates the received signals and converts them to the baseband. The electrical signal is then filtered using a Bessel lowpass filter. The purified data output of the filter is then correlated with the transmitted sequence, and the number of errors and hence the Bit Error Rate (BER) is estimated [24].

$$BER = \frac{\text{Number of error bits}}{\text{Total number of bits transmitted}} \quad (4)$$

In this work, for a quantitative comparison of performance, BER and Q-factor are used. Ideally, the value of BER should be less than 10^{-9} and Q-factor greater than 6. Bit error rate of 10^{-9} corresponds to one error per 10^9 bits transmitted, and the corresponding Q-factor for this condition is 6.

For performance comparison, SISO and MIMO RoFSO systems with and without WDM inputs are selected. **Figure 3** depicts the simulation setup of a 2×2 MIMO RoFSO communication link. Two transmitter setups (Tx) and 2 receiver setups (Rx) are used in parallel instead of the single transmitter and receiver in SISO link. However, the total power transmitted through the 2 transmitters and the power transmitted through the single transmitter in SISO link are kept same for comparison purposes. In all the schemes chosen in this work for comparison, the total power transmitted is kept constant per channel. To achieve this, the amplified light output from the optical amplifier is split equally into 2 or 4 paths using an optical power splitter. Similarly, at the receiver end, an optical power combiner is used to combine the light power received through different paths. **Figure 4** shows a 4×4 MIMO RoFSO link with 4 transmitters and receivers. The transmission wavelength used is 1550 nm, optical power is 0 dBm, and the data rate is 10 Gbps in SISO, 2×2 MIMO, 4×4 MIMO links.

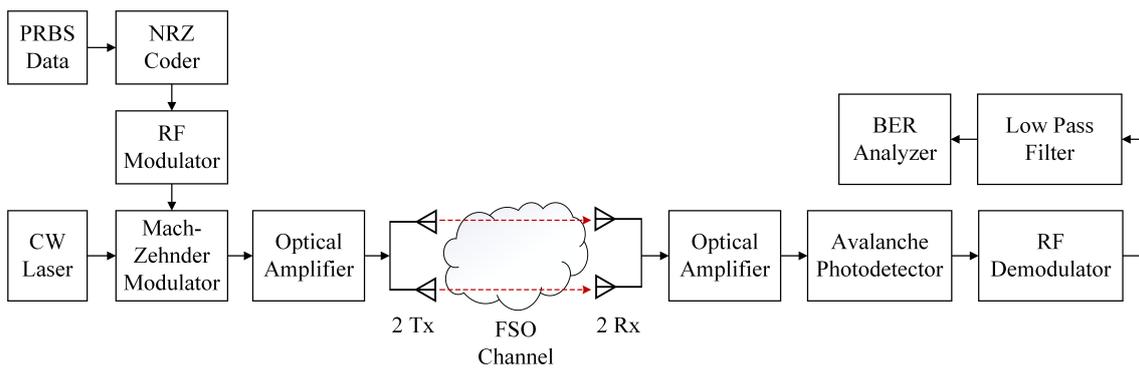


Figure 3 Simulation setup of a 2×2 MIMO RoFSO communication link.

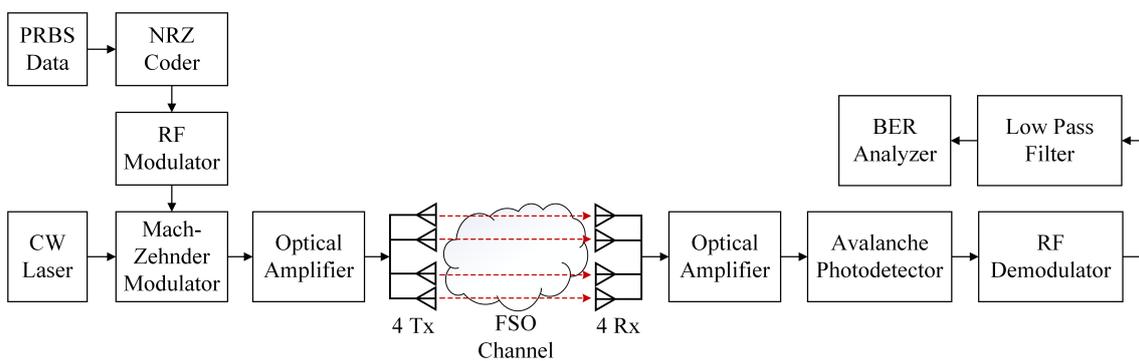


Figure 4 Simulation setup of a 4×4 MIMO RoFSO communication link.

To increase the data carrying capacity of optical networks, more number of channels are added on to the same transmission medium. These channels are different optical wavelengths in practice, and they can be used to transport independent data without interfering with other wavelengths passing through the same medium. This technique is known as wavelength division multiplexing. To analyze and compare the effect of addition of more wavelengths on the data carrying capacity and link performance, WDM channels are enabled. **Figure 5** illustrates the simulation setup of a 4-channel wavelength division multiplexed single input single output Radio over Free Space Optical communication link. The 4 wavelengths used are 1548, 1550, 1552 and 1554 nm each with 0 dBm optical power and 10 Gbps data rate. The 4 channels transport 4 different data streams producing a total throughput of 4×10 Gbps. A WDM multiplexer is used to combine the multiple wavelengths to a single stream. At the receiving end, a WDM demultiplexer is used to separate the wavelengths. The separated wavelengths are then fine filtered using Gaussian optical filters for better performance. Each of the filter is centered at the corresponding channel wavelength and the bandwidth selected for filtering is 55 GHz to accommodate the sidebands of 26 GHz RF signal modulated on the wavelength.

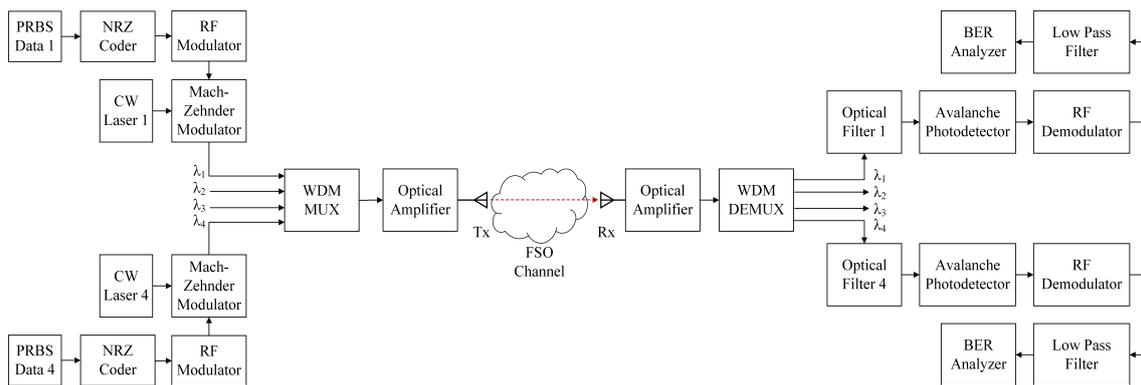


Figure 5 Simulation setup of a 4 channel WDM SISO RoFSO communication link.

Similar to the 4-channel WDM system demonstrated above, **Figure 6** demonstrates an 8-channel WDM SISO RoFSO link. The number of channels is increased to eight. The eight wavelengths used are 1544, 1546, 1548, 1550, 1552, 1554, 1556 and 1558 nm. The power output of each channel is 0 dBm with 10 Gbps data rate. The throughput is further increased to 8×10 Gbps.

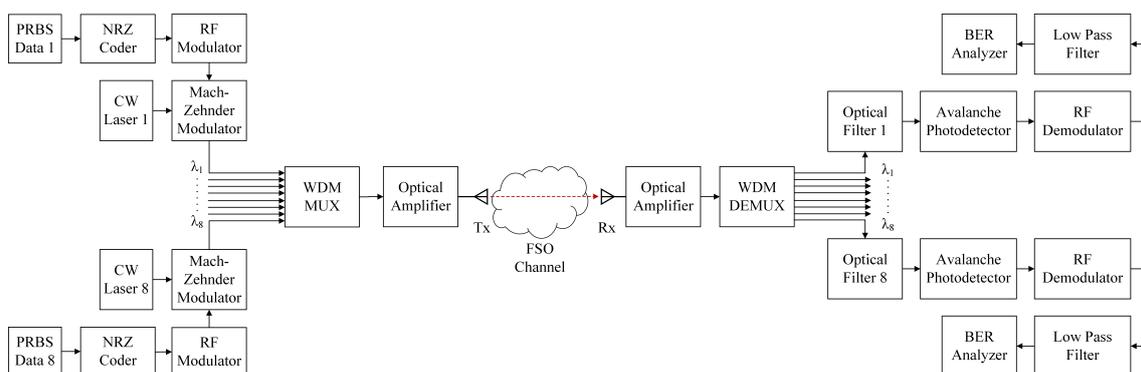


Figure 6 Simulation setup of an 8 channel WDM SISO RoFSO communication link.

The simulation layout of an 8-channel WDM 4×4 MIMO RoFSO system is depicted in **Figure 7**. The eight wavelengths used in the 8-channel WDM SISO system (1544, 1546, 1548, 1550, 1552, 1554, 1556 and 1558 nm) are used in this layout. At the transmitter, 4 transmitter setups (Tx) are used. At the receiving end, 4 receiver setups (Rx) are utilized to collect the incoming light signals.

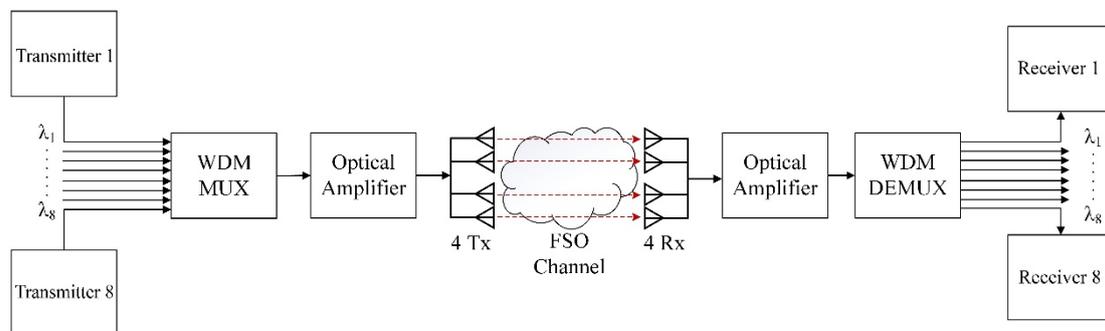


Figure 7 Simulation setup of an 8 channel WDM 4×4 MIMO RoFSO communication link.

The performance analysis and comparison of the systems are carried out by calculating BER and Q-factor performance of each of the links. The range of free space optical communication is varied from 0 to 1.4 km and the bit error rate, Q-factor performances are analyzed. The weather condition is assumed to be clear sky with attenuation of 0.2 dB/km.

Results and discussion

To analyze and compare the performance of the multiple RoFSO links considered, iterations were made on the range of communication and BER and Q-factor were computed for each distance. A maximum distance of 1.4 km was considered for analysis. This was because, beyond 1.4 km the bit error rate performance of one or more links were falling below the minimum acceptable BER of 10^{-9} and hence a proper comparison was not possible. The reference optical wavelength used was 1550 nm and the optical power of each source was kept at 0 dBm. All the PRBS data sources were operating on 10 Gbps rate each. The input bit pattern and the received bits at the output were correlated and BER is calculated. A comparison of the systems based on BER and Q-factor is done. **Figure 8** compares the bit error rate performance of a typical single input single output Radio over Free Space Optic link to multiple input multiple output links. A 2x2 MIMO and a 4x4 MIMO link is considered for this purpose. From **Figure 8**, it is evident that the SISO link fails to maintain a satisfactory BER of 10^{-9} after 1.2 km. When the number of Tx and Rx are increased to 2, the link presented a satisfactory performance maintaining a BER of 10^{-13} up to 1.4 km. It can also be seen that, when the number of Tx and Rx are further increased to 4, the BER performance of the link improves. From this trend, it can be assumed that the use of MIMO i.e., the use of a greater number of transmitters and receivers for the same channel can improve the link performance.

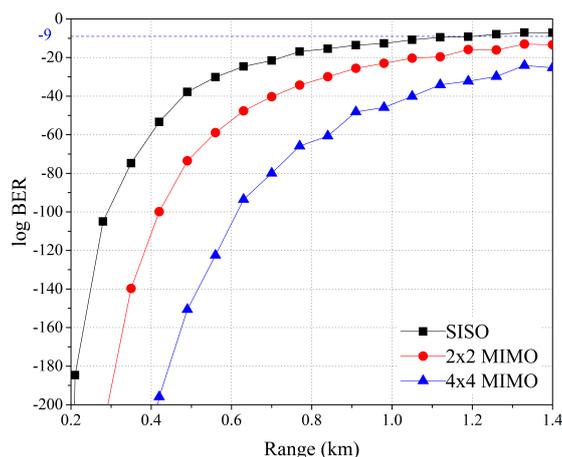


Figure 8 Range vs. BER of SISO, 2x2 MIMO, and 4x4 MIMO RoFSO links.

The Range vs. Q-factor performance of SISO, 2x2 MIMO, and 4x4 MIMO RoFSO links are depicted in **Figure 9**. It can be deduced that, addition of more number of paths for communication helps in providing a better quality factor for the system. This inference is in phase with the BER analysis carried out on the same links. From **Figure 9**, it is clear that the single input single output fails to maintain an acceptable Q-factor of 6 after 1.2 km. The 2x2 MIMO and 4x4 MIMO links provides better Q-factors well above 6 for a distance of 1.4 km and beyond.

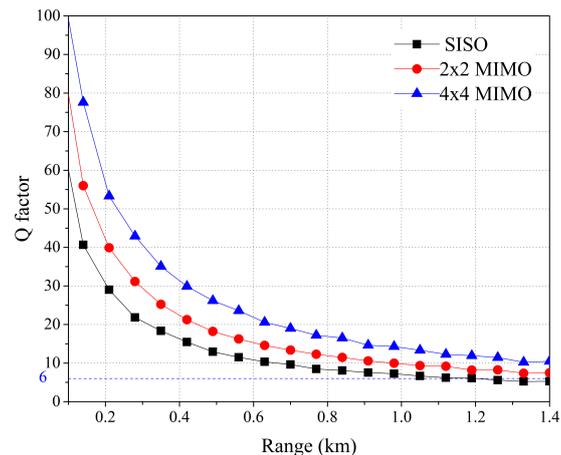


Figure 9 Range vs. Q-factor of SISO, 2×2 MIMO, and 4×4 MIMO RoFSO links.

To increase the data carrying capacity of the SISO RoFSO links, wavelength division multiplexing is incorporated into the system. In a 4 channel WDM system, 4 distinct wavelengths are used as optical carriers. The 4 wavelengths chosen for this study are centered around the reference wavelength 1550 nm. The 4 wavelengths used are 1548, 1550, 1552 and 1554 nm. Similarly, in the 8 channel WDM link considered, eight distinct wavelengths, 1544, 1546, 1548, 1550, 1552, 1554 and 1556 nm are chosen. The wavelengths are selected at a comparatively wide spacing to understand the wavelength dependency of the link. However, all the wavelengths exhibited almost similar performances and hence the reference wavelength 1550 nm only is taken for comparison in this work. The Range vs. BER performance of SISO, 4 channel WDM SISO, and 8 channel WDM SISO RoFSO links are illustrated in **Figure 10**. For ease of understanding and comparison, only the performance of the reference wavelength 1550 nm is plotted in the **Figure 10** for all the 3 systems. Though the capacity of system is increased to 4×10 Gbps and 8×10 Gbps in the 4 channel and 8 channel WDM systems respectively, it can be observed that the systems failed to maintain a satisfactory BER of 10^{-9} beyond 1 km. From this behavior, it can be understood that, even though the data rates can be increased using WDM techniques over SISO RoFSO channels, the transmission range decreases when the number of channels increases. It also must be noted that, each of the wavelength was generated with a constant optical power of 0 dBm and the reduction in range is not due to power sharing effects.

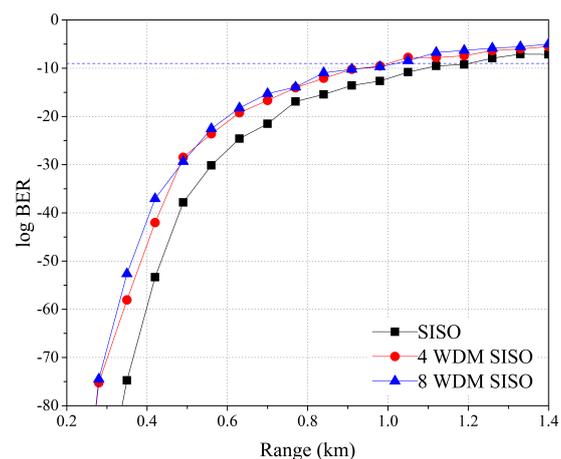


Figure 10 Range vs. BER of SISO, 4 channel WDM SISO, and 8 channel WDM SISO RoFSO links.

The Q-factor of the examined WDM SISO links also hints that, while increasing the data carrying capacity by increasing the number of channels, the transmission distance is reduced. **Figure 11** demonstrates the Range vs. Q-factor performance of single channel SISO, 4 channel WDM SISO, and 8 channel WDM SISO RoFSO links. From **Figure 11**, it is evident that the links fail to maintain a Q-factor

above 6 beyond transmission range of 1 km. This is in coherence with the afore-mentioned analysis. Hence, some additional techniques must be implemented along with the addition of channels to maintain the communication range.

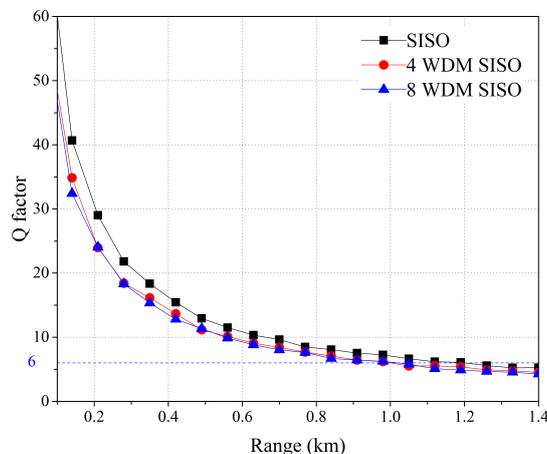


Figure 11 Range vs. Q-factor of SISO, 4 channel WDM SISO, and 8 channel WDM SISO RoFSO links.

The comparison of SISO, 2×2 MIMO and 4×4 MIMO links has already proven that the additional paths could increase the system performance. Hence, to increase the data capacity without compromising the transmission distance, the WDM systems are incorporated with MIMO transceiver setup. The 8 channel WDM setup is evaluated with SISO, 2×2 MIMO, and 4×4 MIMO RoFSO links. To compare their performance, the Range vs. BER performance of the links are depicted in **Figure 12**. While the 8 channel SISO link failed to maintain the acceptable BER of 10^{-9} , the addition of 2×2 MIMO and 4×4 MIMO setups could provide the satisfactory minimum BER up to 1.4 km. From the figure, it is evident that the number of additional paths using MIMO technique can considerably increase the link performance and avoid the reduction in transmission range due to the introduction of WDM.

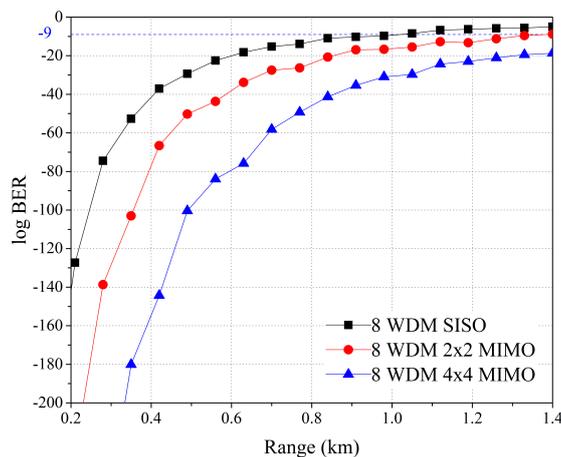


Figure 12 Range vs. BER of 8 channel WDM SISO, 8 channel WDM 2×2 MIMO, and 8 channel WDM 4×4 MIMO RoFSO links.

The Range vs. Q-factor performance of the 8 channel WDM is evaluated with SISO, 2×2 MIMO, and 4×4 MIMO RoFSO links and is illustrated in **Figure 13**. In coherence with our deductions from **Figure 12**, the Q-factor performance also proves that the incorporation of MIMO transmission setups is beneficial to the system. The 2×2 MIMO and 4×4 MIMO links were able to provide a quality factor

above 6 for distances up to 1.4 km while the SISO link failed to maintain the satisfactory Q-factor beyond 1 km.

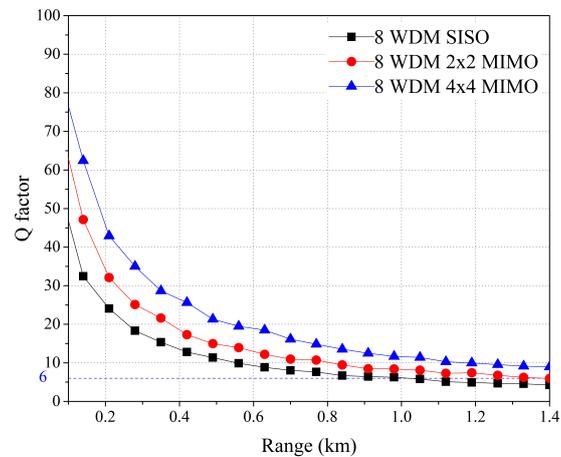


Figure 13 Range vs. Q-factor of 8 channel WDM SISO, 8 channel WDM 2×2 MIMO, and 8 channel WDM 4×4 MIMO RoFSO links.

To understand the actual bit error rate behavior of the superior performance 8 channel WDM 4×4 MIMO RoFSO link, Range vs. BER for a longer distance of 3 km is plotted in **Figure 14**. As evident from the previous discussions, due to the use of MIMO technique, the link is able to maintain its performance by providing a satisfactory BER of 10^{-9} up to a distance of 2.3 km.

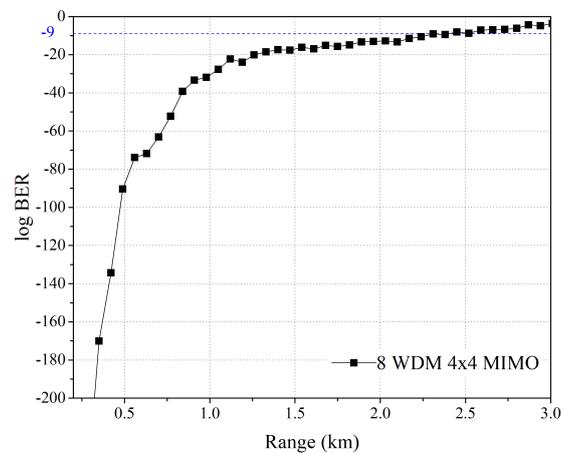


Figure 14 Range vs. BER of 8 channel WDM 4×4 MIMO RoFSO link.

Performance analysis of RoFSO links with and without MIMO and WDM techniques were carried out. From the results obtained, it can be inferred that the use of MIMO technique in the RoFSO link helps to increase the system performance. While the introduction of WDM techniques increases the data capacity, the communication range is reduced. This reduction in transmission range can be abated by using the MIMO technique along with WDM. A combination of WDM and MIMO RoFSO links has proven to provide the best performance among all the schemes inspected in this work. The system successfully delivered 8×10 Gbps data up to 1.4 km using 4×4 MIMO setup. **Table 2** shows the comparison between BER and Q-factor performances of the RoFSO links considered in this study.

Table 2 Comparison of BER and Q-factor at 1.4 km for the studied RoFSO links.

RoFSO Link Type	BER	Q - factor	RoFSO Link Type	BER	Q - factor	RoFSO Link Type	BER	Q - factor
SISO	$10^{-7.13}$	5.25	SISO	$10^{-7.13}$	5.25	8 WDM SISO	$10^{-4.98}$	4.25
2×2 MIMO	$10^{-13.38}$	7.46	4 WDM SISO	$10^{-5.49}$	4.51	8 WDM 2×2	$10^{-8.84}$	5.93
4×4 MIMO	$10^{-25.28}$	10.48	8 WDM SISO	$10^{-4.98}$	4.25	8 WDM 4×4	$10^{-18.71}$	8.93

The paper presents performance analyses of various Radio over Free Space Optical links. It is identified that addition of channels using WDM technique without making changes in the system architecture degrades the link performance. It is also proved that this degradation can be successfully alleviated by using MIMO transceivers. The implementation of WDM MIMO RoFSO links will enable high-capacity data transfer without reduction in transmission range. The whole study is conducted using 5G frequencies and hence methodology will be helpful in setting up RoFSO links for 5G applications.

Conclusions

A quantitative performance analysis and comparison of Radio over Free Space Optical links is carried out using bit error rate and Q-Factor. It is found that the use of MIMO technique helps to increase the overall system performance. The data capacity can be increased by adopting WDM techniques. However, the introduction of WDM reduces the transmission distance and this adverse effect can be overcome by using MIMO technique along with WDM. Hence a combination of WDM and MIMO RoFSO links is identified to be the best among the inspected schemes. Such a network can provide high data rates for RoFSO links for 5G applications. The feasibility of using advanced modulation schemes for further performance improvement can be investigated as future work.

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