A Survey on Ultraviolet C-Band (UV-C) Communications

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***Abstract*—Recent advances in semiconductor laser and light emitting diode devices, able to efficiently operate in the solar blind regime, have brought the oblivious ultraviolet C-Band (UV-C) communications to the fore again. The non-light-of-sight transmission ability as well as the negligible background noise effect are a few of the intriguing benefits offered by this alternative broadband wireless solution. Motivated by such inherent characteristics, the current survey presents a quick and clear entry point to the topic, useful to the researchers who first get confronted with UV-C communications. To better understand the UV-C systems, a brief classification in the introductory section and a trace back to the historical evolution of this technology from its very beginnings to the current trends are provided. Then, several aspects related to the transceiver device characteristics are addressed, whereas particular emphasis is given on channel modeling including the major degrading effects, such as absorption and scattering. Modulation and multiple access schemes as well as other ways for performance enhancement as diversity and encoding techniques are also summarized. Since networking is necessary to overcome the short UV-C range, interference, connectivity, and coverage issues are thoroughly investigated. Finally, the study is concluded with a discussion regarding the challenges needed to make UV-C systems able to meet the high demands of the next generation wireless networks.**

***Index Terms*—Ultraviolet C-Band (UV-C) communications, UV-C devices, channel models, physical layer advancements, networking.**

I. Introduction

A. Preliminaries

FREE space optics (FSO) is a growing research field, as it promises some distinctive advantages compared to radio frequency (RF)-based technology. Some of the inherent benefits of this technology include licence-free operation, high bit rates, immunity to electromagnetic interference, and use of low power transceivers. However, the requirement for line-of-sight (LOS) transmission between optical transmitters (Txs) and receivers (Rxs) constitutes a limiting factor for broadcasting and remote sensing applications. Therefore, FSO is preferred mainly as a cost-effective and high-bandwidth solution alternative for 'last-mile' access instead of fiber cables [1], [2].

To overcome alignment problems of conventional LOS optical wireless techniques, non-line-of-sight (NLOS) optical transmission has been proposed. In the mid 1960's, the ultraviolet C-Band (UV-C) was introduced as a medium for NLOS optical communications (see Fig. 1) [3]. The UV-C band is essentially solar blind; hence, a ground-based photodetector can approach quantum-limited photon counting detection performance. Furthermore, this can be accomplished with a low transmitted power. Within the UV-C band optical transmission exhibits some unique and interesting characteristics. First, most of the solar radiation is getting absorbed by the ozone layer in the upper atmosphere, resulting in almost negligible in-band background noise close to the earth surface. This results in an almost noiseless and ideal transmission channel [4]. Second, the strong scattering of UV light within this band (due to the presence of suspended particles in the atmosphere) can be exploited by terrestrial Txs [5], [6]. Both the high signal-to-noise ratios (SNRs) within the transmission channel itself and the strong atmospheric scattering enable the activation of NLOS communication links with large field-of-view (FOV) Rxs, which capture large amounts of scattered light. In other words, it is possible to operate highly sensitive wide FOV quantum noise-limited photon counting Rxs to provide communication systems that perform very differently from the FSO systems operating at various wavelengths [7].

While initial research on UV-C band communications methods dates back in 1960s, the electronics of these days were not suitable for their exploitation. The UV-C band communication systems of the 1960's used flashtube/lamp/laser as sources and were bandwidth-limited. Recent advances in hardware have led to the emergence of low cost semiconductor laser diodes and miniaturized light emitting diodes (LEDs) at UV-C frequencies, making this new technology a promising solution for short-range communications and sensing [8].

UV-C technology is applicable to NLOS short-range communications, which require dense network configurations. This

Manuscript received April 18, 2018; revised October 14, 2018 and December 29, 2018; accepted February 4, 2019. Date of publication February 13, 2019; date of current version August 20, 2019. The work of Z. Xu was supported in part by the Key Program of National Natural Science Foundation of China under Grant 61631018, in part by the Key Research Program of Frontier Sciences of CAS under Grant QYZDY-SSW-JSC003, in part by the Key Project in Science and Technology of Guangdong Province under Grant 2014B010119001, and in part by the Shenzhen Peacock Plan under Grant 1108170036003286. *(Corresponding author: Harilaos G. Sandalidis.)*

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Digital Object Identifier 10.1109/COMST.2019.2898946

TABLE I
UV C-BAND COMMUNICATIONS

Advantages	Disadvantages
Negligible in-band background noise	Strong channel attenuation
Strong scattering	Low maximum achievable data rate
Use of NLOS communication links	Low transmission range
Robust to meteorological conditions	Requirement of dense network configuration

is because, even though UV-C channels are quite robust to meteorological conditions, they are also characterized by strong channel attenuation. This in turn reduces both the maximum achievable data rate as well as the transmission range, thus, necessitating dense network configurations for applications including sensing, where heavily populated unaligned sensors can communicate with each other using UV-C links [5]. Table I summarizes the advantages and disadvantages of UV-C band communications, as discussed above.

B. Exposure Limits

UV-C band communications can utilize transmit power levels, while complying with safety regulations that govern UV-C exposure. The maximum achievable range is directly related to the latest advances in semiconductor LED and laser UV-C source technologies and strongly depends on the transmitted power of UV-C light sources. So, by increasing the source power this range can be extended. However, the UV-C applications must also comply with eye and skin exposure limits. Since the atmosphere filters deep UV-C, humans are sensitive to this region of the spectrum. In general, wavelengths shorter than 300nm do not penetrate into the dermis, whereas for wavelengths in the UV-C band penetration of no more than 50μm into the epidermal layer takes place [9]. Notwithstanding, a repeated exposure to UV-C radiation may create hazardous health effects including sunburn, skin cancer, and cataract [10]. This entails that UV-C systems must be designed with the above in mind. Practical ways to diminish the adverse effects of UV-C radiation as suggested in [10], include a) obtaining the best communication performance with the lowest UV power or b) employing photodetectors with high responsivity, such as photomultiplier tubes (PMTs), in order to enlarge the transmission distance.

In order to protect humans from UV-C radiation, threshold limit values (TLV) have been determined, which refer to the conditions where nearly all operators may repeatedly be exposed, on a daily basis, over a working lifetime, without adverse health effects [10]. Such exposure limits are regulated by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the International Electrotechnical Commission (IEC) [11], [12]. Since 2005, the American Conference of Governmental Industrial Hygienists (ACGIH) established a TLV of 60J/m^2 based on the only detected acute effect, i.e., erythema to a 'fair-skinned' individual [9]. With all these issues in mind, the trade-off between the available transmit power and UV-C exposure limits is critical for applications in the UV-C band, making the design of communication networks a challenging topic.

C. Classification

1) Terrestrial/Underwater: UV-C technology has been proposed for either terrestrial or underwater applications. Terrestrial networks will be discussed in detail in this study. Underwater systems have been suggested for wireless sensor applications. The most significant works for this case are the following: Dai *et al.* [13] provided a model for the propagation of infrared and UV-C light in turbid water and investigated the relationship among the environment characteristics and the backscattered light intensity from collimated light beams. The performance was validated through simulations and laboratory experiments. Arnon and Kedar [14] investigated the link budget for short-range transmissions near the sea surface. Kedar and Arnon [15] exploited the technologies of semi-conductor LED and laser light sources as well as photon-counting detectors in the UV-C solar blind and explored the feasibility to deploy wireless sensor networks in the subsea environment. Moreover, the marine environment was specially considered as a transmission medium for terrestrial applications. For example Wang and Gao [16] analyzed the influence of several weather effects such as wind, rain, clouds, fog etc. They concluded that wind speeds are not significant but cloud thickness, rain, and fog have a detrimental impact on UV-C transmission.

2) Long/Short Distance: Roughly speaking, the majority of UV-C systems are designed to have a short range up to tens of meters due to the limitations imposed by the transmission media. Notwithstanding, research was also conducted to include longer distances. In [17], field test results including measurements of path loss, pulse broadening, and photon-count distributions in long-distance UV-C systems up to 4km were reported and analyzed. Drost *et al.* [18] extended the common NLOS UV-C channel model to account for dead time, which is a time period after the detection of a photon where a photon counting Rx can not detect other photons. They examined the dead time effect to distances over 1km. Finally, in [19], a Monte-Carlo multiple-scattering method was employed to estimate attenuation over wide optical spectra, including UV-C, visible, and infrared, for long range systems up to 10km. Path losses at different wavelengths and communication ranges, and data rates for on-off keying (OOK)

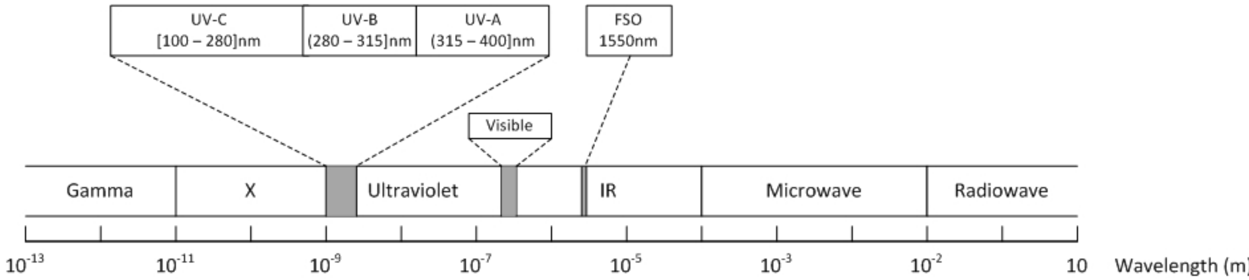

Fig. 1. Electromagnetic spectrum and UV sub-bands.

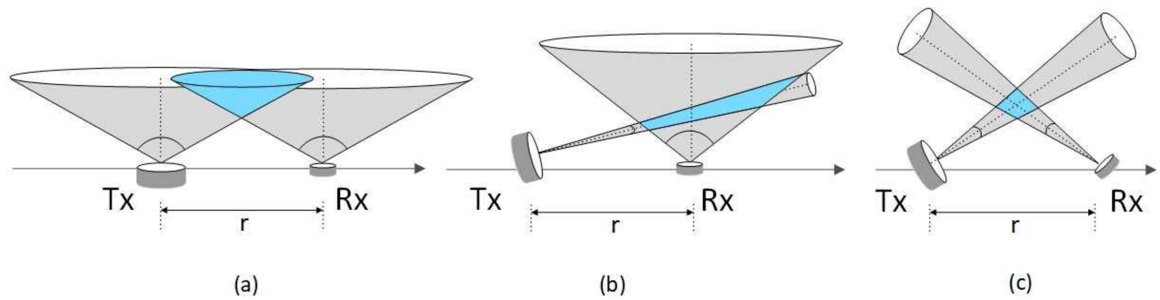

Fig. 2. Typical UV-C NLOS configurations. In configuration (a), the common volume and the resulted delay spread are high, limiting, thus, the communication bandwidth. As the pointing accuracy increases in configurations (b) and (c), the delivered bandwidth becomes higher.

and visibilities were numerically studied. It was concluded that the visible and infrared light have low path loss and high data rate advantages in long-range scattering communications. A comparison between infrared and UV-C wave propagation was also conducted in [20], where it was shown that the Rayleigh scattering effect cannot be ignored in the case of UV-C systems.

3) NLOS Geometry Configuration (Tx Beam Divergence Angle - Rx FOV): Different configurations of Rx-Tx pairs can enhance the reliability of scatter-based optical wireless NLOS communication networks. Figure 2 shows three typical NLOS configurations [5], which depend on the Tx divergence angle and Rx FOV. Adjusting these parameters may result in increasing either the transmission range or the maximum data transfer rate. For example, the configuration Fig. 2(c) requires more pointing accuracy but can deliver higher bandwidth because of the resulting low channel delay spread.

LOS configurations in the UV-C band have additional desirable characteristics when compared to conventional optical wireless networks operating outside this band. The performance of conventional FSO networks operating either at 850nm or at 1550nm can deteriorate rapidly as a result of adverse meteorological phenomena such as fog, snow, or haze. When link deterioration or outages occur, most FSO systems rely on RF backup links [1]. Transceivers produced by industry are almost always hybrids of optical and RF pairs. On the other hand, LOS UV-C networks can benefit from adverse meteorological phenomena due to amplification from scattering. As the communication range increases or the visibility decreases, the strong forward molecular and aerosol scattering becomes a key factor to link quality. In this case, multiple scattering is more pronounced and the achievable data rates may be a few orders of magnitude greater than in NLOS. Typical LOS geometries in the UV-C are shown in Fig. 3 [5]. The configuration Fig. 3(a) requires minimum Tx and Rx positioning but yields smaller bandwidth because of the resulting long channel delay spread. LOS configurations could potentially find applications with moving terminals as a result of the large FOV. Here, terminals on-the-move with a reasonable Tx beam divergence can maintain connectivity in contrast to a conventional optical system with much stricter pointing and tracking requirements.

D. Applications

The majority of studies on UV-C transmission refer to commercial communications applications and/or networking aspects. These studies will be further discussed in this survey. However, other applications include:

1) Lidar: An UV lidar system in which the upward laser beams and the telescope field of view are made to overlap at any specified location in space was studied in [21]. A schematic representation of the arrangement and diagram of the experimental setup was also provided. Furthermore, in [22], the key parameters of the detection characteristics, based on a turbulence model regarding a lidar design were investigated.

2) Aircraft Landing Aid: An interesting study regarding the potential of UV radiation as an aircraft landing aid under low visibility conditions was analyzed in [23].

3) Military/Battlefield Applications: In [24], the UV-C spectrum was exploited for a short range networked communications system with 28kbps bandwith for tactical communications. A similar study examined another system able to provide the capability for NLOS 1.2Mbps for ranges more than 1km [25].

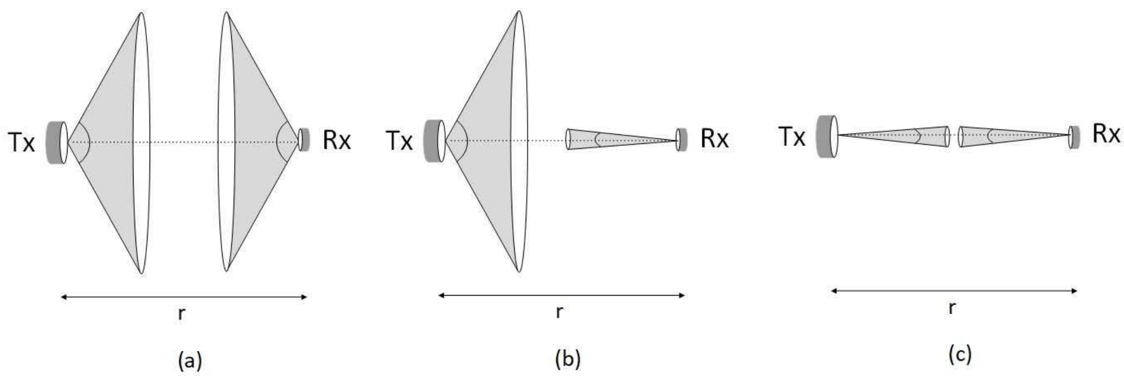

Fig. 3. Typical UV-C LOS configurations. The pointing accuracy increases from configuration (a) to (c) and the delivered bandwidth becomes higher.

E. Motivation

Although several works on UV-C communication systems have already been published, a detailed study to describe the major up-to-date findings in this area is not currently available in the open technical literature. The seminal paper of Xu and Sadler [5] is an excellent introduction on this topic; however, it was published several years ago, and moreover, it does not provide the collected bibliography due to paper size limitations. Drost and Sadler [6] presented a more comprehensive survey but they confined their discussion in channel modeling and system analysis issues. Finally, the study of Yuan and Ma [26], which recently appeared, gives a thorough historical evolution of UV-C networks in USA and China. Since all the above surveys lack to span the UV-C area in detail, the present study aims to fill this gap by providing the following i) a quick and clear entry point to the topic, useful to the researchers who first get confronted with this new technology ii) a complete summary for the current achievements that have appeared till very recently, and iii) a highlighting of the challenges and research trends for future UV-C applications.

F. Survey Organization

The rest of the survey is organized as follows. Section II traces back the historical evolution of the UV-C technology from the very beginnings since 1940 to the current trends. In summary, research on this field was mainly conducted in USA and China; hence the key efforts in these two particular geographical areas are briefly outlined. Section III focuses on the basic trends on transceiver devices (sources, detectors) used in UV-C transceivers. Section IV reviews the basic UV-C channel models that have appeared in the open technical literature. Since the consideration of a proper channel model is crucial for the performance evaluation of UV-C links, the majority of published works is devoted in this topic. The dominant interaction mechanism that deteriorates the transmission including absorption and scattering is included. Particular focus is given on the description of single and multiple scattering models. Turbulence and atmospheric particle effects are discussed, as well. Section V summarizes several techniques including advanced modulation and multiple access techniques, diversity schemes, and coding schemes proposed to enhance the performance of UV-C systems. Networking issues are described in Section VI. Effects such as multi-user interference, connectivity and coverage, neighbor discovery, and medium access control are discussed. Finally, Section VII refers to the challenges and future prospects of this interesting technology regarding its possible utilization in the communication systems of the future.

II. Historical Background

The idea to utilize the UV-C spectrum to provide wireless communications was conceived before World War II at the Naval Research Laboratory in USA [27]. However, the first UV-C systems appeared just after the war. They normally used obsolete, cumbersome, power ineffective, and bandwidth-limited devices such as flashtubes and lamps-lasers as sources. Typical such systems include [28]–[30]. These and some other early studies are well described in [3], where the author provides in brief the state of the art of UV-C communications before 1964. In 1968, Sunstein [31] analyzed the performance of a long distance UV-C link implemented in MIT Lincoln Laboratory using the general scatter communication link. During the 1970s, Fishburne *et al.* [32] investigated the possibility of scattered UV-C radiation as a medium for low data-rate voice communications. To this end, a frequency modulated, high repetition rate UV-C flash lamp and a combination of solar blind filters and a photomultiplier tube were used as a Tx and Rx, respectively. In the same decade, Reilly [33] proposed an efficient analytical channel response model and studied the pulse broadening effect of NLOS UV-C communications, whereas Junge [34] developed Monte Carlo simulations for a NLOS laser communication system operating in the middle UV solar blind region. From a theoretical perspective, an interesting technique to calculate the aureole radiance field about a point source in a medium that absorbs and scatters according to an arbitrary phase function was proposed in [35] and found application in some later studies on the UV-C communications field.

Unfortunately, the research on UV-C communications was not progressively continued during the next two decades. This was due to the fact that the available UV-C systems required large size transceivers with high power consumption and unaffordable cost and hence were unable to compete with alternative emerging technologies such as RF communications [36]. During these years of stagnancy, only a limited number of studies can be found in the literature. As an example, Ross and Kennedy [37] studied the scatter propagation in low visibility atmospheric environments and focused on the determination of the necessary parameters for a UV-C system design, such as the angular spread and the multipath time spread. Patterson and Gillespie developed a simplistic model accompanied by a program to investigate the atmospheric propagation and the lidar return at UV-C and visible wavelengths [38]. A generic single scatter radiative transfer model to include noncoaxial Tx-Rx geometries was discussed in [39]. That pioneering model became the springboard for a variety of special purpose propagation models that have appeared in the recent years. Geller [40] presented a NLOS system that enables simultaneous communications using different frequency channels. Moreover, several works to address the military needs for short range applications made their appearance such as [25] and [41].

The commercialization of semiconductor UV-C solid state optical sources in the advent of the new millennium breathed new live in the UV-C communications area. Semiconductor UV-C LEDs offer the ability of low cost, small size, low-power consumption, and increased bandwidth making, thus, the implementation of productive UV-C systems becomes quite attractive. Two research programs by the U.S. Defense Advanced Research Projects Agency (DARPA), namely, the Semiconductor UV-C Optical Source (SUVOS) and the Deep UV Avalanche Photodiode (DUVAP) programs initiated in 2002 and in 2007, respectively, helped towards this end [5]. USA and China were the two countries that showed an interest in developing UV-C communications systems after 2000. A solid review citing the history of modern UV-C research in these two countries is provided by [26] and the reader may turn to it for more details when necessary.

In the United States, a variety of outdoor experiments for a short range UV-C link ($\sim$100m) took place by the researchers at MIT Lincoln laboratory. The researchers built an appropriate hardware platform, used either LED arrays or lasers as a source and a PMT as a detector, obtained measurements, and developed suitable scattering models. They also examined the performance for several modulation formats and various wavelengths and managed to achieve a bit error rate in kbps at a distance of several meters ($\sim$10m) [8], [42]–[44]. Since the laboratory was also involved in the DUVAP program, research on semiconductor detectors for usage in the deep UV-C was also carried out [45]. With availability of those devices, the research on UV-C communication systems had ever been actively conducted by research teams in USA and all over the world, particularly the team from the University of California, Riverside. In a plethora of published works in seminal journals and conferences the researchers therein conducted innovative studies on scattering models, modulation schemes, networking issues, as well as system performance analysis trade-offs in terms of several parameters such as system geometry, transmitted power, data rate, communication range, bit error rate), see [46]–[48]. Some notable studies from other teams also include [49], where the researchers from the University of Virginia used an M-array amplification method to improve the detection performance, as well as [50], where an extended scattering model to handle the nocoplanar geometry case was presented and the use of spatial diversity techniques was explored.

The interest to explore the potential of the UV-C transmission medium as a means to carry communication data was also ignited in China in the mid 2000, even though some previous works have already appeared in [26]. In the Beijing Institute of Technology, the researchers designed and implemented a UV-C platform for short distance using a mercury lamp and a PMT as source and detector, respectively, simulated the transmission characteristics, and did experiments for distances more than 1km [51]. They also adopted a practical scattering model, performed simulations, and discussed the relationship between several parameters including distance, system geometry, received power, and bit error rate [52]. Experiments were also carried out by the Chinese Academy of Science. In one of these studies, a bit error rate (BER) of 10^{-4} was attained for a Tx apex angle of 60^{o} and a bit rate of 1200bits/s, using a 254nm low pressure mercury lamp [53]. The Beijing University of Posts and Telecommunications was remarkably active especially during the second decade of the 2000s where significant works either on theoretical analysis or experimental set-ups appeared. The analysis involved new scattering models, the turbulence effect, as well as simulations of path loss assuming multiple Rxs [54]–[56]. An in-depth study on the UV-C technology was also carried out in Tsingua University. In [57], a general framework to model the received signal irradiance under scattering and turbulence was introduced. Moreover, in [58] the spectrum sensing approach was proposed for the first time and detection rules were designed to check whether the optical signals fall into the Rx field of view. Furthermore, a team by the National University of Defense Technology analyzed the factors influencing the range of NLOS transmission and derived suitable propagation models. In [59], an analytical single-scatter model with no integral form was deduced and in [60], the existing Monte-Carlo-based multiple-scatter model was extended to include polarization and the occurred vectorized formula improved significantly the simulation speed. Research on UV-C communications was also carried out in several other universities including Chongqing University, Xi'an University of Technology, Naval University of Engineering, Guilin University of Electronic Technology, and Harbin Institute of Technology [26].

Besides USA and China, research on UV-C communications did not receive much attention in the rest of the world. An exception was the trial made in Ben-Gurion University of Israel where Prof. Arnon and his team focused their research on UV-C sensor networks and studied the multi-user interference and node crosstalk issues [61], [62]. Very recently, some studies from Greek universities on connectivity analysis and multiple access schemes have been published [63], [64]. However, with the advent of compact, low-power, silicon based, UV-C devices and the congestion of the available bandwidth for RF transmissions, it is foreseen that the interest for this alternative technology will increase in the near future. Hence, since the advent of 5G networking opens a window on the utilization of UV-C systems, new prototype studies both in theory and application are expected.

III. UV-C Devices

A. Sources

Research into semiconductor based UV-C light sources has increased during the last decades due to the DARPA SUVOS program leading to major breakthroughs. Contemporary UV-C LEDs offer a number of advantages compared to traditional UV-C sources, such as lasers, xenon flash lamps, or low/medium pressure mercury lamps, which were used in the early years of NLOS UV-C communications. Their miniature size may lead to new, striking applications whereas the extremely short interval between turn on and off may significantly enhance the system sensitivity [65]. These devices can operate at high modulation frequencies, offer low noise, and have very long lifetimes [66], [67].

Typical UV-C LED heterostructures are grown on (0001) oriented c-plane sapphire substrates with III-V semiconductor alloys of gallium nitride (GaN), aluminum nitride (AlN), and indium nitride (InN), using metalorganic chemical vapor deposition (MOCVD) techniques. The active region comprises extremely thin AlGaN or InAlGaN quantum wells (QWs) which are separated by (In)AlGaN quantum barriers. These materials offer emission wavelengths in the range of 200nm–365nm since the band gap is 6.2eV for the AlN and 3.4eV for the GaN. The operating wavelength is tuned by the aluminum and indium mole fractions in the AlGaN or InAlGaN QWs [68]. Their emission spectra have a relatively low ($\sim$10nm) spectral bandwidth [69].

From a communication perspective, the output power is critical since it determines the communication range and is directly related to the external quantum efficiency (EQE). This metric describes the percentage of the charge carriers injected into the device that are converted to UV-C photons emitted from the LED. The EQE values and power levels of current solar blind UV LEDs are still modest compared to their UV-A counterparts. Typical UV-B and UV-C LEDs exhibit an EQE of 1%–3% [70], whereas LEDs in the UV-A spectral region exhibit an EQE beyond 30% [71]. This, in terms of output power, corresponds to a few milliwatts in the solar blind UV band [72], while the power per LED has reached 12W at 365nm [73]. Table II summarizes the most important parameter values for UV LEDs, which have been recently reported. The small EQE values are due to a number of factors, including poor radiative recombination efficiencies and modest injection efficiencies, resulting in low internal quantum efficiencies as well as in inferior light extraction and high operating voltages [68]. Improving EQE is a key challenge, nowadays, and novel products are expected soon since an increasing number of companies enter the commercial market, to cope with the demanding applications in sterilization in hospitals and water purification.

In the upcoming years, an expected increase of the emitting area by ten times will significantly improve the thermal management, increasing, thus, the LED lifetime, which is highly temperature-dependent [74]. At the same time, this evolution will substantially increase the operating DC current that is directly related to the total output power. Without doubt, technological roadblocks have been overtaken and UV-C LEDs with high power and high efficiency will be soon available with a progressively lower cost per milliwatt.

B. Detectors

Because solar blind signals are weak, researchers have focused on the design and evolution of high performance photodectors (PDs). In general, each detector technology follows the 5S requirements of high sensitivity, i.e., high SNR, high spectral selectivity, high speed, and high stability [80]. Detectors are often accompanied with proper external or integrated solar blind filters. The case of NLOS UV-C communications has some additional requirements. Among them, the most critical is the internally generated false count (also referred to as dark count), which is proportional to the active area of the detector [45], whereas the acquisition cost should not be underestimated for large scale applications. Besides EQE, a fundamental metric to describe a PD is the responsivity, which is the capability to convert the optical power into an electric current. In general, the performance of UV-C detectors depends on their active area and sensitivity for in-band transmission, out-of-band rejection, and dark current [5].

The primary technology for photon counting in the solar blind UV region of the spectrum was the use of PMTs. PMTs may achieve low dark count rate ($<$ 10 count per second) and high amplification having a relatively large active area ($\sim$ 2cm). However, several inhibitors, such as the high bias voltage, the low EQE, and the fragility prevent their use in practical applications.

In 2007, DARPA initiated the DUVAP program to develop arrays of avalanche PDs (APDs) capable of operating in the deep UV-C. Following this program, $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{N}$-based alternative devices [81], [82] have attracted the research interest in the field of solar blind PDs where the aluminum mole fraction x specifies the cut-off wavelength and ensures the solar blindness for values $x \geq 0.45$ [68]. These devices provide an adequate blocking of unwanted signals without using additional filters. Their operation is based on individual photon counting and on the dead time between firing of the APD and resetting [45]. Furthermore, research in semiconductor PDs made of other materials such as Si, SiC, and GaP has seen significant advantages including smaller sizes, higher reliability, and lower power consumption [83], [84]. Another approach to overcome the dead time effect and increase the active area is the parallel connection of individual APDs [45]. However, the production of highly crystallized $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{N}$ thin films, with the required Al quantity to ensure solar blindness, is technically difficult limiting, thus, their practical applications. Alternatives as the metal oxide semiconductors (Mg-ZnO, $\mathrm{Ga_2O_3}$) have been researched due to their single crystal structure, simple growth, and high responsivity [85], [86]. Another factor affecting the performance of NLOS UV-C systems is the appropriate optical antenna design. Such an antenna requires a rather large FOV in order to increase the scattering receiving area. As the relative positions of the TXs and the Rxs

TABLE II
REPORTED UV LED SPECIFICATIONS

Wavelength (nm)	Power output (mW)	Driving current (mA)	Viewing angle (deg.)	Reference
265	12	350	130	[75]
280	25	350	130	[75]
285	30	350	130	[75]
285	45	350	130	[75]
265	90	350		[76]
265	59	200		[76]
265	150	850		[77]
275	30	350	120	[78]
265	30	350	105	[79]
275	30	350	105	[79]

change in time, an omnidirectional antenna is required where the optimum FOV should be determined and noise reduction techniques should be considered. An example of such an efficient design was provided in [87].

IV. CHANNEL MODELS

The determination of a realistic NLOS communication channel model is still an open issue even though considerable progress has been achieved during the last decade. In UV-C communications, the wavelength of the transmitted radiation is comparable to the size of the atmospheric constitutes. As a result, molecular scattering and absorption, as well as aerosol scattering and absorption are involved. These interactions are quite complex and the channel behavior is hardly predictable. Attempts to reduce the complexity of the propagation effects and extract elegant models have been made in the literature. Obviously, the validity of these models is related to the accuracy of the underlying assumptions.

NLOS channel models are distinguished to either single or multiple scattering models as illustrated in Figure 4. In both models, the Tx emits UV-C radiation towards the Rx, with elevation angles of β_T and β_R degrees. The distance between Tx and Rx is *r*. The Tx produces a cone, which has a beam divergence angle of θ_T degrees, and intersects the Rx FOV cone of θ_R degrees. A communication link is established when the optical power is backscattered by atmospheric particles and reaches the Rx.

A. Atmospheric Optical Properties

The dominant interaction mechanisms of the transmitting UV-C photons and the atmospheric constitutes are scattering and absorption. These mechanisms determine the percentage of the transmitting photons arriving at the Rx. In the literature, a homogeneous atmosphere is usually adopted which is characterized by the Rayleigh (molecular) scattering coefficient, k_s^{Ray}, the Mie (aerosol) scattering coefficient, k_s^{Mie}, the absorption coefficient, k_a, and the extinction coefficient, k_e. The total scattering coefficient is the sum of the two scattering coefficients $k_s = k_s^{Ray} + k_s^{Mie}$. The extinction coefficient is the sum of the scattering and the absorption coefficients, i.e., $k_e = k_s + k_a$. The scattering atmosphere is characterized by the composite phase function, $P(\mu)$, as suggested in [35]

$$P(\mu) = \frac{P_{Ray}(\mu) + \frac{k_s^{Mie}}{k_s^{Ray}} P_{Mie}(\mu)}{1 + \frac{k_s^{Mie}}{k_s^{Ray}}}, \quad (1)$$

where $\mu = \cos\beta_s$, $\beta_s = \beta_R + \beta_T$ is the scattering angle, $P_{Ray}(\mu)$ and $P_{Mie}(\mu)$ are the phase functions modelled by a generalized Rayleigh model and a generalized Henvey-Greenstein function, respectively, given by [35]

$$P_{Ray}(\mu) = \frac{3[1 + 3\gamma + (1-\gamma)\mu^2]}{16\pi(1+2\gamma)}, \quad (2)$$

$$P_{Mie}(\mu) = \frac{1-g^2}{4\pi}\left[\frac{1}{(1+g^2-2g\mu)^{3/2}} + f\frac{0.5(3\mu^2-1)}{(1+g^2)^{3/2}}\right], \quad (3)$$

where $\gamma, g,$ and f are model parameters.

B. Path Loss

The primary goal of the Rx is to maximize the SNR and then make decisions on the transmitted bits. In optical communications, it is well known that the SNR is directly related to the detected optical power. But, the atmospheric channel severely deteriorates the amount of the received optical power since the photons are traveling in a medium where scattering and absorption take place. Therefore, the path loss modeling is strongly dependent on the order of the photons' scattering during the propagation; hence, an exact expression will vary according to a plethora of parameters. The estimation of an appropriate path loss model, either analytical or numerical, is a major research challenge. The next subsections present the recent progress on this topic. A first classification can be made with respect to the number of scattering photons. As a result, two general models have been proposed in the literature, i.e., single scattering and multiple scattering models.

1) Single Scattering Models: Pioneering studies on single scattering models for NLOS optical communications were introduced in [39] and [88]. The analysis was based on the prolate-spheroidal coordinate system, that arises by rotating the two dimensional elliptic coordinate system. This coordinate system exploits the equitemporal scattering surfaces, which are produced when the Tx and the Rx are each located at a focal point. A simplifying assumption was that the axes

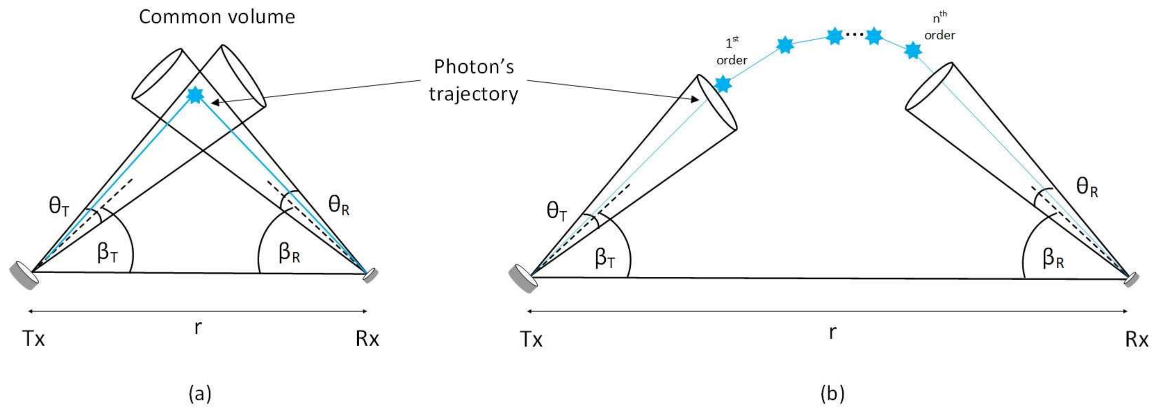

Fig. 4. The order of scattering on NLOS UV-C communications systems. (a) In single scattering models, the photons undergo scattering at most once. (b) In multiple scattering models, the photons undergo scattering at most *n* times.

of the Tx and Rx lie in a common plane (the so called coplanar geometry). As an outcome, the path loss was obtained in an integral form. Based on this framework, a number of studies have been presented in the literature. As an example, the received signal power was calculated in [89]. Under the assumption of a small common volume *V*, an elegant path loss approximation that clearly demonstrates the effects of the system parameters was obtained in [90]. Towards this direction, Yin *et al.* [59] presented a similar expression that is fit for large FOVs and Gupta *et al.* [91] proposed a simulation method using numerical integration that was applicable for Rxs with wide FOV. An indirect calculation of the path loss was introduced in [92]. More precisely, a parametric single scattering model was suggested and the gamma function was selected as the matching function for the impulse response. The path loss was calculated by integrating this fitting model, without taking the system geometry into account. This approach was also adopted in [93], where the mean value theorem of integrals and L'Hôpital's rule were combined and a closed form model for the impulse response was extracted. The applicability of approximate models, which have been proposed for the irregularly common scattering volume, was studied in [94]. Furthermore, the effects of the different operating wavelengths and visibilities were examined in [95]. Recently, a new model, based on the spherical coordinate system instead of the prolate-spheroidal one, where the zenith and the azimuth angles show the emission direction of photons and the radial distance corresponds to the propagation distance of the photons before scattering, was presented in [96].

Coplanar models may provide useful approximations; however, in many cases the Tx and the Rx axes are rarely located on the same plane and the use of noncoplanar geometry is unavoidable. Hence, during the last years, efforts have been made aiming to extend coplanar models to noncoplanar geometries (see Fig. 5 for the geometry parameter definition). As a first step, in [97], a single scattering propagation theory and trigonometry were applied and a closed-form model, for arbitrary Tx pointing and vertical Rx orientation, was deduced. Based on this model, the case of a small intersected volume of the Tx beam and Rx FOV was investigated in [98] and the best approximation was observed when the Tx apex angle and the off-axis angle are relatively small. Generalizations of this model were presented in [54], [99], and [100], where the Tx beam and Rx FOV can be pointed towards arbitrary directions. A further extension was also introduced in [101] for the case of a narrow Tx beam or an Rx FOV. In addition, for the case of a vertically pointing Rx, an empirical path loss model based on extensive field measurements was presented in [102]

$$L = \xi r^{a} e^{b\phi}, \tag{4}$$

where L is the path loss, ξ is the path loss factor, r is the distance, α is the path loss exponent, b is the exponent factor and ϕ is the Tx off-axis angle in degrees. The polarization extension of the single scattering model was developed in [103]. Eventually, in an attempt to analyze the path loss and provide versatile solutions, the Riemann sum method was applied to a channel model in noncoplanar geometry based on the spherical coordinate system [104].

2) Multiple Scattering Models: The probability of single scattering decreases significantly as the atmospheric particle density becomes higher or the propagation range increases. The consideration of the multiple scattering effect is consequently inevitable towards a more accurate channel prediction. While the development of a corresponding channel model is crucial for UV-C NLOS communications system performance analysis, there is no a simple closed-form expression as in the case of the single scattering effect. For this purpose, Monte Carlo numerical techniques or analytical calculations are often adopted to obtain both the impulse response and the corresponding path loss.

In view of the above, a stochastic analytical method was derived in [105], in order to estimate the *n*-th order scattered signal energy collected by the detector, and compared with a Monte Carlo simulation model providing a high degree of accuracy. A combination of numerical methods and simulations was suggested in [106]. In that study, the scattering characteristics of spherical particles along with the atmospheric coefficients values were numerically estimated and a Monte Carlo method used to simulate the scattering process.

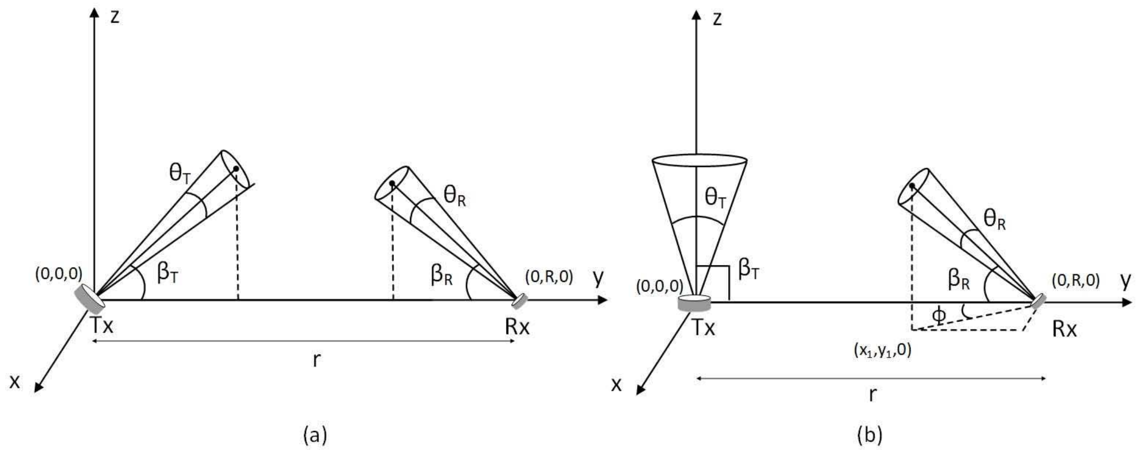

Fig. 5. (a) In coplanar models, the Tx and Rx axes are located in the same plane. (b) In noncoplanar models, there is an off-axis angle ϕ between the Tx pointing direction and the plane of the Rx and its projection onto the horizontal plane.

The relationship between path loss and range was investigated in [107]. Using analytical calculations and assuming an arbitrary but fixed order of scattering, the path loss was found to be proportional to r^{2-n} at short ranges, where *n* denotes the order of scattered radiation. Moreover, the Monte Carlo framework was adopted in [108] and [109] taking account of the system characteristics. In [110], the impulse response and the path loss were investigated using the Monte Carlo method. Experimental results revealed the validity of the proposed framework and presented an increased accuracy in comparison with a single scattering model. Based on this, a stochastic analytical path loss model was presented in [111], which provides useful outcomes under high order scattering. The model was developed by employing the probability density functions (PDFs) of the scattering distance and of the angles. An extension of the Monte Carlo based path loss models was introduced in [60] in order to take polarization into account. Recently, a simplified integral model for two-order and three-order scattering was proposed in [112] by considering a narrow Tx beam and a Rx FOV. This approach provides better estimations of the NLOS path loss compared with the single scattering model. A non-coplanar ultraviolet multiple-scatter model with a height difference between the Tx and Rx was investigated in [113] and was validated by Monte Carlo methods.

3) Experimental Results: Many experiments have been conducted either to validate numerical/analytical results or to propose empirical channel models. In [114], a communication test-bed was employed for the experimental evaluation of NLOS UV-C links in outdoor environments. The effects of key system parameters such as Tx/Rx zenith and azimuthal angles, communication range and filter/PMT responses were considered. The UV-C LEDs were centered at two different wavelengths (250nm and 280nm). In [115] and [116], path loss measurements were obtained for different Tx/Rx geometries and separation distances. The effect of different atmospheric conditions was not included while the predictions of the single scattering model can be applied only for limited geometries. In [117], experimental path loss measurements were compared and validated with a multi-scattering Monte Carlo photon tracing technique. Furthermore, in [105] and [118], a simple analytical path loss expression was introduced as

$$L = \xi r^{a}, \tag{5}$$

where the path loss factor, ξ, and the path loss exponent, α, were carefully estimated as a function of pointing angles and communication range. Recently, a high performance in terms of the transmission rate was reported in [119], where the data rate was measured at 921.6kbps with a BER of less than 10^{-7} in a 150m separation distance between a UV-LED array and a Rx equipped with a two-stage differential preamplifier.

C. Turbulence

In the initial studies, the propagation medium was considered homogeneous since this assumption simplifies the complex mathematical expressions used for the performance evaluation of UV-C systems. However, it is well known for decades, that turbulence may hamper or even impede the propagation of optical signals through the atmosphere. This factor arises from the turbulent mix of warmer and cooler atmospheric air layers which causes random air temperature fluctuations. A number of theories have been reported in the literature to describe the turbulent medium. The major quality indicators are the irradiance PDF, $f_I(I)$, as well as the scintillation index, σ^2, which is associated with the irradiance fluctuations detected by the Rx. In the case of FSO networks, a variety of models have been proposed to characterize a wide range of turbulence conditions (weak to strong). The first studies ignored the turbulence effect because normally UV-C systems operate at short ranges. Nevertheless, recent progress on UV-C sources and detectors gave the possibility to make systems working effectively at longer communication distances. Hence, the effect of turbulence has been investigated in a systematic manner during the last years.

A mix of analytical, numerical, and experimental methods have been proposed in the literature. A set of collected measurements of irradiance scintillations, expressed in terms of the normalized variance, σ_I^2, was presented in [120].

A good agreement between measurements for a path length of 185m and predicted values based on aperture averaging, was observed. In [121], the NLOS atmospheric scintillation PDF was modeled by adapting an existing LOS scintillation log-normal distribution considering two LOS links (from the Tx to the common volume and common volume to the Rx). The turbulence effect was also studied in [17] and [122]. The partition of a random medium volume V into infinitesimal elements δV was proposed in [55] and [123] and a single scattering model was adopted in order to analytically evaluate the received power. Similarly, the emitted beam decomposition into a set of infinitesimal beams was proposed in [57] and the effects of a wide range of turbulence conditions was studied through a Monte Carlo simulation framework. In order to reduce computational complexity, the researchers in [124] presented a combination of numerical and analytical methods. A Monte Carlo simulation method was employed to track the trajectory of the emitted photons, while an analytical calculation of the received irradiance distribution after multiple scattering was performed. Experimental results regarding the effect of turbulence on the received signal energy distribution instead of the average path loss were collected in [125]. Extending this study, the researchers in [126] proposed a Monte Carlo channel model which incorporates the multiple scattering effect into channel behavior under turbulence conditions. A series of experiments were conducted to validate the simulation results. A modified quality indicator for weak turbulence conditions, namely the scintillation attenuation, was calculated in [127]. Following this approach, the atmospheric extinction coefficient was modified and a new analytical expression for the single scattering path loss model was extracted. Recently, a notional difference for turbulence-induced fading between UV-C and RF or FSO communications, arising from the large path loss of UV-C links, was investigated in [128]. More specifically, it was observed that the extremely weak signal at the Rx introduces a doubly stochastic process arising from the fluctuations of the transmitted signal according to a log-normal distribution and that the number of detected photoelectrons follows a Poisson distribution.

D. Other Effects

A series of other channel effects have also been considered in several studies. The most significant of them are presented in the following.

1) Effect of Atmospheric Particles: The boosting effect of the scattering mechanism has been particularly investigated in a series of studies. In [129], the impact of the atmospheric visibility on the NLOS UV-C communication system performance was investigated. The results indicated that the performance deteriorates significantly only in very low-visibility weather. A multiple scattering path loss model, considering the influence of haze particles (also known as Mie particles), was studied in [19] over wide optical spectra. This work was extended in [130] to incorporate the influence of fog droplets. Simulation results showed that the density or the size of the particles and the communication range are the two determinant factors for this interaction. The beneficial effect of fog droplets on system performance was confirmed in [131] by experimental results. The fog channel was also investigated in [132] for the single scattering integral model. Moreover, the influence of visibility, rainfall and wind speed on transmission range was investigated in [133]. As intuitively expected, the influence of wind speed was proved to be negligible. An NLOS model in the inhomogeneous atmosphere was introduced in [134]. It was found that the scattering phase function depends on the height and there exists an optimal apex angle in which the received energy is the highest. Finally, a system performance analysis was performed in [135] for various altitudes. Since the atmospheric particle density is altered as the altitude increases, the scattering and absorption processes will be different. Indeed, simulation results indicated that the scattering link in a 20km altitude had a stronger intensity in comparison with the link in a 5km altitude for a short communication range.

2) Pulse Broadening Effect: As the transmitted pulses propagate through the atmospheric channel, they become broader and the achievable data rate is getting limited. This effect, also called pulse broadening, was investigated in [17], [53], and [136] while the full width at half maximum (FWHM) was set as the appropriate metric for evaluation. Thus, experimental pulse width measurements have been collected for various system geometries providing useful insights for the system design. In [137], the NLOS scattering channel properties and the resulting communication performance over broad spectra in polydisperse aerosols were examined using a Monte-Carlo ray tracing method. The results indicated that the pulse delay spread initially increases and then decreases with the wavelength from the deep UV to the near infrared spectrum. Moreover, it was found that variations in relative humidity do not significantly affect the NLOS link.

3) Dead Time Effect: A limiting factor, which appears when a pulsed laser is adopted as a UV-C Tx, is the dead time effect, that is, the time interval during which impinging photons are ignored in the Rx after a successful detection. This is due to the reset procedure that must be applied in practical photon-counting devices. The researchers in [18] and [138] demonstrated the magnitude of this effect on path loss as well as its dependence on system geometry through simulation and experimental results. It is clear that dead time compensation algorithms are an open issue for future research.

4) Intersymbol Interference (ISI): The ISI is caused by channel dispersion which is longer compared to the symbol duration. A preliminary work on this topic was presented in [139]. A linear time invariant (LTI) Poisson channel model was adopted in [140] and [141], where the ISI characteristics were studied and several channel-based estimation schemes were proposed. Furthermore, the achievable information rate in the presence of ISI was numerically estimated in [142] for broad and narrow temporal dispersive channels. The channel capacity was computed assuming OOK and 4-pulse position modulation (PPM) and a coding system was launched in the presence of ISI in [50] and [143]. In [144], the researchers designed a Viterbi scheme to estimate the informative bits for a finite-state Markov channel. Finally, a Bayesian scheme to combat the ISI effect was investigated in [145], by simultaneously estimating the channel characteristics and by detecting the information signals.

5) Miscellaneous: An expansion of the classical single scattering model was presented in [146], where the Rx aperture size was considered to have finite dimensions. This assumption is of great interest when the amount of scattering is significant near the Rx aperture. The polarization characteristics of the UV-C channel were investigated in [147] for various system geometries. The use of polarization multiplexing is an open topic and can significantly improve the supported data rate. The effects of obstacles on NLOS UV-C communication links were investigated in [148] using a Monte Carlo based multiple scattering model, whereas the predictions were validated by experimental measurements. When the position of the obstacle (such as a mountain or a building) is close to the Tx or Rx, the path loss increases, since the common scattering volume significantly decreases. Moreover, a set of algorithms for the impulse response estimation were reported in [149] and the classical algorithm of double local estimate was the most efficient, since the procedure is performed twice for each collision point. Finally, an analytical model for the link bandwidth, applicable for various geometries appeared in [150]. Based on this model, a square array reception was proposed and the FOV in each Rx can be significantly reduced without signal power loss.

V. Physical Layer Advancements

Although the research on channel modeling is rapidly evolving, one of the major incentives for researchers and potential network operators remains to determine and evaluate performance metrics as well as to study the optimal design by choosing the adequate system parameters. This task is of great importance since it is the springboard for the effective deployment of practical UV-C networks in order to satisfy the forthcoming traffic demands. In the literature, the most important key system parameters are the path loss and the communication BER under different Tx and Rx geometries (i.e., Tx elevation angle, Rx FOV, Tx/Rx separation distance) [151]–[153] along with the supported data rates for a specific target BER [154]–[156]. These parameters have been investigated not only in clear atmospheric conditions but also in the presence of turbulence [157], [158]. It must also be pointed out that the choice of UV-C source (laser/lamp/LED) and the detector at the Rx side (APD/PMT) significantly affects the system performance characteristics [159], [160].

It is commonly accepted that the provision of Gbps data rates will be the comparative advantage of the next generation optical wireless networks against other wireless technologies. However, this data rate is still at a theoretical basis for the current UV-C NLOS communications [161]. So, performance enhancement techniques are vital for the evolution of this technology in parallel with innovations in hardware. These techniques include advanced modulation and/or coding, sophisticated multiple access, diversity schemes, and adoption of multiple transmit and/or receive antennas. In this section, recent efforts towards these directions are briefly reported.

A. Modulation/Multiple Access Techniques

A low data rate is typical in NLOS UV-C communications due to the high path loss. An obvious solution to overcome this limitation is the increase of the transmitted power. However, because the exposure safety limits are quite strict, power efficient optical modulation and/or coding techniques are adopted as an alternative solution. As a baseline, the error probabilities of uncoded OOK and multi-PPM (MPPM) were calculated in [46] assuming an empirical path loss model and considering two detector noise models. These are, the Gaussian noise model, which is applied in the case of thermal noise domination, and the Poisson noise model which is adopted for a photon counting based detection. A test platform was set up in [162] with a pulse laser as source to measure the energy density and the pulse response for different communication ranges and Rx elevation angles. The pulse frequency-shift keying (FSK) modulation scheme was considered. The results indicated that the bit rate is limited to 12.5Mbps. The BER was estimated to be less than 10^{-7} at 300m for LOS and less than 10^{-6} at 80m for NLOS conditions. More powerful symbol-length-variable modulation schemes, namely differential pulse-interval modulation (DPIM), dual head pulse interval modulation (DH-PIM), and differential PPM (DPPM) were investigated in [163] and [164] and the BER performance was analytically calculated. Furthermore, the binary phase shift keying (BPSK) subcarrier intensity modulation technique was presented in [165] and was compared with the OOK and PPM modulation formats. Simulation results revealed that this method is substantially better in terms of BER performance, data rate, and transmitted power, than OOK and PPM. Furthermore, a technique to capture and recover the transmitted signal by employing a GPS was presented in [166]. Photon counting and adaptive threshold methods have been utilized to recover the original signal and the BER for different configuration geometries and OOK modulation schemes. Spectral amplitude coding (SAC) was investigated in [49] and [167] assuming an array of UV-C LEDs and a visible laser, respectively. In the second case, the IR region was employed for the encoding, and then the encoded signal was frequency-doubled/tripled to the UV-C portion of the electromagnetic spectrum. Polarization is also a fundamental characteristic of light. The configuration and the working process of polarization modulation in UV-C communication was investigated in [168]. This modulation format is at an early stage and is not practicable at the moment due to hardware limitations. The types of modulation that have been proposed in UV C-band communications are summarized in Table III and an overview of recent performances is presented in Table IV.

Optical OFDM is an attractive solution for mitigating dispersion. A discrete Hartley transform (DHT)-based asymmetrically-clipped optical (ACO)-OFDM method was proposed in [169]. This method provides simpler Tx and Rx structures, while the positive-realness of the transmitted symbols is satisfied which is prerequisite for an indirect modulation/direct detection (IM/DD) system. A direct sequence spread spectrum (DSSS)-based UV-C communication system was examined in [170] in order to improve system performance and mitigate the deleterious effects of ISI.

TABLE III
MODULATION SCHEMES FOR UV C-BAND COMMUNICATIONS

Modulation type	Modulation	Advantages	Refs
Amplitude based	OOK	Easy to implement.	[46]
Time based	PPM	Better power efficiency than OOK.	[46]
Time based	DPIM, DH-PIM, DPPM	Better PER performance than OOK, but worse than PPM.	[164]
Phase based	Subcarrier PSK	Performance gains (in terms of BER, data rates, transmitted power) compared to both OOK and PPM.	[165]
Wavelength based	SAC	It combats ISI and offers higher rates and ranges than OOK.	[49]
Polarization based	Polarization-modulation	It has the potential to achieve higher data rates than single intensity modulated systems.	[168]

TABLE IV
REPORTED UV-C SYSTEM PERFORMANCES

Transmitted power P_t (mW)	Tx elevation angle β_T (deg)	Rx elevation angle β_R (deg)	Wavelength λ (nm)	Data rate R_b (kbps)	Error probability P_e	Range (m)	Modulation	Ref.
50	30	30	250	10	10^{-3}	24	OOK	[46]
50	70	70	250	10	10^{-3}	105	OOK	[46]
50	30	30	250	10	10^{-3}	40	PPM	[46]
50	70	70	250	10	10^{-3}	155	PPM	[46]
	30	30	266	0.6	$< 10^{-6}$	80	2–FSK	[162]
	30	30	266	1.2	$< 10^{-6}$	80	4–FSK	[162]
10	30	0	265	10	10^{-3}	20	OOK	[163]
10	30	0	265	10	10^{-3}	17	4–PPM	[163]
10	0	50	265	10	10^{-3}	80	OOK	[163]
10	0	50	265	10	10^{-3}	65	4–PPM	[163]
100	30	30	250	80	10^{-3}	110	DPIM	[164]
100	30	30	250	50	10^{-3}	110	DHPIM	[164]
5	20	40	265	10	10^{-3}	230	BPSK subcarrier	[165]
1000	60	60	250	1000	10^{-3}	95	SAC	[167]

Simulation results indicated that the performance of the DSSS system is better than that of the OOK system even for relatively low elevation angles. The code division multiple access (CDMA) technique, associated with several modulation formats, was investigated in [64] and [171] for a networking scenario considering either a low or a high density of atmospheric particles and molecules. Simulation results indicated that the application of this method is quite better for a thicker atmosphere. Moreover, the signal detection using the maximum- likelihood (ML) criterion of OOK modulation for discrete Poisson multiple access channel for CDMA and non-orthogonal multiple access (NOMA) was thoroughly examined in [172]. Sufficient conditions were investigated in order to reduce the computational complexity, which is growing exponentially with the number of users using the ML detection scheme. As a result, the proposed detection scheme achieves a linear dependence with the number of users accompanied by negligible performance loss. The achievable rate regions and the optimal power allocation strategy were found, as well.

B. Performance Improvement Techniques

In order to enhance the performance of UV-C communications, several techniques used in conventional RF systems including diversity at the Tx or the Rx, multi-input-multi-output (MIMO) configurations, advanced Rx designs, and encoding were proposed. The most important studies on these topics are described below and summarized in Table V.

1) Diversity and Advanced Rx Design: Diversity schemes have been extensively used in RF and FSO technologies along with advanced Rx design and detection techniques. Building on this experience, a lot of effort has been given to appropriately modify and adapt these solutions for the case of the UV-C channel. In this way, the performance of the maximum ratio combining (MRC) diversity reception algorithm was studied in [173], whereas the equal-gain combining (EGC) algorithm was presented in [56] and [174]. It was observed that the MRC algorithm reduces the system BER more effectively than the EGC, since it can compensate for the channel differences between each PMT and produce larger output power. It was also found that the BER reduction has a nonlinear relationship as the number of Rxs increases. A variation of MRC, named selective MRC (SMRC), was proposed in [175]. This algorithm captures the Rx mobility effect in an indoor environment, assuming a typical speed of 1m/s. Experimental results showed that the influence of mobility is almost negligible for typical working distances (10m–30m). The design

TABLE V
PERFORMANCE ENHANCEMENT TECHNIQUES USED IN UV C-BAND COMMUNICATION SYSTEMS

Performance enhancement technique	Advantages	Refs
MRC & EGC diversity combining	Compensate channel differences between each PMT and improve system BER.	[56], [173], [174]
Selective MRC	Captures mobility effect in indoor environment for typical working distances	[175]
Spatial Diversity	Achieves significant improvement in terms of information rate.	[176]–[178]
Spectrum sensing combined with detection rules	Improves transmission scheduling.	[58]
Beam reshaping	Improves received intensity.	[180]
MIMO (LMMSE, Alamouti coding)	Increase received power, reduce ISI and reduce BER.	[182]–[187], [189], [193]
Reed-Solomon and LDPC encoding	Extend average communication distance for a given BER.	[195]–[197]

of a spatial diversity Rx for NLOS UV-C links was suggested in [176], which is based on imaging optics and a focal-plane detector array. A significant improvement can be achieved, in terms of information rate performance, depending on the link geometry and the detector device technology. Furthermore, the ML and the optimal combining (OC) detection schemes were compared, for spatially correlated NLOS UV-C links under turbulence conditions, in [177] and [178]. Simulation results showed that the ML diversity detection outperforms the OC method when the atmospheric turbulence is weak. This situation is reversed, as the turbulence becomes stronger. A way to mitigate turbulence was also analyzed in [179], where a dual-branch switch and stay combining (SSC) at the Rx is adopted.

The introduction of spectrum sensing combined with two detection rules was introduced in [58], for the case of optical wireless scattering communications, in order to improve the transmission scheduling. A generalized likelihood ratio test was adopted assuming that the data symbols or channel parameters are unknown. Asymptotic results on the miss detection probability were derived. The rectangular and the elliptical beam reshaping of the Tx beam or of the Rx FOV was reported in [180] to comparatively study the channel gain with respect to the cone-geometrical case. Monte Carlo simulation results demonstrated that the elliptical reshaping is better than the rectangular reshaping in improving the received intensity. Finally, a sequential detection to the spectrum sensing for both a photon-counting Rx and a PMT Rx was reported in [181]. An one-term approximation for the log-likelihood ratio computation was considered in order to reduce the computational complexity for the PMT Rx. It was shown that the sequential detection requires fewer samples to obtain specific miss detection and false alarm probabilities in comparison with the fixed sample size detection.

2) MIMO/SIMO: MIMO using multiple beams transmitted simultaneously, is a well known technique often adopted as a means to increase the received power and reduce the ISI. The first work towards this direction was presented in [182] where a 2×2 MIMO UV-C NLOS communication system was investigated. Several Rxs assumed including the zero forcing (ZF), the ML for nondispersive channels, the minimum mean square error (MMSE), the maximum-likelihood sequence estimation (MLSE), and the maximum-a-posteriori (MAP) one shot for dispersive channels. A single Tx and multiple Rxs, also called single-input multiple-output (SIMO) system, was introduced in [183] and [184]. Moreover, linear minimum mean square error (LMMSE) Rxs having linear complexity with the number of detectors were considered. This system was further investigated in [185], where the link gain correlation was studied both analytically and numerically. It is worth mentioning that the numerical results exhibit a smaller diversity gain than that for the LOS FSO communications. The modified Alamouti code was adopted in [186] to obtain the diversity gain in UV-C communication systems. Simulation and experimental results indicated that the Alamouti code can reduce the system BER more effectively than the single-input single-output (SISO) and SIMO technologies. A 1×4 SIMO UV-C communication system was constructed in [187]. Experimental results showed that the EGC produces a significant diversity gain for smaller Tx elevation angles or shorter distances between Tx and Rx. As a result, the BER performance improves at low Tx power. However, when the Tx elevation angle was larger than 17^o or the distance longer than 20m, this gain becomes negligible, whereas a further increment of the Rxs number had also a negligible contribution. Another experiment in [188] indicated that an Alamouti coding scheme for a 2×2 UV-C system outperforms other diversity schemes. Approximate BER expressions of MIMO systems over log-normal turbulence channels were deduced in [189]. The results revealed that the fading variance is scaled by the number of Txs and Rxs and MIMO arrangements improve the BER performance. Experimental measurements of link gain and correlation for a MISO system were also conducted in [190]. Moreover, the secrecy rate for the multi-input single-output (MISO) system was examined in [191]. More specifically the authors proposed the non-jamming protocol and the cooperative jamming protocol, formulated, and solved the power and duty cycle optimization problems under peak power and average power constraints. Towards this direction, the secrecy performance of noncoplanar single-input multiple-output multiapertures eavesdroppers (SIMOME) NLOS UV-C communication system with atmospheric turbulence was investigated in [192]. Simulation results showed that the secrecy performance is enhanced with the adoption of spatial diversity techniques with smaller off-axis errors. The first attempt towards the mobile support for MIMO UV-C networks was presented in [193]. Recently, experiments for the performance of a symmetrical optical pulse position orthogonal space-time block code (SOPP-OSTBC) applied to (M-PPM) were conducted for a multi-output (MIMO) configuration in [194].

3) Encoding: Encoding is another common technique in telecommunications to enhance system performance and guarantee the transmission quality. A simple repetition code employed for OOK modulation format was reported in [46] and the subsequent range extension was calculated. Moreover, a Trellis coded MPPM was considered and its impact on range extension was studied. Traditional powerful forward error correction (FEC) codes, such as Reed-Solomon (RS) and low-density parity-check (LDPC) codes, were applied in [195]–[197] in order to achieve a possible performance improvement. As a result, the average system communication distance, by using the RS and the LDPC codes, was extended in [195] by 25% and 42% at 10^{-3} BER, respectively. This trend was evaluated in [196] where the communication range was increased by 42% and 94% at 10^{-6} BER, correspondingly. Moreover, a BER lower than 10^{-5} at data rate of 2Mbps was reported in [197] using delayed sampling (DS) binary PPM (BPPM). The main challenge of the LDPC code is to reduce the hardware resources, which are prohibitive for typical system applications. Recently, a polar code with specific channel correlations was applied in [198] and the computational complexity was derived in terms of the code length. Another approach was presented in [199] where both LDPC and polar codes were investigated in terms of physical layer security performance. The results showed an improved link security when the polar codes are used.

VI. NETWORKING

Since conventional NLOS UV-C systems are not able to provide communications at large distances, a network by means of multiple hops is often applied [61]. In this way, information propagates from the Tx (also called the source) to the Rx (also called the destination) through a number of intermediate nodes, which are usually called relays. Although this type of communications has been extensively investigated in FSO systems, several particular aspects of NLOS UV-C communications make this technique greatly challenging. As an example, Fig. 6 presents a typical NLOS multihop UV-C network having R_n relays lying at a distance *r* between a source, *S*, and a destination, *D*.

The first attempts towards this direction were presented only recently in [200] and [201] where a three node communication scenario with orthogonal cooperation was examined. It was shown that the performance of multi-hop transmission is highly dependent on relay location and system geometry. For example, for a symmetrical system configuration, i.e., all nodes have the same FOVs and elevation angles, a relay, placed at midpoint between source and destination, provides the highest performance gain. The work was extended in [202] to include turbulence effects where it was shown that with proper design the turbulence variance for the NLOS link can be lower than that of the LOS link yielding higher-diversity gains. However, since the cone of one Tx beam of a given divergence can intersect more than one Rx FOV cones, multi-user interference (MUI) emerges as a performance bottleneck. In addition, the specific Tx/Rx configurations for NLOS operation induce an increased complexity of the interference estimation making, thus, the transmission coordination and related higher network layer issues become very important. Furthermore, the short range imposes a high node density of the deployed network and connectivity issues need to be investigated. It has to be stressed that networking research on NLOS multi-hop UV-C networks is gradually evolving in the literature. As an example, Gong *et al.* [203], suggested two protocols, i.e., the detect-and-forward and decode-and forward for a full-duplex relaying system with self interference at the relaying node assuming OOK modulation. They proved that for the detect-and-forward relay protocol and for high self interference intensity, the achievable transmission rate can be lower than that of the half-duplex relaying system, whereas the decode-and-forward relay protocol always has a higher achievable transmission rate compared to the half-duplex relay system. Recently, a NLOS multi-hop UV-C network over lognormal turbulent channel with best relay selection technique was investigated in [204]. The effect of the node elevation angle on system performance was demonstrated highlighting, thus, its impact on the design procedure. Several studies on networking for UV-C systems have appeared in the literature examining topics such as MUI, connectivity and coverage, neighbor discovery techniques, and medium access control (MAC). The most significant of them are summarized in the following subsections.

A. MUI

In NLOS UV-C multi-hop networks, interference is originating from the directional nature of transmissions and receptions since an intermediate node may receive a transmitted signal from more than one preceding relay. In [205], the performance degradation due to interference was evaluated against the link geometry and the number of hops. A spatial reuse technique of coordinated transmission and cooperative reception was introduced. It was indicated that the consideration of relays can decrease the power requirement of both individual nodes and the whole system. The advantages in both range extension and power savings are made clear through error performance and data rate analysis. The dominant effect of MUI in system performance degradation was investigated in [62] and [206]. The first study adopted the multiple scattering channel model discussed in [109] and provided persuasive system design directions considering several parameters such as the transmitted power, the bit rate, and the interferer's location. A scenario was taken into account where both a Tx and an interferer were located 25m to the Rx. Simulation results were

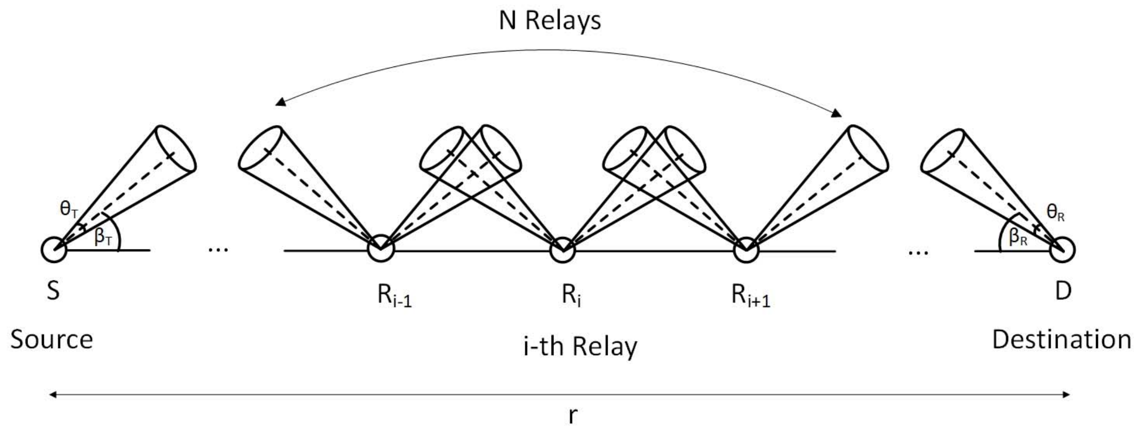

Fig. 6. In NLOS multihop UV-C networks, a long link between source (S) and destination (D) with length r is divided into N+1 short distances and N intermediate transceivers (also called relays) forward the information.

illustrated to reveal the impact of MUI and indicate guidelines for a proper design. The second study assumed different node densities and traffic levels and used a Poisson model for the node distribution. It was shown that the reduction of the number of simultaneously transmitting nodes leads to a significant increase in signal-to-interference ratio (SIR). As a result, guidelines were outlined considering the cumulative effect of interference from distant nodes, the expected number of hops, as well as the trade-off between node redundancy and node isolation.

Apart from interference estimation, a lot of effort has been performed towards interference management and mitigation. A technique to compensate interference and improve network performance was proposed in [207] by introducing the use of wavelength division multiplexing (WDM) on NLOS UV-C networks. Every transceiver node contains a multi-interface and multi-channel device, and a band-pass filter is configured in the receiving nodes. Three types of NLOS configurations were simulated and the results validated that multi-channel access technology can increase the throughput. Moreover, a fast power control and channel assignment scheme (FPCCA) was suggested to reduce interference in [208]. This scheme controls the transmitted power of each node and coordinates the concurrent transmissions ensuring both energy savings and network throughput improvement. The performance with different angles and different network traffic loads was simulated and analyzed. An energy saving more than 10% was achieved, whereas the algorithm provides the advantages of fast convergence and small degree of conflict.

B. Connectivity/Coverage

Connectivity, a fundamental property in multi-hop networks, has been extensively studied in wireless RF networks (see [209] and the references therein). A fully connected multi-hop network provides a communication path between a source-destination pair. In a number of cases, k-connectivity needs to be satisfied in order to enhance communication reliability [210]. This term refers to the property that a random node can communicate with at least k neighbors. Towards this direction, k-connectivity was investigated for NLOS UV-C multi-hop networks in [63], [211], and [212]. The study in [63] adopted an empirical path loss model described in [151] and focused on the interaction between various network parameters in order to obtain a k-connected two-dimensional UV-C network. Uncoded OOK and PPM modulation formats as wells as Gaussian and Poisson noise models were taken into account. This work was extended in [212] to capture the effect of MUI on k-connectivity. Different system configurations were analyzed and compared showing the existence of trade-offs between the probability of k-connectivity and the coverage area with a fixed number of nodes. The ability of the Txs to track the desired Rxs is quite critical, whereas an interesting scenario was discussed based on multi-Tx transceiver design. Moreover, the interaction of the node isolation probability and various network parameters, including the node density, the data rate, the required amount of power to achieve a certain error probability floor, was investigated in [211] for a serial UV-C multihop network. The approximate single scattering path loss model suggested in [90] and different geometrical transceiver configurations were considered.

Finally, the k-connectivity properties of unmanned aerial vehicles (UAVs) network were examined in [213], where two typical mobility models were used to describe the movement of the nodes, i.e., the random waypoint (RWP) model and the circle movement based model (CMBM). The impact of node density, transmission power, and data rate on k-connectivity is considered. Numerical results showed that the mobility degrades the connectivity probability, e.g., in order to achieve 2-connectivity for 500 nodes and data rate 10kbps, the required transmission power for nodes moving according to RWP is lower than CMBM.

Coverage is also a primary concern in the network design procedure. Using a random node deployment, appropriate algorithms were proposed in the literature in order to maximize the coverage of a service area with the minimum activated nodes. In the case of NLOS UV-C networks, a graded area coverage optimization algorithm based on genetic algorithms (GACOA) was proposed in [214]. This algorithm selects the suitable communication angle to improve network coverage and estimates the network deployment cost in order to extract an optimum network deployment scheme. Several numerical results were depicted, showing that the proposed algorithm is quite efficient to provide a reliable deployment. Moreover, the deployment cost is low and the coverage ratio is higher than random deployment schemes. Furthermore, a networking strategy for a 3D wireless UV-C communication network (UVNNS) was proposed in [215] to investigate the coverage and connectivity of the UV-C network against several communication parameters (including apex angle, transmitted power, data rate, error probability and node density), modulation (including OOK and PPM), as well as Gaussian and Poisson noise. Focus is given on the deployment cost of network when nodes are located in several positions and regions of interest with obstacles. Moreover, the optimum deployment scheme taking coverage ratio, connectivity, and deployment cost was derived.

C. Neighbor Discovery

In most applications, multi-hop networks are deployed in a random manner which means that a node is unlikely to have an a priori information about its neighbors or about the network topology. In such a case, the problem of neighbor discovery is getting quite challenging. This topic has been adequately investigated in RF wireless networks assuming either directional or omni-directional antennas (see [216] and the references therein). In the context of UV-C networks, [48] and [217] were the first studies on this topic. In [48], a mobile ad hoc UV-C network was examined where each node transmits or receives signals through NLOS links in different directions. The nodes correspond to transceivers able to transmit in multiple directions and perform omni-directional receptions, whereas full-duplexing capability is considered. Effective neighbor discovery protocols were implemented taking account of the varying channel qualities for different scattering directions. A table containing a list of node pointing directions between each pair of nodes in terms of channel qualities was employed. Two algorithms were proposed with and without the need for direction synchronization. Moreover, the second algorithm was enhanced with neighbor feedback. In order to attain the appropriate direction for the best performance, every node collects ‘credits’ to rank all the possible directions. Since this approach is quite time consuming, a more efficient approach was proposed in [217]. The key idea was the introduction of leader nodes, i.e., nodes which are allowed to perform neighbor discovery at any given time. In that way, the negative effects of random access based collisions are properly treated. The approach does not require a prior knowledge of the number of nodes and, thus, effectively facilitates neighbor discovery in a fast and effective way. Simulation results indicated that the time needed for the neighbor discovery process decreased by as much as 90% compared to the method presented in [48].

D. MAC

The design of higher layer protocols for UV-C communications has not received much attention since most of the recent research efforts focused on physical layer issues. However, an efficient protocol design is crucial for a reliable UV-C network operation. Several preliminary proposals on MAC protocol design have been presented in the literature, based on the recent progress made in channel modeling. In this way, a MAC protocol for UV-C outdoor communications (UVOC-MAC) was proposed in [218]. This design was based on the exploitation of NLOS links, the use of multiple rates, and the opportunistic use of full-duplex communications. In more detail, UVOC-MAC belongs to random access slot-based protocols where a pulse is transmitted in every slot. The protocol makes uses of spatial reuse by selecting in an adaptive manner the direction, the pointing angle, and the data rate. Normally, nodes are in the idle state and the control signals are decoded. When new data arrives, a node first examines proper tables to assure if transmission is possible. If the selected pointing angle is less than or equal to a predetermined value, a full-duplex mode or a half-duplex mode is selected, respectively. Half-duplex communications are possible only for higher pointing angles. The channel sharing problem was studied in [219], where the proposed algorithm adopted the coloration technique of the classical graph theory. This work was extended in [220], where a time division multiple access (TDMA) protocol was proposed and a hybrid genetic algorithm was used to colorize the conflict nodes in the network. The results, derived by a proper simulation framework, reveal the ability of the protocol to improve the throughput and control the end-to-end delay. Finally, a count-and-forward (CF) protocol was introduced in [221], as a means to enhance the weak optical communication link and improve the Rx characteristics. The relay and the destination both utilize an ideal photon counting Rx. A relay forwarding power optimization problem was formulated to minimize the destination detection error probability depending on the relay forwarding power budget and an optimal solution for a piecewise exponential approximation was provided. Numerical results prove that the proposed relay scheme outperforms the relay hard-decision forwarding one, and approaches the performance of the optimal power allocation when simulated annealing is used.

VII. Conclusion, Challenges, and Future Trends

UV-C communications have advanced significantly in the recent decade, mainly driven by the breakthrough in the source technologies in the solar blind band. Lasers and LEDs are the typical Txs adopted for long and short range NLOS scattering communications, respectively. A commercial compact UV-C laser can deliver a continuous optical power of hundreds of milliwatts, suitable for communication at a distance of multiple kilometers. A commercial LED chip has achieved a capacity of 1mW/0.8mW optical power at a wavelength of 280nm/265nm operating in a normal driving current condition such as 20mA. Utilizing arrayed packaging, a Tx module can integrate dozens of LED chips to deliver a total power up to tens of milliwatts. If operated in a low duty cycle mode, the driving current for the LED chip can increase over 1A, and thus the peak optical power increases dramatically. This sum-power capability helps a communication system to extend the distance for a fixed data rate or increase the data rate for a fixed distance. Multiple modules can be further integrated to boost the transmission power. However, the power efficiency of all the current UV-C optical sources is still very low. Novel materials and optimal internal structures of LEDs need to be pursued to deliver tens of watts power, as the visible light sources do.

Following improvements over an earlier real-time NLOS SISO experimental system [222], the latest reported high data rate and long distance real-time system employs a SIMO setup to better mitigate channel distortions [223]. At the Tx, a field-programmable gate array (FPGA) board is equipped with a digital-to-analog converter (DAC). It realizes random bit stream generation, OOK data modulation, cyclic redundancy check (CRC) coding and different FEC coding. Its output drives an external acousto-optic modulator to control on/off states of a 266nm continuous-wave solid-state laser at 0.8mrad divergence angle and maximum output power of 200mW. At the Rx, three PMTs with the solar blind optical filters convert the optical signals to the electrical signals which are fed into analog-to-digital converters (ADC) and subsequently combined to form a digital sequence in a FGPA board. Then synchronization, channel estimation, data demodulation and decoding are implemented as well. The system was tested on a cloudy day in the Spring, and achieved real-time performance of bit rate 1.1Mbps over 1km distance, when the optical transmission power was 120mW and the Rx pointing offset angle was about 1^o. The experimental system and results have further advanced the study on NLOS UV-C communications. The utilization of more powerful optical devices and advanced modulation schemes can achieve higher data rate and longer transmission range.

From the communication viewpoint, there still exist significant challenges from the Tx to the channel and Rx. As an NLOS UV-C communication system is both power-limited (the source power is limited and the path loss is huge) and bandwidth-limited (numerous multiple scattering paths can even spread the transmitted pulse temporally by orders of magnitude), power and bandwidth efficient data modulation schemes are critical at the Tx side for efficient information transmission. A good channel coding technique helps to tackle channel fading due to atmospheric turbulence while maintaining a reasonable processing complexity at the Rx, when communication distance is more than hundreds of meters. Pulse shaping needs to be optimized to better match the channel frequency characteristics and transfer information. In addition, beam shaping techniques with proper optical design are necessary to transfer energy to the destination efficiently. Signal propagation characteristics require new tools and analysis for a more precise description in terms of power decay, pulse broadening, and signal fluctuation. Due to the nature of scattering, more accurate models based on transport theory or ray tracing should be derived. Perhaps it requires quantum mechanics to completely understand the channel.

At the Rx side, advanced demodulation and signal detection techniques are essential to extract the desirable signal which has been overwhelmed by various noises, including optical background noise, device dark noise, and post-processing circuit thermal noise. Towards this end, there is still a lack of appropriate signal models spanning a large range of received signal intensity. Optimal signal detection methods are tightly tied to the models, from waveform processing techniques when the signal is strong, to photon counting techniques when the signal is extremely weak, and mixed continuous-discrete processing techniques when the signal exhibits a transition behavior. Meanwhile, ISI might be a killing factor for communication performance in rich scattering, and, thus, channel post-equalization and ISI cancelation techniques are necessary. To enhance link reliability and diversity, a MIMO configuration can be set up using multiple light sources and multiple detectors. Coding and modulation have to be generalized to the joint space-time domain to either maximize the channel capacity or improve the communication performance. This rational follows from the recent study conducted in [224], where the authors demonstrated a near-solar-blind UV-B-LED based communication channel with the remarkable data rate of 71Mbit/s based on QAM OFDM. Similar trials are also anticipated for systems working in the UV-C band.

In addition to point-to-point communications, multi-node communications allows users to share the medium. For a mobile ad hoc network, ways to enable multiple access in time, space, code, electrical frequency, or wavelength are not fully understood in NLOS UV-C communications. Omnidirectional to quasi-directional and even directional antennae require different MAC protocols. Even though NLOS UV-C scattering communication shows range-dependent security, attributed to the power decay profile from a square law to an exponential law as distance increases, information security is still a big concern since the signals can be easily intercepted if an eavesdropper is within the coverage area. Physical layer security enhancement techniques coupled with light sources or driving circuits may provide feasible solutions to overcome this important issue.

In conclusion, rich theoretical results have been reported by different researchers worldwide so far, but experimental studies are by far inadequate, leaving various developed models and methods in the literature experimentally unverified. For example, so many channel models have been developed, but which ones are more applicable in a practical environment? It is more desirable to obtain first-hand comprehensive measurement data in field trials, such as in different geographic, seasonal, weather, and all-day long operation conditions, and apply data mining techniques to analyze correlations of the events. Along this line, one may hopefully reach some concrete models and tabulate typical model parameter settings for practical use. Meanwhile, different network and MAC protocols proposed in the literature have not been fully validated by experiments. It is also in an urgent need to develop multi-node prototypes to test relevant methods and protocols.

With those issues resolved, it is anticipated that NLOS UV-C scattering communications will be very suitable for communications on-the-move, Internet of Things, and machine-to-machine communications in harsh environments. It will serve uniquely for its own sectors or as a prominent complementary solution to existing mobile communications.

In particular, the synergy with the optical wireless technologies briefly discussed in [225], will take on a special importance in the near future.

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