Connectivity Issues for Ultraviolet UV-C Networks

Alexander Vavoulas, Harilaos G. Sandalidis, and Dimitris Varoutas

***Abstract*—This paper focuses on the connectivity issues of a non-line-of-sight (NLOS) optical wireless network operating in the ultraviolet UV-C spectral region. NLOS UV-C transmitters have a limited effective coverage and, hence, a dense node distribution is required in order to efficiently cover a large geographical area. Under this assumption, the concept of connectivity is more than important since it provides a strong indication of the network reliability and robustness. In the present study, we consider transmission with on–off keying and pulse position modulation schemes assuming both Gaussian and Poisson noise and adopt an effective experimental path loss model. Then, we evaluate the *k*-connectivity properties in terms of several network parameters. More precisely, we present and analyze the trade-off between node density and the degree of *k*-connectivity against other parameters (i.e., transmitted power, supported data rate, and error probability). The derived results are depicted using appropriate figures and tables and constitute the theoretical basis for the design and implementation of a reliable UV-C network in practice.**

***Index Terms*—*k*-connectivity; Multi-hop networks; Non-line-of-sight (NLOS) propagation; Ultraviolet (UV-C) transmission.**

I. Introduction

Non-line-of-sight (NLOS) optical transmission in the ultraviolet UV-C spectral region is an effective solution for overcoming alignment problems of conventional line-of-sight (LOS) optical wireless systems[1] [1]. The transmission in this region (particularly from 200 to 280 nm), also known as the solar-blind band, exhibits some unique characteristics. Firstly, most of the solar radiation is getting absorbed by the ozone in the upper atmosphere, leading to almost negligible background noise at the Earth's surface. Secondly, the UV-C light generated from terrestrial sources is strongly scattered due to the presence of suspended particles in the atmosphere [2]. The insignificant background solar radiation and the strong atmospheric scattering enable the activation of NLOS communication links with large field-of-view (FoV) receivers which allow a large amount of scattered light collection. Recent advances in hardware have led to the emergence of low cost semiconductor laser diodes and miniaturized LEDs at UV-C frequencies making this new technology a quite promising solution for short-range communications [3].

Roughly speaking, UV-C communications meet both commercial and military applications needs. Some commercial applications include aircraft landing aid under low visibility conditions, moisture tracking in agriculture, public building surveillance, and environmental monitoring around chemical industries. Military applications include unattended ground sensor (UGS) networks for perimeter surveillance and monitoring troop movement along established routes, flame sensing, biological fluorescence detection, and ground-to-air communications. Obviously, more applications will emerge in the near future due to the continuous evolution of this new communication technology [4].

In general, UV-C technology is applicable to NLOS short-range communications which require dense network configurations. That happens because, even though UV-C channels are quite robust to meteorological conditions, they are characterized by strong channel attenuation. This reduces both the maximum obtainable data rate and the transmission range, necessitating, thus, dense network deployments [3]. Taking into account the above channel characteristics, Keddar and Arnon, in [5], introduced a network of NLOS UV-C sensors operating in a multi-scattering channel and showed the influence of atmospheric parameters on the level of power reception. In [6], Keddar discussed the arising multi-access interference for various sensor node densities and traffic levels. In another study, Shaw *et al.* evaluated and tested a solar-blind UV-C communication link for unattended ground sensors [7].

One way to extend the NLOS UV-C transmission range and cover large areas is to use a network, by means of multiple node-to-node hops. Relay assisted transmission is a common technique in wireless RF communication systems since it provides a broader and more efficient coverage and can be used as a fading mitigation tool [8]. Every intermediate node in a multi-hop network acts as a router that forwards traffic towards its destination. That technique was also proposed to enhance free-space optical (FSO) transmission by mitigating various impairments, such as turbulence [9]. Very recently, a performance analysis on serial relayed UV-C links has been presented in [10] by He *et al.*

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[1] We adopt the term UV-C communications instead of UV communications since the solar-blind region is a part of the UV-C sub-band of the UV spectrum.

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To improve the reliability of communications in a NLOS UV-C multi-hop sensor network, connectivity issues need to be investigated. A fully connected network has a path from any node to any other node. When there is no path between at least one source–destination pair, the network is disconnected [11]. Connectivity was mainly studied for RF wireless networks where the propagation suffers from various severe, random in nature impairments such as path loss, multi-path fading, and shadowing [12,13].

In the context of NLOS UV-C sensor networks, it is more reasonable to examine the k-connectivity performance with respect to the specific impact of attenuation introduced by UV-C channels. To this end, we consider a multi-hop UV-C network model where the nodes are distributed at fixed positions on a service area. The most fundamental modulation formats are considered, i.e., on–off keying (OOK) and pulse position modulation (PPM). Several illustrative examples are presented to show the interaction between various parameters, including the node density, the required amount of power for achieving a certain error probability floor, the range of coverage, etc. To the best of the authors' knowledge such a study is not available in the open technical literature.

The rest of the paper is organized as follows. Section II gives a short description of the network model and outlines the basic concepts of graph theory necessary for our analysis. In addition, the k-connectivity performance is analyzed and the probability that two random nodes are k-hop neighbors is evaluated. In Section III, the UV-C path loss model under consideration is presented. Expressions for the achievable ranges for the above mentioned modulation formats are given considering both Poisson and Gaussian noise models, as well. Numerical results are illustrated and discussed in Section IV. Finally, some concluding remarks are summarized in Section V.

II. Preliminaries

A. The Network Model

We consider a multi-hop network configuration consisting of several NLOS UV-C communication sensors. A typical UV-C link between a transmitter (Tx) and a receiver (Rx) is shown in Fig. 1. Both the Tx and Rx face vertically upwards; i.e., they have 90° apex angle. Although there are other possible UV-C arrangements with different apex angles, we consider this specific scenario because we want to cover a circular area around the UV-C Tx. The use of apex angles less than 90° increases the bandwidth but limits the cover area, like using directional antennas in RF communications. However, a 90° apex scenario is adequate in sensing where low data rates are used, whereas it can be used as a benchmark for other arrangements with different apex angles.

In this scenario, the Tx transmits a signal vertically upwards having a beam divergence angle ϕ_1. The cone produced by the Tx beam intersects the Rx FOV cone of ϕ_2 degrees. The separation between Tx and Rx is r, while the distances from the common volume V to the Tx and Rx are r_1 and r_2, respectively. A communication link is established

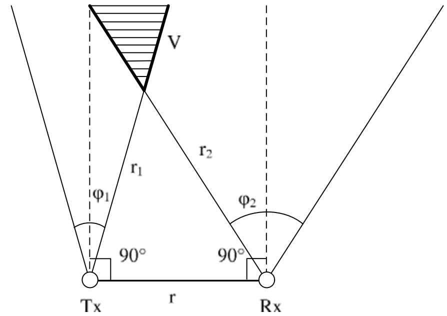

Fig. 1. UV-C NLOS link geometry.

when the optical power is backscattered by particles inside the volume produced by the intersection of the two cones and reaches the Rx node.

Next, we assume that a number of n nodes is distributed at fixed positions on a service area A. Each node is independently placed on the service area according to a homogeneous Poisson point process. Assuming large values of n and A, a constant node density, $\rho = n/A$, can be obtained. Under this assumption, the homogeneous Poisson point process can be obtained as the limiting case of the uniform distribution [14]. Consider, now, the case where all the nodes have the same transmission range r_0, i.e., homogeneous range assignment [15]. This means that every node covers a circular region with area $A' = \pi \cdot r_0^2$. Every source node forwards traffic towards one or more destination nodes provided that their cones are intersected. If this does not happen, the node is getting isolated. If the transmission range is short, the probability of having isolated nodes increases. In contrast, assuming a large range, interference problems may appear. Apparently, if a node can communicate with more than one neighbor, the network robustness significantly increases; hence a proper selection of the transmission range is a critical parameter for the network connectivity robustness.

B. k-Connectivity Issues

The multi-hop UV-C network can be represented as a undirected graph G with a set of vertices V and a set of edges E [16]. The set of vertices has cardinality n and represents the set of nodes, while the set of the edges corresponds to the UV-C communication links between the nodes. The node degree, $d(u)$, is defined as the number of links of a node (i.e., the number of neighbor nodes within its range). An isolated node has a null node degree. The minimum node degree, $d_{\min}$, of G is defined as the minimum value among the node degrees.

Since the nodes are placed in fixed positions, the existence of isolated nodes is undesirable. In terms of communication networks, the probability that no node is isolated in the multi-hop UV-C network depends on the node density, ρ, as well as the transmission range, r_0, of every UV-C node and is given by [17]

$$P(d_{\min} > 0) = \left(1 - e^{-\pi \rho r_0^2}\right)^n. \quad (1)$$

Furthermore, the probability that each node in a multi-hop UV-C network has a minimum node degree $d_{\min} \geq k$ is given by [17]

$$P(d_{\min} \geq k) = \left(1 - \sum_{i=0}^{k-1} \frac{(\pi\rho r_0^2)^i}{i!} \cdot e^{-\pi\rho r_0^2}\right)^n. \tag{2}$$

A path is defined as a sequence of successive edges on G. The existence of a path between two nodes denotes that they are connected. G is connected when a path exists between all pairs of nodes. Similarly, we say that G is *k-connected* ($k \geq 1$) when k mutually independent paths exist between all pairs of nodes [16]. The conditions (1) and (2) ensure that every node has at least one neighboring node within its range. However, the event $d_{\min} > 0$ is not a sufficient condition for ensuring the connectivity of the network. It can be proven that, if $n \gg 1$, then

$$P(G \text{ is } k\text{-connected}) = P(d_{\min} \geq k) \tag{3}$$

for $P(d_{\min} \geq k)$ almost 1 [16].

Apparently, the minimum transmission range ensuring k-connectivity is important for the proper operation of the network. However, the minimum transmission range is directly related to the adopted modulation and/or coding format. Hence, the aim of this paper is to address the following question: *Given a homogeneous range assignment r_0, for a given modulation scheme, what is the minimum node density ρ required to achieve a k-connected network with probability close to 1?*

III. UV-C Channel Modeling and Achievable Minimum Range

Several propagation effects, including molecular, aerosol scattering and absorption, degrade transmitting signals in the UV-C region. Scattering enables NLOS UV-C communications by redirecting the transmitted signal, due to the interaction with atmospheric constituents, towards the Rx. However, this mechanism induces a high attenuation degree making the determination of an effective path loss model quite challenging. The adoption of the single-scattering model, proposed in [18] for examining the attenuation of short-range optical scatter communication links, was initially presented in [19]. That model, however, is not accurate for all Tx and Rx apex angles and is quite complicated to use in practice. To overcome these limitations, Chen *et al.* in [4], proposed an empirical channel path loss model based on a set of extensive measurements. In their study, the authors demonstrated a communication test-bed and collected path loss measurements, for various combinations of Tx and Rx apex angles. On the basis of these measurements, the following simple power decay model was proposed in [20]:

$$L = \xi r^{\alpha}, \tag{4}$$

where ξ is the path loss factor and α the corresponding path loss exponent. The values for both quantities depend on the Tx and Rx apex angles and can be determined using the figure and table formats in [4] and [21], respectively.

The minimum achievable range of each node depends on the adopted modulation and/or coding format. In the literature, the most reported modulation techniques for optical wireless communications are OOK and PPM. In [21], the minimum achievable ranges for OOK and PPM under Poisson and Gaussian noise models have been obtained. The selection of the noise model depends on the detection method as well as the background noise level. Specifically, a Poisson noise model applies when photon counting based detection is adopted and the noise due to dark current in the photodetector or background illumination is kept at a low level. A Gaussian model is assumed when the thermal noise dominates or interference in the UV-C band of interest exists. For the Poisson noise model, the minimum achievable range for OOK is derived according to [21] as

$$r_{OOK,P} = \sqrt[\alpha]{-\frac{\eta\lambda P_t}{hc\xi R_b \ln(2P_e)}}, \tag{5}$$

and for PPM as [21]

$$r_{PPM,P} = \sqrt[\alpha]{-\frac{\eta\lambda P_t \log_2 M}{hc\xi R_b \ln\left(\frac{MP_e}{M-1}\right)}}. \tag{6}$$

In the above equations, h denotes Planck's constant, λ is the wavelength, c is the speed of light, η is the quantum efficiency of the optical filter and photodetector, P_t is the transmitted power, R_b the data rate, P_e the probability of error, and M is the length of the PPM symbol. For the Gaussian noise model, the corresponding range for OOK according to [21] is

$$r_{OOK,G} = \sqrt[\alpha]{\frac{\eta P_t}{\xi\sqrt{N_0 R_b}\, Q^{-1}(P_e)}}, \tag{7}$$

whereas for PPM it can be given by the following approximation:

$$r_{PPM,G} \approx \sqrt[\alpha]{\frac{\eta P_t}{\xi Q^{-1}(P_e)}\sqrt{\frac{M\log_2 M}{2N_0 R_b}}}, \tag{8}$$

where $Q(\cdot)$ is the Gaussian Q function defined as $Q(x) = 1/\sqrt{2\pi}\int_0^{\infty} \exp^{-\frac{t^2}{2}} dt$ and also related to the complementary error function $\operatorname{erfc}(\cdot)$ by $\operatorname{erfc}(x) = 2Q(\sqrt{2}x)$, and

$$N_0 = \frac{q\zeta N_n hc}{\lambda}, \tag{9}$$

is the white noise power spectral density. In Eq. (9), q denotes the electrical charge, ζ is the photomultiplier tube responsivity, and N_n the noise photon count rate. By substituting Eq. (5), Eq. (6), Eq. (7), or Eq. (8) into Eq. (2) we can find the probability of the network k-connectivity for OOK and PPM modulation formats, under either the Gaussian or the Poisson noise model, as a function of a number of parameters, i.e., transmitted power, supported data rate, probability of error, and node density. Specifically, analytical results in Section IV will focus on the effects of each of the above parameters when the others remain fixed.

It has to be noted that the minimum achievable range provided for both the Poisson and Gaussian noise models

TABLE I
SYSTEM MODEL PARAMETERS

Parameter	Value
Wavelength λ	250 nm
Tx average power	50 mW
Tx beam full-width divergence φ_1	17°
FoV angle φ_2	30°
Noise photon count rate N_n	14,500 s^{-1}
Photomultiplier tube responsivity ζ	62 A/W
Optical filter efficiency η_f	0.15
Photomultiplier tube quantum efficiency η_{PMT}	0.30
Data rate R_b	10 kbps
Length of PPM symbol M	4
Path loss exponent α	1.23
Path loss factor ξ	$1.6 \cdot 10^9$

strongly depends on the transmitted power of UV-C light source. By increasing the source power we can extend the distance to some extent. Hence, the range is directly related to the technological progress regarding the development of semiconductor LED and laser UV-C sources. Nevertheless, the trade-off between the available transmit power and the skin and eye exposure limits, which were recently established in [22], is critical for applications in the UV-C region.

IV. Numerical Results and Discussion

In this section, we present analytical results in order to study the connectivity behavior of a NLOS UV-C multi-hop sensor network consisting of $n = 500$ sensors uniformly distributed on a given service area. Most of the model parameters are presented in Table I [21]. Unless specified otherwise, the transmitted power and supported data rate are 50 mW and 10 kbps, respectively.

A. The Impact of the Node Density and Modulation Format

Figures 2 and 3 demonstrate the impact of the node density, ρ, on $P(d_{\min} > k)$, where $k = \{1,2,3,4\}$, assuming OOK for the Gaussian and Poisson noise models, accordingly. At first, we observe that an increase of error probability, P_e, increases the transmission range of each node and reduces the corresponding node density required to achieve k-connectivity, i.e., $P(d_{\min} > k) \approx 1$. Moreover, in order to attain a specific degree of k-connectivity for $P_e = \{10^{-6}, 10^{-3}, 10^{-1}\}$, the required node density, ρ, for the Gaussian noise model is about 2, 3, and 7.5 times, respectively, greater than the corresponding one for the Poisson noise model. A denser node distribution, about 25%, is required to achieve 2-connectivity as compared with 1-connectivity, for a given P_e. This percentage further increases to 40% and 60% from $k = 1$ to $k = 3$ and from $k = 1$ to $k = 4$, respectively. For the Gaussian model, the node density should be doubled in order to reduce P_e from 10^{-1} to 10^{-3} and quadrupled from 10^{-3} to 10^{-6}. On the other hand, the node density for the Poisson noise model becomes triple and ninefold, correspondingly.

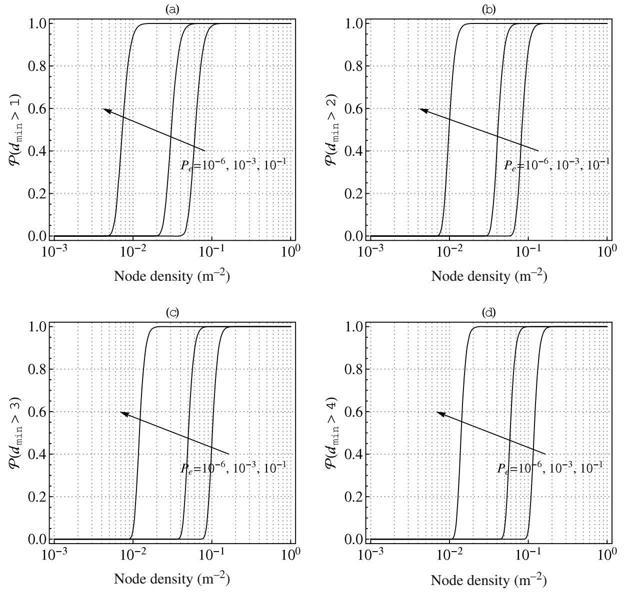

Fig. 2. $P(d_{\min} > k)$ versus ρ for OOK and the Gaussian noise model assuming $P_t = 50$ mW and $R_b = 10$ kbps.

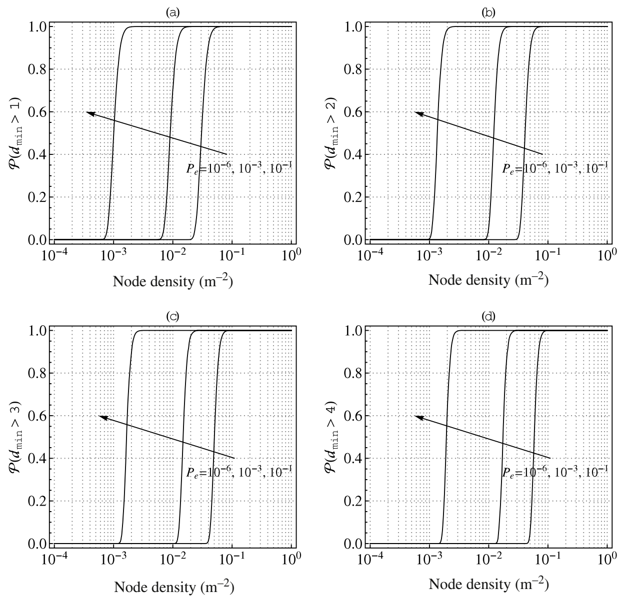

Fig. 3. $P(d_{\min} > k)$ versus ρ for OOK and the Poisson noise model assuming $P_t = 50$ mW and $R_b = 10$ kbps.

Similar results for the PPM format are shown in Figs. 4 and 5 for the Gaussian and Poisson noise models, respectively. Here, to achieve a specific degree of k-connectivity for $P_e = \{10^{-6}, 10^{-3}, 10^{-1}\}$, the required node density, ρ, for the Gaussian noise model is about 2, 3, and 5 times greater than the one for the Poisson noise model. In addition, keeping a constant value of P_e, an increase from $k = 1$ to $k = 2$ requires a node distribution denser by 25%, that from $k = 1$ to $k = 3$ one denser by 45%, and that from $k = 1$ to $k = 4$ one denser by 65%. In this case, the reduction of P_e from 10^{-1} to 10^{-3} leads to a

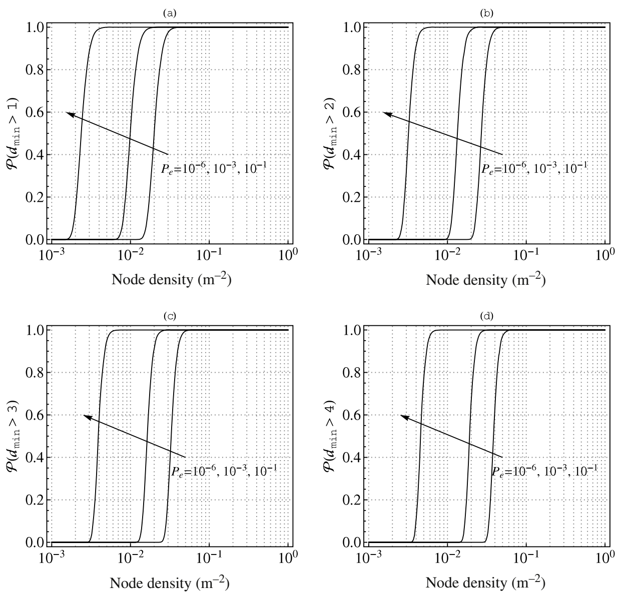

Fig. 4. $P(d_{\min} > k)$ versus ρ for PPM and the Gaussian noise model assuming $P_t = 50$ mW and $R_b = 10$ kbps.

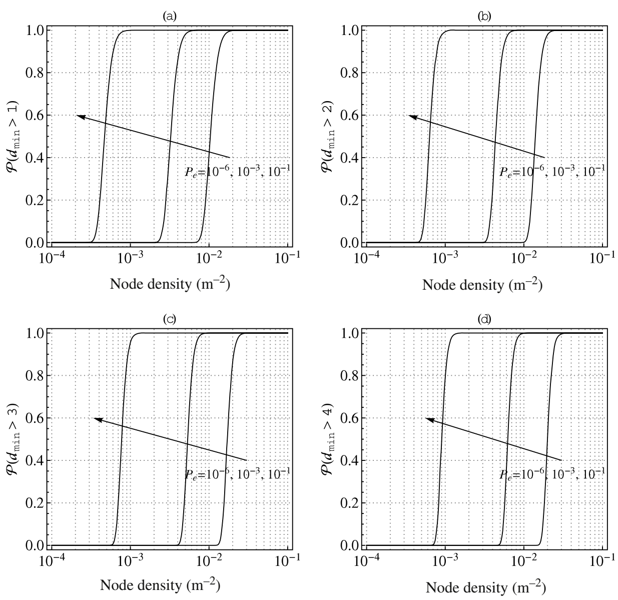

Fig. 5. $P(d_{\min} > k)$ versus ρ for PPM and the Poisson noise model assuming $P_t = 50$ mW and $R_b = 10$ kbps.

multiplication of ρ by 4 (Gaussian noise) and 7 (Poisson noise). A further reduction from 10^{-3} to 10^{-6} requires multiplication by 2 (Gaussian noise) and 3 (Poisson noise).

Comparing Figs. 2 and 4 as well as Figs. 3 and 5, we observe that the node density required to achieve a specific k-connectivity degree for a given P_e is notably smaller on adopting the PPM format. This is expected since the PPM scheme is generally more efficient than the OOK.

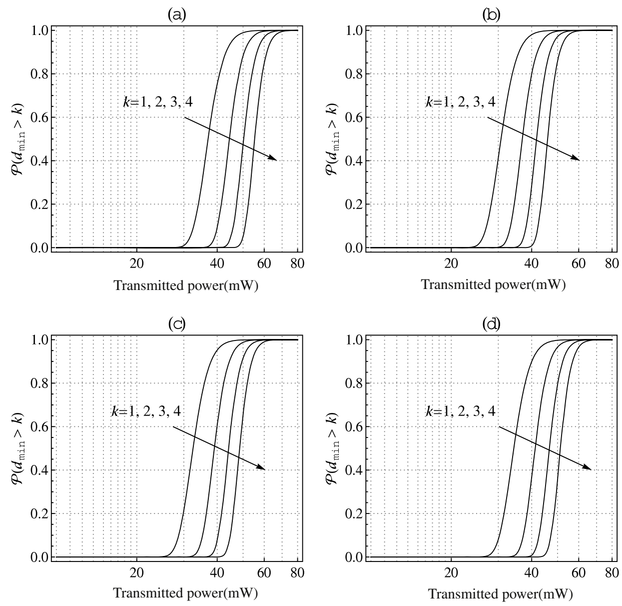

Fig. 6. $P(d_{\min} > k)$ versus transmitted power for $R_b = 10$ kbps and (a) OOK and the Gaussian noise model ($\rho = 5 \cdot 10^{-2}$), (b) OOK and the Poisson noise model ($\rho = 2 \cdot 10^{-2}$), (c) PPM and the Gaussian noise model ($\rho = 2 \cdot 10^{-2}$), and (d) PPM and the Poisson noise model ($\rho = 6 \cdot 10^{-3}$).

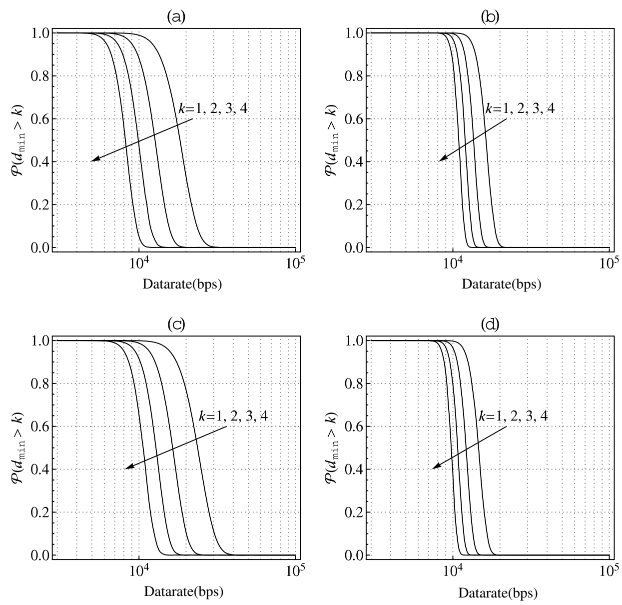

Fig. 7. $P(d_{\min} > k)$ versus supported data rate for $P_e = 10^{-3}$ and (a) OOK and the Gaussian noise model ($\rho = 5 \cdot 10^{-2}$), (b) OOK and the Poisson noise model ($\rho = 2 \cdot 10^{-2}$), (c) PPM and the Gaussian noise model ($\rho = 2 \cdot 10^{-2}$), and (d) PPM and the Poisson noise model ($\rho = 6 \cdot 10^{-3}$).

B. The Impact of the Transmitted Power and Supported Data Rate

Figures 6 and 7 illustrate the probability $P(d_{\min} > k)$ against the transmitted power and the supported data rate, respectively. The value of ρ in each case has been chosen so as

TABLE II
COVERAGE ANALYSIS FOR THE GAUSSIAN NOISE MODEL

(a) $n = 500$

Modulation format	OOK			PPM		
P_e	10^{-1}	10^{-3}	10^{-6}	10^{-1}	10^{-3}	10^{-6}
$P(d_{\min} > 1)$	41,667 m^2	10,000 m^2	5000 m^2	125,000 m^2	33,334 m^2	15,625 m^2
$P(d_{\min} > 2)$	33,334 m^2	8334 m^2	3847 m^2	104,167 m^2	25,000 m^2	11,905 m^2
$P(d_{\min} > 3)$	29,412 m^2	7143 m^2	3334 m^2	89,286 m^2	20,834 m^2	10,417 m^2
$P(d_{\min} > 4)$	25,000 m^2	6250 m^2	3125 m^2	76,924 m^2	17,858 m^2	9260 m^2

(b) $n = 5000$

Modulation format	OOK			PPM		
P_e	10^{-1}	10^{-3}	10^{-6}	10^{-1}	10^{-3}	10^{-6}
$P(d_{\min} > 1)$	357,143 m^2	83,334 m^2	41,667 m^2	1,063,830 m^2	250,000 m^2	125,000 m^2
$P(d_{\min} > 2)$	294,118 m^2	62,500 m^2	33,334 m^2	877,193 m^2	208,334 m^2	104,167 m^2
$P(d_{\min} > 3)$	250,000 m^2	55,556 m^2	29,412 m^2	769,231 m^2	178,572 m^2	89,286 m^2
$P(d_{\min} > 4)$	227,273 m^2	50,000 m^2	26,316 m^2	675,676 m^2	161,291 m^2	80,646 m^2

to ensure 1-connectivity for $P_e = 10^{-3}$. When the transmitted power of each node increases and its data rate decreases, the number of neighboring nodes lying in its range increases. As a result, the degree of k-connectivity increases, as well. In Fig. 6, we note that about 15% more power is required to get from $k = 1$ to $k = 2$, whereas this percentage is dropped to 10% from $k = 2$ to $k = 3$. This is quite important since the available transmitted power is limited from both manufacturing technology and regulations on UV-C exposure limits. In Fig. 7, we observe that the data rate reduction required from $k = 1$ to $k = 2$ is about 18%, whereas this percentage is dropped to 15% from $k = 2$ to $k = 3$.

C. Coverage Analysis

We define the network coverage as the geographical area required to deploy a specific number of UV-C nodes, n, and achieve a k-connected network. Under this framework, Table II presents a numerical example for the achievable coverage, assuming several values of error probability and degree of k-connectivity, for $n = 500$ and $n = 5000$, respectively. We adopt the Gaussian noise model and assume $P_t = 50$ mW and $R_b =$ 10 kbps. As an example, we observe that the same coverage is required to deploy 500 nodes in order to achieve 2-connectivity with $P_e = 10^{-1}$ for OOK and 1-connectivity with $P_e = 10^{-3}$ for PPM. Hence, an appropriate trade-off of the error probability, the degree of k-connectivity, and the coverage is required for the successful deployment of a given UV-C network.

V. CONCLUSIONS

Recent advances in the UV-C spectral region have enabled the development of short-range, NLOS optical communications. In order to extend the coverage region, we proposed network operation via multiple node-to-node hops and investigated the system performance in terms of the k-connectivity property. The effect of several network parameters, such as the node density and the probability of error, were examined for uncoded OOK and PPM modulation schemes, assuming Poisson and Gaussian noise models. Various numerical results were illustrated, showing a useful outcome for telecom system designers for constructing a reliable UV-C network.

Apparently, better results can be obtained by using more efficient modulation schemes, e.g., subcarrier intensity modulation, as well as incorporating coding, e.g., repetition or convolutional codes. Moreover, the use of different deployment geometries, e.g., use of directional beams, can obviously enhance the performance; however, the connectivity analysis in this case is getting much more complicated and is a subject of ongoing research. Therefore, the present study can be considered as a benchmark for the performance evaluation of more complicated scenarios.

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