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Employing Visible Light Communication for Evolving Network Performance of Next Cellular Systems

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Abstract

A developed optical air interface for forthcoming short-range transmission in mobile networks, in which visible light communication (VLC) is utilized with orthogonal generalized frequency division multiplexing (OGFDM), is introduced, explored, and evaluated. The presented waveform, termed VLC-OGFDM, is used in a back-to-back optical wireless transceiver system that employs a high-frequency light carrier for optical modulation. The proposed design aims to overcome the channel bandwidth limitations of the waveform by maximizing the transmission bit rate in short-range optical wireless communication scenarios (indoor/outdoor) for future smart cities. Hence, although both the proposed VLC-OGFDM and the conventional OGFDM operate in the wireless domain, the VLC-OGFDM channel bit rate is significantly higher than that of OGFDM because it operates at a higher frequency (VLC) than radio frequency (RF). Besides, using optical rather than electrical modulation in wireless communications provides a high level of protection by avoiding interference with surrounding electrical signals. As such, the VLC-OGFDM waveform is a sophisticated version of the old-style RF-OGFDM, which enables the transmission of large amounts of data over short and safe distances. For electric-to-optic transformation and vice versa, the VLC-OGFDM requires auxiliary optical equipment such as a light-emitting diode (LED), an intensity modulator (IM), and a photodetector. The performance of the VLC-OGFDM system, including essential signal power, error level, and maximum transmission bit rate, is investigated relative to the electrical OGFDM. Ultimately, a MATLAB simulation based on the proposed system's parameters is used for performance validation.

Keywords: Visible Light Communication, Short-Range Transmission, Optical Wireless Transceiver, Indoor/Outdoor Communication.

1. Introduction

Due to the key advantages of visible light communication (VLC), which mainly include higher throughput rate, interference immunity, and energy efficiency relative to wireless radio frequency (RF), the VLC has gained extensive attention, particularly in modern short-coverage domains [1]. In addition, other features like unlicensed spectrum, illumination, etc., make the VLC an imperative need for economic communication networks [2]. Accordingly, because of the simultaneous multiple functionalities of the VLC with light-emitting diode (LED), the THz communication of optical wireless is considered a promising approach for the upcoming limited-domain applications.

Since most of today's huge data traffic happens in short ranges, where the demand for data services is extremely growing among indoor/outdoor consumers, it is quite important to offer alternative enhanced bands of spectrum[3]. As such, introducing the VLC for the next cellular networks like 6G and beyond draws notable interest around the world [4]. Therefore, network researchers have concentrated their efforts on utilizing the VLC technology to tremendously raise the channel transmission rates in advanced confined-coverage communications [5].

The VLC technology that operates in the visible spectrum with an enormous carrier frequency between 380 and 750 THz can support, with very high-speed communication, varied proximity-based services related to the Internet of Things, machine-type communication, etc. [6]. Thus, the rapid demand for massive data rates by the mobile applications market comes up with a higher priority for expanding transmission bit rate, apart from distances [7]. Hence, optical wireless communication systems are employed to effectively control the burst expansion of data traffic, particularly in restricted-coverage cases [8].

Since obtaining a developed optical wireless waveform mainly depends on an advanced electrical wireless one, big efforts have been devoted to enhancing the electrical signal processing of the employed waveforms [9]. This, in turn, led to investigating the already applied waveforms and the emergence of the developed shapes for the wireless systems [10]. Thus, opening the door for releasing improved filtered styles of the orthogonal frequency division multiplexing (OFDM), which suffered from several drawbacks [11]. For example, the filtered OFDM [12], the filter bank multi-carrier, etc. [13]. However, extremely enlarged needs of mobile internet pushed towards another advanced form of waveforms [14], like generalized frequency division multiplexing (GFDM), which has been strongly nominated for the fifth-generation (5G) mobile networks [15].

On the other hand, losing perpendicularity against flexibility cannot be considered an efficient solution for the sophisticated requests [16], which leads to presenting the advanced orthogonal generalized frequency division multiplexing (OGFDM) for upcoming generations of mobile [17]. Among all the offered waveforms, the developed waveform has played a major role in generating robust processing for next mobile transmission [18]. Worth mentioning that the wired optical style of the waveform with fiber optics has been launched recently for long-range communications [19].

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Since this paper focuses on vastly raising the wireless transmission rate of the modern short-range channels, it's very necessary to continue expanding the waveform in the wireless optical domain. Thus, as the VLC represents a significant mode of the forthcoming mobile networks, the anticipated scheme of the waveform manages to attain a smooth functioning in both optical and wireless scopes. In this frame, a new waveform named VLC-OGFDM is proposed herein. The introduced waveform is generated by promoting the OGFDM from the narrow licensed spectrum of the RF to the extensive VLC unlicensed spectrum, supported by necessary electrical-to-optical converters and vice versa. By this, digital signals with huge amounts of data are transferred efficiently from the electrical domain to the optical one via the VLC channel.

The proposed waveform tends to strengthen short-distance transmission by supplying massive, secure, and speedy optical-wireless communication between the sender and receiver. However, the presented optical wireless waveform includes higher computational complexity than the electrical wireless style, since extra optical/wireless requirements like VLC sources, converters, etc. are employed. Nevertheless, technological evolution to speed up the optical wireless components has vastly mitigated the side effects for the applied systems [20]. The paper's rest is categorized as follows: The theoretical part of the proposed VLC-OGFDM, which states the essential principles of the system, is explained in Section 2. The experimental part that investigates the performance of the VLC-OGFDM for the maximum bit rate at an acceptable error rate and minimum required power is demonstrated in Section 3. Finally, the paper is summarized in Section 4.

2. System Model

In the physical layer (PHY), a developed waveform called VLC-OGFDM, which is able to work in an optical wireless channel, is proposed here. The offered technique represents a sophisticated stage of the conventional electrical wireless waveform (OGFDM) presented recently [21]. Using the intensity modulator (IM) and photodetector, VLC-OGFDM is presented in an optical wireless back-to-back transceiver scheme. Compared to the wireless RF mode of the conventional waveform, VLC is utilized for transmitting a signal with a powerful channel rate performance for short-range coverage both indoors and outdoors. Therefore, the VLC-OGFDM waveform represents a progressive level of the OGFDM with an outstanding ability to transfer massive amounts of data relatively.

By introducing the VLC waveform to future mobile networks of smart cities, the transmission level is elevated from low-bit wireless to high-bit optical wireless transmission. Hence, the introduced VLC system utilizes optical attocell and vehicle-to-vehicle (V2V) or infrastructure (V2I) communications to improve the response time (latency) for indoor and outdoor conditions, respectively. Nevertheless, from a physical point of view, the signal transmitted by the specified RF band reaches longer distances than the VLC spectrum.

As apparent in Fig.1, the typical processing of the VLC-OGFDM transceiver against the wireless one is described. Hence, the wireless variation between the electrical and optical shapes of the waveform is clarified herein. In the transmitter of the VLC-OGFDM system, the optical wireless procedure is initiated when a core base station (big cell) of mobile networks starts converting the input electrical signal to the optical domain before transmission. Then, to connect the core network to the next LED transmitter, an Ethernet cable is used for short distances, while a fiber cable is utilized for long distances. Afterward, the optical signal is transmitted through a wire to an optical access point (attocell / V2I). Later, the genuine VLC mode begins by transmitting the optical signal wirelessly to the nearby optical receivers, establishing an optical wireless path.

The involved optical transceivers function as relays to forward or backward the obtained signal based on the constructed control plan. As such, each optical access point can work as a transmitter (forward mode) or receiver (backward mode) to smoothly pass optical signals between the main source and destination. In the receiving process, reverse manipulation is applied, where the optical signal is handled as input, while the converted electrical signal is delivered to the last end as an output.

For real transmission, to avoid the obstacles that possibly prevent the optical signal from passing through, the position of both transmitter and receiver must be considered accurately, making sure that the path between them is clear. Hence, compared to the electrical wireless waveform, which is fundamentally employed for long-haul and low bit rate, the improved VLC-OGFDM with massive channel rates is strongly recommended for the line-of-sight transmission, particularly for short-haul distances. The main comparisons between the introduced VLC-OGFDM and the traditional one with RF are summarized in Table 1.

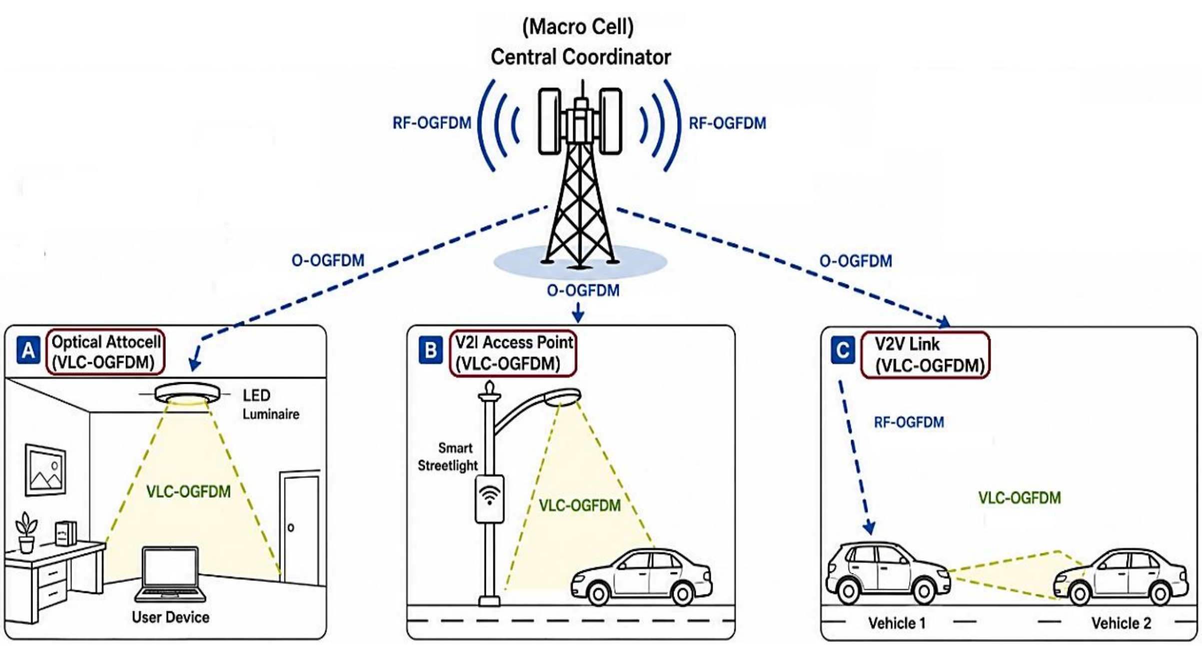

Fig. 1: Typical operation for the developed VLC-OGFDM vs RF-OGFDM.

Table 1: Comparison of VLC-OGFDM and RF-OGFDM.

	VLC-OGFDM (Proposed)	**RF-OGFDM (Conventional)**
Coverage Distance	Short	Long
Medium	VLC	RF
Complexity	High	Low
Interference Level	Immune	Vulnerable

As shown in Fig. 2, the VLC-OGFDM transceiver system, which includes both the transmitter and receiver, is composed of two levels of processing (electrical and optical). At the transmission side, the process starts with the electrical part, where the digital signal of the OGFDM is modulated before being transferred to the digital-to-analog converter. Then, the process is moved to the optical part, where the VLC is applied. To convey the information in the optical wireless domain, the transmitted data is carried by the visible light, where the intensity of light is used for modulation [22]. Thus, utilizing both IM and LED, the electrical signal is converted to the optical domain, where the obtained optical signal is transmitted wirelessly via the available VLC spectrum.

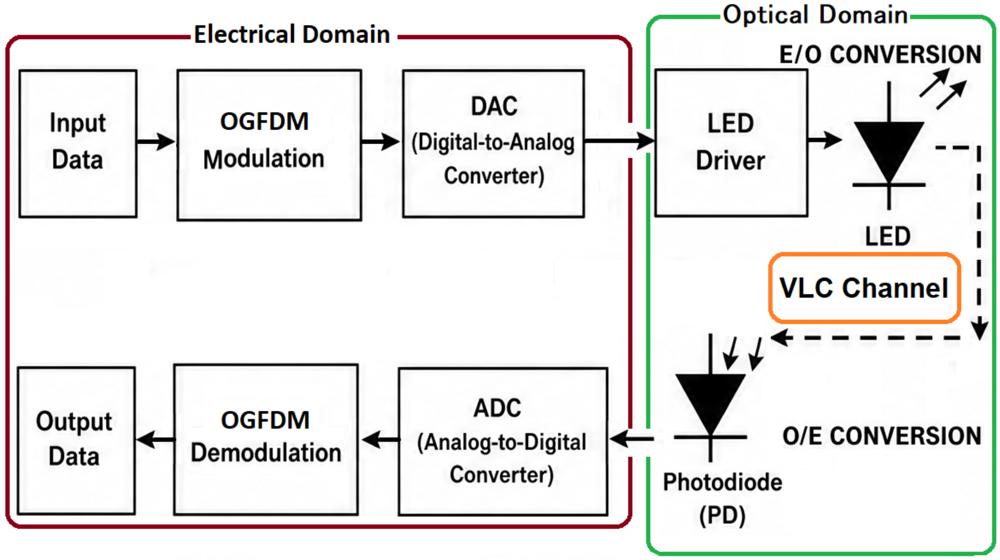

Fig. 2: Transceiver system model of the proposed VLC-OGFDM.

Regarding transmission power, the data signal values (t) are strengthened with the magnitude of the power allocated for injection (p) to send a set of waveform samples (K) in the time domain as follows [23]:

$$t = \sum_{i=1}^{k} \sqrt{p_i} \cdot t_i \qquad (1)$$

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For the proposed optical wireless transmission media, the yellow light wave used for illumination is recommended for visible communications with a 512 THz frequency and 570 nm wavelength. At the reception side, reverse action is taken where the optical signal is converted to the electrical domain using a direct detector. Afterward, the analog signal is converted to digital form, where the demodulation operation is applied to reconstruct the original information. Therefore, at the wireless receiver, the short-haul optical waveform is wirelessly received and moved forward to the photosensitive processing level. The captured signal (r) can be represented as follows [23]:

$$r = \sum_{i=1}^{k} h_i \otimes t_i + a \qquad (2)$$

where h indicates the channel response convoluted by the obtained signal t and combined with receiver noise (a).

3. Experimental Part

To demonstrate the proposed VLC-OGFDM experimentally, a MATLAB numerical simulation is employed in an optical wireless back-to-back communication system. The designed model explores, through experimental tests, the ability to combine both the VLC technique with the electrical style of the conventional OGFDM. Consequently, the electrical waveform used in the VLC-OGFDM is prepared to work in the time domain rather than the frequency domain of the conventional wireless waveform. Physically speaking, the transmission performance of VLC-OGFDM is evaluated based on the maximum obtained transmission rate, minimum BER level, and signal-to-noise ratio (SNR). Considering that the VLC-OGFDM waveform is introduced for developed cellular networks, the high modulation formats are used.

For system performance validation, the achieved VLC-OGFDM results of bit loading and SNR are compared to the current electrical waveform. Worth noting that it is better, before examining the VLC-OGFDM performance, to check the signal from a spectral point of view. Thus, to ensure that the transmitted signal works in one compatible optical wireless system, the shape of the tested signal is required to be as a Gaussian form at the sender and receiver.

Concerning the suggested medium for VLC real transmission, a yellow light with a wavelength equal to 570 nm and a frequency of 512 THz can be used.

Regarding VLC-OGFDM performance for an optical wireless back-to-back transmission system, the lowest accepted SNR and the highest achieved bit rate of the waveform are examined compared with traditional RF-OGFDM.

In this context, two main case studies are considered to clarify how the VLC waveform can be used efficiently in the optical wireless domain.

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Regarding the first case study, the specified bandwidth is limited and equivalent in both VLC and RF modes of OGFDM. As seen in Fig. 3, the gained bit rate of the proposed VLC system is down to half the obtained throughput rate of the RF waveform. This basically occurs due to converting from the electrical to the optical domain, which in turn causes a loss of half the bandwidth. As such, even though the tested optical and electrical waveforms use the same modulation format, the RF system overcomes the VLC one, as only the real positive side of the spectrum is used in the optical domain.

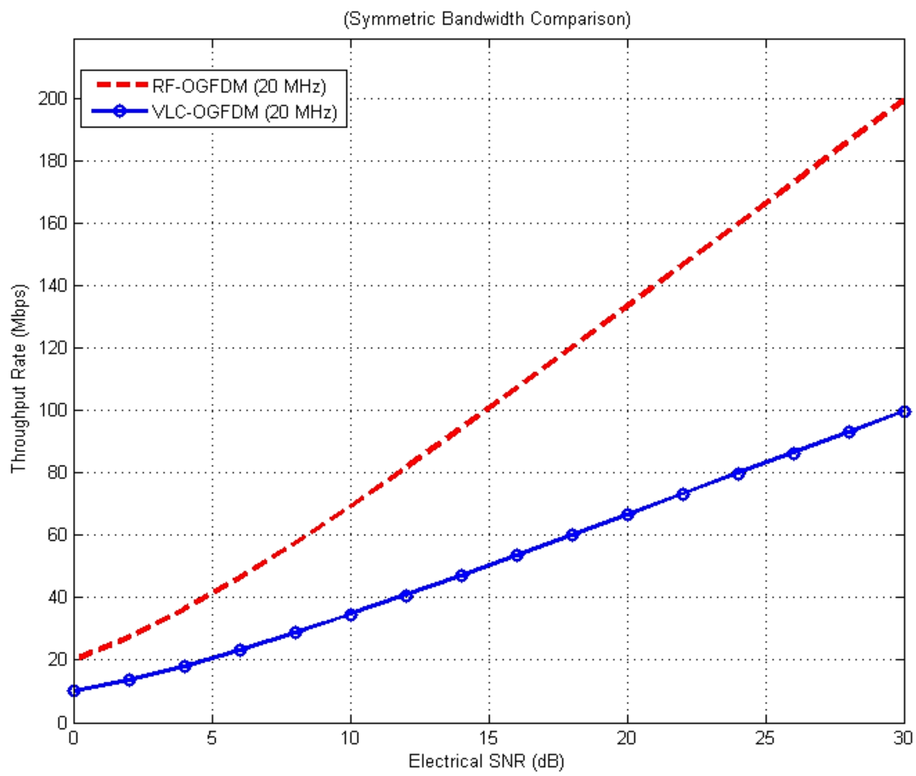

Fig. 3: First case study (limited): Throughput rate of VLC-OGFDM vs RF-OGFDM (identical bandwidth).

In the second case study, the problem is solved by leveraging the large contiguous spaces available in the VLC spectrum, which is very hard to achieve in the conventional RF area. As shown in Fig.4, the transmission bit rate of the VLC-OGFDM far outweighs the traditional RF by 5 times the RF throughput rate. The key reason for this massive bit rate is offering a higher bandwidth for VLC-OGFDM than the RF-OGFDM, where the applied test increases the bandwidth of VLC to 10 times the value assumed for the RF. Thus, by moving from the narrow GHz sampling frequency ranges with RF to wide THz bands of VLC, extreme amounts of data are transferred. Worth noting, only 50 % of the expected throughput rate is realized for the VLC-OGFDM because half the frequencies are wasted for optical conversion. Therefore, instead of achieving full usage of the allocated bandwidth of the VLC spectrum by getting a 10 times bit rate increase, only half the bit rate is captured while leaving the other half for the domain conversion process. Besides, an additional computational complexity appears with the introduced optical wireless waveform compared to the wireless OGFDM.

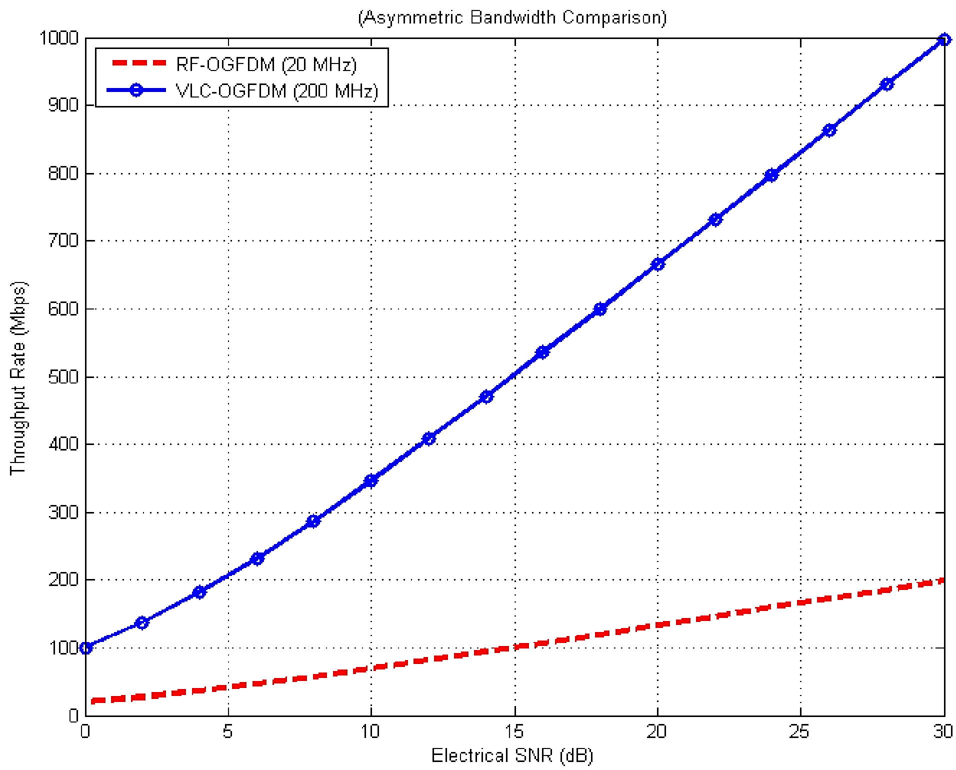

Fig. 4: Second case study (unlimited): Throughput rate of VLC-OGFDM vs RF-OGFDM (non-identical bandwidth).

Moving to the other part of the system performance, as is clear in Fig. 5, the relation between the BER and SNR is considered for the electrical and optical domains. The recorded difference between the minimum spent power (SNR) for VLC-OGFDM and RF-OGFDM waveforms is around 11 dB. The optical wireless waveform tends to consume higher power relative to the wireless electrical waveform, where the variance in power consumption mainly depends on optical configurations. As such, for an acceptable transmission process, the spread optical signal faces a wider error degree than the wireless, which makes it need a higher power than the other to be recognized at the accepted BER line.

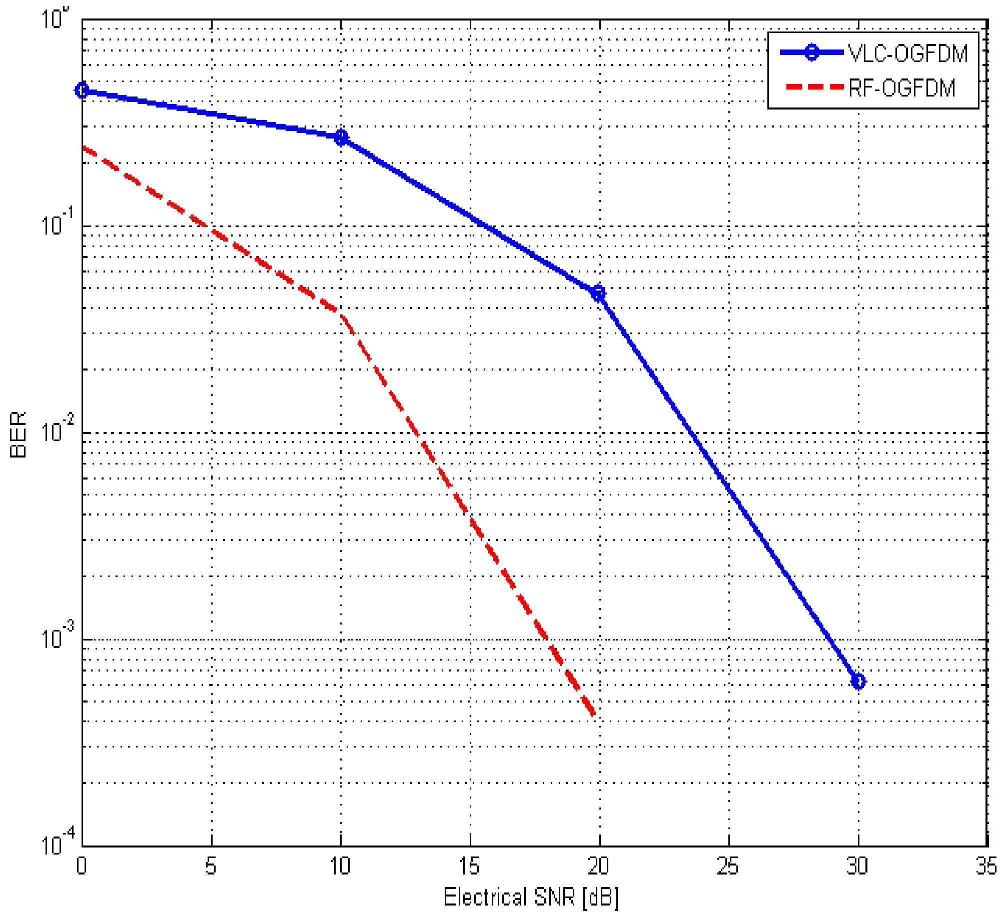

Fig. 5: SNR required by the VLC-OGFDM vs RF-OGFDM.

Ultimately, the main parameters of the demonstrated system performance are stated in Table 2.

Table 2: System Parameters of Experimented VLC-OGFDM.

Parameter	**Values**
Transmission Mode	VLC
Spectrum Size	THz
Bandwidth	20-200 MHz
(E/O - O/E) Converter	IM - Photodetector
SNR	5 - 35 dB
Modulation Schemes	QPSK - 32 QAM

4. Conclusion

In this work, a new optical wireless air interface termed VLC-OGFDM that employs the visible light spectrum for transmission in upcoming smart cities is presented. The key characteristic of the developed waveform is the massive increase in transmission bit rate for short-haul coverage of wireless networks. The VLC-OGFDM performance is examined in terms of the maximum throughput rate and the minimum limit of SNR at an acceptable level of errors. The findings obtained from the presented VLC-OGFDM are compared with those of the conventional RF-OGFDM to clarify the strengths and weaknesses of the proposed system. Regarding the experimental outcomes, the VLC-OGFDM bit rate is roughly 5 times better than that of the OGFDM. This is mainly due to specifying a very wide contiguous bandwidth for the tested signal relative to the narrow bandwidth of RF by moving the sampling frequency from GHz to THz. Nonetheless, the VLC-OGFDM signal requires a larger level of power to be recognized compared to the OGFDM. As such, nearly an 11 dB difference in the essential SNR is recorded between the VLC-OGFDM and RF-OGFDM. The extra level of power consumption occurred due to the addition of supplementary optical configurations, which in turn increased the computational complexity of the VLC waveform.

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