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Optical Wireless and Millimeter Waves for 5G Access Networks

Mark Stephen Leeson and Matthew David Higgins

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Abstract

Growing bandwidth demands are driving the search for increased network capacity leading to the exploration of new wavelength ranges for future communication systems. Therefore, we consider two technologies that offer increased transmission bandwidths by virtue of their high carrier frequencies, namely optical wireless and millimeter-wave transmission. After highlighting the relevant electromagnetic (EM) spectrum region, we briefly describe the applications and properties of each approach coupled with a short history of their development. This is followed by a performance comparison in two possible 5G links: outdoor point-to-point and indoor hotspots. We find that in both cases, there are regions where optical wireless communications (OWC) are better, but others where millimeter waves are to be preferred. Specifically, the former outperforms the latter over distances up to approximately 50 meters outdoors and a 10-meter hotspot radius indoors.

Keywords: optical wireless communications (OWC), visible light communications (VLC), free space optics, infrared (IR) communications, millimeter-wave communications, 5G access

1. Introduction

Mobile data traffic is projected to increase by several orders of magnitude by the year 2030 [1] and to address this expansion requires increased system capacity. The now ubiquitous wireless systems in modern life operate using carrier frequencies below 6 GHz. The next generation of provision must be designed to meet future wireless data demands, and so the search for further regions of the electromagnetic (EM) spectrum with untapped bandwidth has continued with renewed vigor in recent years. This has prompted research interest in underutilized
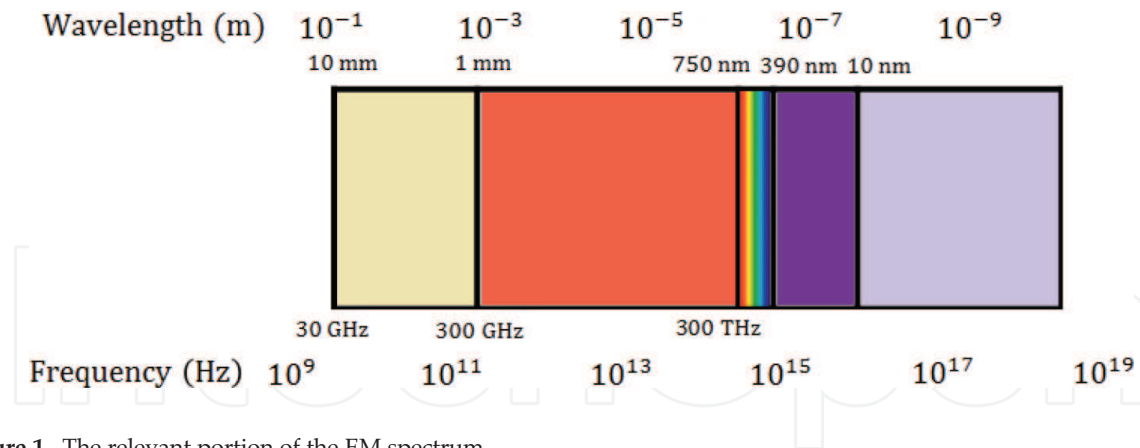
Figure 1. The relevant portion of the EM spectrum.

higher frequency bands, with millimeter [2] and optical [3] waves being prime areas of interest. **Figure 1** below shows a portion of the EM spectrum that includes the ranges for optical and millimeter-wave communication. The former includes a large span of frequencies that encompasses the infrared (IR) region through visible light and into the ultraviolet (UV) range. The latter includes wavelengths from 1 to 10 mm, equating to 300 GHz and 30 GHz, respectively.

As may be seen from **Figure 1**, millimeter-wave and optical frequencies live side-by-side in the EM spectrum and share the characteristics of propagation but are often seen as disparate entities. In many ways, it would seem sensible to classify optical communications as nanometer wave communications, but this has not been the case to date. However, both spectral regions offer significantly increased transmission bandwidths by virtue of their increased carrier frequencies, and this is the reason for their entry into the 5G arena. Nevertheless, the realization of the potential of both optical wireless communications (OWC) and millimeter waves requires solutions to the significant challenges that arise from the utilization of higher frequency carriers. Transmissions using both OWC and millimeter waves occur in relatively demanding propagation conditions. Both systems suffer from increased path loss, extra channel losses, and potentially useful technology that is not as established as that commonly deployed at present [4, 5].

A notable difference is that OWC has leveraged component advances from fiber systems [6], whereas the technological advances needed to make millimeter-wave radio cost-effective are more recent [7]. The rest of this chapter presents brief reviews of OWC and millimeter-wave systems and subsequently compares their performance in likely 5G scenarios.

2. Optical wireless

The use of optical carriers in free space is a technology that combines the mobility of radio frequency (RF) wireless communications with the high-potential bandwidth of optical communications. Moreover, the optical spectrum is not subject to license fees with easy spectrum reuse since light beams cannot penetrate walls. The major design challenge for OWC is to achieve a sufficiently high signal-to-noise ratio (SNR) at useful data rates given that the transmitter (TX) power is limited by eye safety considerations [8].

2.1. Application areas and properties

OWC systems can be broadly classified into categories, namely indoor and outdoor. Within both of these, a large number of possible operating modes have been demonstrated that may be grouped using the sub-categories shown in **Figure 2**. A good overview of the classification of optical wireless systems has recently been given by Son and Mao [9], to which the reader is referred for more details, so here we provide only an overview.

The two fundamental designs for indoor OWC are directed line-of-sight (LOS) and diffuse links, illustrated in **Figure 3**. In the former, a narrow beam TX sends light to a narrow field of view (FOV) receiver (RX) over the LOS. Such a link thus experiences minimal impacts from the multipath dispersion, noise, and path loss. Although the data rate is limited by the power budget allowed, such LOS links are very suitable for high-speed hotspots. The idea of tracking a user to support mobility with a TX and RX array [10] was demonstrated during the early revival of OWC [11], and this concept is likely to be employed with the light emitting diode (LED) lighting discussed later in this chapter.

A diffuse link relies on a wide-beam TX and a wide FOV RX and mirrors the operation of current WiFi systems by scattering an optical beam from surfaces within a room. Although this offers the advantage of more than one path, the differing path lengths produce a multipath dispersion effect that limits the achievable bit rates [12]. Despite innovations such as quasi-diffuse systems [13] and alternative modulation methods [14], the increased path loss produces
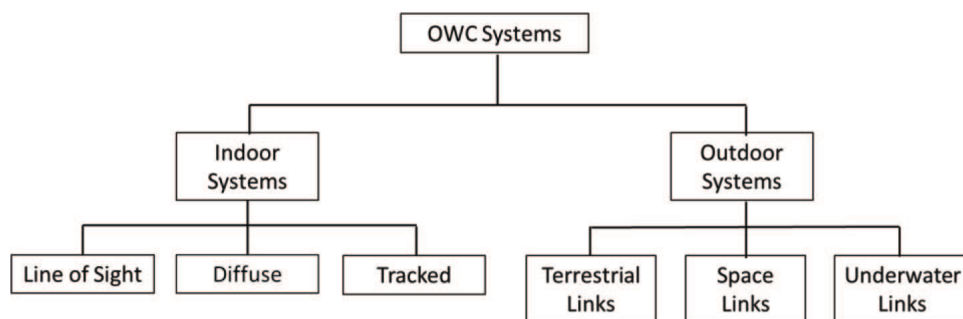

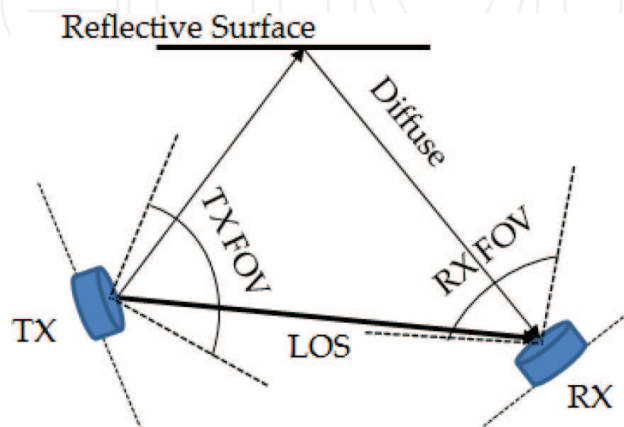**Figure 2.** Simplified taxonomy of OWC.

Figure 3. Schematic view of LOS and diffuse OWC links.

a need for higher power levels meaning that the diffuse systems are not competitive with RF solutions and unlikely to be employed in 5G systems.

Outdoor OWC is usually referred to as free space optical (FSO) communication and makes use of LOS links as the only feasible option given the path loss. We can consider FSO systems by means of their distance from the center of the earth. First, there are OWC satellite networks that can cover large portions of the globe [15]. Second, terrestrial FSO links [16] are usually established between buildings. Finally, there is the rapidly developing area of underwater OWC [17] where the incumbent acoustic technology is extremely limited in its bit rate, and OWC offers enhanced performance. Of these, we concentrate on terrestrial systems here since they are closest to the interface with 5G. We recognize that the satellites may be needed in the overall 5G landscape, but many of the issues will be similar (particularly in the area of ground to satellite communications), whereas underwater OWC is an important but distinct area with different propagation conditions.

2.2. Brief history

Communication using light through the air has a long history, beginning with the employment of reflected sunlight and smoke signals by ancient civilizations [18]. However, the birth of what may be regarded as a "modern" system dates from Bell's 200-meter photophone in 1880 [19]. With respect to FSO, the invention of the laser in the 1960s provided the means for a range of FSO applications [20]. Optical fiber developments in the next two decades made these preferable for long-distance optical transmission. Continued military and space work provided the basis for commercial FSO [21]. The 1990s saw growth in the civilian usage of FSO links driven by increasing data rates and high-quality connectivity requirements. FSO deployment rather than fiber offers a cheaper and quicker way of providing customer bandwidth, and may also be employed in disaster scenarios [22]. Substantial research efforts to improve FSO system performance in adverse atmospheric conditions mean that multi-gigabit rates are possible in the presence of turbulence [23].

Modern developments in indoor systems, commonly known as OWC, began with the seminal work of Gfeller and Bapst [24] in 1979. This considered an IR system based on a diffuse link using a wavelength of approximately 950 nm. The data rate achieved was just 125 kbps, but the work prompted the development of IR OWC systems through the 1980s and 1990s. Thus, LOS bit rates reached 155 Mbps [25], and diffuse systems achieved 70 Mbps [26]. This period of substantial development for OWC using wavelengths between 780 and 950 nm was driven largely by the ready availability of inexpensive optical sources and the coincidence of the peak sensitivity of mass-produced photodiodes. To maintain the essential simplicity and low-cost of OWC, most systems employed intensity modulation with direct detection (IM/DD), but many modulation schemes were investigated [27]. OWC did not achieve mass market status during this period but progress in IR systems has nevertheless continued with recent results demonstrating multi-gigabit performance [28] and localization and tracking [10]. However, it has been the developments in the visible light range that have really brought OWC to the fore as an option for integration with 5G. The development of solid-state lighting has led to the emergence of visible light communications (VLC) [29]. This approach makes use of the

communication potential of the lighting system that is offered once white LEDs (WLEDs) are installed. VLC in its modern form was initiated primarily by work at Keio University in Japan during the early part of the millennium [30]. Over the next period of years, the increasing research interest in the field led to the creation of the Institute of Electrical and Electronics Engineers (IEEE) 802.15.7 VLC task group, which has standardized physical (PHY) and medium access control (MAC) layers, and characterized these for short-range data transmission [31].

Advances have continued thanks to the orthogonal frequency division multiplexing (OFDM) scheme where parallel orthogonal subcarriers are used to achieve high data rates [6]. Direct current biased OFDM (DCO-OFDM) enabled the demonstration of a data rate of in excess of 3 Gbps using a commercial LED [32]. In recent years, the term light fidelity (LiFi) has been introduced [33] to encompass the aspect of mobility envisaged in the latest systems compared to the original fixed point-to-point concept of VLC [34]. Development of the technology continues with the investigation, *inter alia*, of modulation schemes, modeling, and applications [35].

The twentieth century also saw the use of UV light for communications, making use of the wavelength range 200–280 nm where there is very low background noise due to strong atmospheric absorption, so UV offers non-LOS (NLOS) secure communication [36]. During the 2000s, work at Massachusetts Institute of Technology (MIT) Lincoln laboratory replaced bulky, slow gas discharge lamps with UV LEDs [37] but the employment of photomultiplier tubes (PMTs) until relatively recently [38] has been a weakness of UV and OWC. The modern alternative of an avalanche photodiode (APD) adds complexity, and although UV systems system work continues, it is difficult to envisage 5G UV deployment.

3. Millimeter waves

There has been considerable interest in millimeter waves, particularly around 28-, 38-, 60 GHz, and the E-band (71–76 GHz and 81–86 GHz) [39]. The progress in complementary metal-oxide-semiconductor (CMOS) RF integrated circuits for 60 GHz systems [40] offers future prospects for products. Millimeter-wave communications have similarities with OWC since the higher carrier frequency suffers a high propagation loss, and is more sensitive to blockage than existing RF systems.

3.1. Application areas and properties

The applications of millimeter waves may be broadly classified as shown in **Figure 4**, in which systems where the millimeter waves convey information are distinguished from those where they serve another purpose. In the first category, outdoor cellular transmission for 5G has attracted substantial attention. The reduced propagation range of millimeter waves means that to achieve the increased bandwidth and throughput, smaller outdoor transmission ranges will be used [2] as illustrated later schematically in **Figure 6**. As will be discussed further when millimeter waves are compared with OWC, both technologies can form the basis for high-speed WiFi links to offer increased bandwidth and thus greater capacity [41]. Millimeter waves
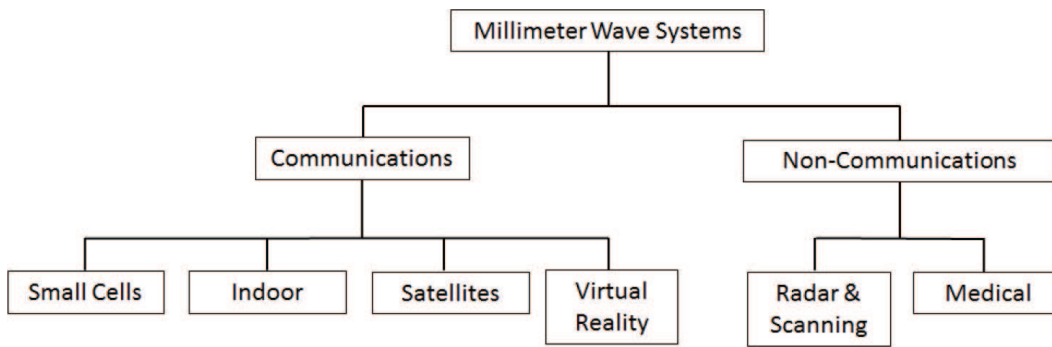
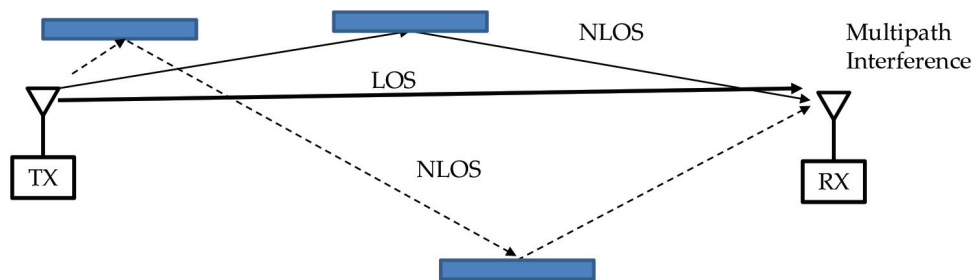**Figure 4.** Major application categories of millimeter waves.

Figure 5. Multiple propagation paths in millimeter-wave transmission.
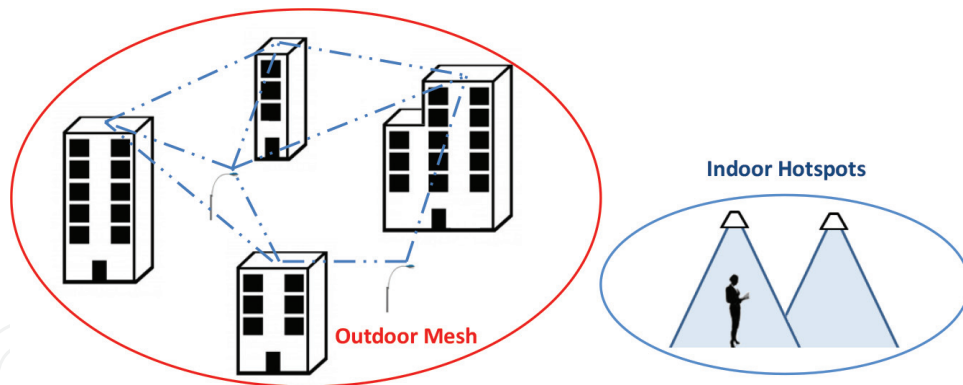

Figure 6. Comparison scenarios.

are ideal for satellite communications because of their significant bandwidth [42] and for high-speed transmission of video and audio for virtual reality (VR) applications [43]. Millimeter-wave radar has also been widely applied, most latterly in autonomous vehicles [44] and contraband detection [45]. Medical applications include cancer treatment by the use of immune system therapy [46].

A schematic representation of a millimeter-wave link is shown in **Figure 5**, which illustrates two possible reflected paths by which the transmitted waves may reach the RX. In contrast to OWC,

these NLOS links cause multipath interference fading effects at the scale of a wavelength [47] because constructive and destructive effects can occur. This not seen in OWC because photodiodes are typically many thousands of wavelengths across providing spatial diversity that prevents the fading although not pulse dispersion. The advances in beamforming that are outlined in the next section have enabled NLOS transmission to be implemented [48].

3.2. Brief history

Transmissions using millimeter-wave carriers have a long history but millimeter-wave mobile communications arose in the 1980s [49]. There was then a substantial gap in millimeter-wave communications research until the release of the unlicensed band near to 60 GHz [50]. This led to the development of short-range Gbps point-to-point links and wireless network standards [51]. As with OWC, military applications were developed over a similar time period [52], recognizing the potential benefits of increased bandwidth, sophisticated antennas, greater directionality, and reduced size compared to traditional microwave links.

Two key technological developments have enabled 60 GHz systems to become a reality, namely high-speed integrated circuits [40] and the use of multiple antennas [53]. With respect to the first of these, the work that has led to the emergence of low-cost millimeter-wave circuitry began in the 1990s [54], employing III-V semiconductor compounds that were hard to integrate with digital circuitry. Some of the earliest work using 60GHz CMOS appeared in the 2000s [55] progressing to the low-power implementation of Alldred et al. [56]. Strides in integration later resulted in chips of only a few square millimeters in area, including an antenna and with power consumption under 100 mW [57]. Gbps speeds over 2 meters were also demonstrated using integrated architectures [58]. The technology is now at a point where sophisticated modulation techniques can be employed at multi-gigabit rates for the latest IEEE standards using low supply voltages and small chip areas [59].

With respect to multiple antennas, the formation of arrays added considerable design flexibility to millimeter-wave systems. The fundamental driver of the technology was, and remains, the need to compensate for the large propagation loss incurred by this wavelength range. The utilization of highly directional antennas provides the necessary gain and the ability to implement beamforming that will be discussed below. The small wavelength is an advantage since the antenna size is half a wavelength as is the antenna separation permitting many antennas to be fitted into a relatively small space (several per square centimeter). Although the idea of using antenna arrays and adapting their beam patterns has its origins in radar systems and has existed for some time [60], interest in the concept for wireless communications started in the 1990s. Beamforming describes a signal processing technique used to achieve directional transmission or reception of a wireless signal. The selectivity in the antenna patterns is implemented by adapting the beams in an operation that may be seen as linear filtering in the spatial domain. The phases and amplitudes of the signals may be controlled to produce maxima or minima in desired and undesired communication directions, respectively [61]. Beamforming can be implemented in the digital baseband, the analog baseband or the RF front-end [53], and each of these has its own particular design features [62]. The filter weights employed to drive the antennas may be fixed, but a more flexible method (particularly for

mobile communications) is adaptive or smart beamforming because it can adapt the RF radiation pattern in real-time to accommodate changing transmission conditions [63].

4. Performance comparison

Based on the properties of the both OWC and millimeter-wave transmission, we now focus on a comparison of their performance in the two of the most likely application scenarios shown in **Figure 6**. Firstly, in the outdoor arena point-to-point links may be used to establish a mesh network using individual "point-and-shoot" links. Secondly, high-speed indoor connectivity may be offered using hotspots.

4.1. Methodology

We adopt a simplified approach so that the broad sweep of the performance of the technologies is captured. It is inevitable that some subtleties will be overlooked (such as shadowing and the mechanism to provide a primarily LOS path), but the analysis enables a meaningful indication of the relative performance of the two PHY layers. We now describe the simplified link budget models of the optical and millimeter-wave channels. These are along the lines originally described in [64] for a previous technology generation and inspired by the analysis of Wolf and Kress [65]. We consider both outdoor and indoor LOS scenarios.

4.1.1. Point and shoot

Figure 7 shows the geometry of the outdoor application where both transceivers have emission and FOV half angles of θ_h for simplicity and are not necessarily aligned to be facing each other.

4.1.1.1. Optical wireless

Applying the Friis formula [66] to an optical link produces unrealistic results because it applies to narrow, diffraction limited beams that require very precise alignment. Therefore, we adopt the more customary approach for OWC [67] where a link is considered that launches a beam with half-angle θ_h that evenly illuminates the area within the emitter cone. The intensity profile is assumed to be a constant value of I_0 over an angle $[0, \theta_h]$. This profile is beneficial so
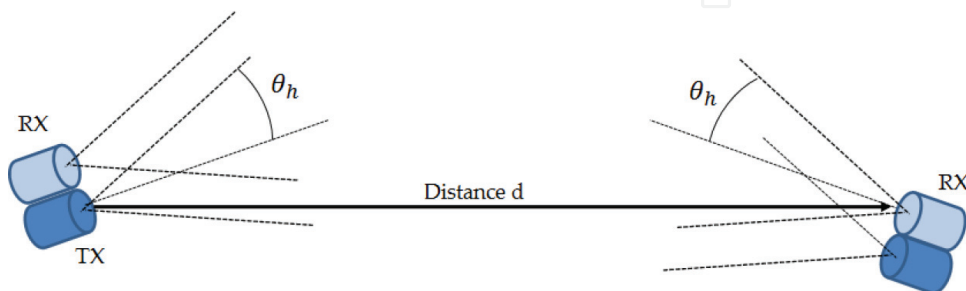

Figure 7. Point and shoot configuration.

that there is no off-axis fall-off, and may be obtained using a holographic diffuser [68]. Considering the solid angle of the cone results, for an emitter source power P_S, in:

$$I_0 = \frac{P_S}{2\pi r^2(1 - \cos\theta_h)} \tag{1}$$

The RX has a collection area, and in the worst case, this is orientated at an angle θ_h, meaning the received optical power P_O is:

$$P_O = \frac{P_S}{2\pi r^2(1 - \cos\theta_h)} A_{coll}\cos\theta_h \tag{2}$$

The photocurrent resulting from the received optical power is $i_O = RP_O$, for a photodiode responsivity R. Therefore, the electrical power S, delivered to a load R_L is:

$$S = I_O^2 R_L \tag{3}$$

The noise at the RX comprises shot noise from the signal, shot noise from any DC photocurrent caused by ambient light and amplifier noise. Thus, the noise power delivered to the load over an amplifier bandwidth Δf is:

$$N = \left(2q(RP_O + i_{Amb})\Delta f + i_{Amp}^2 \Delta f\right) R_L \tag{4}$$

where i_{Amb} is the photocurrent due to ambient illumination and i_{Amp} is the input referred noise of the amplifier. Hence, the overall signal to noise ratio is given by:

$$\frac{S}{N} = \frac{(RP_O)^2}{\left(2q(RP_O + i_{Amb})\Delta f + i_{Amp}^2 \Delta f\right)} \tag{5}$$

Leading to:

$$\frac{E_b R_b}{N_0} = \frac{(RP_O)^2}{\left(2q(RP_O + i_{Amb}) + i_{Amp}^2\right)} \tag{6}$$

This expression allows the bit-rate available R_b to be related to the range for a given required E_b/N_0. Then the modulation and detection scheme employed will determine the value of E_b/N_0 needed for a particular biterrorrate (BER). The value of the ambient light current varies considerably with the FOV and optical filtering conditions prevalent in the system. Therefore, for a 60-degree FOV, we take the pessimistic value of 1000 µA from [65], which assumes coarse optical filtering. The ambient light collected depends on $\sin^2(\theta_h)$ [69], and so we scale i_{Amb} appropriately as θ_h varies. Amplifier current noise is another quantity that varies somewhat depending on the device used in the optical RX. A typical device such as the Texas instruments OPA847 [69] offers a value of 2.7 pA Hz$^{-1/2}$, so we adopt a slightly more conservative value of 3 pA Hz$^{-1/2}$ in our calculations.

4.1.1.2. Millimeter-wave communications

We assume that the system will utilize 60 GHz as its frequency of transmission given the established products for this choice. Determination of the path loss for a 60 GHz mm-wave system is not straightforward, so for the outdoor scenario we use the International Telecommunication Union (ITU) LOS model [70]:

$$PL_{dB}(d) = 92.44 + 20\log_{10}(f) + 10n\log_{10}(d) \tag{7}$$

where d is the transmission distance in kilometers, f is the frequency in GHz and n is the path loss exponent, which is approximately two for this scenario. This is used in combination with the standard Friis model to produce a value of the received power as follows. In contrast with lower frequencies, the antennas will not be isotropic, and have numerical gains of G_T and G_R for TX and RX, respectively, so the overall received power in watts so for a transmitted signal power P_T will be:

$$P_R(d) = P_T G_T G_R 10^{-PL_{dB}(d)/10} \tag{8}$$

The antenna gains above are assumed to be equal, which provides asymmetric transmission system. Their values are determined based on the acceptance angle defined for optical transmission to give a fair comparison. For an ideal antenna, the gain is equal to the directivity, and so we can say that [71]:

$$G_T = G_R = \frac{4\pi}{\Omega_A} \tag{9}$$

where Ω_A is the beam area, taken to be the solid angle formed by the angle θ_h. As a result, we can write:

$$G_T = G_R = \frac{4\pi}{2\pi(1 - \cos\theta_h)} = \frac{2}{(1 - \cos\theta_h)} \tag{10}$$

We assume that the RX antenna feeds a matched preamplifier with noise factor F so that the signal to noise ratio S/N at the RX is:

$$\frac{S}{N} = \frac{P_R(d)}{FKTB} \tag{11}$$

where K is Boltzmann's constant and T is the temperature in Kelvin. For a bit-rate R_b average energy per bit E_b and noise power density N_0, we can then write:

$$\frac{E_b R_b}{N_0} = \frac{P_R(d)}{FKT} \tag{12}$$

4.1.1.3. Results

We assume the same transmission power for the links of 1 W and a light collection area of 15 cm diameter using an optical concentrator. This would have a value of θ_h equal to approximately 20 degrees. The noise factor is taken to be 5 dB as per the IEEE802.11ad standard

giving $F = 3.2$. The results of the calculation are shown in **Figure 8** where it may be observed that FSO performs well for short distances, but millimeter waves offer better performance once the transmission distance exceeds 20–30 m. It may also be observed that for very short distances there is no appreciable free space loss (FSO) given the large collection area but no gain mechanism resulting in the flat portion of the characteristic until the loss begins to increase. We must also state that both systems could be impacted by adverse transmission conditions, rain for millimeter-wave and fog for FSO. Given the variability of these factors, the figure is intended to present a best-case comparison of the two systems.

4.1.2. Hotspot

The application scenario is a "hotspot" in a 3-meter high room as shown in **Figure 9**. As is apparent from the figure, the TX launches power within an emission cone with a half angle θ_h, and the RX has an acceptance angle that is also θ_h. This pairing of angles is optimum since a larger RX acceptance angle would mean that since terminals are transceivers, the uplink would transmit radiation that would miss the ceiling base station and vice versa. The geometry of this scenario means that for a hotspot radius d and range r:

$$\theta_h = \tan^{-1}(d/3); \quad r = \sqrt{d^2 + 9} \tag{13}$$

4.1.2.1. Optical wireless

The TX power is taken to be 10 W obtained from an LED lighting source, and a smaller RX diameter of 15 mm is used to represent the size possible on portable computing devices.
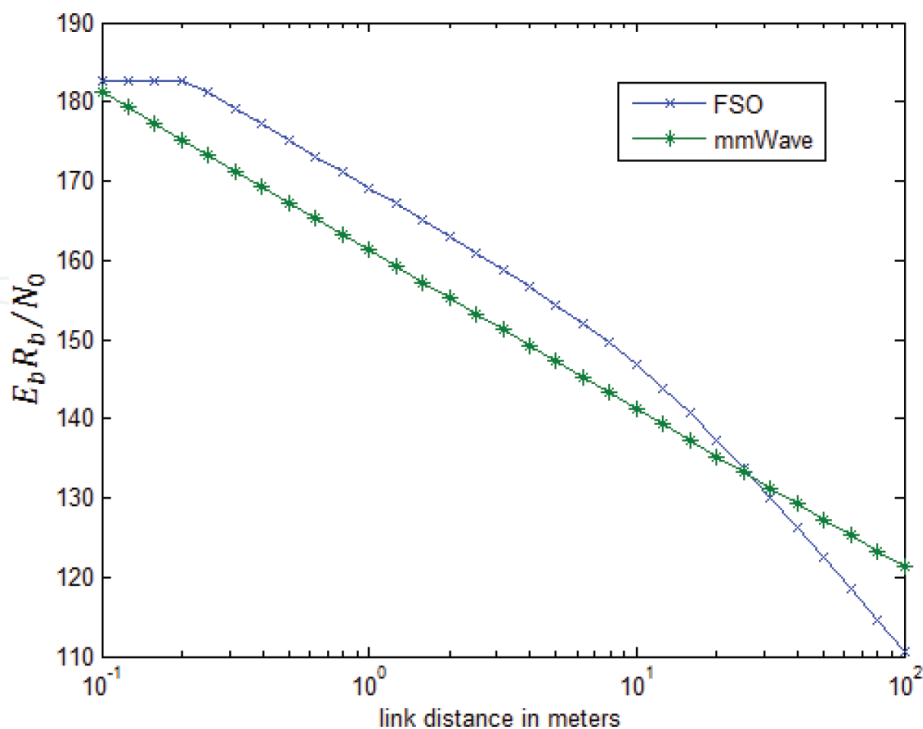

Figure 8. Comparison of FSO and millimeter-wave performance over a point-to-point link.

4.1.2.2. Millimeter-wave communications

In this example, we adopt the empirical model from the IEEE 802.11ad standard for a simple indoor LOS link [72]:

$$PL_{dB}(d) = 32.5 + 20\log_{10}(f) + 10n\log_{10}(d) \tag{14}$$

where d is the transmission distance in meters, f is the frequency in GHz and n is the path loss exponent, which is approximately two for this scenario. The antenna gains will again be given
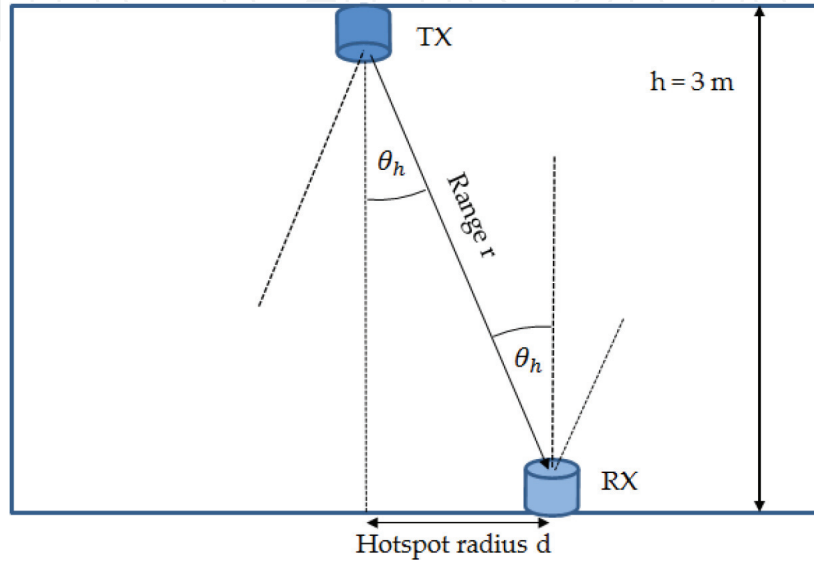

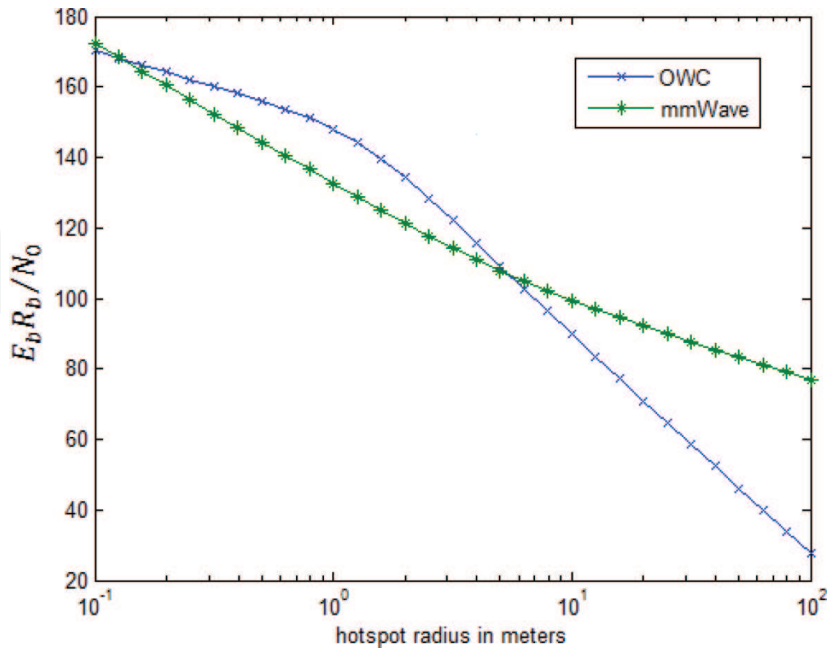**Figure 9.** Geometry of the worst case hotspot alignment.

Figure 10. Comparison of OWC and 60 GHz performance for indoor hotspots.

by Eq. (10), but the angle will be that used for OWC obtained from Eq. (12). Here, the TX power is taken to be 10 mW since this represents a value that is permitted by many international standards [73] when one takes into consideration the antenna gains.

4.1.2.3. Results

In this indoor application, there will be no atmospheric losses, so the predictions will most likely be closer to the performance that could be seen using real links. The results obtained are shown in **Figure 10** and differ somewhat from the point-to-point case. Here, the change in FOV for both systems with hotspot radius assists their performance somewhat, particularly for the OWC link. It can be seen from the figure that there is a radius of up to a few meters where OWC is extremely competitive and could outperform millimeter-wave transmission. Furthermore, the infrastructure for the lighting will already be present so fewer extra components will be needed since the link uses the existing lights rather than a separate link.

5. Conclusions

This chapter has provided a brief introduction to potential 5G transmission systems based on optical and millimeter waves. It may be seen that both technologies have long histories and have been employed in military scenarios. Moreover, technological advances such as LiFi and increasing CMOS integration have brought both options to the fore in recent years. With respect to the future 5G integration, LOS transmission appears to be likely application given the significantly reduced performance of both methods once NLOS links are considered. Millimeter-wave transmission is probably more likely outdoors in most scenarios since its performance is increasingly superior to FSO once distances exceed a few tens of meters. It is the indoor sphere where OWC offers its best prospects for 5G because the LED lighting is becoming widespread. Thus, a relatively high-power visible light source is available for transmission as part of an office infrastructure. Transmission power at 60 GHz is restricted by international standard, especially when high antenna gains are employed as would be the case in small hotspots. Thus, OWC provides superior transmission performance over hotspots with diameters of a few meters, which is a realistic size. We have taken a simplified view of the application scenarios to compare them, and we acknowledge that significant developments are occurring, such as multiple input multiple output (MIMO) systems [74, 75]. Thus, the next stage of the future investigation is to incorporate these into the comparative modeling work. This can be coupled with experimental trials to determine the utility of OWC and millimeter waves in future 5G implementations.

Acknowledgements

Conflict of interest

The authors declare that they have no conflicts of interest.

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