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5G-28 GHz Signal Transmission Over Hybrid All-Optical FSO/RF Link in Dusty Weather Conditions

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ABSTRACT 5G wireless networks promise to provide massive bandwidth for various types of connections. In such networks, the backhaul/fronthaul sections should be easy to deploy and support the required high bandwidth. To improve the free space optic (FSO) link bandwidth so that it can replace fiber cables and support 5G networks, all-optical FSO systems were proposed which exploit advanced modulation formats in the transmitter side and coherent detection in the receiver side. However, such links will suffer much under harsh outdoor environment, especially under fog and dust conditions than traditional FSO links that have limited bandwidth. Effect of fog on such links has been investigated in the literature. However, the dust effect is not covered. In this paper, we first experimentally analyzed the effects of dust storms on the performance of an all-optical FSO link carrying a 1-Gbaud/16-quadrature amplitude modulation 5G signal. The results demonstrate that the all-optical FSO link is significantly affected by low visibility range, with severe bit-error-rate (BER), and error vector magnitude (EVM) limits appearing at a 50-m visibility range for a 2.7-m channel length. For a visibility range greater than 200-m, the BER and EVM were improved to 10^{-9} and 5.5% of the root mean square, respectively. Furthermore, the analysis showed that the dust storm condition introduces flat fading over the frequency range under study, i.e., 21–29 GHz. Second, a comparison between FSO and radio frequency (RF) channels under the same dusty conditions were performed. The results showed that the effects of the dust storm are negligible for the RF link which makes it suitable as a backup for FSO link under severe dust conditions. Finally, a hybrid cascaded FSO/RF link was installed and analyzed in terms of visibility range, BER, and EVM.

INDEX TERMS Free space optics, dust storm, 5G wireless network, all-optical hybrid FSO/Fiber network.

I. INTRODUCTION

Mobile wireless networks are evolving rapidly to cope with massive capacity demands that are dominated by video consumption and social network applications. Ever increasing video resolution, numbers of viewers, and viewing time have accelerated the evolution of wireless communications toward 5G networks. Currently, 4G wireless networks are able to connect individuals with a download speed of up to 100 Mbps. However, this connection speed must be improved to match the increased bandwidth consumption. In addition to connectivity for individuals, 5G is designed to provide interconnection for devices and machines through the internet of things, as well as in smart city networks with the capability to control such devices, thereby facilitating new services and industries [1]. Therefore, future 5G networks are expected to provide broadband high-speed connections of up to 20 Gbps.

Providing higher capacity in addition to enhanced broadband services requires the connectivity of machines and sensors to be managed on multiple radio bands.

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Therefore, 5G is expanding radio spectrum usage to bands at less than 1 GHz (low bands), 1–6 GHz (mid bands), and above 24 GHz (high bands). Working at high frequencies helps to overcome the frequency spectrum shortages of access networks. One of the most promising bands for 5G is the 28 GHz (27.5–28.35 GHz) band, where certain countries, such as the USA, Japan, and South Korea, have allocated significant resources [2].

In 5G wireless networks, the backhaul/fronthaul sections of the network are the main challenges. 5G cell planning is expected to be ultra-dense with 40–50 base stations (BSs)/km^2 [3]. Dense traffic cells in such networks will be connected to the core network through backhaul/fronthaul sections. Copper, microwave, fiber, and even satellite links can be used in backhaul/fronthaul sections. Among these media, fiber is the most feasible solution for satisfying bandwidth requirements. However, fiber cable installation is costly or even impossible in some areas. Recently, free space optic (FSO) technology has attracted significant attention as an alternative medium to fiber. With FSO, data is transmitted across free space, rather than through fiber cables. This promising technology can replace fiber cables in the backhaul/fronthaul sections of networks to ensure the provision of sufficient bandwidth for access networks [4].

FSO has many advantages, including quick and easy installation, free licensing, cost effectiveness, immunity to electromagnetic interference, and large bandwidth. However, FSO links are heavily impacted by outdoor weather conditions, such as fog, dust, and rain. Among these conditions, fog and dust have the greatest impacts on FSO channels because their particle sizes are comparable to FSO signal wavelengths in the infrared band, which leads to high signal scattering. Previous studies have explored the effects of different weather conditions on FSO links [5]–[6]. However, the effects of dust storms have not been thoroughly covered in the literature. In [7]–[9], controlled environment chambers were used to investigate the effects of dust on FSO signals. Ghassemlooy *et al.* [7] analyzed the performances of different low rate (in Mbps) intensity modulation (IM) formats in dusty weather conditions. A study of dust effects on intensity modulation FSO signal at a wavelength of 1550 nm and a terahertz signal at a frequency of 625 GHz was reported in [8]. The results demonstrated that the terahertz signal was two orders of magnitude lower than the FSO signal in terms of attenuation. Recently, Libich *et al.* [9] investigated the combined effects of dust and turbulence on IM FSO's signal in the near-infrared band. This study showed that FSO signal with an 830-nm wavelength provides better performance than that with a 760-nm wavelength. In [10], we experimentally investigated and proposed a model for signal attenuation for direct detection (DD) FSO systems under dust storms conditions by using a controlled chamber.

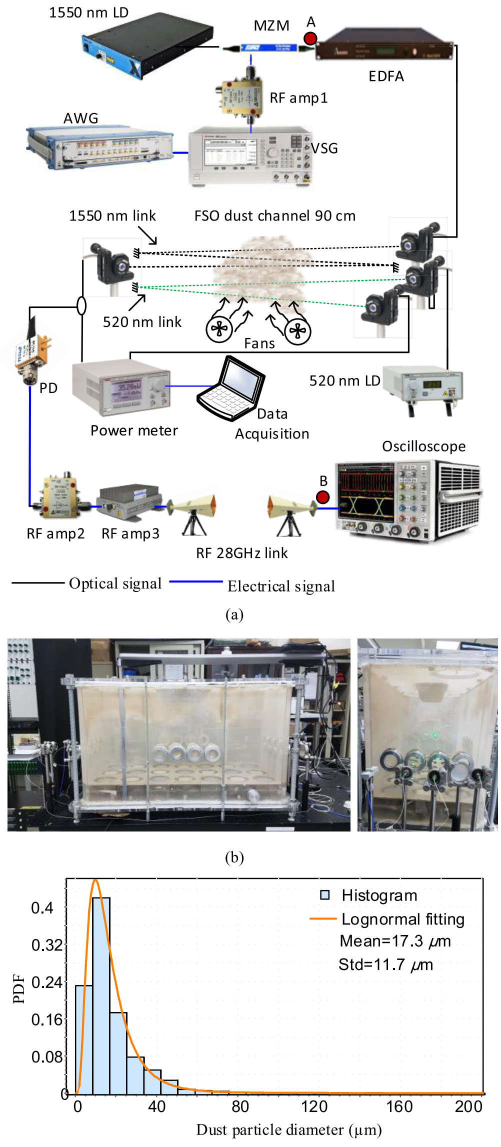
Instead of using traditional IM/DD FSO systems that are limited in bandwidth, future demonstrations will use all-optical coherent FSO system and exploit advanced modulation formats to improve the bandwidth efficiency and hence support high bandwidth links, needed by 5G networks [11]. However, the channel in such systems is more challenging and can highly limit their applications. Therefore, in this study, we experimentally investigate and analyze the performance of all-optical coherent FSO links that can support 5G networks under harsh dusty conditions. The analysis will consider first the performance of an FSO link carrying a 1-Gbaud/16-quadrature amplitude modulation (QAM) 5G signal. Then, we investigate and compare the effects of dust on parallel hybrid FSO/RF links, both carrying the same signal. After that, we analyze the performance of a cascaded hybrid FSO/RF link carrying a 5G signal in terms of received power, bit-error-rate (BER), and error vector magnitude (EVM). To the best of our knowledge, this study is the first to consider all-optical coherent FSO transmission of 5G signals over dusty weather conditions.

The remainder of this paper is organized as follows. In Section II, we describe our experimental setup. In Section III, we analyze the obtained results. In Section VI, we discuss our conclusions.

II. EXPERIMENTAL SETUP DESCRIPTION

An experimental setup including both the hybrid FSO/RF link and dusty environment chamber is depicted in Fig. 1(a). A 1-Gbaud/16-QAM 5G signal was generated using a Keysight M8190A 12-GSa/s arbitrary waveform generator. This baseband signal was up-converted to a 28-GHz frequency using a Keysight E8267D vector signal generator (VSG). The VSG's output signal was amplified using an SHF807 linear broadband amplifier (RF amp1) before applying a 40-GHz EOspace optical modulator to create a drive signal. The laser light input applied to the modulator was generated using a 1-kHz linewidth TeraXion laser diode with a 1550-nm wavelength. The output of the optical modulator was amplified by using an Amonics Erbium-doped fiber amplifier to compensate for optical modulator insertion loss. The signal was then transmitted over a 2.7-m dusty channel for performance investigation.

After passing through the dusty channel, 5% of the signal was coupled to a power meter and the remaining 95% of the signal was converted back into an electrical signal by using a Finisar 70-GHz bandwidth photodetector (PD) with a responsivity of 0.6 A/W. Because of the high power loss in an RF link at a 28-GHz frequency, two cascaded RF amplifiers were used to enhance the signal power. The signal was first fed into a low-noise broadband linear amplifier (SHF807 40-GHz) (RF amp2) and then into a 26.5-GHz Keysight 83017A high-power amplifier (RF amp3). The amplified signal was then transmitted over a 1-m RF link consisting of two horn antennas with 10-dBi gains and 26.5–40-GHz bandwidths. The received signal was analyzed using a 32-GHz Keysight DSO-X 93204A oscilloscope. To analyze the received signal, the Keysight VSA89600 software was used as a signal analyzer. This software demodulates a signal and applies an equalizer to compensate for channel linear impairments.



(a)

(b)

(c)

FIGURE 1. **(a) Experimental setup for the hybrid FSO/RF link in a dusty FSO channel, (b) chamber side view (left) and front view (right), and (c) dust particle size distribution.**

To emulate the effects of a dust storm, we designed a controlled-environment chamber with dimensions of $90 \times 40 \times 40$ cm^3, as illustrated in Fig. 1(b). Transparent windows at the input and output of the chamber were used to reduce transmitted light signal power loss. The dust particles were distributed homogeneously using fans installed at the bottom of the chamber. Such a controlled environment enables us to perform characterization and performance measurements without waiting for specific outdoor events, which would require long wait times, and with specific visibility values. Additional information regarding the chamber design and measurement reliability is reported in our previous work [10], which focused on developing a model for FSO IM/DD signal attenuation in dusty weather and did not consider all-optical FSO for 5G systems.

To transmit signals over free space, two identical aspheric-lens-based fiber collimators were installed at the input and output of the chamber. This type of FSO is referred to as an all-optical FSO link, where optical-to-electrical or electrical-to-optical signal conversion is eliminated. Therefore, the bandwidth limitations of traditional FSO links are avoided. The collimator's output beam has a diameter of 3.6 mm with a 558-μrad full-angle beam divergence. To increase the FSO link distance, two mirrors were used to extend the free space distance to 2.7 m. At the chamber output, 5% of the collimated signal power was coupled to measure the signal power loss caused by dust effects by using a dual-channel Thorlabs PM320E power meter. Similarly, another link operating at 520 nm was installed for visibility range measurements with a 1.8-m link length by using a single mirror. This link uses two identical fiber-based collimators with 2.1-mm output beam diameters and 349-μrad full-angle beam divergences. The collimated light at the chamber output was connected to the power meter to measure the total amount of signal attenuation caused by dust. The signals received by the power meter are acquired every 1 sec and stored using an acquisition system. From the visible link power measurement, the visibility range can be calculated using (1) from [10]. Visibility range is a parameter that defines the severity of a dust storm. Low visibility indicates a high concentration of dust particles in the atmosphere.

To investigate the effects of dust storms on 5G signals carried over the hybrid FSO/RF link, sample dust collected from a natural dust storm was used. The dust particle diameter was analyzed using an SALD-2300 particle size analyzer. The dust sample was found to have an average particle diameter of 17.3 μm and standard deviation of 11.7 μm. Additionally, the dust sample particle size distribution was examined. A lognormal distribution was found to fit the data accurately, as shown in Fig. 1(c), with significance level of 0.2. Table 1 summarizes the key parameters of the experimental setup.

TABLE 1. **Experimental setup parameters and values.**

	Parameter	Value
Signal generation	Modulation format	16 QAM
	Signal symbol rate	1 Gbaud
	RF frequency	28 GHz
FSO link	Signal wavelength	1550 nm
	Optical modulator bandwidth	40 GHz
	Divergence angle	558 μrad
	Beam diameter	3.6 mm
	Link length	2.7 m
Chamber	Chamber size	$90 \times 40 \times 40$ cm^3
	Dust particle diameter distribution	lognormal
	Dust particle diameter size	mean=17.3 μm, Std=11.7 μm
	RF Amp1 bandwidth and gain	65 kHz–40 GHz, 24 dB
	RF Amp2 bandwidth and gain	65 kHz–40 GHz, 24 dB
	RF Amp3 bandwidth and gain	0.5–26.5 GHz, 25 dB
	Tx antenna bandwidth and gain	26.5–40 GHz, 25 dBi
	Rx antenna bandwidth and gain	26.5–40 GHz, 25 dBi
	PD BW and responsivity	70 GHz, 0.6 A/W
	Oscilloscope bandwidth	32 GHz

III. RESULTS AND DISCUSSION

We began our experiment by analyzing the performance of the FSO link and compare its performance with the RF link, where both carried 28-GHz 5G signals with a 16-QAM

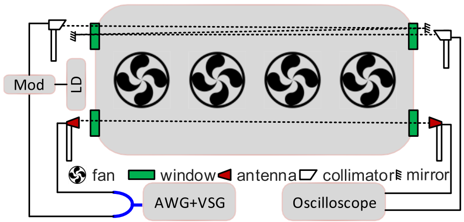


FIGURE 2. Experimental setup with parallel FSO and RF links across the dusty chamber.

modulation format and 1-Gbaud symbol rate. For this purpose, we modified the experimental setup in Fig. 1 such that the two links were subjected to the same dusty conditions simultaneously, as illustrated in Fig. 2. For the FSO link, transparent windows with 4% signal attenuation at a wavelength of 1550 nm were used. Regular glass windows were used for the RF link. Because of dust sticking to the windows, each window introduced additional signal attenuation of ∼1.4 dB for the FSO signal. Using the setup illustrated in Fig. 2, we investigated the signal performance of the parallel links under the same dust storm conditions. Figures 3(a)–(c) present the performance of the RF and FSO signals over the dusty channel in terms of RF received power, EVM, and BER, respectively, as a function of visibility range. We noticed that under severe dust storm conditions with a visibility range of less than 200 m, the FSO signal was highly degraded. For a visibility range larger than 200 m, the effects of dust were minor over the 2.7-m FSO channel. A BER with a forward error correction (FEC) limit of 3.8×10^{-3} and EVM limit of 12.5 dB was achieved at a visibility range of approximately 50 m. For a visibility range greater than 200 m, the BER and EVM were improved to 10^{-9} and 5.5% of the root mean square, respectively.

Furthermore, the results revealed that the RF signal was unaffected by dusty conditions. The received power, as well as the EVM and BER, were nearly constant as the visibility changed from a very low range to the 1-km range. This is because the dust particle diameter, which is in the range of a few micrometers, is much smaller than the RF signal wavelength, which is in the millimeter range. Therefore, the signal scattering by dust particles is negligible. However, the FSO signal wavelength is in the range of a few micrometers, which is comparable to the dust particle size. Therefore, the signal scattering is high and performance is low in dusty conditions.

The obtained results in Fig. 3 illustrate the benefits of using hybrid parallel FSO/RF links to overcome dusty channel conditions. The FSO link can support a high bandwidth but is heavily impacted by dusty conditions with low visibility ranges. In contrast, RF links have better performance in dust storms but have limited bandwidth. Therefore, both links can work in a hybrid parallel system where the RF link operates at low visibility ranges (heavy dust storms) and the FSO link is used when dusty weather conditions improve (light dust storms or clear weather). For example, in Fig. 3(c), the RF link provides a constant BER of $\sim 10^{-4}$. For visibility ranges lower than 50 m, we use the RF link because the FSO link incurs a higher BER. However, for visibility greater than 50 m, we use the FSO link. By using such a configuration, link transmission can be maintained at all times. Constellation diagrams of the 5G signal are also presented in Fig. 3(c) for the FSO and RF links at two extreme values for the visibility range.

Next, we investigated the performance of the FSO/RF cascaded link carrying a 5G signal, as shown in the experimental setup in Fig. 1(a). Using the Keysight N4373D lightwave component analyzer, we characterized the entire system frequency response between points A and B in Fig. 1(a). The obtained results for signal loss as defined by the S21 parameter are depicted in Fig. 4. The channel bandwidth was limited to 21–29 GHz, where the horn antenna introduces a lower cutoff frequency and the Keysight 83017A RF amplifier introduces an upper bandwidth limit for the link. The traces in Fig. 4 for different visibility ranges show that as the visibility range value decreases, the signal loss increases. For example, the power decreased by approximately 21 dB at a frequency of 28 GHz as the visibility range dropped to 24 m. However, as the visibility range increases, the power loss decreases. For a visibility range of 200 m, the power loss was only approximately 1 dB. In general, the curves in Fig. 4 indicate similar trends, with the only difference being

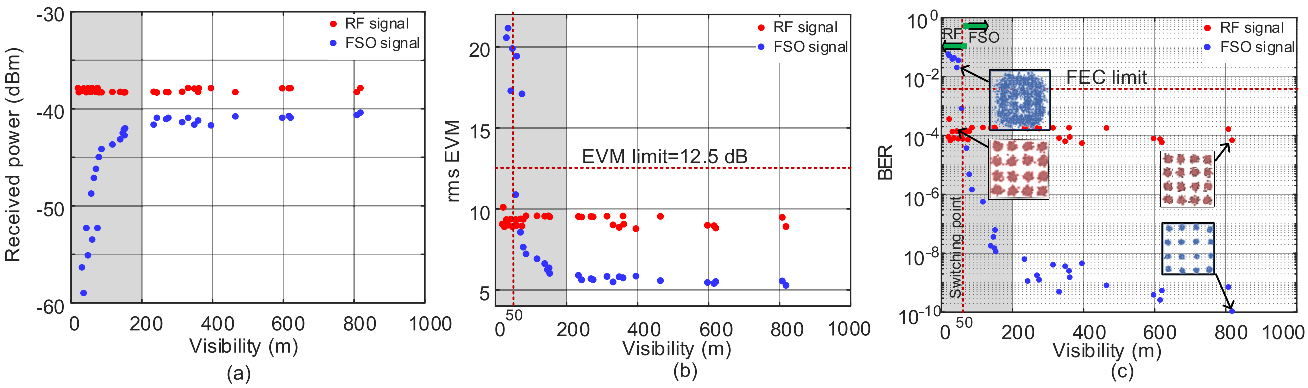


FIGURE 3. Comparison of RF and FSO link performance in dusty environment as a function of visibility: (a) received electrical signal power, (b) EVM, and (c) BER. The constellation diagrams shows the 5G signal at two extreme values for the visibility range of the RF and FSO links.

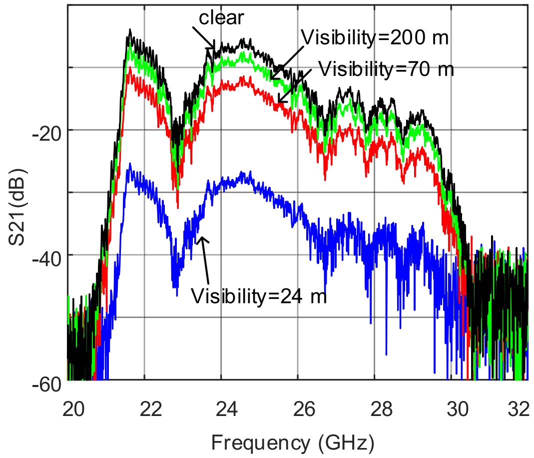


FIGURE 4. **Characterization of the entire link in Fig. 1(a) with different visibility ranges.**

the amount of power loss. This indicates that dusty conditions induce flat fading over the frequency spectrum under study.

Using the experimental setup in Fig. 1(a) with the cascaded FSO/RF link, we investigated the performance of 5G signal transmission under dust storm effects. This cascaded FSO/RF link scinario is useful when there are some mobile nodes try to access the cannel and FSO does not help in this case because of line-of-sight requirements. A mobile node can connect to an access point using an RF link and then an FSO link can be used to forward the information to the final destination. Figures 5(a)–(c) present the performance of the signal as a function of RF received power, EVM, and BER, respectively. We noticed that in Fig. 5(a), the RF received power significantly degraded to less than –55 dBm under severe dust storm conditions, which are defined by very low visibility ranges of tens of meters. However, as visibility improves, the signal achieves its maximum strength for a visibility range greater than 200 m. Similarly, the EVM results in Fig. 5(b) reveal that the EVM limit of 12.5 dB for a 16-QAM signal is achieved at a visibility range of approximately 50 m. For visibility ranges over 200 m, the EVM reaches its maximum at 7.5 dB. In Fig. 5(c), we plotted the performance of the 5G signal as a function of BER. The results reveal that the signal reaches the FEC limit at a visibility range of approximately 50 m. Similar to EVM, BER performance reaches its maximum at visibility ranges greater than 200 m. The insets show the 5G signal constellations at two extreme visibility range values.

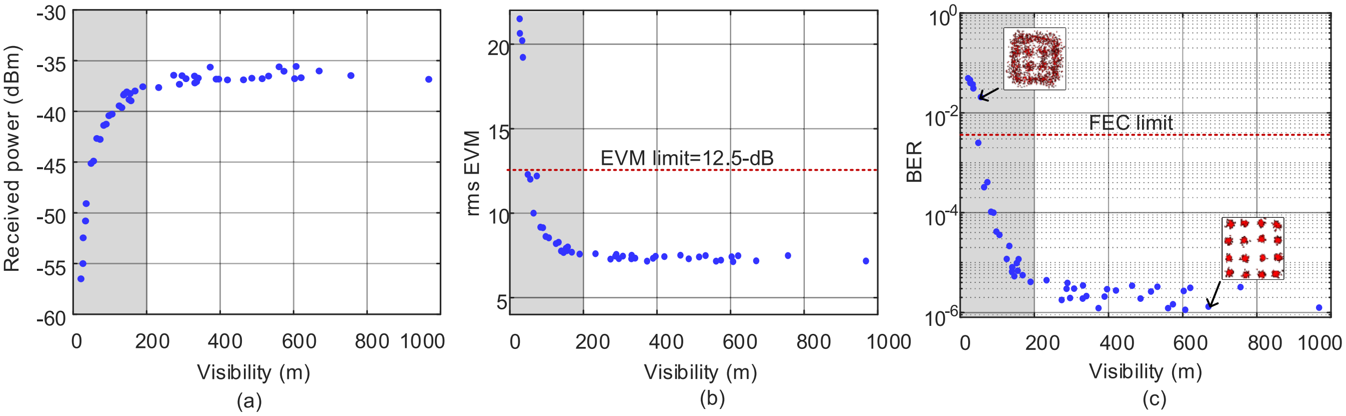


FIGURE 5. **Performance of the FSO/RF cascaded link depicted in Fig. 1(a) under dust storm effects as a function of (a) received electrical power, (b) EVM, and (c) BER. The constellation diagrams show the 5G signal at two extreme values for visibility range for the hybrid RF/FSO cascaded link.**

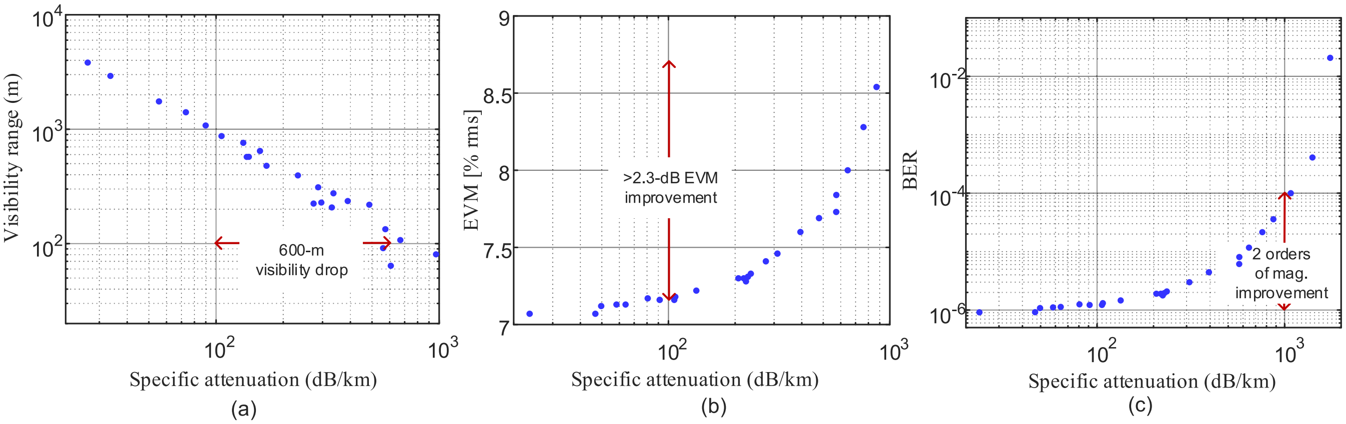


FIGURE 6. **(a) Visibility range, (b) EVM, and (c) BER versus signal specific attenuation in dB/km.**

To achieve a more general assessment of signal performance, in Figs. 6(a)–(c), the performance of the 5G signal in terms of signal specific attenuation in dB/km as a function of visibility range, EVM, and BER, respectively, is illustrated, ignoring geometrical loss. In Fig. 6(a), we noticed a high signal attenuation value exceeding 1000 dB/km for visibility ranges lower than 100 m, which makes the system impractical for long distances. For this value of specific attenuation (i.e. 1000 dB/km), the achieved EVM is larger than 8.5 dB and the BER is 10^{-4}, as illustrated in Fig. 6(b) and Fig. 6(c), respectively. Once the visibility range improves to 600 m, the specific attenuation drops to 100 dB/km. Consequently, the EVM and BER improve by more than 2.3 dB and two orders of magnitude, respectively.

Although the dust particles introduce high signal attenuation at low visibility ranges, the occurrence of such dust storms is rare. For example, a study of dust storms with visibility less than 200 m in the area surrounding Riyadh city showed that such storms are present for only 0.17% of yearly time (approximately 15 hours) [12]. In 5G networks, cell radius is tens of meters only, resulting in improved received signal power and making FSO links an excellent candidate for the backhaul/fronthaul sections of networks.

IV. CONCLUSION

In this paper, we experimentally analyzed the performance of 5G signals carried by an all-optical hybrid FSO/RF link for high-speed backhaul/fronthaul links in 5G networks. The obtained results show considerable signal degradation for the FSO link under severe dust storms. The RF link was unaffected because of its large wavelength compared to the dust particle size. Therefore, a hybrid FSO/RF parallel link is an excellent choice to overcome dusty channel effects because the RF link with low bandwidth works under severe dust storm conditions and the FSO operates when weather conditions improve above a certain threshold. Furthermore, because 5G networks have ultra-dense cells that are only tens of meters apart, FSO links are the best alternative to fiber cables in the backhaul/fronthaul sections of such networks.

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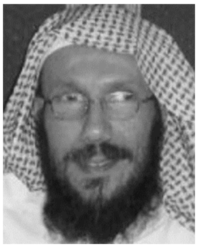

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