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Characterization of optical mm-wave signals for 5G communication systems: A study of their potential and challenges

Rawa M Mahmood and Omer N MahmmoudDOI: <https://www.doi.org/10.22271/27084558.2025.v6.i2b.64>**Abstract**

This study aims to explore the characteristics of optical millimeter-wave (mm-wave) signals in 5G communication systems, focusing on the advantages and limitations arising from the use of these high frequencies. The mm-wave frequency range, from 30 GHz to 300 GHz, offers high bandwidth that can be utilized for high-speed video and data transmission services for both fixed and mobile users. While this technology offers numerous benefits, such as enhanced speed, security, and power efficiency, there are challenges related to interference, power loss due to atmospheric absorption, and limited coverage range. Additionally, the paper discusses the use of optical mm-waves in Radio over Fiber (RoF) systems as a potential future solution that combines optical infrastructure with wireless technologies to achieve high performance. The goal of this study is to evaluate the technical performance of optical mm-wave signals in 5G networks, focusing on the design of system components such as lasers, modulators, amplifiers, and filters.

Keywords: Optical mm-wave signals, 5G communication, radio over fiber (RoF)**1. Introduction**

The frequency range of mm-waves from 30 GHz to 300 GHz is of increasing interest to operators and network designers due to the availability of huge bandwidth in this high-frequency range ^[1]. The wide spectrum segments available in the mm-wave band make it very attractive for providing high-speed video and data transmission services to fixed and mobile users ^[2]. One of the main reasons for the popularity of mm-wave technology is the previously unused, high bandwidth available in these high frequencies, which are now licensed for research and other applications. This range of mm-waves offers high potential in terms of capacity and flexibility, making it particularly attractive for modern wireless applications ^[3].

The 60 GHz mm-wave has unique features that make it ideal for short-range communication, with high bandwidth and improved security ^[4, 5]. The 60 GHz band is subject to attenuation due to atmospheric oxygen absorption, with a rate of approximately 15 dB/km ^[6, 7]. Figure 1 illustrates the attenuation of 60 GHz from 1 to 350 GHz for dry air and water vapor with a density of 7.5 g/m ^[2]. Absorption increases at higher frequencies, unlike lower frequencies typically used for wireless communications. While long-range communications are not possible due to this attenuation, the 60 GHz band provides additional spatial isolation that aids in frequency reuse for indoor networks, lowers interference between channels, and enhances security for near-point links. Compared to systems operating in the crowded 2 to 2.5 GHz and 5 to 5.8 GHz bands, those operating in the 60 GHz band experience less interference ^[2].

1.1 The advantage of optical mm-waves

The important question that must be asked here is: Is it necessary to use the mm-wave band for today's daily applications? The answer to that is yes, we are forced to use waves because they contain high frequencies that were not widely used previously. Spectrum shortage is a problem and the only way to reach higher potential is by increasing the amount of spectrum. The amount of spectrum and frequency bands can be increased by using high-frequency

in the mm-wave band that was not previously used and it is time to take advantage of them^[8]. The system may benefit from the 60 GHz band's focus on short-range communication because it will face less interference from nearby users using the same frequency, increasing the

possibility of frequency reuse. Furthermore, significantly faster wireless data speeds will be possible due to the huge bandwidths offered by mm-wave frequency bands. For example, uncompressed wireless HD video streaming may be made possible^[9, 10].

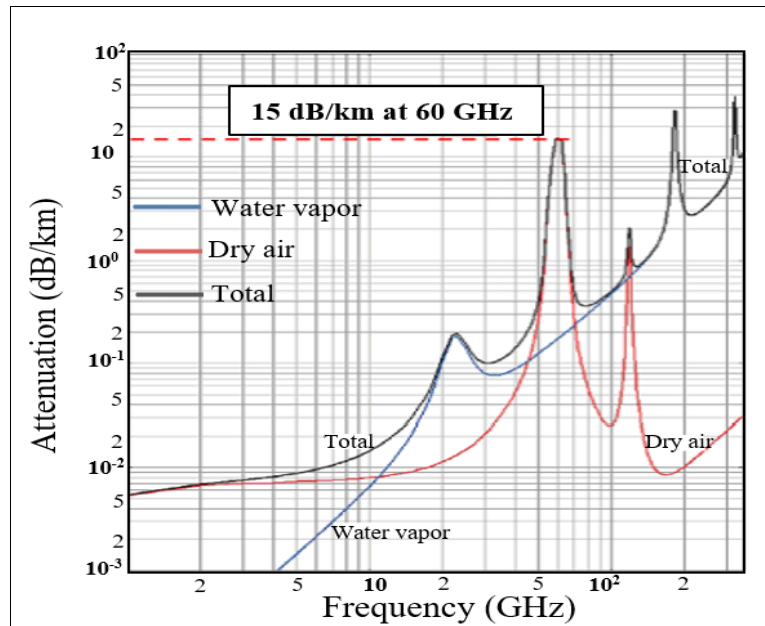


Fig 1: The levels of attenuation of 60 GHz at dry air and water vapor^[2].

In addition to the higher data rates that can be achieved at the mm-waves, the mm-wave band has security and privacy better than others due to the mechanism of using a unique link to each user. Furthermore, this unique link to each user allows for power savings, thus making mm-waves less power-consuming. The antennas' compact form factor is another fascinating feature of mm-wave systems. Multiple antenna elements can be packaged into a compact area and even integrated on a chip because the antenna size is related to the wavelength^[11]. The high-frequency optical mm-waves possess different benefits as well. The mm-wave has a very high frequency and a wider bandwidth, enabling extremely high-capacity data transfer. Its information transfer rate can go up to 1Tbps and several hundred Gbps^[12]. Also, the systems using mm-waves have more miniature radio antennas, which is particularly beneficial for installation, maintenance, and function expansion. The mm-waves are well-focused and have good directivity during space propagation. Additionally, less interference in the high-frequency range where the mm-wave is propagating. Therefore, with a high safety factor, propagation is comparatively stable and trustworthy^[13]. For optical mm-wave, it is allowing the modulation of the optical source by electrical signals, and then the optical signal will be transmitted via optical fiber to the remote station^[14]. In an OMA, the benefits of optical systems and the wireless system can be combined to use the high-frequency range of mm-wave. The OMA is an economic architecture considering that the legacy infrastructure for optical systems can be used to generate and employ the mm-wave technology.

1.2 The disadvantages of optical mm-waves

Despite several advantages of mm-wave technology such as

high bandwidth and compact antenna size, there are several significant disadvantages to consider. One major disadvantage is the limited range of mm-waves, which needs improvement to expand the 5G-based cellular mobile deployment. The mm-wave is vulnerable to atmospheric conditions and other meteorological parameters, which could result in inaccurate distance measurements of nearby objects, thus weakening the threat identification process^[15]. Additionally, the technology is oversensitive and often creates false alarms even in the absence of a real threat. The mm-wave is affected by interference from nearby electric poles, cellular towers, hotspots, and other sources, and has a high penetration loss and poor diffraction^[16]. The wave also goes through different losses such as penetration and rain attenuation, limiting the distance coverage requirement of mm-wave^[17]. The power consumption is higher at mm-wave due to the greater number of RF modules required due to a greater number of antennas^[18]. To avoid this drawback, a hybrid architecture with fewer RF chains than the number of antennas needs to be used at the receiver^[19]. Foliage loss is also significant at such mm-wave frequencies^[20]. Therefore, it is essential to consider these disadvantages during the 5G mm-wave link budget calculation to ensure successful 5G mm-wave deployment.

1.3 The optical mm-wave in the RoF system

The RoF systems have a wide range of applications in various areas, including wireless access systems, mobile backhaul networks, small cell networks, and satellite communications. RoF systems can be used for high-speed data transmission over long distances, providing flexibility in network deployment and reducing the need for laying additional fiber. RoF systems can also improve the reliability and quality of communication, especially in areas with high electromagnetic interference. Additionally, they

have potential applications in military and defense systems, where they can be used for secure and reliable communication.

The fundamental schematic of the RoF system, depicted in Figure 2, includes the central station (CS) where numerous wireless signals are created, multiplexed, and converted from an electrical signal to an optical signal (E/O) before being sent across an optical fiber to the remote antenna units (RAUs). After being converted from an optical signal to an electrical signal (O/E) at the RAU, the signal is then radiated to the wireless user terminal.

In a typical RoF transmission scenario, the LD intensity is modulated by the RF signal. There are two ways to use the intensity modulation technique: externally modulated laser

(EML) and direct modulated laser (DML). In DML, the signal is directly driven and modulated, but in EML, the signal is modulated using a separate optical modulator. The advantages of DML are that it is simple, cheaper, and not complex in the modulation process. However, the disadvantage of this modulation is that it is slower compared to indirect or external modulation types, and it can only be used below 3 GHz. On the other hand, EML is much faster in processing and is compatible with high-power laser equipment. It can be used in high-speed applications such as cable TV head ends or long-distance telecommunications. However, this type also has drawbacks, including higher costs and greater complexity [21].

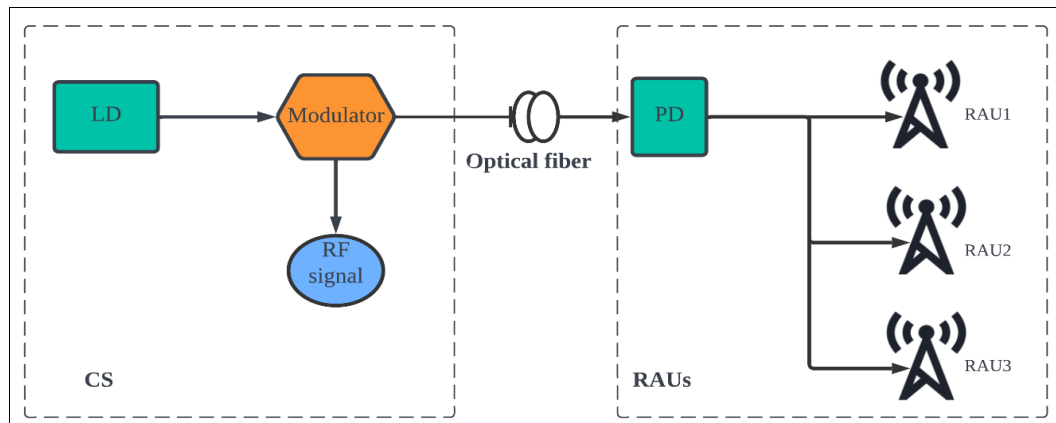


Fig 2: The basic schematic structure of the RoF system

After the signal is transmitted over SMF, a photodiode (PD) immediately converts the optical signal into an electrical signal using intensity modulation-direct detection (IM-DD) technology. According to the ITU's recommendation, RoF systems are easily improved by incorporating optical links, which can transfer high data rates of up to 10 gigabits per second [22-24]. Additionally, RoF systems are a premium product due to their ability to support legacy home services and new services and applications. The optical mm-wave with RoF system is cost-effective and provides transparency in modulation technique and supports various data forms [25]. RoF systems have long been studied as a potential solution for ultra-broadband wireless signal delivery, as using optical fiber infrastructure as a backhaul medium offers more capacity and expand the range of wireless communications. Therefore, studies are focused on RoF and the distribution network based on optical links to enhance the performance of the hybrid system [26]. RoF technology is considered a suitable technology for future systems due to its advantages, including lower attenuation, larger bandwidth, easier installations and maintenance, lower power consumption, and dynamic resource allocation [27].

2. Problem Statement: The main issue addressed in this research lies in the challenges of using optical mm-wave signals in 5G systems, such as atmospheric absorption, interference, and limited coverage range. As demand for high-speed, low-latency communication increases, overcoming these limitations becomes essential for the successful deployment of 5G networks.

3. Research Objective: The objective of this research is to analyze the characteristics of optical mm-wave signals in

the context of 5G communication systems, focusing on their advantages, such as high-speed data transmission and security, as well as their limitations. The study aims to propose solutions and techniques to improve performance and overcome the current challenges, particularly by utilizing Radio over Fiber (RoF) systems to extend coverage and enhance energy efficiency.

4. Characterization of optical mm-wave signal in 5G system

4.1 Laser diode: The CW laser is utilized in mm-wave systems to transmit laser light. Its characterization is influenced by several parameters, such as output power, wavelength, beam quality, coherence, polarization, and stability. These parameters can change based on the type and specific application of the CW laser.

Output power is a critical aspect of the laser's characterization, measured in watts (W) or milliwatts (mW), and represents the energy emitted as laser light per unit of time. The output power affects the intensity and range of the laser light and can be controlled by adjusting the voltage or current supplied to the laser or by using optical components to focus or direct the light. Higher output power can result in more intense light and a longer range, but it also generates more heat and may be harder to control [28, 29]. The output power of a laser can be regulated using various methods, including controlling the current or voltage supplied to it. Figure 3 demonstrates the output power plot against the injection current. It is shown that the laser diode has a threshold current of 9 mA at a wavelength of 1550 nm. A threshold current of 9 mA for a laser diode at a wavelength of 1550 nm indicates that the laser diode will

only begin to emit laser light when the current supplied to it exceeds 9 mA. This threshold current is a characteristic of

the laser diode and is dependent on the material used in its construction and the design of the laser diode cavity.

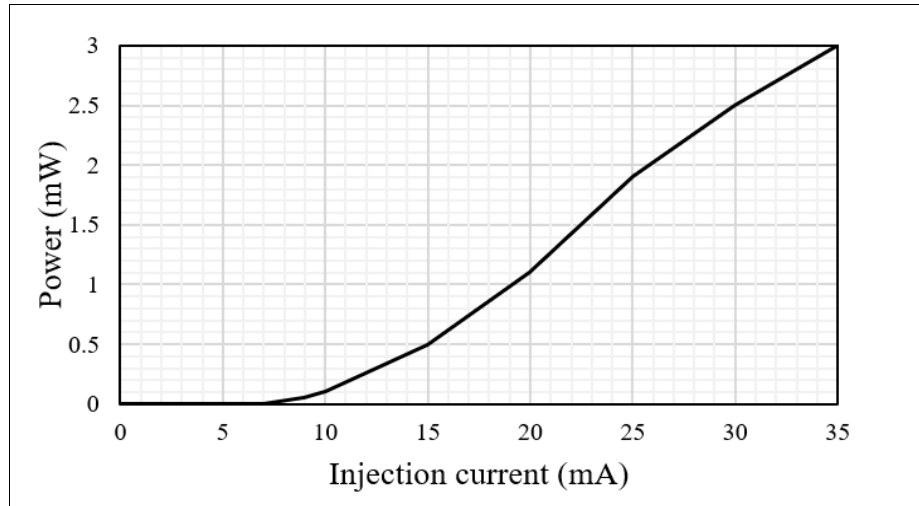


Fig 3: The characteristics of the CW laser diode based on the power and injection current.

Laser diodes typically require a certain minimum current to overcome the lasing threshold and produce laser light. This threshold current is one of the key parameters in the characterization of a laser diode and can be used to evaluate the performance of different laser diodes. A lower threshold current can be desirable as it may indicate a more efficient laser diode that requires less power to operate. In this case, the laser diode has a threshold current of 9 mA at a wavelength of 1550 nm, which may indicate that it is a high-quality laser diode optimized for operation at this wavelength.

4.2 Mach-Zehnder Modulator

The biasing of the MZM has a significant impact on the

optical mm-waves. The voltage used for biasing the MZM is illustrated in Figure 4. In the simulation, the bias voltages, V_1 and V_2 , for the MZM were varied between 0 and 12 volts, and the resulting optical power of the mm-wave was recorded. Figure 5 depicts the optical power of the mm-wave when V_1 is 0 volts, V_2 is 4 volts, and the extinction ratio is 30 dB. A 20 dB difference in power between the carrier and subcarrier is observed. This difference in optical power can vary based on the values of V_1 , V_2 , and the extinction ratio of MZM. The simulation also varied the extinction ratio from 10 dB to 40 dB to examine its effect on the power transfer function of the optical mm-wave, as shown in Figure 6.

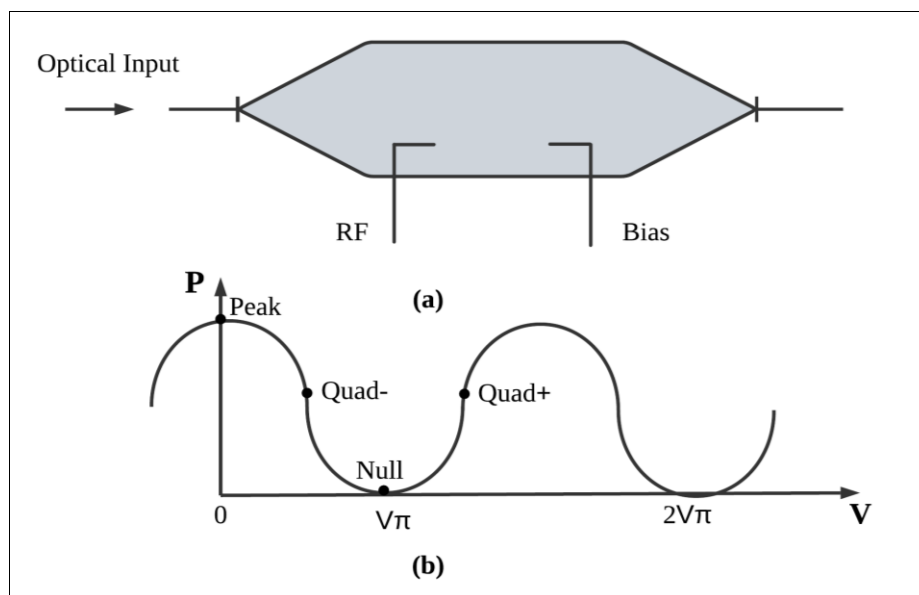


Fig 4: The voltage and the peak power of the MZM

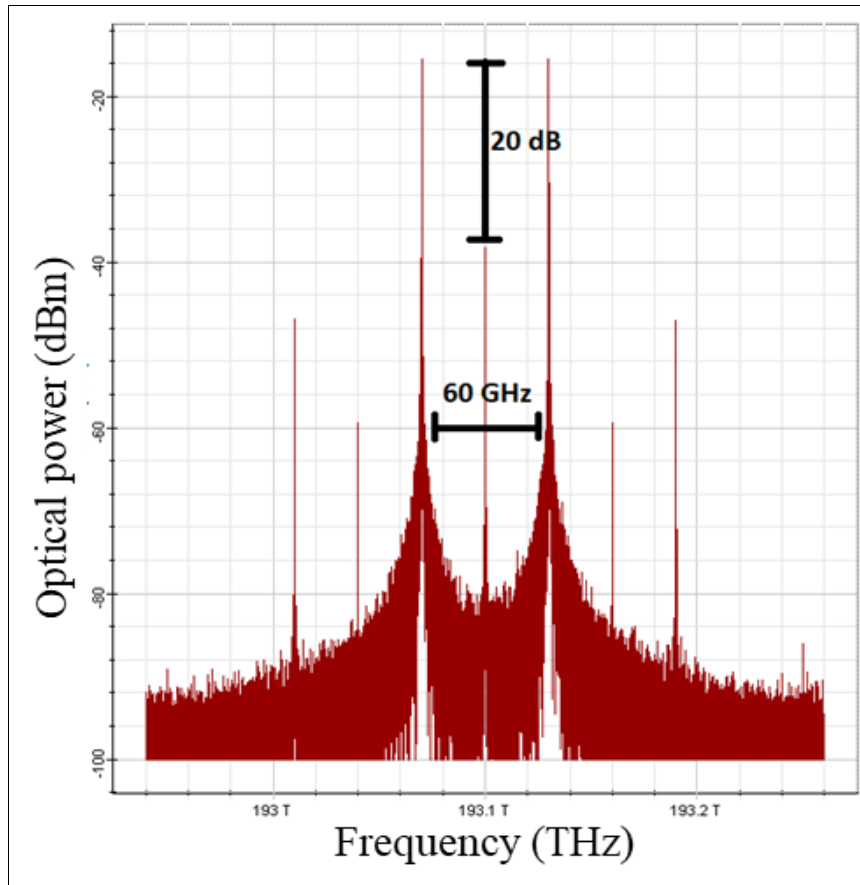


Fig 5: The optical power of the mm-wave signal at ER of 30/dB.

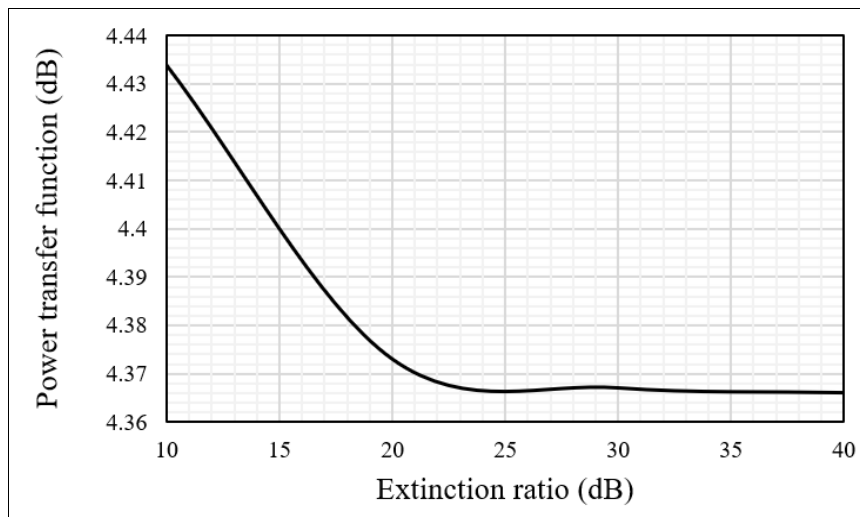


Fig 6: The power transfer vs the function extinction ratio

4.3 EDFA Amplifier: Amplifiers are used in communication systems to amplify signals. In mm-wave systems, the amplifier is used before sending the signal to the optical fiber. The primary function of the amplifier is to increase the input signal by a known factor, referred to as the gain, to convert a small input voltage into a larger output voltage. Amplifiers can compensate for signal weaknesses or attenuation and increase signal strength when needed.

To characterize the optical mm-wave, the gain of the EDFA used in the system was varied from 3 dB to 17 dB, as shown in Figure 7. It was observed that the receiver sensitivity and optical mm-wave power increased as the gain increased. This is because the amplifier boosts the signal power at the receiver end, resulting in increased power. The optimal gain value can be determined by calculating the end-to-end power link budget.

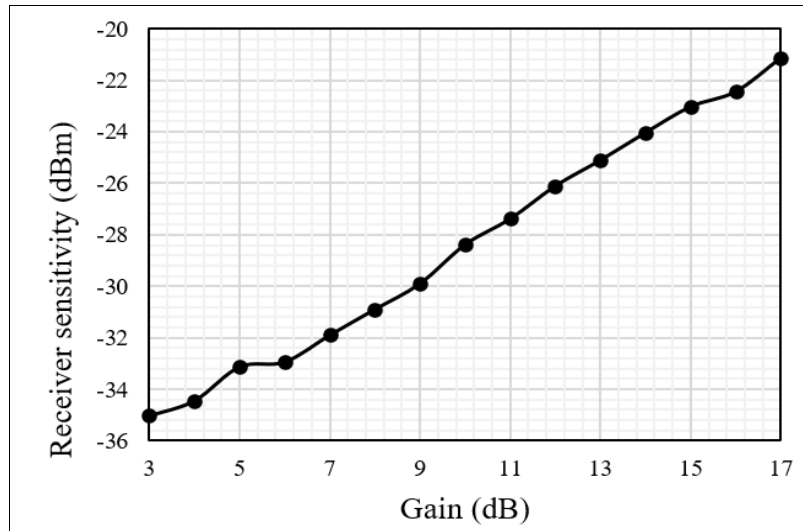


Fig 7: The relation between receiver sensitivity and the gain in the mm-wave system

4.4 DWDM Multiplexer: The DWDM technology has been developed for communication network applications, and ITU-T G.694.1 specifies the DWDM at 100 GHz spacing (0.8 nm). DWDM is widely implemented across utility, cable, mobile, and telecom service provider networks, with applications extending to 5G networks. In the OMA, the photodiode is verified at a different range of wavelengths

that are accumulated in the DWDM multiplexer and then distributed as an OMS to 8 channels. Figure 8 shows eight wavelengths starting at 1550 nm and spaced by 0.8 nm, with each wavelength passed to a specific channel. Thus, each received channel has a unique wavelength due to the use of the BPF to isolate certain wavelengths for each channel in the OMA.

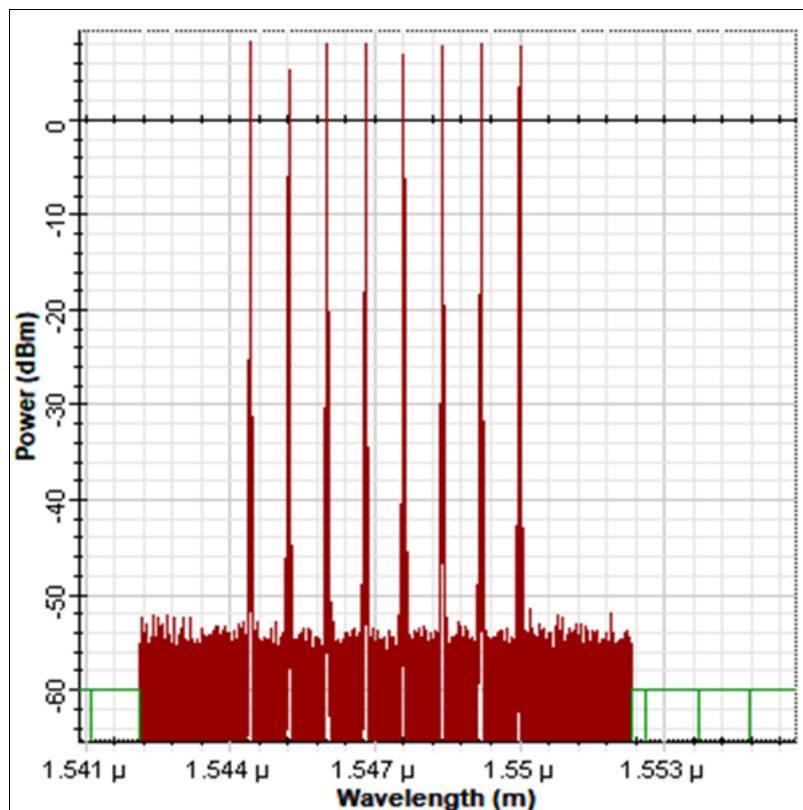


Fig 8: The wavelengths at the DWDM multiplexer

4.6 Photodiode

Photodiodes are used in simulations to recover the mm-wave signal from the optical fiber. A bandpass filter (BPF) is employed to isolate or exclude specific frequencies falling within a given band or range of frequencies that are selected in the OMA. The selected frequencies are then passed

through to the photodetector to detect the OMS. To investigate the photodiode power response in the mm-wave system, the BER of the OMS is collected. From Figure 9, it can be observed that the power of the photodiode, measured in dBm, provides better results of less than -26 dBm at BER values of 10^{-8} and 10^{-9} .

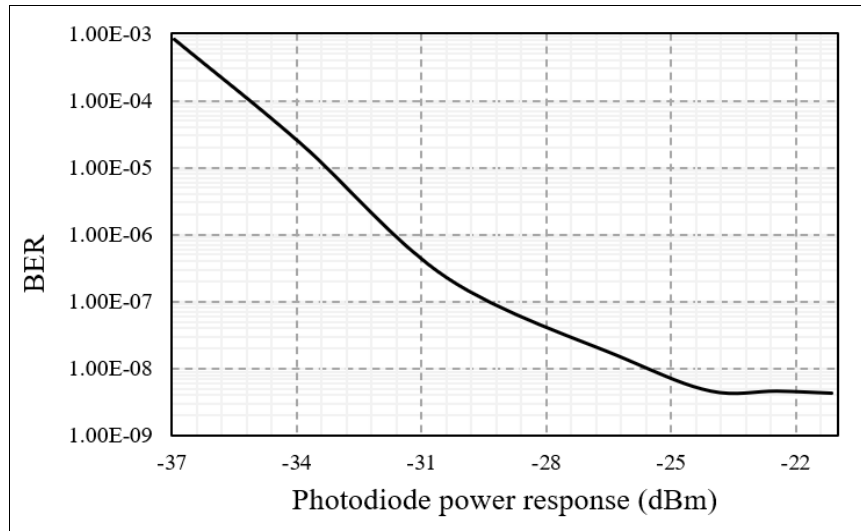


Fig 9: BER of OMS vs photodiode power response.

Additionally, the results of the photodiode power response can provide insights into the overall performance of the OMA. A lower power response from the photodiode can lead to a decrease in the overall SNR of the system, resulting in a higher BER. Thus, the measurement of photodiode power response and its correlation with BER can be critical in optimizing the system performance. The results from the simulation can be used to determine the optimal power levels for the photodiode in the mm-wave system, which can help in improving the overall system performance and reliability.

4.7 Filters

In the simulation, the BPF passes the signals within a certain frequency without generating additional noise or altering the incoming signal. The filter bandwidth refers to a range of frequencies that can have any width. The frequency range between two designated frequency cut-off points (f_c) that are 3 dB below the maximum center frequency is known as the bandwidth. While the LPF is reducing or weakening everything else in addition to these two points. The same technique is used to determine the BPF's upper and lower cut-off frequency points as well as its LPF and HPF:

$$f_c = \frac{1}{2\pi RC} \text{ Hz}$$

Where the RC component is a resistor in series with a non-polarized capacitor. The Centre Frequency (f_r) which is the point of the BPF where the output gain peaks or reaches its highest value, it can be given by this formula:

$$f_r = \sqrt{f_L \times f_H}$$

Where f_L is the lower -3dB cut-off frequency point, f_H is the upper -3db cut-off frequency point.

6. Conclusion

This research investigated the characteristics of optical millimeter-wave (mm-wave) signals in 5G communication systems, emphasizing both their potential and challenges. The results show that utilizing high-frequency mm-waves

offers high bandwidth and ultra-fast data rates, making them ideal for wireless applications such as HD video streaming. However, challenges such as power loss due to atmospheric conditions, interference, and limited coverage remain significant concerns. The study explored potential solutions, including the integration of optical mm-wave systems with Radio over Fiber (RoF) architectures to improve performance and reduce limitations. Future work should focus on developing new technologies to enhance coverage and energy efficiency, which will play a crucial role in the adoption of optical mm-waves in advanced 5G networks.

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