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Free Space Optic and mmWave Communications: Technologies, Challenges and Applications

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SUMMARY Increasing demand in data-traffic has been addressed over the last few years. It is expected that the data-traffic will present the significant part of the total backbone traffic. Accordingly, much more transmission systems will be required to support this growth. A free space optic (FSO) communication is the greatest promising technology supporting high-speed and high-capacity transport networks. It can support multi Gbit/s for few kilometers transmission distance. The benefits of an FSO system are widespread, low cost, flexibility, immunity to electromagnetic field, fast deployment, security, etc. However, it suffers from some drawbacks, which limit the deployment of FSO links. The main drawback in FSO is the degradation in the signal quality because of atmospheric channel impairments. In addition, it is high sensitive for illumination noise coming from external sources such as sun and lighting systems. It is more benefit that FSO and mmWave are operating as a complementary solution that is known as hybrid FSO/mmWave links. Whereas the mmWave is susceptible to heavy rain conditions and oxygen absorption, while fog has no particular effect. This paper will help to better understand the FSO and mmWave technologies and applications operating under various atmospheric conditions. Furthermore, in order to improve the system performance and availability, several modulation schemes will be discussed. In addition to, the hybrid FSO/mmWave with different diversity combining techniques are presented.

key words: *free space optic, millimeter wave, wireless applications, losses, availability, turbulence, diversity combining, modulations and hybrid networks*

1. Introduction

The exponential growth in the demanded services with high speed, high capacity, real time data, and high reliability forcing to change the current transport technology of wireless networks. Currently, the optical fiber technology has successfully met all expectations for traffic increasing, that it can provides links with high-speed data rate, low-latency, reliability and high security. However, in many places, there is no existing fiber deployed, or there is insufficient fiber infrastructure. In this case and until fiber is deployed, another communications technology is needed rapidly. The most proper technologies that can replace the optical fiber are free space optics (FSO) and millimeter wave (mmWave). FSO is an optical communication technology that uses light propagating in free space for wireless data transmission. Furthermore, mmWave is a communication technology that uses the band of radio spectrum between range 30−300 GHz to wirelessly transmit the data from source to destination. The FSO and the mmWave transport technologies can support multi-Gbit/s transmission over few kilometers distance [1], [2].

The atmosphere is the medium in which the mmWave and FSO laser beam propagate. This medium is changing dynamically over time and along the path of the signal propagating. Rain, fog, haze, smog, snow and other conditions have an adverse effect on the communication signal.

The mmWave and FSO links have similar advantages regarding offered data rates and flexibility of setup. However, they operate under different conditions. The benefit of a combination between the two technologies is the complementary behavior of each system during different weather conditions as shown in Fig. 1. For example, the rain is the "dominant cause" of attenuation in mmWave link, whereas the fog is the largest source of attenuation in FSO. For the stand-alone FSO system, fog can cause attenuations up to 100 dB/km in the climate around Graz, Austria [3], while rain can cause attenuations up to 25 dB/km at a rain rate of 150 mm/h, which has a lesser impact compared to fog attenuation. In mmWave, the same rain rate provides an attenuation equally to 50 dB/km, while fog causes less than 5 dB/km.

To increase the reliability and availability of the wireless communication link, a combined FSO/mmWave link has been introduced [4]. In this system, FSO overcomes the rain attenuation using the mmWave technology. On

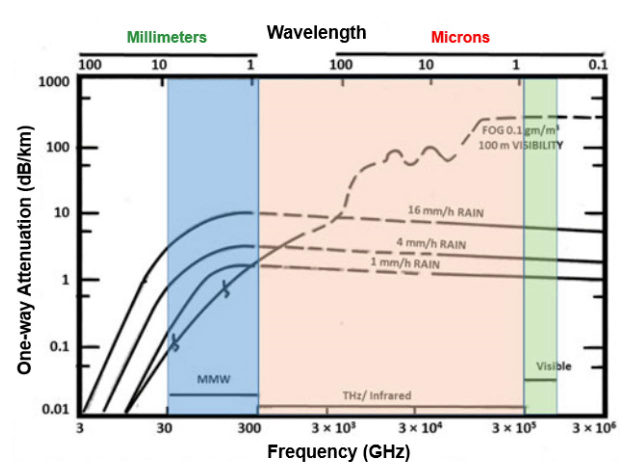

Fig. 1 Attenuation effect for mmWave and FSO wireless transmission [11].

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the other hand, the mmWave helps the FSO technology to overcome the link degradation due to the fog, humidity and clouds. An experimental setup has been installed in Graz to measure the performance of an hybrid FSO/mmWave link [5]. During this experiment, the data was continuously sent simultaneously over each FSO and mmWave link over 15 months. By the end, the total availability was recorded with 99.93%.

The main contribution of this paper is in defining, explaining and comparing the FSO and the mmWave technologies. The list of possible solutions that improve the reliability of FSO link including the modulation schemas, the diversity techniques and the combining with mmWave are discussed.

The paper is organized as follows. Section 2 describes the concept of FSO and mmWave systems, including the differences in propagation and technology. In Sect. 3, the attenuation and losses in FSO and mmWave due to weather conditions are discussed. The different modulation techniques for FSO systems are presented in Sect. 4. The hybrid links consisting of FSO and mmWave with different diversity combining techniques are shown in Sect. 5. Finally, the conclusions are drawn in Sect. 6.

2. mmWave and FSO Wireless Communication

2.1 mmWave Wireless Communication

mmWave is a wireless enabled technology for multi Gbit/s data transmission communication systems. It refers to wavelengths from 1 to 10 mm, which is corresponding to frequencies in the range 30–300 GHz. These bands got well established over time and used to serve for communications purposes in a proper way. Bose demonstrated the first millimeter communication more than 100 years ago [2]. mmWave bands as mentioned are widely used in several applications such as, satellite communication, fronthaul networks and side to side communication. The mmWave link can be used in line of sight (LOS) (like directional radio) and non-line of sight (NLOS) applications [1], [2].

In case of LOS, the signal propagates in conditions that transmitter and receiver stations are in view of each other without any obstacles residing between them. The NLOS case is given when transmitter and receiver stations are not in the direct visual line of sight, which trades to use multiple paths in signal propagation. NLOS transmissions suffer from significant attenuation and cannot support high data rates. The coverage is possible up to approximately 200 m with 1 W of transmit power. To achieve high data rates, a long distance transmission and a maximizing of the power efficiency, mmWave communications rely on the LOS transmission.

IEEE 802.11ad standard was developed in 2014 for outdoor backhaul. It specifies the physical layer and MAC layer in the frequencies above 40 GHz and supports wireless transmission with multi Gbit/s data rate but with limited range [6]. Current research has shown that the point-to-point systems using mmWave either in V-band (57–64 GHz) or E-band (71–76 and 81–86 GHz bands) can achieve high data rates (up to 10 Gbit/s), while reducing interference over long distance. The V- and E-band spectra are regulated or are being considered for regulation for the deployment of communication systems by most countries and regions in the world [7], [8].

The mmWave in V-band (57–64 GHz) has been proposed in 2009 which allows very high data rate over 2 Gbit/s. The advantages of using this band include interference mitigation, security and QoS is it is an unlicensed band. However, V-band suffers from high atmospheric attenuation (about 15 dB/km) and limitation of the transmitted power (< 0.5 W) [9].

The mmWave in E-band (71–76 and 81–86 GHz bands) is favorable for high-rate and long-range wireless communication due to the small atmospheric attenuation (0.5 dB/km) [7], [10]. Furthermore, the E-band technology offers various advantages over the other wireless communication technologies such as low cost of construction, quick development, flexibility, high reliability and security of the system. Moreover, the E-band can operate with up to 3 W of output power, highly focused signals and high gain antennas. On the other side, the E-band is a licensed spectrum and requires a high antenna gain.

2.2 FSO Wireless Communication

FSO wireless communication is the other competitive wireless solution for multi Gbit/s data transmission. FSO technology is an LOS link depending on the propagation of the optical beam through the atmosphere. The vast majority of currently available commercial FSO systems are using a long-wave IR (LWIR) region between 780 nm to 1550 nm [11]. In order to overcome the misalignment in an LOS system either mmWave or FSO, a self-tracking and acquisition system has been deployed to maintain continuous alignment of the transmitter/receiver pair. In general to locate, align and maintain alignment, there are three main operations: acquisition, pointing, and tracking [1].

Basically, an FSO system uses the intensity modulation with direct detection (IM/DD) whereby in the transmitter the electrical signal is converted to be optical by modulating the intensity of a laser source using the on off keying (OOK) modulation scheme. At the receiving end, a photodiode converts the received optical intensities into the corresponding photocurrent. Nowadays, FSO communication links are widely used in several applications include, emergency communications link deployment, inter-satellite communication, up-and-down links between satellites and earth stations, deep-space communications, and among the mobile stations as a fronthaul connectivity.

A 100 Gbit/s FSO transmission has previously been reported for short-distance backhaul using polarization-multiplexed and higher-order modulation formats [12]. Furthermore, 1 Tbits/s was achieved by multiplexing four light beams with different values of orbital angular momentum and encoded with quadrature amplitude modulation [13]. Several modulation techniques have been proposed to overcome the limitations of wireless optical communication, the most popular schemes will be presented later in Sect. 4.

Usually in FSO systems, any optical wavelength can be used. However, it is very important to consider eye safety regulations. These regulations are set by international organizations such as, American national standards institute (ANSI), European committee for electrotechnical standardization (CENELEC) and international electrotechnical commission (IEC) [1]. Laser products are classified in different levels [51] depending on the greatest possible hazard ("Class 1" = not dangerous; "Class 4" = very hazardous, emitted power exceeds 0.5 Watt). The cornea of the eye acts like a band-pass for wavelengths between 400 nm to 1,400 nm. That means laser communications below approximately 400 nm and beyond 1,400 nm have the advantage of higher usable energy densities. Laser sources operating within the visible light spectrum (380 nm–780 nm, relevant emitted power and exposure time) can be detected by the eye and it can take countermeasures like the normal eye-shut-reflex. That fact makes systems at 1,064 nm so hazardous because laser light is still focused directly on the retina, but it cannot be detected. So we can derive that the ancient FSO systems (~ 850 nm) are more dangerous than newer developments like 1,550 nm or even 10 μm. A 1,550 nm FSO system is capable to transmit ten times the power of a system at 780 nm (at the same safety class).

3. Attenuation and Loss in FSO and mmWave Channel

3.1 Attenuation and Losses in FSO Channel

FSO technology in general depends on the propagation of the laser beam through the atmosphere, in which the optical signal is affected by several factors including geometric loss, atmospheric loss, atmospheric turbulence induced fading and ambient noise [14]. In this section, we discuss these factors and the effects on the signal.

3.1.1 Geometric and Misalignment Losses

The geometric and misalignment losses occur because of the divergence of the beam when it propagates. Due to the narrowness of the transmitted beam just a few centimeters movement can cause a large misalignment between the transmitter and receiver which interrupts the communication link. Therefore, we have to carefully consider all possible misalignments factors such as beam wander, building sway, or errors in the tracking system [14], [15]. The beam wander comes due to the divergence of the beam when it moves through the atmosphere. This change influences the received optical power at the receiver. Considering a Gaussian beam profile and Rayleigh distributed radial displacement at the receiver, the half-divergence angle θ and the received power can be described as

$$\theta = tan^{-1}[w(z)/z] \rightarrow w(z) = ztan\theta \quad (1)$$

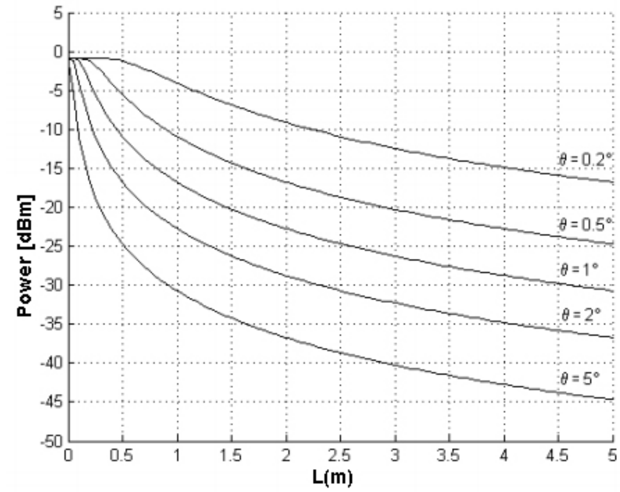


Fig. 2 Received power versus the path link L with different divergence angles θ [15].

$$P_{RX}(z) = P_{Tot}(z)[1 - exp[-2(r_{RX}^2)/(w^2(z))]] \quad (2)$$

where w is beam half-width of the Gaussian beam, $P_{Tot}(z)$ is the total power at distance z, and r_{RX}^2 is the radius of the receiver aperture. Accordingly, the small change of the beam half-divergence angle θ will affect the beam half-width w therefore the less optical power is received (see Fig. 2) [15]. On the other hand, building sway is the result of a variety of factors, including thermal expansion, wind loads, small earthquakes and vibrations. For a long distance communication link, an automatic pointing and tracking system should be used at the receiver to reduce the effects of misalignment and to avoid a high geometric loss [16].

3.1.2 Atmospheric Losses and Weather Influences

The molecules and particles in the atmosphere interact with the light and cause absorption, scattering and attenuation (fog, rain and snow). The quality of the optical propagating signal is therefore affected [20]. Among various atmospheric attenuation effects on optical signal, fog is the most important factor. As the size of fog particles is comparable to the transmission wavelength of optical and near infrared waves, it causes attenuation due to scattering, which deflects the incident light from its initial direction, causing a spatial, angular, and temporal spread. The most common way to calculate the attenuation due to fog is used the visibility data. The visibility is known as the distance to an object where the image contrast drops to 5% instead of near view. The wavelength used to measure the visibility is 550 nm, which is used as visibility reference. There are several models used to predict the attenuation based on the visibility such as Kruse [17], Kim [18] and Al Nabulsi [19]. The resulting attenuation of the optical signal is given as follows:

$$\alpha_{Fog} = 3.912/(V_{km})(\lambda/550)^q \quad (3)$$

whereas $V(km)$ is the visibility, λ is the wavelength of the

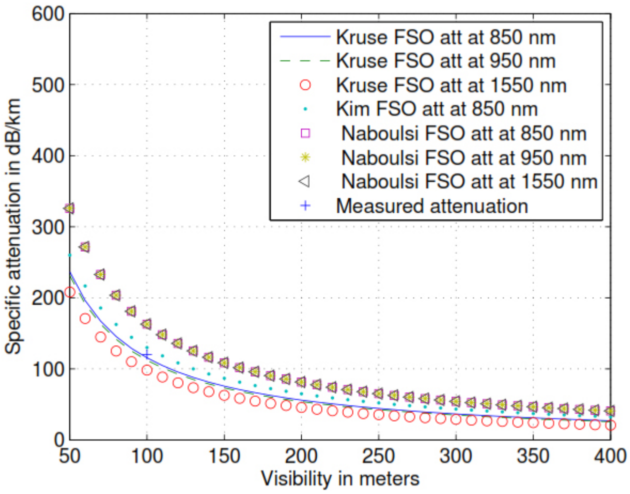


Fig. 3 Comparison of attenuations by different models specified for Graz fog event [19].

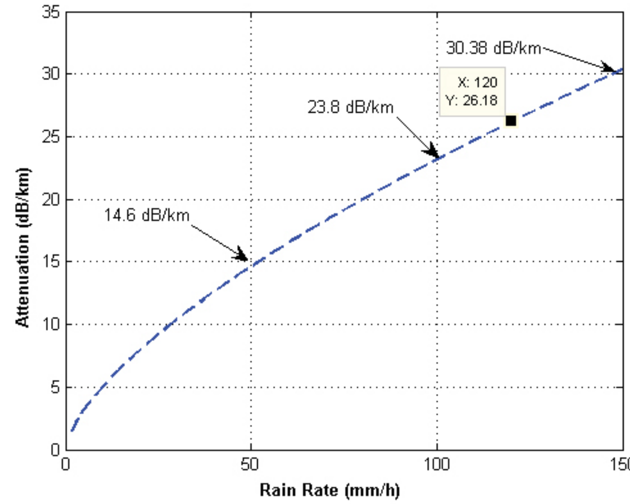


Fig. 4 Simulation of rain rate versus attenuation [23].

transmitted signal (nm) and q is the attenuation coefficient which is defined different by Kim and Kruse. Figure 3 shows comparison of attenuations by the three models at wavelengths 850 nm, 950 nm and 1550 nm including an experimental measurements due to fog at Graz [19].

Other factors that affect the light when it propagates through the atmosphere are rain and snow. They cause the scattering of the laser beam power resulting attenuation of the received signal. This attenuation depends on the dropsize of rain or snow. The most commonly used raindrop size distributions that have been proposed by Marshal and Palmer [22]. Rain or snow does not influence optical transmissions heavily, because they have the size of a few millimeters and are relatively large compared to laser wavelengths (1.5 microns) and thus cause minimal scattering of the laser energy. Furthermore, water is hardly absorbing the 1550 nm laser wavelength. Therefore, it is not surprising that the optical transmission is not heavily impacted by rain and snow (about 14 dB/km at rain rate 50 mm/h) as seen in Fig. 4 [23].

The rain attenuation coefficient with rain-rate R (mm/hr) is given by [24]

$$\alpha_{Rain} = a_r R^{b_r} \tag{4}$$

where a_r and b_r are the model parameters which depend on the rain drop size and temperature. The values of a_r and b_r based on measurements at R less than 90 mm/h equal 1.58 and 0.63, respectively.

On the other hand, the attenuation due to snow is classified into dry and wet. The wet snow is partially melted and denser. The attenuation coefficient due to snow (dB/km) with snow-rate S (mm/hr) is given by [25]

$$\alpha_{Snow} = a_s S^{b_s} \tag{5}$$

where a_s and b_s are the model parameters which depend on the type of the snow (dry or wet) and the wavelength of FSO link (λ) as following:
dry snow $\Rightarrow a_s = 5.42x10^{-5}\lambda + 5.5, b_s = 1.38$
wet snow $\Rightarrow a_s = 1.02x10^{-4}\lambda + 3.79, b_s = 0.72$

3.1.3 Ambient Noise

An ambient light is unwanted electromagnetic radiation in the bandwidth of the detector considering a shot noise. The dominant source of the ambient noise is the sunlight that degrades the performance of the optical wireless system. This noise reduces signal-to-noise ratio (SNR) and effective receiver sensitivity. Whereas the electrical signal at the receiver S_e is given by:

$$S_e = \eta(I_S + I_B) + n \tag{6}$$

where, I_S is the light intensity of received signal, I_B is the ambient light intensity, η is the optical-to-electrical conversion efficiency, and n is the additive white Gaussian noise [26].

3.1.4 Atmospheric Turbulence Induced Fading

Atmospheric turbulence is a random fluctuation in the temperature and pressure of the atmosphere, which leads variations in the refractive index along the transmission path. The refractive index can be denoted as $n(r,t) = n_0 + n_1(r,t)$, where n_0 is the average index and $n_1(r,t)$ is the fluctuation induced due to the variations of temperature and pressure. This change in the refractive index causes fluctuations in both the intensity and the phase of the propagating signal which is known as scintillation or fading. These fluctuations can increase the probability of error and impair the performance of FSO system, especially for long-distance communication [27].

The effect of atmospheric turbulence becomes dominant in a clear atmosphere, where the loss associated with visibility is negligible. The atmospheric turbulence can characterize by three parameters: the inner and the outer scales of turbulence which are denoted by l_0 and L_0, respectively, and the wavenumber spectrum structure parameter C_n^2, which is altitude-dependent. The value of C_n^2 varies from 10^{-17} for weak turbulence to 10^{-13} for strong turbulence [27].

Several probability density functions (PDFs) have been proposed for the intensity variations at the receiver end of an FSO link. Generally, a gamma-gamma (GG) distribution is used to model the PDF of the intensity fluctuation as following [28]:

$$p(i_t) = \frac{(2\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)}\ i_t^{((\alpha+\beta)/2)-1}\ K_{\alpha-\beta}(2\sqrt{\alpha\beta i_t})) \tag{7}$$

where i_t is the signal intensity at time t, α, β are parameters of the PDF, Γ is the gamma function, and K is the modified Bessel function of the second kind of order $\alpha - \beta$. The parameters α and β are related to the scintillation, and in the case of zero inner scale l_0 are expressed by:

$$\alpha = \frac{1}{exp[\frac{0.49\sigma_R^2}{[1+1.11\sigma_R^{12/5}]^{7/6}}] - 1} \tag{8}$$

$$\beta = \frac{1}{exp[\frac{0.51\sigma_R^2}{[1+0.69\sigma_R^{12/5}]^{5/6}}] - 1} \tag{9}$$

where σ_R^2 is the Rytov variance at propagation distance L and it is defined as $\sigma_R^2 = 1.23\ C_n^2\ (2\pi/\lambda)^{7/6}\ L^{11/6}$.

According to the previous analysis of attenuation and turbulence effects, we can calculate the instantaneous received electrical SNR per symbol of FSO link as:

$$\gamma_1 = \overline{\gamma_1}\ i_t^2 \tag{10}$$

where $\overline{\gamma_1}$ is the average electrical SNR per symbol and is given by:

$$\overline{\gamma_1} = \left(\frac{\mu\eta P_{at}A_T}{\sigma_n}^2\right)\frac{E_g}{2} \tag{11}$$

whereas μ is the modulation index $(0 < \mu < 1)$, η is the responsively of the receiver, P_{at} average transmitted optical power, A_T is the total link attenuation due to weather effects (rain, fog, or snow), E_g is the energy of the pulse shaping, and σ_n is the scintillation index [29].

The outage probability is the probability that the SNR falls below a certain threshold which determines the link availability. Therefore, it is important to measure the FSO link performance based on the availability. In practical, five-years-monitoring (4/2006–6/2011) of the FSO communication link installed by Graz University of Technology over a distance of 300 m has shown that the availability of this link is approximately 97.55% [30].

3.2 Attenuation and Losses in mmWave Channel

Wireless communication using mmWave suffers from several losses, which limit the propagation range. The free space propagation loss (FSPL), atmospheric attenuation, rain attenuation, and the fading due to multi-path are represented the main causes of energy degradation in wave propagation. In this section, we discuss the propagation losses in mmWave due to these affects. Furthermore, link budget calculation including the all sources of attenuation is provided [31].

3.2.1 Free Space Propagation Loss (FSPL)

FSPL is the drop in the density of power while it travels through the space over a distance. The FSPL is proportional to the square of the frequency of the signal as well as the square of the distance between the transmitter and receiver. Thus, the PL is frequency and distance dependent and can be expressed by the following equation (in dB) [32]:

$$L_{FSPL}(dB) = 10log_{10}\left(\frac{4\pi L}{\lambda}\right)^2 \tag{12}$$

3.2.2 Atmospheric Attenuation; Absorption by Molecules

Atmospheric attenuation is the second major source of losses in mmWave. It occurs when the radio waves traveling through the atmosphere are absorbed or scattered by oxygen molecules (O_2), water vapor (H_2O) or other gaseous. The atmospheric attenuation is significantly varies with the frequency as shown in Fig. 5. The large beaks of attenuation are at 60 GHz and 180 GHz due to the oxygen and water molecules. They absorb about 15 to 30 dB/km for the signal energy. So, it is not recommended to use these frequencies for long-distance and real-time communication due to a high signal degradation. On the other frequencies, the attenuation drops again and increase slightly as the frequency increases [31], [33]. So, the most of the current research is focused on the 28 GHz band, the 38 GHz band, and the E-band (71–76 GHz and 81–86 GHz).

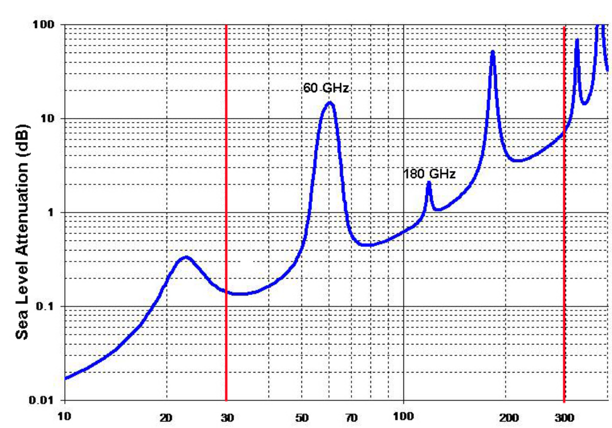


Fig. 5 Attenuation versus frequency in mmWave band [31].

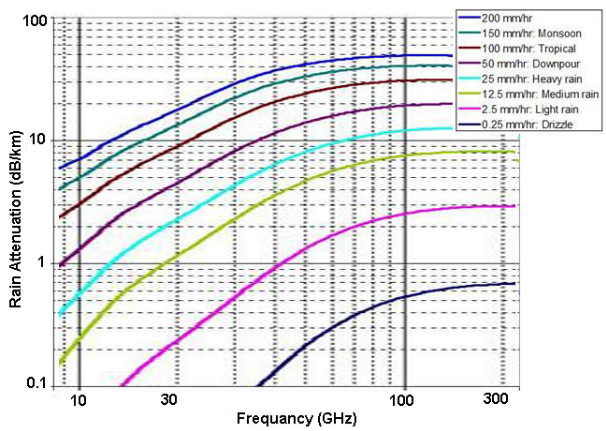


Fig. 6 Rain attenuation for different rainfall rate [31].

3.2.3 Rain Attenuation; Weather Influences

The rain attenuation occurs as a result of the absorption and scattering of electromagnetic waves by rain particles. It depends on the frequency of that wave, the temperature, the size of raindrops, and the rainfall velocity. Figure 6 shows several rain attenuation with different values of rainfall rate given by the international telecommunication union radio communication sector (ITU-R). An approximate relationship between rain attenuation coefficient L_{Rain} (dB/km) and different rainfall rate R (mm/h) as following [31], [34]:

$$L_{Rain}(dB/km) = a_r R_r^b \tag{13}$$

where a_r and b_r are functions of frequency given by ITU-R recommendation. As shown in Fig. 6, the rain attenuation is very significant in mmWaves. For example, for the rainfall rates of 12.5 mm/h it yields about 7 dB/km attenuations at 60 GHz. While in the case of tropical rainfalls (100 mm/h), the attenuation can reach up to 25 dB/km at the same frequency. In addition, we can see that the rain attenuation does not change notably for frequencies greater than 60 GHz.

3.2.4 Induced Fading Loss

Induced fading occurs when the waves travel along different paths and interfere with the waves traveling in a direct line-of-sight path. The type of fading causes a destructive interference for the arrival waves due to differences in their phases. The worst case occurs when the waves traveling in different paths reach the receiver out of phase and cancel each other. Thus, the fading can result a signal reduction of more than 30 dB [33]. It is highly recommended to overcome this problem by adding more extra power in the radiated wave which is called fading margin or fading gain. The value of the fading gain is dependent on the desired reliability of the link and receiver sensitivity.

3.2.5 Link Budget

A link budget is a signal-power plan for a specific radio system. The following equation shows the basic elements that should be considered when calculating the link budget:

$$Received\ Power = Transmitted\ Power + Gain - Losses$$

If the estimated received power is sufficiently large (typically relative to the receiver sensitivity), the link budget is said to be sufficient for sending data under perfect conditions. The amount by which the received power exceeds receiver sensitivity is called the link margin. For the purposes of link budget analysis, the most important aspect is the SNR required for the receiver to achieve an acceptable level of reliability in terms of Bit Error Rate (BER), where,

$$SNR = Received\ Power - Channel\ Noise.$$

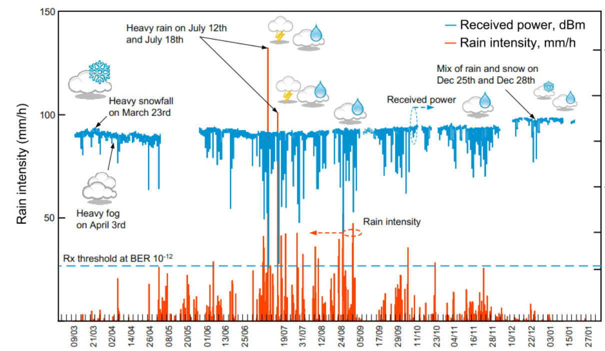


Fig. 7 Received power in the 71–76 GHz band (blue) versus rain intensity (red) [35].

A 70/80 GHz mmWave link developed by Ericsson Research was installed in Mölndal, Sweden in 2010 [35]. The communication distance between the two testing points is 1 km with 1 Gbit/s data rate. Figure 7 presents ten months monitoring the link reliability, the rain intensity denoted by red while the received power represented with blue. The measured data indicates that the link availability including path attenuation < 30 dB is 99.9992%.

4. Modulation Techniques in Optical Wireless Communications

The most of optical wireless communication systems use the IM/DD (intensity modulation with direct detection) scheme. It appears to be the best solution to overcome the attenuation problems. However, due to the limitation either on data rate or eye safety consideration on the optical transmitted power, several schemes have been proposed to resolve these limitations. We can divide the modulation schemes in wireless optical communication systems into two types, binary and multi-level modulation formats [36], [37].

In the binary-level modulation techniques, the information transmit in each symbol period is done through the variation of two intensity levels. The most popular schemes are on-off keying (OOK), pulse position modulation (PPM), pulse width modulation (PWM) and digital pulse interval modulation (DPIM). The multi-level modulation techniques transmit symbols in a range of intensity levels. The advantage of these schemes is that they provide a higher bandwidth efficiency than binary level techniques. The common used multi-level schemes are quadrature pulse amplitude modulation (QAM), L-PPM and L-PWM.

In this section, a number of popular modulation schemes are discussed as well as other terms like error probability, power efficiency and bandwidth or spectral efficiency are presented. A comparative study of the different modulation schemes is included.

4.1 Basic Definitions

4.1.1 Power Efficiency

Power efficiency (η_p) is the average power required to obtain an acceptable BER at a given data rate.

$$\eta_p = \frac{E_{pulse}}{E_b} \tag{14}$$

where E_{pulse} is the energy per pulse and E_b is the average energy per bit.

4.1.2 Bandwidth Efficiency

Bandwidth or spectral efficiency (η_B) is the ability of a modulation scheme to accommodate data within a limited bandwidth.

$$\eta_B = \frac{R_b}{B} \tag{15}$$

where R_b is the achievable bit rate and B is the required bandwidth.

4.1.3 Transmission Reliability

Transmission reliability is defined as the expected BER in the communication system. It is inversely proportional to the SNR, ($SNR = E_b/N_0$). In order to improve the reliability, it is required to increase the transmitted energy per bit, which decreases the power efficiency. Another solution is to change the modulation type, which requires more bandwidth and consequently, decreases the spectrum efficiency. Therefore, it is important to trade-off between the power and spectral efficiencies to select the best schemes according to achieve the desired reliability. The transmission reliability in terms of BER can be defined as [36]:

$$BER = Q\left(\frac{d_{min}}{2\sqrt{N_0}}\right) \tag{16}$$

where d_{min} is the minimum Euclidean distance between two points in the signal constellation, and N_0 is the power spectrum of the channel white Gaussian noise.

4.2 Modulation Schemes

The most popular scheme is OOK, which makes use of IM/DD technique. It is a binary-level modulation consisting of two symbols (*one* and *zero*). In OOK, the transmitter emits a rectangular pulse of duration $T_b = 1/R_b$ and energy $E_p = 2E_b$ to signify a *one* bit while a *zero* bit is represented by the absence of an optical pulse. If the signal returns to zero between each sent pulse it is called return-to-zero (RZ). The other case where the level is held during the transmitted bit is known as non-return-to-zero. The bandwidth (B) required for OOK-NRZ equals $1/T_b = R_b$. OOK is simple to implement, but it relatively suffers from poor power and spectral efficiencies [38].

PPM is one of the alternative IM schemes used to improve the BER, the transmission reliability and power efficiency with respect to OOK. Furthermore, it does not require a dynamic thresholding in a detection process such as OOK does. In PPM scheme, the signal which is represented by M bits is encoded by a signal pulse in L time-slots, where $L = 2^M$. So, the transmitter sends only one optical pulse with time T_b in each symbol interval of duration T_s, where $T_s = M/R_b$. In terms of power efficiency, if L is greater than 2, the PPM modulation scheme provides a higher power efficiency than OOK. Unfortunately, an increase in L causes an increase in the bandwidth requirement where $B = L \times R_b/log_2 L$. The relationship between the average power requirements of PPM with respect to OOK is given by [37]:

$$\eta_p = \frac{P_{PPM}}{P_{OOK}} = \sqrt{\frac{2}{L log_2 L}} \tag{17}$$

Two different versions of PPM have been proposed for optical wireless communication, pulse width modulation (PWM), and digital pulse interval modulation (DPIM) [39]–[41]. In the PWM, the width of the pulses is modulated to convey the transmitted signal. The PWM offers a higher spectral efficiency than PPM, where it is required a bandwidth, $B = R_b/Log_2 L$, however, it needs more average power requirements than PPM. The average power required in PWM with respect to OOK can be expressed as following:

$$\eta_p = \frac{P_{PWM}}{P_{OOK}} = \frac{L+1}{\sqrt{log_2 L}} \tag{18}$$

DPIM is an asynchronous modulation scheme with variable symbol length. Data is encoded as a number of discrete time slots, between adjacent pulses. In DPIM, the symbol length is variable and is determined by the information content of the symbol. The minimum and maximum symbol lengths are $2T_s$ and $(L+1)T_s$ respectively. Assuming that the symbol length is random and uniformly distributed between 2 and $L+1$ slots, the average bit rate, $R_b = 2B log_2 L/(L+3)$. Alternatively, a higher number of bits per symbol can be transmitted without increasing the slot duration, thereby improving the transmission capacity. Furthermore, DPIM improves the power efficiency compared to OOK but not as well as that of PPM. The average power required in DPIM with respect to OOK is as the following:

$$\eta_p = \frac{P_{DPIM}}{P_{OOK}} = \frac{\sqrt{8(L+1)}}{(L+3)\sqrt{log_2 L}} \tag{19}$$

BPSK subcarrier intensity modulation (BPSK-SIM) is another IM schemes used to improve the BER and the transmission capacity of the system. In BPSK-SIM, the data is first modulated by RF subcarrier signal using BPSK modulator in which bits (*one* and *zero*) are represented by two different phases 180^o. The pre-modulated signal is used to modulate the intensity of a continuous-wave optical carrier. A proper DC bias should add to the pre-modulated signal to grantee that there are no negative values are included. The main argument for using BPSK-SIM is to increase the transmission capacity by modulating multiple sources by different subcarriers (N). Furthermore, it offers a high immunity to intensity fluctuation and does not require thresholding. Moreover, using SIM-BPSK results $log_2 N$ more transmission efficiency compared to the OOK. However, it increases the power requirement [42], [43]. The power required for BPSK-SIM modulation is given as:

$$\frac{P_{BPSK-SIM}}{P_{OOK}} = \sqrt{2N} \tag{20}$$

Finally, multi-level modulation schemes offer greater transmission bit rate and lower bandwidth requirements compared to binary modulations. However, they increase system complexity, which is not preferred by most of FSO communication systems.

4.3 Modulation Schemes Comparison

As mentioned, the most important parameters affecting the performance of the different modulation schemes are the transmission reliability, the power efficiency and the bandwidth efficiency. Figure 8 shows the transmission reliability in terms of BER versus the received SNR. As we can see, PPM and DIPM offered higher reliability than the other types of modulations specially while increasing the values of L.

The power efficiency and the bandwidth efficiency of different modulation schemes have been normalized to OOK and presented in Fig. 9 and Fig. 10, respectively. Among the results, we observe that the bandwidth efficiency of PPM and DIPM is decreasing with increasing the value of L. Therefore, it is important to consider when selecting a modulation scheme, the inconsistency between the power and the bandwidth efficiencies. For example, the applications that do not require a high data rate but need to optimize the power efficiency, the PPM scheme appears to be the first option. On the other hand, for the systems that require a high data rate without considering the power efficiency, PWM is the best selected scheme. A similar analysis is presented in Table 1, including the transmission capacity and system complexity.

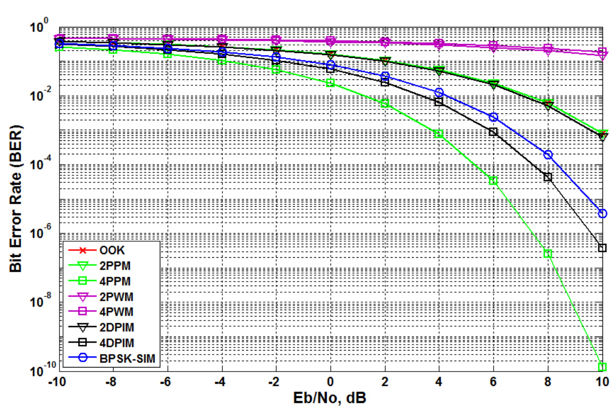


Fig. 8 BER for different modulation schemes versus SNR (E_b/N_0).

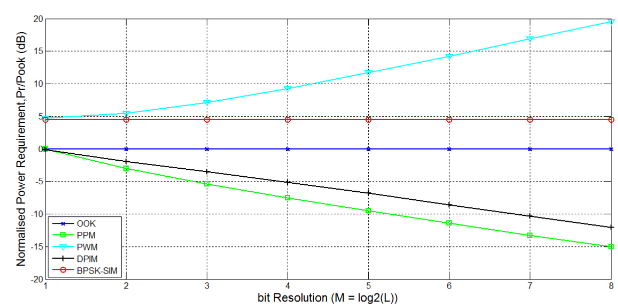


Fig. 9 Normalized received power versus bit Resolution (M).

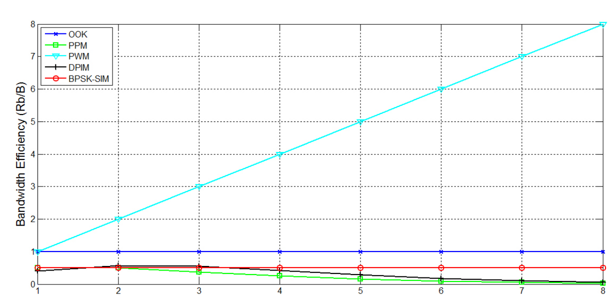
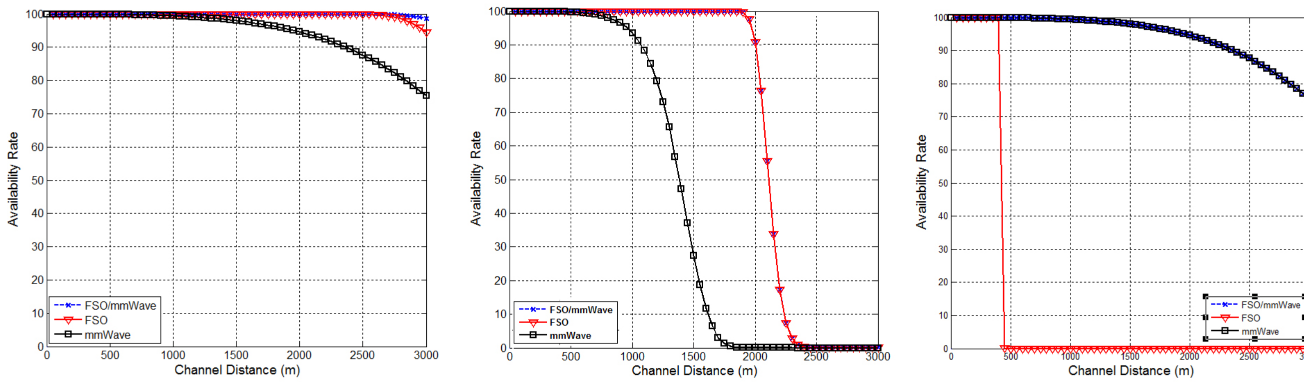


Fig. 10 Bandwidth efficiency versus bit resolution (M).

Table 1 Modulation schemes comparison.

	OOK	PPM	PWM	DPIM	BPSK-SIM
BER	$Q(\sqrt{SNR})$	$Q(\sqrt{\frac{L}{2} log_2 L\, SNR})$	$Q(\frac{1}{L+1}\sqrt{log_2 L\, SNR})$	$Q((L+3)\sqrt{\frac{log_2 L\, SNR}{8(L+1)}})$	$Q(\sqrt{2\, SNR})$
$\eta_p = \frac{P_.}{P_{OOK}}$	1	$\sqrt{\frac{2}{L\, log_2 L}}$	$\frac{L+1}{\sqrt{log_2 L}}$	$\frac{\sqrt{8(L+1)}}{(L+3)\sqrt{log_2 L}}$	$\sqrt{2N}$
$\eta_B = \frac{R_b}{B}$	1	$\frac{log_2 L}{L}$	$log_2 L$	$\frac{2log_2 L}{L+3}$	$\frac{1}{2}$
$C_{T_C} = \frac{T_c}{R_b}$	$log_2 L$	$log_2 L$	$log_2 L$	$\frac{2L\, log2(L)}{L+1}$	$log_2 L\, log_2 N$
Simplicity	Low	Moderate	Moderate	Moderate	High



(a) Clear Weather (b) Raining Weather (c) Foggy Weather

Fig. 11 Link Availability of hybrid FSO/mmWave under different weather conditions.

5. Hybrid FSO and mmWave with Diversity Combining Techniques

The benefits of FSO motivate its use for high data rate demanding communication applications. FSO yet poses some important challenges such as sensitivity to misalignment, atmospheric turbulence induced fading and signal attenuation caused by adverse weather conditions such as fog. This degrades the performance of the link strongly and the overtime availability achievement is impossible. The results of the previous section show that the performance degradation associated with decreasing of SNR can be improved by changing the modulation scheme according to the system requirement. In contrast, there are limitations on the different schemes regarding the power, bandwidth or capacity efficiencies. So, another alternate solution has been proposed to improve the FSO link availability by using the RF backup link. This link is used in order to cope the weather effected reduced availability of FSO link, which is called hybrid FSO/RF. Several combinations of FSO and RF for different wireless applications have been proposed in [4].

The idea behind a combination between RF and optical waves is the complementary behavior of each technology during different weather conditions. As mentioned before, the rain is the dominant cause for attenuation in the RF link, whereas the fog is the most important cause for attenuation in the FSO link. An experiment setup for a hybrid network of FSO and 40 GHz backup link was established over a period of one year in Graz, Austria and prove that the combination of both technologies leads 99.93% instead of 96.8% availability of FSO alone [43], [45].

Recently, mmWave became a feasible solution in the hybrid FSO/RF system; due to the mmWave technology can provide high data rates similar to FSO (multi Gbit/s). In addition, the mmWave (70/80 GHz) bands are particularly attractive for long range communications because these bands have a very low O_2 and H_2O atmospheric absorption [46]. Therefore, when the FSO link fails the mmWave can provide nearly the same throughput requirements in data transmission. Conventional systems use only the mmWave channel as a backup when the FSO channel fails. Furthermore, the switching between the two links is depending on variations in the channel conditions. This technique results in an inefficient use of network resources. Thus, it is an attractive solution for high-throughput wireless connectivity, when both FSO and mmWave links are simultaneously in use [47], [48].

Figure 11 demonstrates the improvement in the system availability by using hybrid FSO/mmWave under different weather conditions (clear, moderate rain and moderate fog). In this system, the FSO link uses a wavelength of 1550 nm with an optical power of 12 dBm while the mmWave operates at frequency 72 GHz and transmitted power of 10 dBm over 2 km distance. As it can be seen, the instantaneous availability is 100% at clear weather and is reduced to 95% and 90% under fogy and raining weather, respectively.

The hybrid FSO/mmWave link combines the advantage of high-availability and large-capacity. For maximizing the overall SNR, the high-availability structure is used, where both of links are carrying the same portion of data using temporal or spatial diversity technique [49]. A diversity refers to the availability of multiple copies of the desired signal at the receiver, however each one is affected by different channel characteristics. Hence, the signals which are received from each individual link can be directly combined using a diversity combiner. The diversity combiner measures the SNR of received signal from different branches and offers an enhanced SNR. The popular combining schemes are used to improve the SNR are selection combining, maximum ratio combining (MRC) and equal-gain combining (EGC) [50].

The SC measures the SNR at each available link and selects the output signal with the highest SNR value ($\gamma_{SC} = max(\gamma_1, \gamma_2)$), where γ_1 and γ_2 are the instantaneous SNR of the FSO and RF links, respectively.

In MRC, the received signals of each link are weighted by the channel gains i.e. a stronger signal is weighted more than a weaker signal before combining. The overall SNR is the mean of the SNRs of each link ($\gamma_{MRC} = mean(\gamma_1, \gamma_2)$). Similar to MRC, the total SNR in EGC is determined by adding two SNRs, however, each signal is weighted with the

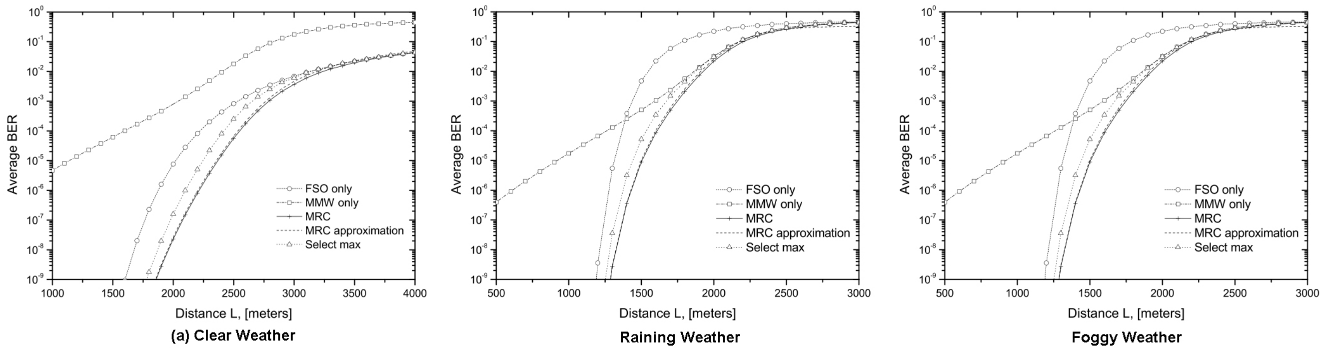


Fig. 12 BER performance of hybrid FSO/mmWave with diversity combining under different weather conditions.

same factor, irrespective of the signal amplitude. For hybrid FSO/mmWave, usually EGC is used at the receiver where the signals generated from a single source. Thus, it provides performance close to the MRC while having the advantage of lower implementation complexity [29].

Figure 12 shows the BER improvement by using the diversity combining techniques under different weather conditions (clear, moderate rain and moderate fog) [29]. As shown in the figures the combining techniques efficiently use the complementary of FSO and mmWave links. As the performance of system is identical with the performance of the reliable link when the other is completely unreliable. Furthermore, the performance is significantly improved when the two links are available.

6. Conclusions

In this paper, we have presented the benefits of FSO and mmWave technologies, which are representing the promising solution for next deployment transport networks. We have carried a survey for both FSO and mmWave links, including the characterization of the channels and also we are addressed their challenges. Several solutions which improve the overall performance of both FSO and mmWave have been presented including the modulation schemas, complementary integration and diversity combining. We believe that there are many topics need more investigation in both technologies such as MIMO, cooperative diversity, channel coding, adaptive transmission rate, . . . etc. We hope that this survey helps for more understanding the current research contributions in the growing area of FSO and mmWave communications and hopefully prompt further research efforts in the proposed areas of research.

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