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Posted Date: 21 February 2024

doi: 10.20944/preprints202402.1214.v1

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Article

Exploring UFMC Waveform for Last Meter Connectivity in 6G: A Street Lighting-Driven Approach with Enhanced Simulator for IoT Application Dimensioning

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Abstract: In the dynamic landscape of 6G and smart cities, Visible Light Communication (VLC) assumes critical significance for IoT (Internet of Things) applications spanning diverse sectors. The escalating demand for bandwidth and data underscores the need for innovative solutions, positioning VLC as a complementary technology within the electromagnetic spectrum. This paper focuses on the relevance of VLC in the 6G paradigm, shedding light on its applicability across smart cities and industries. The paper highlights the growing efficiency of lighting LEDs in infrastructure, facilitating the seamless integration of VLC. The study then emphasizes VLC's robustness in outdoor settings, demonstrating effective communication up to 10 meters. This resilience positions VLC as a key player in addressing the very last meter of wireless communication, offering a seamless solution for IoT connectivity. By introducing an a freely available open-source simulator combined to an alternative waveform, UFMC, the study empowers researchers to dimension applications effectively, showcasing VLC's potential to improve wireless communication in the evolving landscape of 6G and smart cities.

Keywords: Visible Light Communication (VLC); 6G; IoT applications; smart cities; wireless communication; last meter connectivity; open-source simulator; application dimensioning; outdoor VLC communication; efficient lighting LEDs

1. Introduction

6G, the anticipated sixth generation of wireless communication technology, represents a paradigm shift in connectivity, aiming to surpass the capabilities of its predecessor, 5G. Envisioned as a transforming force, 6G seeks to provide ultra-fast data rates, incredibly low latency, and unparalleled connectivity, fostering innovations that extend beyond conventional wireless communication boundaries [1]. The technology envisions a seamless integration of diverse communication paradigms, including Terahertz frequencies, new waveforms, edge computing, holographic communications, and advanced artificial intelligence [2]. The overarching goal is to create an ecosystem where connectivity is not just pervasive but also intelligent and adaptive to the diverse needs of users. In the pursuit of 6G, the emphasis on continuous innovation becomes paramount. The optimization of resources, efficient spectrum utilization, and sustainable practices are integral aspects that drive the evolution of 6G. Embracing innovation is crucial not only for achieving unprecedented levels of performance but also for addressing the evolving demands of a connected world, ensuring that technological advancements contribute to a more resource-efficient and sustainable future.

In that context, Terahertz (THz) band emerges as a promising domain with its vast bandwidth and exceptionally high data rates [3], offering robust support for diverse 6G applications, including wireless data centers [4], ultra-short-distance communications, and other novel scenarios. Optical Wireless Communications (OWCs) harness various bands within the optical spectrum, comprising infrared (IR), visible light, and ultraviolet (UV) bands, presenting nearly thousands of Terahertz

 doi:10.20944/preprints202402.1214.v1

of untapped spectral resources. Notably, the visible light band shows several merits, including its eco-friendliness, cost-effectiveness, freedom from spectrum regulation, heightened security, and immunity to electromagnetic interference [5,6]. Particularly in settings where Radio Frequency (RF) communications encounter limitations, OWCs demonstrate substantial application potential, giving rise to a range of optical communication technologies such as Visible Light Communications (VLC), Light Fidelity (Li-Fi), Optical Camera Communications (OCC), Free Space Optical (FSO) Communications, and Light Detection and Ranging (LiDAR), all being more than relevant for 6G.

In the pursuit of 6G technologies, it is imperative to recognize that not all applications demand ultra-high data rates but mainly robustness. In that context, considerations for IoT applications, dedicated industrial use cases, and certain vehicular communications underscore the importance of diverse communication solutions. VLC emerges as a pertinent technology [7]. Unlike bandwidth-intensive applications, VLC offers a balanced and resource-efficient approach for different types of scenarios. Integrating VLC into the portfolio of 6G technologies holds particular relevance for smart cities and industries. Its adaptability, low power consumption, and suitability for specific use cases align seamlessly with the varied communication needs in urban environments and industrial settings. By acknowledging the nuanced requirements of different applications, 6G can position itself as a holistic and inclusive technological ecosystem, where innovations like VLC contribute to the optimization of resources and the realization of a technologically advanced yet tailored connectivity landscape.

The potential applications of Visible Light Communication (VLC) within the 6G technology landscape are diverse and strategically aligned with the demands of contemporary urban and industrial scenarios, as depicted in Figure 1. Each sector, starting with automotive, exemplifies the adaptability of VLC to meet specific communication needs. In the automotive domain, VLC can leverage LED headlights for vehicle-to-vehicle (V2V) communication, facilitating short warnings and creating communication daisy chains in heavy traffic conditions [8]. Similarly, private and office spaces benefit from consumer-oriented Li-Fi products, offering internet connectivity through visible or infrared lights [9]. Smart cities stand to gain from VLC's capacity to relieve RF spectrum usage outdoors, providing alternative communication for local, line-of-sight, and short-distance applications [10]. The smart industry sector, including factory automation and logistics, witnesses the potential of VLC in optimizing wireless connectivity within industrial warehouses [11]. Deploying Free Space Optical (FSO) communication as a backhauling system in cities characterized by towering skyscrapers offers a high-capacity and wireless solution for data transmission across urban landscapes [12,13]. The military sector explores the secure, non wall-penetrating nature of VLC, potentially replacing wired communication means for local applications [14]. Healthcare applications leverage VLC for remote health monitoring, aligning with smart health strategies in smart cities [15]. Finally, underwater communication, a traditionally challenging domain, sees VLC's potential to achieve communications in harsh turbulent conditions [16]. This paper critically analyzes and provides essential tools for integrating VLC communication in short-distance scenarios within urban and industrial settings, contributing to the dynamic landscape of 6G technologies.

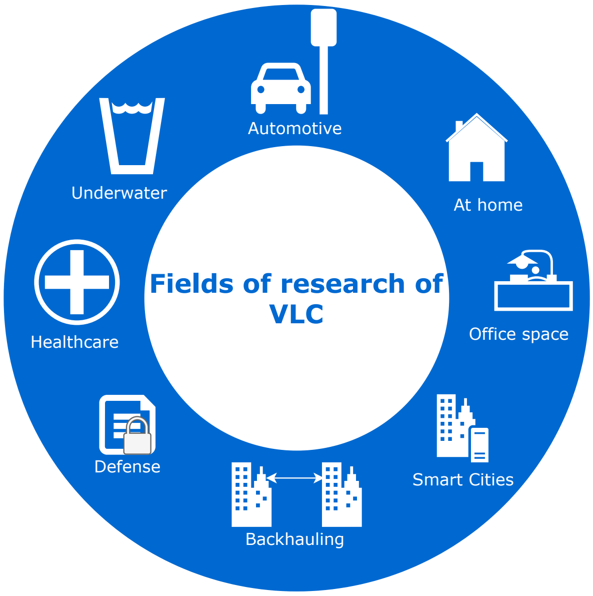

Figure 1. Few examples of related 6G VLC fields of research

In the evolution from 5G to 6G, the incorporation of novel waveforms emerges as a pivotal consideration. While 5G's development was encumbered by material limitations, 6G signifies a phase of unconstrained exploration. A central tenet of 6G's objectives lies in augmenting spectral throughput, particularly for IoT applications. This trajectory may initiate with a transition from the prevailing OFDM (Orthogonal Frequency-Division Multiplexing) standards, thereby paving the path for potential migration towards UFMC (Universal Filtered MultiCarrier) for enhanced efficiency.

This study delves into the strategic utilization of Visible Light Communication (VLC) as a means of short-range communication within urban and industrial environments. By concentrating on scenarios where ultra-high data rates are non-essential, the investigation explores VLC's pragmatic applications in optimizing communication resources. Prior research, such as studies examining VLC's efficacy in industrial automation or urban infrastructure monitoring, furnishes invaluable insights [17,18]. This study advances this domain by proposing a methodology for calculating indoor and outdoor VLC channels, augmenting the existing body of knowledge. Additionally, it offers a comprehensive suite of open-source tools for designing and simulating VLC scenarios, accessible via the Github platform. Leveraging these resources, the study advocates for simulating VLC communications in a tailored smart city scenario using the UFMC waveform, assessing performance metrics such as bit error rate and spectral efficiency. The promising outcomes position UFMC-VLC technology as a prospective component of future 6G systems. Through this endeavor, the study seeks to expedite the integration of VLC within the broader spectrum of 6G technologies, fostering an adaptive framework conducive to smart city and industrial applications.

The study begins by establishing the relevance of VLC as a communication resource for scenarios where ultra-high data rates are not paramount. Emphasizing the significance of diverse communication solutions, the paper positions VLC as a tailored and efficient option for specific applications within smart cities and industries. Subsequently, attention is directed towards the introduction of an open-source simulator designed to provide researchers with fundamental tools for designing and simulating VLC scenarios. The simulator serves as a versatile platform, enabling the modeling and analysis of VLC communication systems in various urban and industrial environments. The paper then presents insightful results derived from simulations using innovative modulation schemes such as UFMC, a general and enhanced version of OFDM, showcasing the practicality and efficacy of integrating VLC in short-distance communications. Finally, a concluding section synthesizes the findings, emphasizing the role of VLC within the 6G landscape, and underscores the importance of

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continued exploration and innovation in optimizing communication resources for diverse applications in urban and industrial domains.

2. Materials and Methods

In the realm of Visible Light Communication (VLC), even in outdoor environments, the optical power propagation from emitter to receiver is profoundly influenced by the specific scenario. Given that VLC operates with light, obstacles pose a significant challenge, acting as disruptors to communication. Additionally, reflections in the environment can have varying effects, either adds up constructively to the signal or introducing noise-like contribution at the receiver [19]. Recognizing these factors, smart city applications capitalizing on VLC could strategically align with scenarios where these requirements are inherently met, where there is mainly Line of Sight (LoS). This is particularly possible and advantageous for applications such as IoT, Urban Li-Fi or OCC, vehicle-to-vehicle (V2V) communication, Vehicle-to-Infrastructure (V2I) communication, communication among drones, and various supplementary scenarios illustrated in Figure 2.

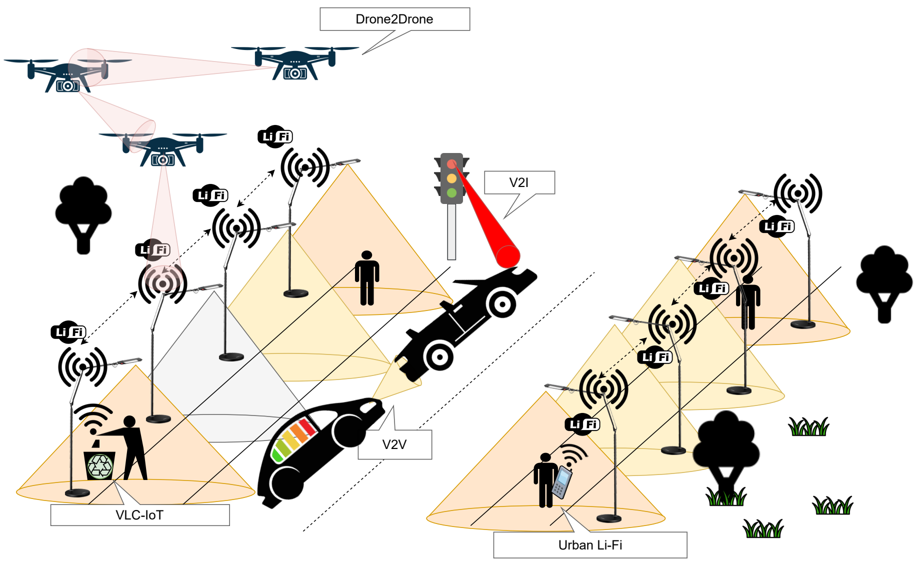

Figure 2. Potential applications of VLC in Smart Cities

Moving beyond the scenario considerations, it is essential to understand that while VLC utilizes LEDs for communication, the diversity of LEDs introduces a range of parameters within the emitter itself. Each LED functions akin to an antenna, possessing a distinct radiation pattern that delineates how the power consumed by the LED is distributed through space in an angular manner [20]. Notably, LEDs employed in different applications exhibit unique radiation patterns. For instance, LEDs designed for indoor lighting, also called Lambertian emitters, disperse light evenly in the room [21], while car headlights, street lights, and industrial lighting each carry their distinctive angular radiation signatures [17,18,22]. Figure 4 shows a plane representation of the radiation pattern of a Lambertian emitter for three different half power angles (on the left side of the figure) and a NIKKON streetlight (on the right side of the figure). A Lambertian emitter has a uniaxial symmetry to the radiation pattern and its half-power angle parameter gives it directionality. Two perpendicular planes of the streetlight 3-D radiation pattern are represented on the right side of the figure. It can be seen that there is no axial symmetry and a preferred direction in the radiation of light power.

This paper underscores the nuanced interplay between the materials employed in Visible Light Communication (VLC) systems, the configuration setup, and the surrounding environment. Recognizing the distinctiveness of each LED and its crucial positioning relative to the receiver in diverse scenarios, this paper introduces a simulator designed to empower end users to define these

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pivotal parameters. In its primary phase, the simulator allows users to intricately characterize the LED properties and spatial arrangement, considering the unique features of each light emitter. Additionally, it facilitates the assessment of communication performance under an innovative modulation scheme, UFMC. Notably, the simulator, also meant for outdoor communication, extends its functionality relatively to the baseline literature, to incorporate environmental factors, allowing users to specify the quantity of particles in the air and consequently identify optical power loss attributable to atmospheric presence. While a more comprehensive exploration of these atmospheric effects can be found in our earlier work [17], this paper concentrates on highlighting the simulator's versatility and the pertinence of VLC within the 6G paradigm. Figure 3 shows how both simulator work together to study a scenario. The MATLAB simulator focuses on generating the point-to-point communication data stream and the Python channel simulator takes into account the path loss computation of the communication. The two combined give us communication performance metrics of a point in space in a scenario.

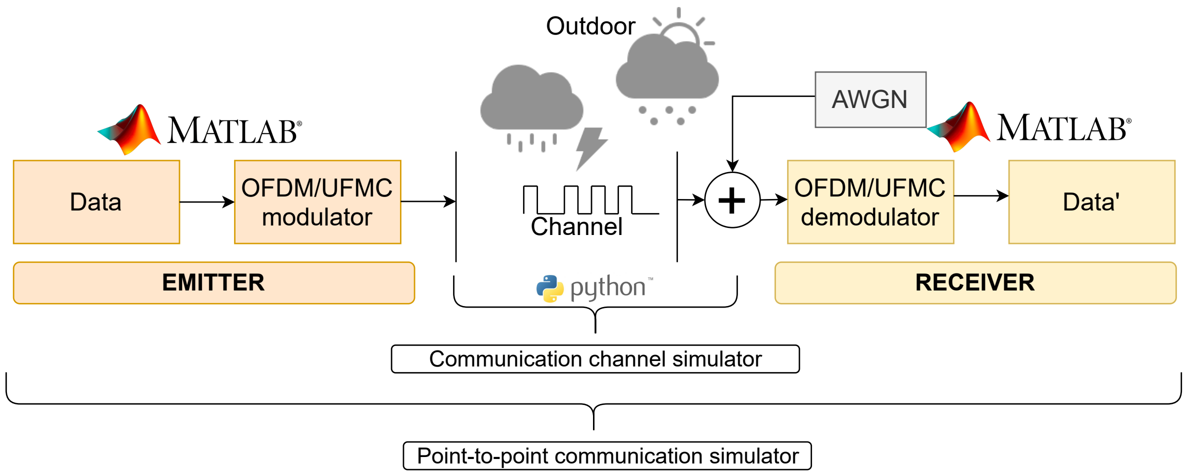

Figure 3. Representation of the contatenation of both simulators

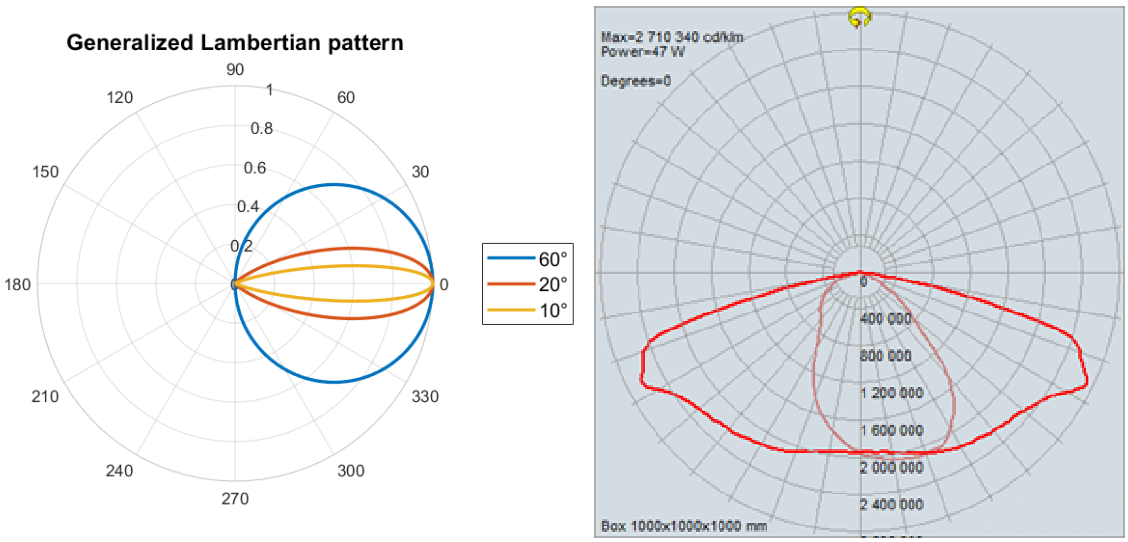

Figure 4. (left) Lambertian LED emitter and (right) real radiation pattern of a streetlight [?]

The subsequent section delineates the simulator's key features and presents primary outcomes obtained while employing the UFMC modulation scheme in regards to OFDM performance.

 doi:10.20944/preprints202402.1214.v1

2.1. The channel simulator

The material employed in this study comprises a communication channel simulator crafted using Python. Initially, the foundation for this simulator drew inspiration from a primary MATLAB version as documented in Reference [23]. Our improved Python simulator not only operates on an open-source platform but also brings novel simulation parameters. These enhancements encompass the introduction of an innovative smoke model, the integration of 3-D graphical representations, increased flexibility for customizing simulation "room" parameters or outdoor configuration, and the consideration of authentic lamp radiation patterns.

The channel simulator presented in this study can be found on Github [24]. It empowers users to incorporate radiation measurements provided by light fixture manufacturers, typically available in formats such as Illuminating Engineering Society (IES) or EULUMDAT [**?**]. These files encompass comprehensive information about the light fixture, its characteristics, and the associated radiation pattern. Users can integrate this data into the simulator for precise simulation in each specific situation, enhancing the accuracy and realism of VLC performance assessments. The simulator has for example been applied in various Smart City or concrete industrial use cases in the past [17,18]. Both paper explain how a scenario can be simulated, and output the corresponding communication coverage of the optical signal.

The present simulator is an enhanced version of our previous work where the communication simulator has been upgraded to include several modulation schemes such as Orthogonal Frequency Division Multiplexing (OFDM) and Universal Frequency Multi Carrier (UFMC), together with the introduction of performance measures.

Figure 5 explains the simulated environment and the basic principle of the simulator. The aim of the simulator is to assess the optical power distribution of a VLC system in a scenario under study. To do so, the software creates first a virtual three-dimensional room where the axes' origin is in the center. Here, the light is in the center of the ceiling and the reception plane is located at the same distance from the origin as the emitter but in the negative applicate of the cartesian coordinate system. Then, several parameters can be set such as the presence of walls or not, their reflection coefficients and the position of the emitter in the virtual room. Afterward, the reception plane where the communication coverage needs to be assessed is set. It should be noted that the tilting of the emitting light or receiver are not taken into account. As mentioned before, only scenarios that can benefit from a major part of LoS are considered here.

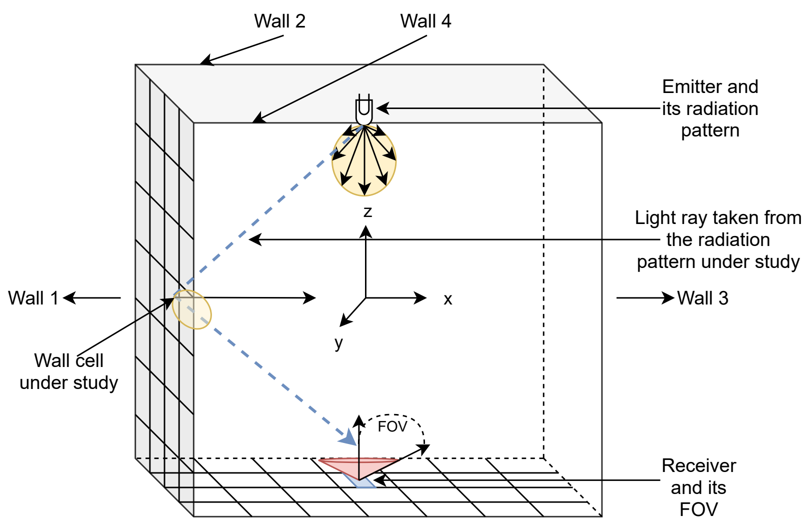

Figure 5. 3-D environment simulated when using the software - wall can be made transparent to take into account outdoor scenarios or the presence of windows

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Figure 6 shows (left) an example of setup under study where the light source is hanging on a wall, enlightening the pedestrian under it and its connected device, and (middle and right) the resulting optical power coverage map.

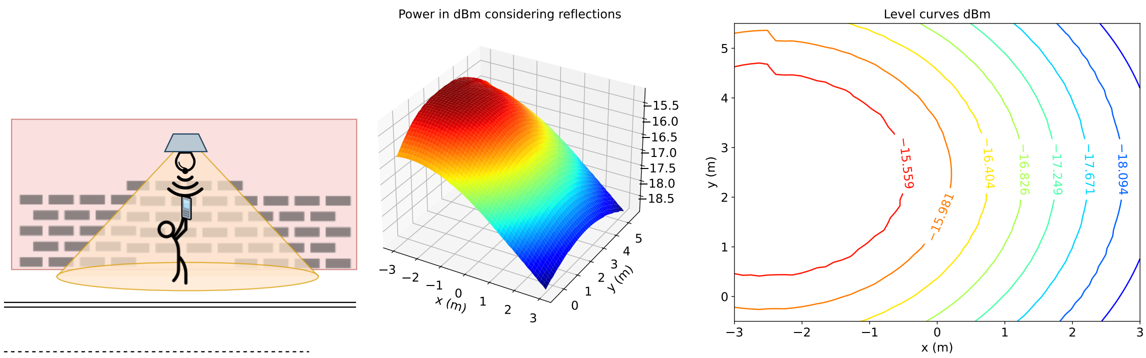

Figure 6. 3-D environment simulated when using the channel simulator for the NIKKON streetlight hanging on a wall

The studied light is the NIKKON street light which radiation pattern is represented in Figure 7. The non-axial symmetry is clearly visible. Thanks to the power map, it's possible to choose a location in space where we'd like to quantify the performance of optical communication.

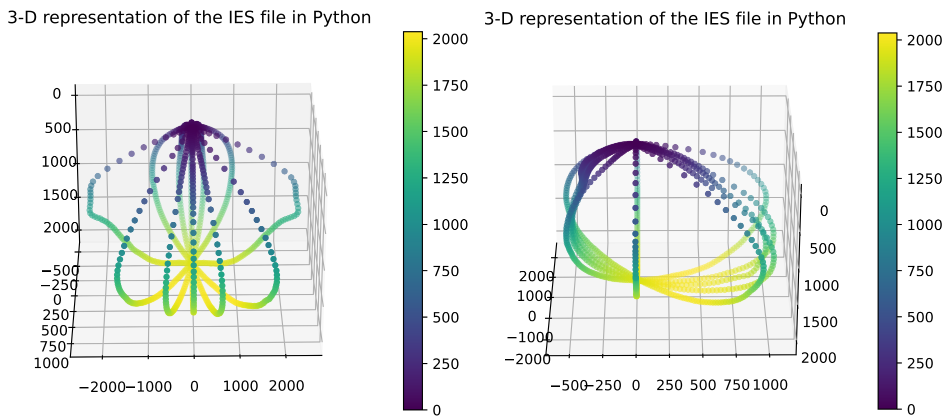

Figure 7. Raw point cloud of the IES file of the real radiation pattern of a streetlight

2.2. The Communication Simulator

A point-to-point communication simulator as illustrated in Figure 3 is used in this study. Both OFDM and UFMC modulation schemes are implemented in this simulator to estimate the system's performance in terms of BER (Bit Error Rate) and spectral efficiency (bit/s/Hz). The paper's use of OFDM simulation is interesting, especially as it's widely standardized. What sets it apart is comparing OFDM with UFMC, a 5G candidate waveform that wasn't selected. Also, the inclusion of a realistic lamp pattern adds originality to the study. Figure 8 shows the functional bloc of UFMC adapted to VLC. This section highlights the key parameters for OFDM and UFMC that were studied. On top of the use of UFMC, the originality of this study is the use of realistic LED optical spatial distributions and real photodiode models in the scenario under study.

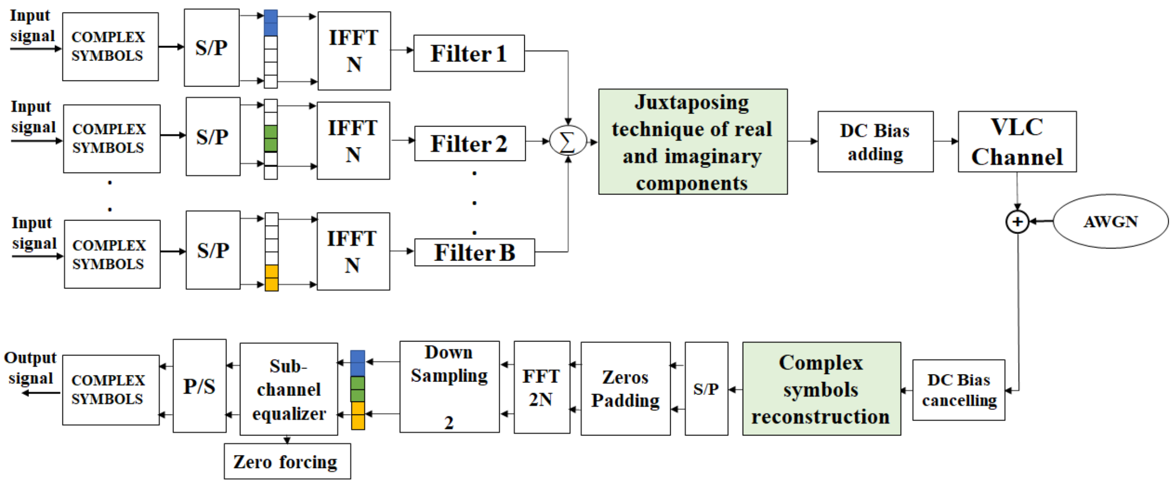

Figure 8. Schematic of a UFMC communication system

The OFDM and UFMC data is generated thanks to a MATLAB program. The constraint of the VLC technology is using a real and positive signal to modulate the LED's current. This implies that the two modulations, developed in the framework of RF transmission, require adequate changes to fulfill these constraints. The juxtaposition method has been chosen to have a real-valued signal and a constant bias is added to have a positive-valued signal (see Figure 9) compared to the classical hermitian symmetry [25].

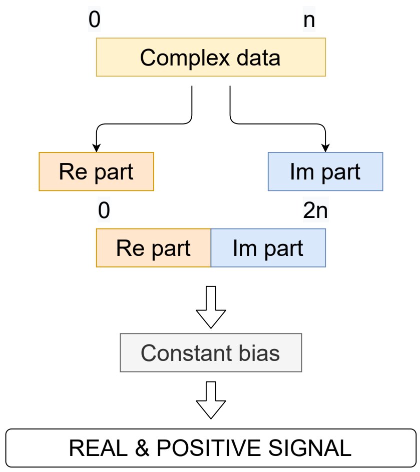

Figure 9. Representation of the juxtaposition mechanism on complex data

The main parameters that are studied to optimise VLC-OFDM and VLC-UFMC parameters are mentioned in Table 1. The parameters that both modulations have in common are the number of bits per subcarrier m, the number of subcarriers N, the total number of symbols generated for the simulations N_{symb}, and the number of bits coded per subcarrier $bitsPerSubCarrier$. Several sizes of QAM modulation have been used to encode bits. They are the 2-QAM (also called Binary Phase Shift Keying (BPSK)), 4-QAM (also called Quadrature Phase Shift Keying (QPSK)) and 16-QAM. For OFDM, the size of the Guard Interval (GI) is often proportional to N. Logically, the important parameters of the UFMC scheme are the number of sub-bands $N_{subband}$, the number of subcarriers per sub-band $SubbandSize$, the Side-lobe attenuation $slobeAtten$, the Type of filter used $FilterType$ and the Filter's length $filterLen$.

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Table 1. Key simulation parameters for OFDM and UFMC

OFDM	UFMC
m	m
N	N
N_{symb}	N_{symb}
$bitsPerSubCarrier$	$bitsPerSubCarrier$
GI	$N_{subband}$
	$SubbandSize$
	$slobeAtten$
	$FilterType$
	$filterLen$

The strategy followed to generate the OFDM waveform was to adopt the OFDM parameters of the ITU G.9991 standard [26]. It proposes a set of 256, 512 or 1024 subcarriers for bandwidths of 50, 100 or 200 MHz respectively. As we target as a first step the lowest bit rates and simplest settings, it was decided to work with 256 subcarriers for both modulation schemes. The GI suggested in the standard for 256 subcarriers (N) is $\frac{N}{32}$.

The parameters for UFMC were subsequently adapted to have a similar comparison base. This involved setting the number of effective subcarriers to N 256, employing 21 sub-bands, each containing 12 subcarriers, and using a Chebyshev filter length (L) of 19, approximately twice the size of the Guard Interval (GI). To calculate the Bit Error Rate (BER), $10,000$ symbols were generated, leading to the following results.

3. Results

3.1. General Observations

The first step was to validate if the Hermitian Symmetry and the juxtaposition methods are comparable in terms of performance. As only OFDM is able to do both techniques, Figure 10 represents the result for OFDM with a simple back to back communication. As expected, both techniques behave the same way and the juxtaposition method can indeed replace the Hermitian Symmetry.

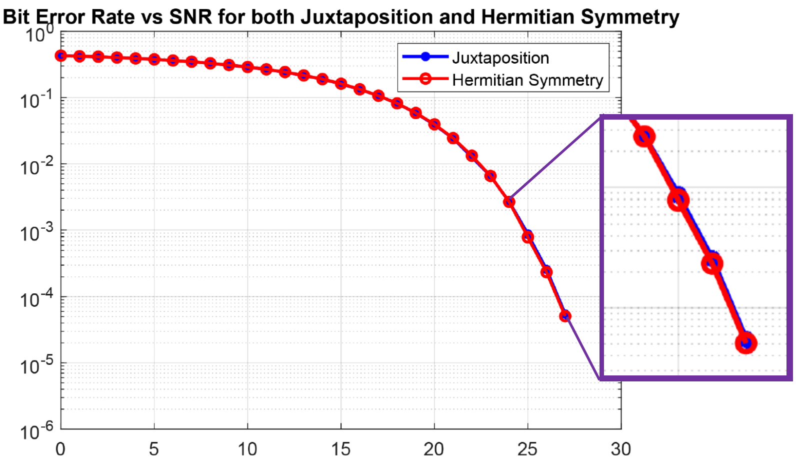

Figure 10. The use of juxtaposition or Hermitian Symmetry for OFDM

Even though the use of a constant bias is a necessity to have a real and positive valued signal on the LED for both OFDM and UFMC, it is however an extra source of power consumed. Figure 11 shows a UFMC communication taking place with a DC (Direct Current) bias of 0.5 and without a DC bias with BPSK modulation per subcarrier. A bias of 0.5 normalized unit is chosen as the UFMC waveform is generated in a normalised way in the simulator. Thus adding 0.5 on all the values will necessarily make the signal positive.

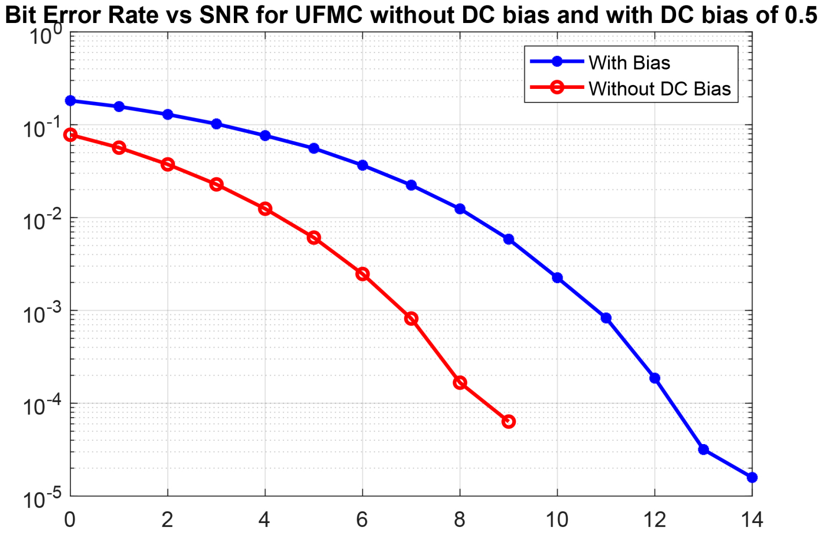

Figure 11. Comparison of the use of a DC-bias for UFMC with a BPSK modulation per subcarrier

It can be seen that there is a shift between the two curves, introducing a penalty of about 6 dB in SNR for the use of the bias. The advantage with VLC is that this extra power is not wasted but essential for the room to be lit. On the other hand, when infrared lighting device are used, the question sometimes arises as to the relevance of Li-Fi in infrared as this extra DC-bias is not used to enlighten the room and could be considered as wasted power. However, there are other methods of making a signal positive in OFDM. From clip-OFDM, which uses only the odd carrier, to other more sophisticated forms [27]. To the best of our knowledge, these have not yet been explored in the scientific literature for UFMC. In terms of computational complexity, as UFMC requires more computational steps compared to OFDM due to the filtering stages, a physical implementation of a UFMC communication on an electronic board would consume more power than OFDM. Indeed, the power consumed by programming boards are proportional to the number of computations it is required to do. Furthermore, it is easy to understand that the use of optical OFDM or UFMC is less spectrally efficient due to the Hermitian symmetry condition or the juxtaposition of real and imaginary data. Indeed, both techniques require at least twice the resources to send the desired information compared to the RF version. Nevertheless, VLC still is interesting where RF cannot reach.

3.2. Comparison of OFDM and UFMC

The parameters for OFDM are derived from the G.9991 standard, utilizing 256 subcarriers. To ensure a consistent basis for comparison, the parameters for UFMC were then adjusted. This adjustment includes the use of 256 effective subcarriers, organized into 24 sub-bands, each containing 12 subcarriers, with a filter length (L) of 19.

A set of 10,000 symbols was generated to produce the results presented in Figure 12. The DC bias is set to 0.5, and the graph illustrates the trends for DC-OFDM and DC-UFMC in terms of BER as a function of SNR.

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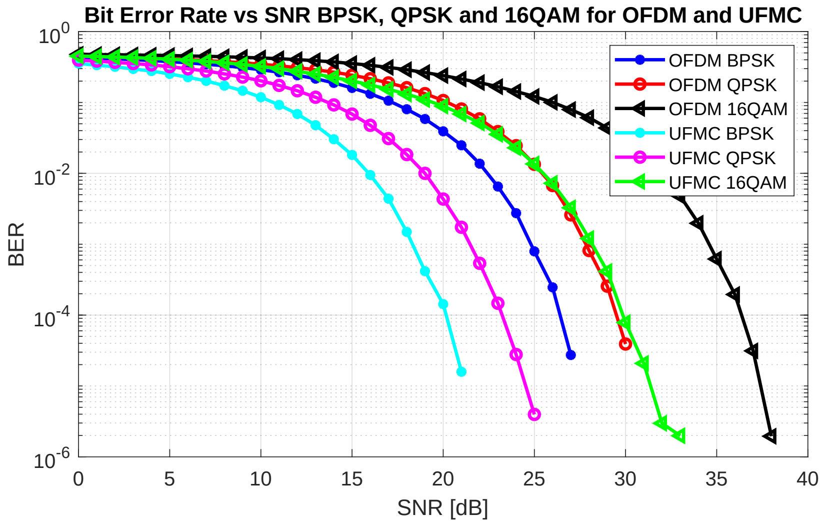

Figure 12. UFMC and OFDM performance for different constellation sizes

It can be observed that in general, the UFMC performs better than the OFDM. The difference between the QPSK and 16-QAM for both modulation techniques is the same and is about 6 dB of penalty.

The observed 6 dB enhancement in UFMC, attributed to its superior spectral efficiency compared to OFDM, may effectively offset the 6 dB loss incurred due to the introduced DC bias. Consequently, the implementation of DC-UFMC demonstrates a significantly improved performance compared to DC-OFDM.

Thanks to the analytical computation of the relative spectral efficiency gain between OFDM and UFMC, its result highlights a gain of 16% when the UFMC is used instead of OFDM [28]. To compute this value, the results of the following work was used [29]. The spectral efficiency of UFMC compared to OFDM is defined in Equation 1.

$$P_{OFDM-UFMC} = 100\left(1 - \frac{M_{OFDM}}{M_{UFMC} + (N_{FFT}GI)}\right) \tag{1}$$

Where M_{OFDM} is the number of effective subcarriers, M_{UFMC} is the effective number of UFMC subcarriers, N_{FFT} is the total number of subcarriers, and GI the number of subcarriers used as GI. The effective number of subcarriers refers to those used to carry the data. In terms of complexity, the filtering stage in UFMC is more constitutionally intensive than OFDM. Further studies should be carried on to quantify it but the most important fact is laid down. UFMC can improve significantly the performance.

4. Discussion

In conclusion, the relevance of Visible Light Communication (VLC) in the 6G era is underlined by its application versatility in various scenarios. From facilitating communication between vehicles in smart cities to enabling connectivity in outdoor spaces, VLC proves instrumental in addressing the evolving communication landscape. This paper aims to contribute to the understanding and optimization of VLC systems through the introduction of open-source tools. These tools assess the optical power distribution, allowing researchers to configure scenarios by specifying parameters like space size, wall presence, and reflective properties. The methodology incorporates realistic LED radiation patterns, enhancing scenario precision. Visualization of 3D-curves and evaluating of power loss. The second part delves into multicarrier modulation schemes, OFDM and UFMC. Adaptations for UFMC in VLC are explored, revealing superior performance compared to OFDM. The computed relative spectral efficiency gain demonstrates a 16% improvement with UFMC to be balanced by the increased computational complexity, particularly the filtering stage, that still has to be studied. On a practical note, the paper reflects the relevance of VLC in the 6G communication technologies landscape as well as the integration of UFMC.

Author Contributions: "Conceptualization, V.G., M.D. and V.M.; Data curation, V.G. and A-C.H.; Formal analysis, V.G. and A-C.H.; Funding acquisition, V.M.; Investigation, V.G. and A-C.H.; Methodology, V.G., A-C.H. and V.M.; Project administration, M.D. and V.M.; Resources, V.G.; Software, V.G. and A-C.H.; Supervision, M.D. and V.M.; Validation, V.G.; Visualization, V.G. and A-C.H.; Writing—original draft, V.G.; Writing—review & editing, V.G., M.D. and V.M."

Funding: "This research was funded by the project Wal-e-Cities, a research project supported by the European Regional Development Fund (ERDF) of the European Unionand BEL6GICA (https://www.6g.be) is supported by FOD 'Economie, K.M.O., Middenstand en Energie' of Belgium" and "The APC was funded by BEL6GICA. "

Data Availability Statement: All the codes can be found at: github.com/veroniquegeorlette.

Conflicts of Interest: "The authors declare no conflicts of interest." "The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results".

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