IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received October 10, 2019, accepted November 5, 2019, date of publication November 18, 2019, date of current version December 5, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2954049

Efficient Exploitation of Radio Frequency and Visible Light Communication Bands for D2D in Mobile Networks

MEHYAR NAJLA, (Student Member, IEEE), PAVEL MACH, (Member, IEEE), ZDENEK BECVAR, (Senior Member, IEEE), PETR CHVOJKA, AND STANISLAV ZVANOVEC, (Senior Member, IEEE)

Faculty of Electrical Engineering, Czech Technical University in Prague, 166 27 Prague, Czech Republic

Corresponding author: Mehyar Najla (najlameh@fel.cvut.cz)

This work was supported in part by the Czech Science Foundation under Grant GA17-17538S, and in part by the Czech Technical University in Prague under Grant SGS17/184/OHK3/3T/13.

ABSTRACT The concept of device-to-device (D2D) communication, combining common radio frequency (RF) and visible light communication (VLC), is seen as a feasible way how to cope with spectrum crunch in the RF domain and how to maximize spectral efficiency in general. In this paper, our objective is to decide when RF should be utilized or if VLC proves to be the more profitable option. The selection between RF and VLC is defined as a multi-objective optimization problem targeting primarily to minimize the outage ratio while the secondary objective is to maximize the sum capacity of D2D pairs, composed by D2D transmitters and D2D receivers. To solve this problem, we design a centralized low-complexity heuristic algorithm selecting either RF or VLC band for each D2D pair relying on the mutual interference among the pairs. For interpretation of the mutual interference among the D2D pairs, we exploit directed weighted graphs adopted from the graph theory. The simulation results show that the proposed algorithm outperforms state-of-the-art algorithms in terms of the outage ratio, sum capacity and average energy efficiency. What is more, despite a very low complexity, the proposed algorithm reaches a close-to-optimum performance provided by the exhaustive search algorithm.

INDEX TERMS Band selection, device-to-device, radio frequency, visible light communication.

I. INTRODUCTION

The device-to-device (D2D) communication represents a very alluring technology due to its promise in delivering exceptionally high data rates and its potential to significantly decrease the energy consumption of contemporary mobile networks [1]. As the name suggests, the D2D communication facilitates a direct communication between any two devices in the vicinity to each other without a need to communicate through a base station, referred to in this paper as gNodeB (gNB), to be in line with 3GPP terminology for 5G mobile networks. In terms of spectrum usage, the D2D pairs (composed of D2D transmitters and D2D receivers) exploit the D2D communication in one of two basic operational communication modes: 1) the communication over a licensed spectrum dedicated for conventional cellular users (known as in-band D2D communication) or 2) the communication in an unlicensed spectrum assigned, for example, to WiFi or Bluetooth technology (also known as out-band D2D communication) [2]. Moreover, under the in-band D2D communication, the D2D user equipments (DUEs) may access the licensed radio resources in either shared or dedicated mode (more details can be found, e.g., in [2]–[5]).

In general, the D2D pairs using in-band communication suffer from high interference either from other D2D pairs or from conventional cellular users (i.e., users communicating through gNB) exploiting the same radio frequency (RF) resources. This mutual interference can partly or fully scale down the advantages offered by D2D communication and, in extreme cases, can even result in an outage situation. To avoid the outage situation, the D2D pairs should be able to use out-band frequencies, if needed. An interesting way how

The associate editor coordinating the review of this manuscript and approving it for publication was Anandakumar Haldorai.

to exploit out-band frequencies for D2D communication is presented in [6], where the DUEs within a formed cluster are allowed to use WiFi-Direct while the conventional in-band frequency is used only for the communication between the individual clusters. Even though the paper shows that the out-band D2D communication is able to enhance the network's throughput, the interference within the cluster cannot be easily mitigated since the DUEs share frequencies with conventional WiFi devices [3]. Another feasible technology for out-band D2D can be seen in visible light communication (VLC). VLC is an enticing technology as it addresses many challenges, such as bandwidth limitation, energy efficiency, electromagnetic radiation, and safety in the wireless communication systems in general [7], [8]. The VLC systems operate in higher frequency bands and have at their disposal a much wider spectrum when compared to the conventional radio systems (400-790 THz) [9], [10]. As a consequence, VLC is able to provide data rates in the order of Gbps [11], [12] while, at the same time, low power consumption is assured [13].

Hybrid VLC/RF networks have been presented in several existing papers, such as [14], [15] and [16]. Nevertheless, these papers focus on *indoor downlink exploitation of the VLC band without any D2D communication*. In contrast, VLC as an out-band D2D technology has been considered in several recent studies. While [17] and [18] *study only a stand-alone VLC for D2D*, a combination of RF and VLC bands for D2D communication has been initially studied in [19], where potential benefits and performance limits of the hybrid RF/VLC D2D are shown. However, the paper focuses only on a simplified scenario considering just two D2D pairs, which is not very realistic in future mobile networks with a high density of users. On top of that, the paper *does not address in any way the problem of the selection between RF and VLC bands for each D2D pair*.

Thus, in this paper, we investigate the problem of the selecting between RF or VLC for individual D2D pairs in a multi-user scenario, where the D2D pairs using the same technology (either RF or VLC) mutually interfere with each other. Note that the initial idea of this paper has been presented in our conference paper [20] in a simplified version. To this end, we extend [20] by formulating the problem in a more general way as a constrained discrete sum capacity maximization problem that might not always be solvable under the zero outage constraint. Then, we show that this problem should be transformed into a multi-objective optimization problem to guarantee the existence of a solution. In addition, this paper describes the proposed solution in more details and shows new results by evaluating the proposed algorithm in a wider scope and from several additional perspectives related to specific aspects of VLC (e.g., an impact of radiance and irradiance angles) and to the energy efficiency of the whole system, which plays a prominent role in future mobile networks. To this end, the contributions of this paper can be summarized as follows:

- We formulate the RF/VLC selection as a constrained discrete sum capacity maximization problem that might not always be solvable under the zero outage constraint. Then, we transform the problem into a solvable multi-objective optimization problem aiming to achieve a minimization of the outage as well as a maximization of the sum capacity of D2D pairs.
- We use a Lexicographic ordering to transform the multi-objective optimization problem into two single-objective optimization problems, outage minimization and sum capacity maximization, taking into account the higher priority of the outage minimization.
- We derive the optimal solution of the two problems, outage minimization and sum capacity maximization, sequentially via an exhaustive search algorithm.
- We propose an iterative two-phase heuristic centralized algorithm, which switches D2D pairs from RF to VLC aiming to minimize outage and maximize sum capacity. The switching itself occurs sequentially based on: 1) the sum of the interference generated to other D2D pairs in the vicinity and 2) the sum of the interference received from other D2D pairs.
- We show that the proposed algorithm introduces a substantial complexity reduction and reaches a close-to-optimum performance in terms of outage ratio, sum capacity and average energy efficiency compared to the optimal solution derived by the exhaustive search algorithm. In addition, we show that the proposed algorithm overcomes the state-of-the-art algorithms.

The rest of the paper is structured as follows. Section II describes the system model and formally defines the objective of the paper. Then, Section III is allocated for the presentation of the proposed heuristic algorithm including a description of the main practical assumptions and introduction of the graph theory framework for the interpretation of interference among D2D pairs. The simulation scenario and simulation results are presented in Section IV. The last section concludes the paper and further discusses future research direction.

II. SYSTEM MODEL AND OBJECTIVES

This section describes the system model and, then, the objective of the proposed algorithm is formulated.

A. SYSTEM MODEL DESCRIPTION

The system model assumes N D2D pairs (including N transmitters and N receivers) deployed inside a rectangular area (as shown in Figure 1, where $N = 5$ is considered). Any transmitting DUE (DUE_T) is supposed to send data to a specific one receiving DUE (DUE_R), thus creating one D2D pair. The DUEs are assumed to be equipped with an RGB-based light-emitting diode (LED) and a photodetector for transmitting and receiving the optical signal in VLC D2D, respectively. Irradiance angle (ϕ) and incidence angle (ψ) (i.e., users' directions) influencing the VLC performance [10] are either set to zero (i.e., angles are optimal), or generated according to Gaussian distribution [19].

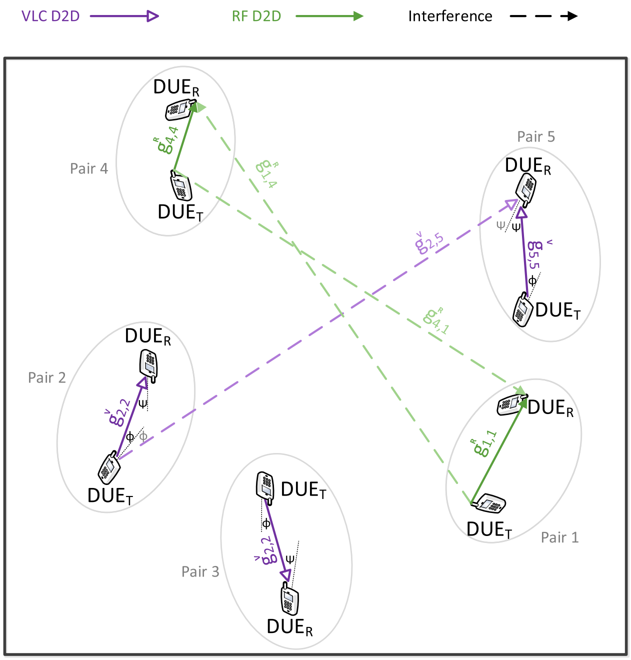


FIGURE 1. System model with an example of five D2D pairs operating in RF and VLC bands. Note that not all D2D pairs communicating over the VLC band interfere among each other due to the effect of the irradiance and the incidence angles.

The D2D pairs communicating over the RF band suffer from an interference caused by the active users communicating in the neighboring cells. This RF interference from neighboring cells is denoted as I_{noise} and presented as a part of the RF noise in this paper. Contrary, if the D2D pair operates in the VLC mode, there is no interference from adjacent cells as VLC signal is significantly attenuated by longer distances and existing obstacles. Furthermore, to reach the high spectral efficiency we assume that the D2D pairs operating both in RF and VLC share the whole available bandwidth. In this regard, the individual capacity of each D2D pair is strongly influenced by the interference generated from other D2D pairs in the vicinity and communicating via the same band. Note that there is no interference between the group of D2D pairs exploiting RF to those utilizing VLC at the moment, as these communicate at different frequencies.

1) CAPACITY MODEL

The capacity of the n-th D2D pair in the RF-VLC D2D network is calculated according to Shannon–Hartley theorem as:

$$C_n = B\log_2(1+\gamma_n), \tag{1}$$

where B is the bandwidth allocated to the D2D pair and γ_n is the signal to interference plus noise ratio (SINR) of the n-th D2D pair. Since every D2D pair can communicate with only either RF or VLC at the moment, we introduce two binary variables (indicators), α_n^R and α_n^V for every n-th D2D pair indicating whether the pair communicates via RF or VLC bands, respectively. More specifically, for every n-th D2D pair we set $\alpha_n^R = 1$ and $\alpha_n^V = 0$ if the n-th D2D pair communicates over the RF band and vice versa $\alpha_n^R = 0$ and $\alpha_n^V = 1$ if the n-th D2D pair communicates over the VLC band. Notice that in the rest of the paper, the upper index "R" always represents RF band while "V" always stands for VLC. Thus, the bandwidth allocated to the n-th D2D pair can be expressed as:

$$B = \alpha_n^R B^R + \alpha_n^V B^V. \tag{2}$$

Moreover, the SINR of the n-th D2D pair is calculated as:

$$\gamma_n = \alpha_n^R \frac{p_n^R g_{n,n}^R}{\sigma^R + \sum_{m\neq n} \alpha_m^R p_m^R g_{m,n}^R} + \alpha_n^V \frac{(\mu p_n^V g_{n,n}^V)^2}{\sigma^V + \sum_{m\neq n} \alpha_m^V (\mu p_m^V g_{m,n}^V)^2}, \tag{3}$$

where p_n is the transmission power of the n-th DUE_T, p_m stands for the transmission power of the m-th DUE_T causing interference to the n-th DUE_R, $g_{n,n}$ corresponds to the channel gain between the n-th DUE_T and the n-th DUE_R, $g_{m,n}$ is the channel gain between the interfering m-th DUE_T and the n-th DUE_R, σ represents the noise, and μ is the responsivity of the photodetector of any DUE_R. Note that in this paper, line-of-sight (LOS) communication is considered for VLC D2D [10], and thus, the main VLC channel gain ($g_{n,n}^V$) and the interference VLC channel gain ($g_{m,n}^V$) are LOS channel gains and can be derived as in [21].

The noises for RF and VLC are calculated differently. Consequently, the RF noise (σ^R) is estimated as:

$$\sigma^R = B^R \sigma_o^R + I_{noise}, \tag{4}$$

where σ_o^R stands for the RF thermal noise spectral density. However, the VLC noise σ^V is composed of a thermal $\sigma_{thermal}$ and a shot σ_{shot} noise [21], as follows:

$$\sigma^V = \sigma_{thermal}^2 + \sigma_{shot}^2. \tag{5}$$

Both $\sigma_{thermal}$ and σ_{shot}, are calculated based on [10].

2) OUTAGE

In our model, we assume that each n-th DUE_R is able to receive data with the SINR that satisfies $\gamma_n \geq \gamma_{min}$, where γ_{min} is the minimal SINR. If any n-th D2D pair has $\gamma_n < \gamma_{min}$, then, this D2D pair is assumed to be in the outage (i.e., there is no D2D communication available between the n-th DUE_T and the n-th DUE_R). Therefore, we introduce the outage ratio Θ that represents the ratio of D2D pairs not satisfying above-mentioned condition as:

$$\Theta = \frac{N_o}{N}, \tag{6}$$

where $N_o \leq N$ is the number of D2D pairs in outage.

3) ENERGY EFFICIENCY

Since we also evaluate the system performance in terms of energy efficiency, the power consumption in both the RF and VLC bands needs to be calculated. The power consumption in RF is derived according to the well established empirical model [22] that takes into account the power consumed by both the transmission and the reception of data. Specifically, the power consumed by transmission and the reception consists of base-band signal processing parts P_t^{bb} and P_r^{bb}, radio frequency parts P_t^{rf} and P_r^{rf}, and a consumption of communication parts circuitry P_t^{on} and P_r^{on}. The power consumed by transmission (P_t^R) and the power consumed by reception (P_r^R) are defined as:

$$P_t^R = P_t^{bb} + P_t^{rf} + P_t^{on}, \quad (7)$$

$$P_r^R = P_r^{bb} + P_r^{rf} + P_r^{on}, \quad (8)$$

where the values and the calculations of individual parameters are explained in detail in [22].

The power consumption in VLC by transmission (P_t^V) is calculated according to [23] and [24] considering that the LED-based transmitter circuit is a serial-FET circuit, in which the consumed power can be derived as:

$$P_t^V = P_t^{led} + P_t^{sf} + P_t^{buck}, \quad (9)$$

where P_t^{led} is the illumination power consumption in the LED, P_t^{sf} stands for the power consumption in the serial-FET circuit composed of the modulation power consumption and the power consumed in the LED because of modulation, and P_t^{buck} corresponds to the buck driver power consumption. All, P_t^{led}, P_t^{sf} and P_t^{buck}, are calculated according to [23] and [24] considering the same electronic components in the VLC transmitter circuit. To calculate the power spent by the reception of VLC (P_r^V), we consider that this power consumed in the VLC receiver circuit (in the n-th DUE_R) is equal to the power consumed in the VLC transmitter circuit (in the n-th DUE_T), i.e., $P_r^V = P_t^V$.

Based on the capacity and the power consumption of the n-th D2D pair C_n from (1), the energy efficiency of the n-th D2D pair is derived as:

$$EE_n = \frac{C_n}{\alpha_n^R(P_t^R + P_r^R) + \alpha_n^V(P_t^V + P_r^V)}. \quad (10)$$

B. OBJECTIVE FORMULATION

In general, our objective is to select RF or VLC band for each D2D pair in order to maximize the sum capacity of D2D pairs keeping zero outage, formulated as:

$$\begin{aligned} \boldsymbol{\alpha^R}, \boldsymbol{\alpha^V} &= argmax(\textstyle\sum_{n=1}^{n=N} C_n) \\ \text{s.t. } (a) \quad & \alpha_n^R \in \{0,1\} \quad \forall n \in \{1,\ldots,N\}, \\ (b) \quad & \alpha_n^V \in \{0,1\} \quad \forall n \in \{1,\ldots,N\}, \\ (c) \quad & \alpha_n^R + \alpha_n^V = 1 \quad \forall n \in \{1,\ldots,N\}, \\ (d) \quad & \gamma_n \geq \gamma_{min} \quad \forall n \in \{1,\ldots,N\}), \end{aligned} \quad (11)$$

where $\boldsymbol{\alpha^R} = \{\alpha_1^R, \ldots, \alpha_N^R\}$ and $\boldsymbol{\alpha^V} = \{\alpha_1^V, \ldots, \alpha_N^V\}$ are the two sets of the binary indicators for RF and VLC bands, respectively; constraints (a) and (b) guarantee that every indicator in $\boldsymbol{\alpha^R}$ and $\boldsymbol{\alpha^V}$ is a binary variable and its value should be either zero or one as explained in Section II-A; constraint (c) guarantees that every n-th D2D pair is able to use only either RF or VLC; and constraint (d) keeps the SINR of all D2D pairs above the threshold γ_{min} to maintain zero outage. Note that the problem (11) is an integer (non-linear) programming which is NP-hard.

However, the constrained discrete optimization problem (11) seeks for a solution represented by a combination of RF and VLC band selections for the D2D pairs where, first, the constraint (d) is satisfied and, second, the sum capacity is maximized. In other words, constraint (d) reflects the priority of reaching zero outage before sum capacity is maximized as it is the case in real network implementations where the network operators aim to serve as many users as possible. Nevertheless, there might be no RF/VLC combination that guarantees no outage (i.e, some n-th D2D pairs may always experience $\gamma_n < \gamma_{min}$), especially for a high number of D2D pairs N and the corresponding high interference over both bands (RF and VLC). Thus, to guarantee the existence of a solution, we relax the problem of reaching zero outage to a problem of minimizing the outage ratio as much as possible. Hence, we transform the problem (11) into a multi-objective optimization problem written as:

$$\begin{aligned} \boldsymbol{\alpha^R}, \boldsymbol{\alpha^V} &= argmax(1/\Theta, \textstyle\sum_{n=1}^{n=N} C_n) \\ & \text{s.t. } (a)\text{–}(c) \text{ from (11)}, \end{aligned} \quad (12)$$

where the objective is both to minimize the outage and to maximize the capacity.

Generally speaking, the multi-objective optimization is concerned with optimizing multiple parameters where, in our case, we aim to minimize Θ (achieved by maximizing $1/\Theta$) and to maximize $\sum_{n=1}^{n=N} C_n$ at the same time. However, as mentioned before, minimizing outage has a higher priority in comparison to the sum capacity maximization in the real network. Thus, we consider a Lexicographic ordering of the objectives defined in (12) in a way that the outage ratio minimization is assumed to be the objective with higher priority compared to the capacity maximization, which represents the objective with lower priority. Taking this Lexicographic ordering into account, the multi-objective optimization problem in (12) can be transformed into two sequentially-solvable single-objective optimization problems: outage ratio minimization, and then, sum capacity maximization. Therefore, as a higher priority problem, the outage ratio minimization is formulated as:

$$\begin{aligned} \boldsymbol{\alpha_\Theta^R}, \boldsymbol{\alpha_\Theta^V} &= argmax(1/\Theta) \\ & \text{s.t. } (a)\text{–}(c) \text{ from (11)}, \end{aligned} \quad (13)$$

where $\boldsymbol{\alpha_\Theta^R}$ and $\boldsymbol{\alpha_\Theta^V}$ are two matrices containing the possible binary indicators for RF and VLC bands, respectively, minimizing the outage ratio. In other words, $\boldsymbol{\alpha_\Theta^R}$ and $\boldsymbol{\alpha_\Theta^V}$ represent the set of solutions (RF/VLC combinations) that reach the minimal possible outage Θ (i.e., there might be multiple RF/VLC combinations that achieve the same minimal outage Θ). Then, as a lower priority problem, the sum capacity maximization is formulated as:

$$\begin{aligned}\boldsymbol{\alpha}^{\boldsymbol{R}}, \boldsymbol{\alpha}^{\boldsymbol{V}} &= argmax(\sum_{n=1}^{n=N} C_n) \\ &\text{s.t. } (a)\text{–}(c) \text{ from } (11) \\ &(d) \quad \Theta = \Theta^*, \end{aligned} \tag{14}$$

where Θ^* is the minimal outage ratio achieved by solving (13) and, thus, the constraint (d) in (14) guarantees that the outage achieved by solving outage minimization (13) should be kept while solving (14).

III. PROPOSED BAND SELECTION ALGORITHM

First, we summarize the major assumptions considered in the developing of the proposed algorithm. Second, based on graph theory, we illustrate the exploitation of weighted directed graphs to interpret the interference among the D2D pairs as this interpretation is used to design the proposed band selection algorithm. Finally, we describe the proposed heuristic algorithm in detail.

A. ASSUMPTIONS

In order to implement the proposed heuristic algorithm, several assumptions related to practical aspects and design need to be defined. These are summarized below:

- In the initial phase, before executing the proposed algorithm, all D2D pairs communicate via the RF band as it is more stable and less sensitive to the minor changes in the DUEs' orientations. For this same reason, the RF band is also assumed to serve the needed signaling and communication setup even if the data is transmitted over the VLC band.
- Within every D2D pair, the DUE_T is assumed to be able to send a VLC beacon signal on a periodic basis to the DUE_R even if the D2D pair communicates over the RF band. This VLC beacon is needed to evaluate the quality of the VLC channel. Note that the beacons are equivalent to the RF common reference signals used for channel estimation purposes in, e.g., LTE mobile networks (see [29]). In other words, the beacons represent reference signals transmitted at specific resources by any DUE_T communicating in VLC or willing to switch its communication band from RF to VLC.
- The gNB centrally controls and manages the proposed algorithm. Thus, we assume that the estimated RF and VLC channels (via RF reference signals and VLC beacons, respectively) are reported periodically to the gNB. Then, based on the assumed full knowledge of these channels, the gNB is able to decide the D2D pair that need to switch its communication band from RF to VLC accordingly.

B. GRAPH THEORY-BASED INTERPRETATION OF INTERFERENCE

The communication band selection (either RF or VLC) for each D2D pair is based on the interference relations among individual D2D pairs over both bands. Thus, in this section, we introduce the usage of weighted directed graphs adopted from graph theory for the interpretation of the mutual interference among the D2D pairs.

A fully connected weighted directed graph is defined as $G = (V, E)$, where the set of vertices (V) stands for the D2D pairs and the set of edges (E) represents the interference among them. Then, as the $G = (V, E)$ is supposed to be a weighted graph, any edge $e_{i,j}$, connecting the vertices v_i with the v_j, is assigned with a specific weight $I_{i,j}$ corresponding to the interference from the v_i to the v_j (i.e., interference from i-th DUE_T to the j-th DUE_R). Analogously, the interference from the v_j to v_i is interpreted as $I_{j,i}$, where the j-th DUE_T causes interference to the i-th DUE_R.

In order to select the suitable communication band (RF or VLC) for every i-th D2D pair, we introduce two interference-based metrics from G as follows: 1) the sum of interference caused by the i-th DUE_T (i.e., by the v_i vertex) to all other D2D pairs; and 2) the sum of interference received at the i-th DUE_R (i.e., at the v_i vertex) from all other D2D pairs. The former metric (denoted as $d^+(v_i)$) represents the out-degree of the vertex v_i and it is equal to the sum of the weights of the edges that start from the vertex v_i:

$$d^+(v_i) = \sum_{j=1, j\neq i}^{j=N} (I_{i,j}) \tag{15}$$

The latter metric (denoted as $(d^-(v_i))$) is the in-degree of the vertex v_i and it is equal to the sum of the weights of the edges that end in the vertex v_i:

$$d^-(v_i) = \sum_{j=1, j\neq i}^{j=N} (I_{j,i}) \tag{16}$$

Together, the sum of the in-degrees of all vertices plus the sum of out-degrees of all vertices represent the degree of the graph G (denoted as $d(G)$) calculated as:

$$\begin{aligned} d(G) &= \sum_{i=1}^{i=N} d^-(v_i) + \sum_{i=1}^{i=N} d^+(v_i) \\ &= 2\sum_{i=1}^{i=N} d^-(v_i) = 2\sum_{i=1}^{i=N} d^+(v_i) \end{aligned} \tag{17}$$

It is obvious, from (17), that $\sum_{i=1}^{i=N} d^-(v_i) = \sum_{i=1}^{i=N} d^+(v_i)$. This equality between the in-degrees and out-degrees is due to the fact that every edge $e_{i,j}$ from the vertex v_i to the vertex v_j with a weight $I_{i,j}$ is considered as in-weight with respect to the v_j as well as out-weight with respect to the v_i. In other words, every $I_{i,j}$ weight is a part of $d^+(v_i)$ and a part of $d^-(v_j)$ as well.

Note that when some D2D pairs communicate over the RF band while some other D2D pairs communicate over the VLC band, the D2D pairs can be represented by two separated weighted sub-graphs. The first sub-graph is a fully connected weighted sub-graph representing D2D pairs communicating over the RF band and interfering with each other. In contrast, although the second sub-graph is a weighted directed sub-graph, it does not have to be fully connected as it represents the D2D pairs communicating over the VLC band where the interference might be absent between some D2D pairs due to various orientations of users' devices. However, there are no edges between the two sub-graphs due to the absence of interference among VLC and RF bands.

C. DESCRIPTION OF THE PROPOSED ALGORITHM

The problem (13) can be solved by the exhaustive search algorithm as all RF/VLC combinations are checked and the set of the combinations that minimizes the outage ratio (Θ) is chosen. Similarly, the exhaustive search can be applied to solve (14) by choosing the RF/VLC combination that maximizes the sum capacity of D2D pairs out of the set of combinations that minimize the outage ratio obtained from solving (13). However, the exhaustive search algorithm introduces a time complexity of $O(2^N)$. Thus, even if the number of D2D pairs is low, e.g., $N = 10$, the number of all possible combinations can be seen as too many, making the exhaustive search algorithm impractical for real networks, especially that the channel conditions are likely to change before testing all RF/VLC combinations. Thus, starting from the conventional initial state when all D2D pairs communicate over the RF band, we develop a low-complexity iterative algorithm switching the communication band of the D2D pairs sequentially from RF to VLC and converging to a final close-to-optimum performance.

Algorithm 1 The Proposed Algorithm

1: Estimation of Θ and $\sum C_n$
2: **while** Θ is not minimized or $\sum C_n$ is not maximized **do**
3:   **if** $\Theta > 0$ **then**
4:     First phase: Outage ratio minimization
5:   **end if**
6:   Second phase: Sum capacity maximization
7: **end while**

The high level overview of the proposed algorithm is depicted in Algorithm 1. In the beginning, Algorithm 1 estimates the initial outage (Θ) and the initial sum capacity ($\sum C_n$) when all D2D pairs operate in RF (see line 1). After that, two sequential phases, each solving one part of the multi-objective optimization problem, follow. More precisely, the first phase of the algorithm aims to minimize the outage ratio (line 4) unless the outage ratio is equal to zero (i.e., no outage); and the second phase maximizes the sum capacity (line 6). Both above-mentioned phases (covered by Algorithm 2 and Algorithm 3) are repeated as long as the performance may be further improved either in terms of outage ratio or sum capacity.

The first phase targeting to minimize outage ratio is handled by Algorithm 2. First, D2D pairs are sorted in a descending order according to the out-degree of the vertices, that is, according to $d^+(v_i^R)$ calculated in line with (15). In the next step, the D2D pair with the highest $d^+(v_i^R)$ is selected as the first candidate for the switching to VLC mode as this pair in particular generates the highest sum interference to other D2D pairs in RF. Of course, the D2D pair should change from RF to VLC only if the VLC channel is of a sufficient quality. Thus, the VLC channel quality is estimated by means of a beacon transmitted from the $D2D_T$ to $D2D_R$ (line 3). Then, if the D2D pair is able to use the VLC band, it is switched to the VLC (line 4) and a new outage (Θ^{new}) is calculated according to (6) (see line 5). Obviously, if the outage is decreased by this process (i.e., if $\Theta^{new} < \Theta$), the D2D pair remains in VLC mode (line 7), as this is the main objective of this phase, and the outage value is updated (line 8). If the outage is not decreased by changing from VLC

Algorithm 2 First Phase (Minimization of Outage Ratio)

1: Sort D2D pairs in descending order acc. to $d^+(v_i^R)$
2: **for** $i = 1, 2, \ldots N^R$ (all sorted D2D pairs in RF) **do**
3:   Check VLC channel for i-th pair (send beacon)
4:   Switch i-th D2D pair from RF to VLC
5:   Determine Θ^{new}
6:   **if** $\Theta^{\text{new}} < \Theta$ **then**
7:     Keep i-th D2D pair in VLC
8:     $\Theta = \Theta^{\text{new}}$ (i.e., update outage)
9:     **if** $\Theta = 0$ **then**
10:       Terminate Algorithm 2
11:     **else**
12:       Break and repeat from line 1
13:     **end if**
14:   **else**
15:     Switch i-th D2D pair back to RF
16:     **if** $i = N^R$ (All D2D pairs in RF are tested) **then**
17:       Terminate Algorithm 2
18:     **end if**
19:   **end if**
20: **end for**

Algorithm 3 Second Phase (Maximization of Sum Capacity)

1: Get Θ and $\sum C_n$ from Algorithm 2
2: Sort D2D pairs in descending order acc. to $d^-(v_i^R)$
3: **for** $i = 1, 2, \ldots N^R$ (all sorted D2D pairs in RF) **do**
4:   Check VLC channel for i-th pair (send beacon)
5:   Switch i-th D2D pair from RF to VLC
6:   Determine Θ^{new} and $\sum C_n^{\text{new}}$
7:   **if** $\Theta^{\text{new}} = \Theta$ and $\sum C_n^{\text{new}} > \sum C_n$ **then**
8:     Keep i-th D2D pair in VLC
9:     $\sum C_n = \sum C_n^{\text{new}}$ (update Capacity)
10:     Terminate Algorithm 3
11:   **else**
12:     Switch i-th D2D pair back to RF
13:     **if** $i = N^R$ (All D2D pairs in RF are tested) **then**
14:       Finish, Θ is minimized and $\sum C_n$ is maximized
15:     **end if**
16:   **end if**
17: **end for**

to RF, however, the D2D pair goes back to RF mode (line 15). After that, the other D2D pair with the second highest $d^+(v_i^R)$ is investigated next and the whole process is repeated. This is done as long as the outage is higher than 0 (checked in line 9) or until all D2D pairs in RF have been tested (see line 16). Notice that the number of D2D pairs in RF is denoted as N^R and as the switching process progress (i.e., be repeating while cycle in Algorithm 1), N^R is gradually decreased since less amount of D2D pairs need to be checked.

In the second phase, represented by Algorithm 3, the aim is to improve the sum capacity of D2D pairs without increasing the outage ratio Θ achieved in the first phase. Thus, Algorithm 3 starts by adopting Θ and $\sum C_n$ reached in the first phase (line 1). Then, the D2D pairs are sorted according to in-degree $d^-(v_i^R)$ of the vertices corresponding to the D2D pairs communicating over the RF band (line 2). The first D2D pair to be checked is the one still in the RF mode and experiencing the strongest sum interference from other pairs in RF (i.e., the pair with the highest in-degree $d^-(v_i^R)$ calculated according to (16)). After that, the process is similar to the one described in Algorithm 2 during which the availability of VLC connection for this pair is tested (line 4), and then, the switching to VLC occurs if VLC is available (line 5). Nevertheless, in this second phase, the new sum capacity $\sum C_n^{new}$ is also calculated (besides the Θ^{new}), as the objective of this phase is to maximize the sum capacity (line 6). The D2D pair keeps communicating over the VLC band (line 8) if $\sum C_n^{new} > \sum C_n$ while $\Theta^{new} = \Theta$ (i.e., if conditions from line 7 are satisfied). The fulfilling of both conditions also results in the termination of Algorithm 3. In the opposite case, however, the D2D pair switches back to RF (line 12), and the second pair from the sorted D2D pairs is tested (i.e., Algorithm 3 returns back to line 3). Note that if the Algorithm 3 is terminated in line 10 after a D2D pair switches to VLC, the first phase (Algorithm 2) is repeated as illustrated in Algorithm 1 in order to check the possibility of further reduction in the outage. Nonetheless, if the achieved outage is already zero, the second phase (Algorithm 3) is repeated directly without the need to go through the first phase (see Algorithm 1). After all D2D pairs in Algorithm 3 are tested (line 13) without any possibility to improve sum capacity, the whole proposed algorithm finishes (line 14) as changing any of the D2D pairs from RF to VLC cannot further decrease outage or increase sum capacity.

The graphs-based interpretation of an example with five D2D pairs switching to VLC based on the proposed algorithm is shown in Figure 2. Figure 2a presents the initial state with all D2D pairs communicating over the RF band. In such a case, the D2D pairs mutually interfere with each other leading to a possible outage. This outage is excluded by switching D2D pairs 2, 3 and 5 (represented by v_2^V, v_3^V and v_5^V, respectively) to VLC as illustrated in Figure 2b.

Although the D2D pairs switched to VLC interfere among each other, this VLC interference is expected to be lower than the RF interference due to the higher signal attenuation over the VLC band in comparison to the RF band and due to the various setting of the irradiance and the incidence angles of the DUEs belonging to different D2D pairs.

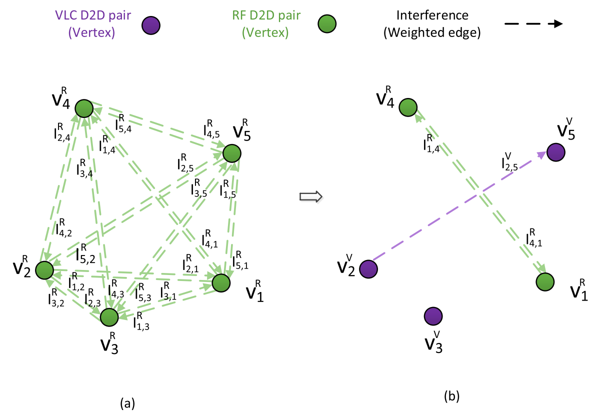


FIGURE 2. An example of five D2D pairs represented by two weighted directed graphs showing: (a) the initial state with all D2D pairs in RF, and (b) the final state where three D2D pairs are switched to VLC (notice that the topology of D2D pairs and the resulted RF/VLC combination are taken from Figure 1).

IV. PERFORMANCE EVALUATION

The performance of the proposed algorithm is evaluated by means of simulations performed in MATLAB. First, this section describes in all the details the simulation scenario and the simulation parameters. Second, the competitive algorithms and the key performance metrics considered for the comparison to our proposal are introduced. Third, the extensive simulation results showing the impact of the number of D2D pairs and/or irradiance and incidence angles are presented and thoroughly discussed.

A. SIMULATION SCENARIO AND MODELS

We assume the scenario, which is identified as the most beneficial for the whole RF-VLC D2D concept [19]. More specifically, we consider an indoor area (representing, e.g., a room or a hall) without any indoor walls. Within this area, up to ten D2D pairs are randomly dropped with a uniform distribution. We assume that the users are aware of each other and that they are willing to exchange data. Therefore, the users try to direct their DUEs approximately towards each other. This assumption is simulated using three different distributions of angles showing three possible cases. The first case is represented by optimal angles (ϕ and ψ are set to zero), where the users direct their DUEs perfectly towards each other. The second and the third case are represented by Gaussian distribution of the irradiance and incidence angles (ϕ and ψ) of every DUE_T and DUE_R of the same D2D pair as in [19], with a mean of 0° and a standard deviation of 30° and 60°, respectively. The simulation consists of 3000 drops, where for each drop the positions and the angles of the all DUEs are generated independently.

For the modeling of RF channel, we follow 3GPP recommendation for indoor D2D communication as defined in [30],

TABLE 1. Simulation parameters.

RF Parameters		
Carrier frequency	f_c	2 [GHz]
Bandwidth	B^R	20 [MHz]
Transmission power of any DUE_T	P^R	200 [mW]
Interference from other cells	I_{noise}	-70 [dBm]
Noise spectral density	σ_o	-174 [dBm/Hz]
VLC Parameters		
Bandwidth	B^V	10 [MHz]
Transmission power of any DUE_T	P^V	200 [mW]
Responsivity of the photodetector	μ	0.5 [A/W]
General Parameters		
Room dimension	d	30 [m]
Number of D2D pairs	N	2-10 [-]
Minimal SINR	γ_{min}	-10 [dB]
Number of simulation drops	S_d	3000 [-]

i.e., the D2D indoor path loss model is defined as:

$$PL = 89.5 + 16log_{10}(d_{TR}) \quad (18)$$

where d_{TR} is the distance between a transmitter and a receiver.

The RF interference from neighbouring cells I_{noise} is set to −70 dBm. It is obvious that this selected value represents a high level of interference which corresponds to the high density of users expected in the future mobile networks (5G networks and beyond) [25].

The VLC channel model is in line with [30] and follows the description from Section II. However, Table 1 summarizes the parameters of RF and VLC channels in addition to the general simulation parameters. Notice that we consider the same fixed p_n for any n-th transmitter DUE_T and the exploitation of power control techniques is left for future research.

B. COMPETITIVE ALGORITHMS AND PERFORMANCE METRICS

To the best of our knowledge, there is no algorithm selecting between RF and VLC for D2D communication. Thus, our proposed heuristic algorithm (labeled Proposed RF-VLC D2D) is compared to the following four competitive solutions:

1) *RF D2D*: The RF band is used for the D2D communication and all the D2D pairs reuse the whole bandwidth [20]. This algorithm illustrates the performance of the D2D communication in the case where only the RF band is available (without VLC D2D).
2) *VLC D2D*: The VLC band is exploited for the D2D communication according to [31]. Notice that the VLC D2D in [31] includes the possibility of relaying the VLC-based data transmission through nearby devices. Nevertheless, we do not consider any relaying in our proposed algorithm and, thus, we leave this feature out also for VLC D2D for a fair comparison. The VLC D2D demonstrates the performance of the D2D communication in the case where only the VLC band is available (without RF D2D).
3) *Random RF-VLC D2D*: This algorithm randomly selects either RF or VLC band for each D2D pair. Note that this simple algorithm is designed only for comparison purposes.
4) *Optimal RF-VLC D2D*: The optimal combination of RF and VLC bands for the D2D pairs is derived by the exhaustive search algorithm, which checks all possible combinations (2^N combinations) as described in Section III-C. First, the combinations with the lowest reachable outage ratio Θ^* are chosen. Then, the algorithm selects the combination with the highest $\sum C_n$ among the previously chosen combinations with the lowest outage ratio. This algorithm is a very high complexity solution that shows the optimal performance of the RF-VLC D2D in a multi-user scenario; and it can be seen as a theoretical upper bound used to evaluate the performance quality of other algorithms.

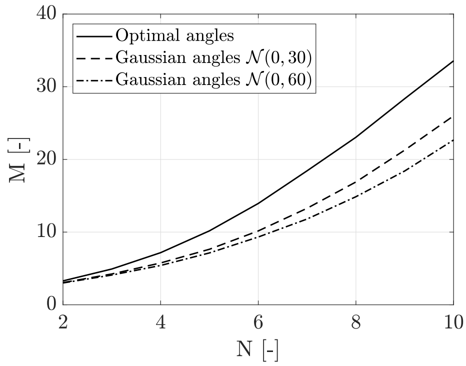


FIGURE 3. Number of iterations *M* needed for the proposed algorithm over number of D2D pairs *N*.

The performance of the proposed algorithm and all four competitive solutions are assessed by means of three performance metrics: 1) the outage ratio Θ (see (6)), 2) the sum capacity of D2D pairs $\sum C_n$ (denoted in figures as C), and 3) the average energy efficiency of D2D pairs EE, calculated as $EE = \frac{\sum EE_n}{N}$. Moreover, we show the complexity of the proposed algorithm presented by the number of needed iterations of the proposed algorithm (denoted as M) and we show the VLC usage ratio calculated as $\frac{N^V}{N}$, where N^V is number of D2D pairs communicating over the VLC band.

C. SIMULATION RESULTS AND DISCUSSION

In this sub-section, we present the results showing that the proposed algorithm is of low complexity and, at the same time, achieves a close-to-optimal performance in terms of the outage, sum capacity and average energy efficiency of D2D pairs.

Figure 3 analyzes the complexity of the proposed algorithm presented by the number of needed iterations (M) averaged over the simulated drops. It is obvious that the number of iterations increases with N as more D2D pairs are checked and switched from RF to VLC. Figure 3 also shows that the further the irradiance and incidence angles (ϕ and ψ) are from the optimal, the less number of iterations are needed. In other words, when ϕ and ψ are optimal (equal to zero), the proposed algorithm needs to go through the highest

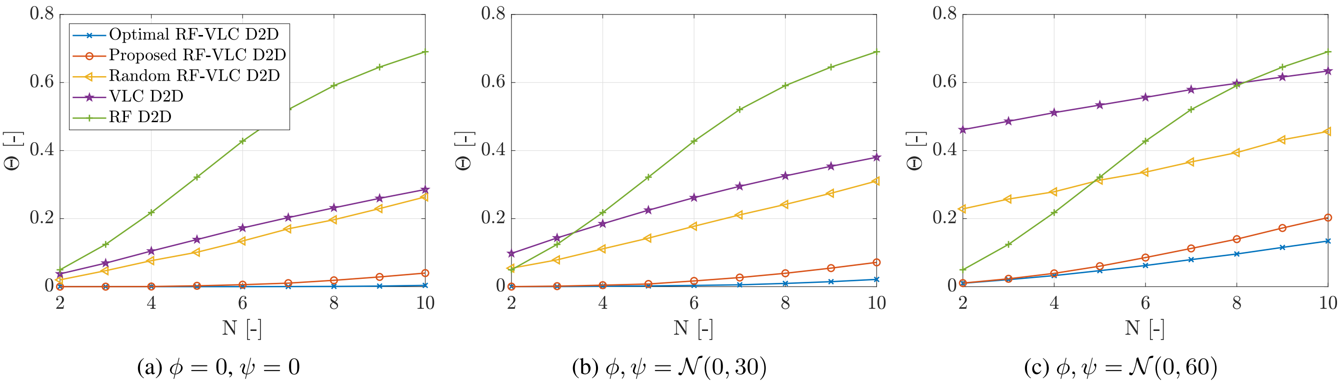


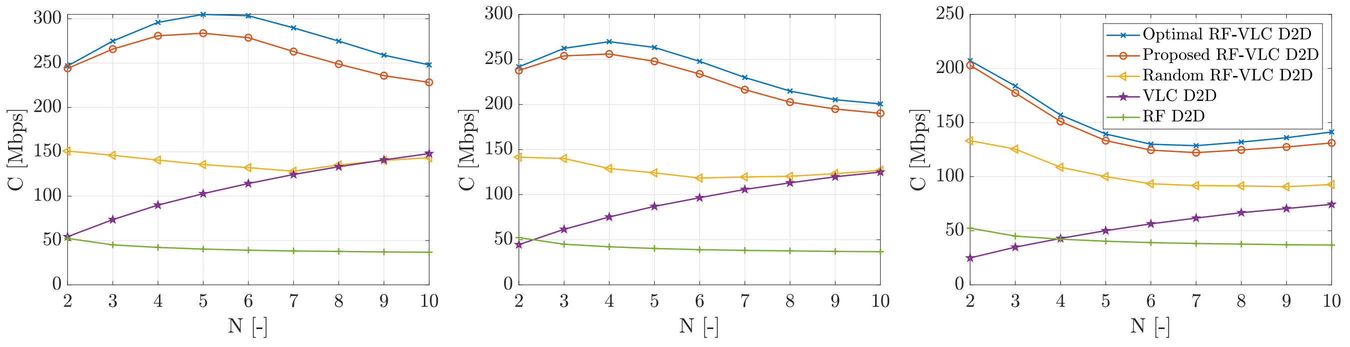
FIGURE 4. **Outage ratio Θ over the number of D2D pairs *N* for ϕ and ψ distributed as: optimal (zero) angles (a), Gaussian distribution with the mean of 0 and the standard deviation of 30° (b) and 60° (c). Note that the common legend is shown in Figure 4a for the sake of clarity.**

number of iterations in comparison to the cases when ϕ and ψ are not optimal. This interesting behavior is, however, quite expected due to the fact that if ϕ and ψ angles are closer to optimum there is a higher probability that a D2D pair is able to communicate over the VLC band. Thus, more D2D pairs need to be checked and switched from RF to VLC as explained in Section III-C. However, regardless of the angular distribution, we see in Figure 3 that the complexity of the proposed algorithm is much lower than the exhaustive search algorithm, e.g., for 10 D2D pairs exhaustive search checks $2^N = 2^{10} = 1024$ combinations (corresponding to 1024 iterations) while the proposed algorithm needs below 35 iterations.

Figure 4 shows the outage ratio Θ depending on number of D2D pairs and for different distributions of ϕ and ψ. For all algorithms, the Θ increases with N, because the interference is inevitably increasing with the density of D2D pairs as well. It can be seen in Figure 4 that the RF D2D and VLC D2D lead to the highest and the second highest outage, respectively, when angles are optimal (Figure 4a). However, when angles are not optimal, the VLC D2D shows an increasing Θ with the increasing standard deviation of the Gaussian distribution of ϕ and ψ from 30° and 60° and, thus, VLC D2D introduces the highest outage ratio for low number of D2D pairs in Figure 4b and Figure 4c. Moreover, the increasing outage ratio of VLC D2D with angles changing from Optimal to $\mathcal{N}(0, 30)$ and then to $\mathcal{N}(0, 60)$ impacts all algorithms combining RF and VLC (i.e., Random, proposed and optimal RF-VLC D2D). The reason is that if the transmitter and the receiver of the D2D pair are in the opposite direction of each other, the D2D pair they compose cannot switch to VLC even if this pair is exposed to (or causing) high RF interference. However, Figure 4 shows that combining RF and VLC in a random RF-VLC D2D introduces unacceptable low gain in terms of outage ratio reduction. On the contrary, the proposed RF-VLC algorithm reduces the outage ratio substantially to a 0.03 and less than 0.09 for all values of N when irradiance and incidence angles are optimal (Figure 4a) or relatively good (Figure 4b). Such a low outage ratio is achieved by relying on the proposed interference-based selection of the candidates for switching from RF to VLC.

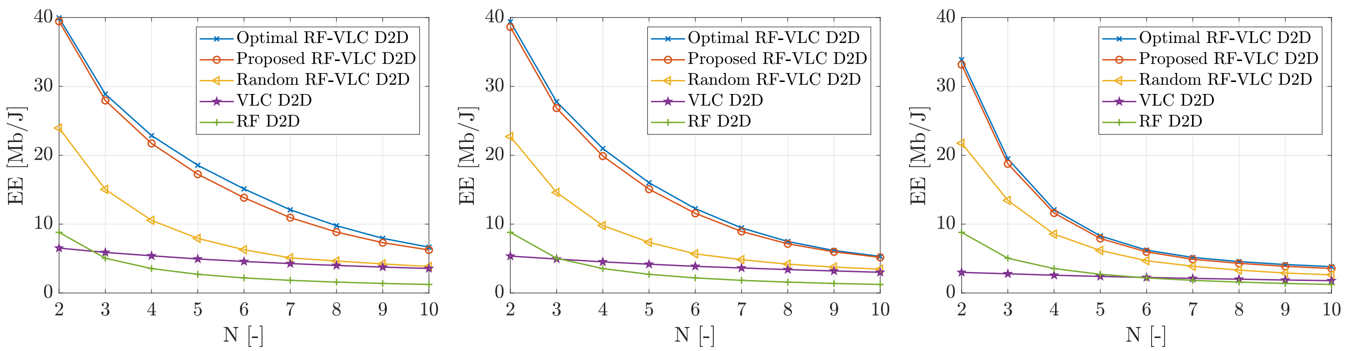
In Figure 4c, where angles might be non-suitable for VLC, the outage ratio of the proposed algorithm increases up to 0.2 for 10 D2D pairs. However, we can see that when the angles are not suitable for VLC, even the optimal selection is not able to fully mitigate outage. What is more, the relatively small gap between the proposed selection and the optimal one (in the worst case the gap is roughly 0.07) can be easily justified by very low complexity of the proposed algorithm (as demonstrated in Figure 3) in contrast to the optimal exhaustive search-based solution for which the complexity increases exponentially (2^N) making this optimal algorithm impractical for real network implementations.

Moving to the another criteria, Figure 5 illustrates the sum capacity of D2D pairs over N. The sum capacity of all algorithms containing a VLC D2D (VLC D2D or RF-VLC D2D), decreases with irradiance and incidence angles changing from optimal to Gaussian distribution with a standard deviation of 30° and then 60°. Still, the bottom line is that the proposed RF-VLC D2D significantly outperforms RF D2D, VLC D2D, and random RF-VLC D2D reaching 6.1, 7.1, and 1.1 times higher sum capacity, respectively. At the same time, the proposed algorithm loses only marginally when compared to optimal RF-VLC D2D (always less than 9.5%). Figure 5 further shows that the behavior of the sum capacity over N for the optimal RF-VLC D2D and the proposed RF-VLC D2D is almost similar. To be more precise, when angles are optimal (Figure 5a) or relatively good (Figure 5b), the capacity increases as long as the increasing N gives more possible RF-VLC combinations that are able to manage and to limit the added interference. With further increasing of D2D pairs, however, the sum capacity starts decreasing due to the fact that further increment in N leads to a high interference even if both RF and VLC bands are considered. Note that in Figure 5c, the sum capacity immediately decreases when N starts to increase as adding more pairs raises the RF interference while most of the D2D pairs are not able to switch to VLC due to the unfavorable ϕ and ψ. With the continuous increase



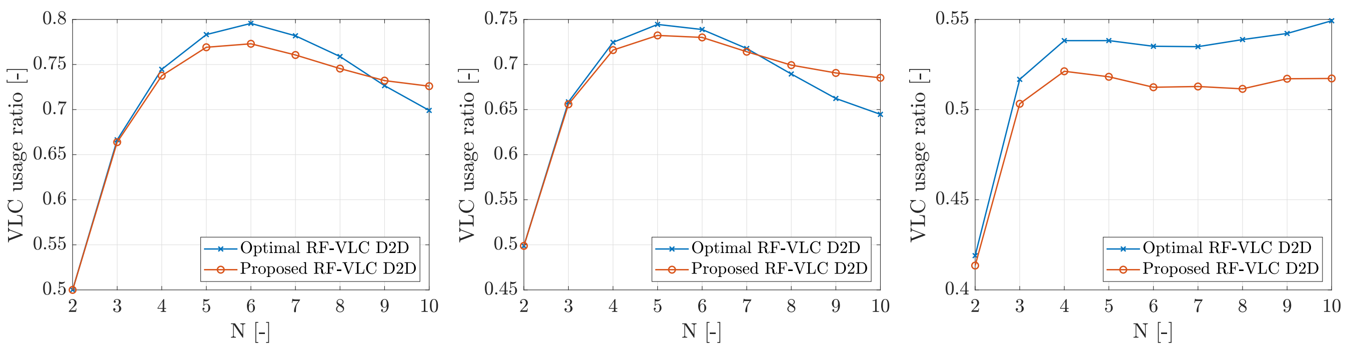
(a) $\phi = 0, \psi = 0$ (b) $\phi, \psi = \mathcal{N}(0, 30)$ (c) $\phi, \psi = \mathcal{N}(0, 60)$

FIGURE 5. Sum capacity *C* over number of D2D pairs *N* for ϕ and ψ distributed as: optimal (zero) angles (a), Gaussian distribution with mean of 0 and standard deviation of 30° (b) and 60° (c). Note that the common legend is shown in Figure 5c for the sake of clarity.



(a) $\phi = 0, \psi = 0$ (b) $\phi, \psi = \mathcal{N}(0, 30)$ (c) $\phi, \psi = \mathcal{N}(0, 60)$

FIGURE 6. The average energy efficiency*EE* over the number of D2D pairs *N* for ϕ and ψ distributed as: optimal (zero) angles (a), Gaussian distribution with the mean of 0 and the standard deviation of 30° (b) and 60° (c).



(a) $\phi = 0, \psi = 0$ (b) $\phi, \psi = \mathcal{N}(0, 30)$ (c) $\phi, \psi = \mathcal{N}(0, 60)$

FIGURE 7. The VLC usage ratio over the number of D2D pairs *N* for ϕ and ψ distributed as: optimal (zero) angles (a), Gaussian distribution with the mean of 0 and the standard deviation of 30° (b) and 60° (c).

of N, however, the capacity starts increasing as well (i.e., if $N > 7$) since more pairs can be switched to VLC and interference among the pairs is partly mitigated.

Figure 6 provides an analysis of the average energy efficiency of D2D pairs. We can see that the average energy efficiency of D2D pairs of all algorithms decreases with N due to the high corresponding increment in the consumed energy by more D2D pairs. Moreover, Figure 6 shows that the users' directions affect all algorithms containing VLC D2D, where EE generally decreases as ϕ and ψ are further from the optimal ones. However, the proposed algorithm outperforms the RF D2D, VLC D2D, and random RF-VLC D2D disregarding N and ϕ and ψ distribution reaching 5.3, 10, and 1.2 times higher average energy efficiency, respectively. In addition, minor losses in EE are introduced by the proposed algorithm comparing to the optimal RF-VLC D2D as we see in Figure 6 (always less than 9.5%).

Finally, we show the VLC usage ratio over N in Figure 7. The first obvious observation is that disregarding N, the VLC usage ratio decreases with ϕ and ψ changing from optimal to Gaussian with a standard deviation of 30° and then to Gaussian with a standard deviation of 60°. This outcome is expected since the VLC links experience lower capacity if ϕ and ψ are further from optimal and, thus, RF is used more often. The second observation is that when ϕ and ψ are optimal (Figure 7a) or relatively good (Figure 7b), the VLC ratio increases with N as long as the increasing interference is handled by switching more pairs from RF to VLC. However, after a certain value of N ($N = 6$ for optimal angles and $N = 5$ for a standard deviation of 30°), the VLC ratio starts to decrease due to the fact that the number of D2D pairs switching to VLC is not increasing any longer with N due to high interference in VLC. In contrast, if ϕ and ψ are generally far from optimal (i.e., case in 7c), the VLC usage ratio is more or less always increasing with N. The reason for this behavior is the fact that increasing the number of D2D pairs when UEs' angles are rarely suitable for VLC communications leads to a limited increment in VLC usage ratio and a corresponding relatively low VLC interference. Thus, VLC usage ratio keeps gradually increasing for all tested values of N (even when $N > 6$).

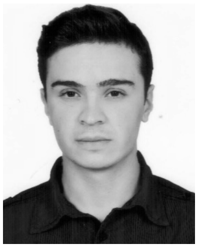
V. CONCLUSION

In this paper, we have proposed the centralized algorithm for the selection of either RF or VLC band for D2D communication in a multi-user scenario. The simulation results show that, compared to the exhaustive search algorithm, the proposed algorithm costs much lower complexity and, at the same time, reaches close-to-optimal performance. Moreover, the proposed algorithm outperforms all state-of-the-art algorithms in terms of capacity by up to 7.1 times and energy efficiency by up to 10 times while outage is significantly minimized.

As future work, the selection between both communication bands should be done by exploiting machine learning in order to further decrease the complexity of the selection.

REFERENCES

[1] M. N. Tehrani, M. Uysal, and H. Yanikomeroglu, "Device-to-device communication in 5G cellular networks: Challenges, solutions, and future directions," *IEEE Commun. Mag.*, vol. 52, no. 5, pp. 86–92, May 2014.
[2] A. Asadi, Q. Wang, and V. Mancuso, "A survey on device-to-device communication in cellular networks," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 4, pp. 1801–1819, 4th Quart., 2014.
[3] Y. Xu and S. Wang, "Mode selection for energy efficient content delivery in cellular networks," *IEEE Commun. Lett.*, vol. 20, no. 4, pp. 728–731, Apr. 2016.
[4] P. Mach, Z. Becvar, and M. Najla, "Combined shared and dedicated resource allocation for D2D communication," in *Proc. IEEE VTC-Spring*, Jun. 2018, pp. 1–7.
[5] R. Wang, J. Zhang, S. H. Song, and K. B. Letaief, "QoS-aware joint mode selection and channel assignment for D2D communications," in *Proc. IEEE ICC*, May 2016, pp. 1–6.
[6] Z. Lin, Z. Gao, and L. Huang, "Hybrid architecture performance analysis for device-to-device communication in 5G cellular Network," *Mobile Netw. Appl.*, vol. 20, no. 6, pp. 713–724, Dec. 2015.
[7] A. Sevincer, A. Bhattarai, M. Bilgi, M. Yuksel, and N. Pala, "LIGHTNETs: Smart LIGHTing and mobile optical wireless NETworks—A survey," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 4, pp. 1620–1641, 4th Quart., 2013.
[8] F. Yang and J. Gao, "Dimming control scheme with high power and spectrum efficiency for visible light communications," *IEEE Photon. J.*, vol. 9, no. 1, Feb. 2017, Art. no. 7901612.
[9] I. Din and H. Kim, "Energy-efficient brightness control and data transmission for visible light communication," *IEEE Photon. Technol. Lett.*, vol. 26, no. 8, pp. 781–784, Apr. 15, 2014.
[10] P. H. Pathak, X. Feng, P. Hu, and P. Mohapatra, "Visible light communication, networking, and sensing: A survey, potential and challenges," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 4, pp. 2047–2077, 4th Quart., 2015.
[11] Y. Wang, X. Huang, L. Tao, J. Shi, and N. Chi, "4.5-Gb/s RGB-LED based WDM visible light communication system employing CAP modulation and RLS based adaptive equalization," *Opt. Express*, vol. 23, no. 10, pp. 13626–13633, May 2015.
[12] X. Huang, Z. Wang, J. Shi, Y. Wang, and N. Chi, "1.6 Gbit/s phosphorescent white LED based VLC transmission using a cascaded pre-equalization circuit and a differential outputs PIN receiver," *Opt. Express*, vol. 23, no. 17, pp. 22034–22042, 2015.
[13] S. Rajagopal, R. D. Roberts, and S.-K. Lim, "IEEE 802.15.7 visible light communication: Modulation schemes and dimming support," *IEEE Commun. Mag.*, vol. 50, no. 3, pp. 72–82, Mar. 2012.
[14] X. Wu, M. Safari, and H. Haas, "Access point selection for hybrid Li-Fi and Wi-Fi networks," *IEEE Trans. Commun.*, vol. 65, no. 12, pp. 5375–5385, Dec. 2017.
[15] M. Kashef, M. Abdallah, and N. Al-Dhahir, "Transmit power optimization for a hybrid PLC/VLC/RF communication system," *IEEE Trans. Green Commun. Netw.*, vol. 2, no. 1, pp. 234–245, Mar. 2018.
[16] H. Tabassum and E. Hossain, "Coverage and rate analysis for co-existing RF/VLC downlink cellular networks," *IEEE Trans. Wireless Commun.*, vol. 17, no. 4, pp. 2588–2601, Apr. 2018.
[17] Y. Liu, Z. Huang, W. Li, and Y. Ji, "Game theory-based mode cooperative selection mechanism for device-to-device visible light communication," *Proc. SPIE*, vol. 55, no. 3, 2016, Art. no. 30501.
[18] S. V. Tiwari, A. Sewaiwar, and Y.-H. Chung, "Optical repeater assisted visible light device-to-device communications," *Int. J. Electr., Comput., Energetic, Electron. Commun. Eng.*, vol. 10, no. 2, pp. 206–209, 2016.
[19] P. Mach, Z. Becvar, M. Najla, and S. Zvanovec, "Combination of visible light and radio frequency bands for device-to-device communication," in *Proc. IEEE PIMRC WS*, Oct. 2017, pp. 1–7.
[20] Z. Becvar, M. Najla, and P. Mach, "Selection between radio frequency and visible light communication bands for D2D," in *Proc. IEEE VTC spring*, Jun. 2018, pp. 1–7.
[21] Z. Ghassemlooy, L. N. Alves, S. Zvanovec, and M.-A. Khalighi, *Visible Light Communications: Theory and Applications*, vol. 17, no. 4. Boca Raton, FL, USA: CRC Press, 2017.
[22] M. Lauridsen, L. Noël, T. B. Sørensen, and P. Mogensen, "An empirical LTE smartphone power model with a view to energy efficiency evolution," *Intel Technol. J.*, vol. 18, no. 1, pp. 172–193, 2014.
[23] X. Deng, K. Arulandu, Y. Wu, S. Mardanikorani, G. Zhou, and J.-P. M. G. Linnartz, "Modeling and analysis of transmitter performance in visible light communications," *IEEE Trans. Veh. Technol.*, vol. 68, no. 3, pp. 2316–2331, Mar. 2019.
[24] X. Deng and J.-P. M. G. Linnartz, "Poster: Model of extra power in the transmitter for high-speed visible light communication," in *Proc. IEEE Symp. Commun. Veh. Technol. (SCVT)*, Nov. 2016, pp. 1–5.
[25] M. I. Poulakis, A. G. Gotsis, and A. Alexiou, "Multi-cell device-to-device communications: A spectrum sharing and densification study," 2017, *arXiv:1711.03498*. [Online]. Available: https://arxiv.org/abs/1711.03498
[26] S. M. A. Kazmi, N. H. Tran, W. Saad, Z. Han, T. M. Ho, T. Z. Oo, and C. S. Hong, "Mode selection and resource allocation in device-to-device communications: A matching game approach," *IEEE Trans. Mobile Comput.*, vol. 16, no. 11, pp. 3126–3141, Nov. 2017.
[27] Y. Wang, Y. Shao, H. Shang, X. Lu, Y. Wang, J. Yu, and N. Chi, "875-Mb/s asynchronous bi-directional 64 QAM-OFDM SCM-WDM transmission over RGB-LED-based visible light communication system," in *Proc. Opt. Fiber Commun. Conf.*, 2013, Paper OTh1G-3.
[28] R. T. Marler and J. S. Arora, "Survey of multi-objective optimization methods for engineering," *Struct. Multidisciplinary Optim.*, vol. 26, no. 6, pp. 369–395, Apr. 2004.
[29] *Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Channels and Modulation, Release 13*, document TS 36.211, v13.5.0, 3GPP, 2017.
[30] *Study on LTE Device to Device Proximity Services; Radio Aspects, Release 12*, document TR 36.843, v12.0.1, 3GPP, 2014.
[31] P. Pešek, S. Zvanovec, P. Chvojka, M. R. Bhatnagar, Z. Ghassemlooy, and P. Saxena, "Mobile user connectivity in relay-assisted visible light communications," *Sensors*, vol. 18, no. 4, p. 1125, 2018.



MEHYAR NAJLA is currently pursuing the Ph.D. degree with the Department of Telecommunication Engineering, Czech Technical University in Prague, Czech Republic, with a topic on device-to-device communication using radio frequency and visible light communication bands.

In 2016, he joined the 5Gmobile Research Laboratory, Czech Technical University in Prague, with a focus on research related to future mobile networks. He was/is involved in two national research projects focused on combination of radio frequency and visible light communication for device-to-device communication and machine learning for mobile networks. In 2019, he was on an internship at EURECOM, France. He has coauthored four conference articles and one journal article. His research interests include radio resource management, device-to-device communication, visible light communication bands for device-to-device communication, hybrid radio frequency and visible light communication systems, machine learning for the optimization of mobile networks, and UAV-aided mobile networks.

PAVEL MACH received the M.Sc. and Ph.D. degrees in telecommunication engineering from Czech Technical University in Prague, Czech Republic, in 2006 and 2010, respectively.

From 2006 to 2007, he joined the Sitronics Research and Development Center, Prague, with a focus on emerging mobile technologies. He was involved in research activities of the Vodafone Research and Development Center at Czech Technical University in Prague, from 2005 to 2008. He is currently a Senior Researcher with the 5G Mobile Laboratory founded in 2015 at CTU in Prague focusing on 5G and beyond mobile networks. He was involved in several European projects, such as FP6 FIREWORKS, FP7 ROCKET, FP7 FREEDOM, and FP7 TROPIC. He was/is Principal Investigator in national research projects focused on allocation of radio resources to cognitive small cells and combination of device-to-device communication with visible light communication. He has published three book chapters and more than 50 conference or journal articles. He was on internship in EURECOM, France, in 2019. His current research areas include radio resource management for device-to-device communication, new techniques for dynamic functional split for C-RAN-based network architectures, positioning of flying mobile base stations, and mobile edge computing.

ZDENEK BECVAR received the M.Sc. and Ph.D. degrees in telecommunication engineering from Czech Technical University in Prague, Czech Republic, in 2005 and 2010, respectively.

From 2006 to 2007, he joined the Sitronics Research and Development Center, Prague, with a focus on speech quality in VoIP. Furthermore, he was involved in research activities of the Vodafone Research and Development Center at Czech Technical University in Prague, in 2009. He was on internships at Budapest Polytechnic, Hungary, in 2007, CEA-Leti, France, in 2013, and EURECOM, France, in 2016 and 2019. From 2013 to 2017, he was a representative of Czech Technical University in Prague, ETSI, and 3GPP standardization organizations. In 2015, he founded the 5Gmobile Research Laboratory at CTU in Prague, focusing on research towards 5G and beyond mobile networks. He is currently an Associate Professor with the Department of Telecommunication Engineering, Czech Technical University in Prague. He has published four book chapters and more than 70 conference or journal articles. He works on development of solutions for future mobile networks, with a special focus on optimization of mobility and radio resource management, device-to-device communication, edge computing, C-RAN, self-optimization, and architecture of radio access networks. He is also a member of more than 20 program committees at international conferences or workshops.

PETR CHVOJKA received the M.Sc. and Ph.D. degrees from the Faculty of Electrical Engineering, Czech Technical University (CTU) in Prague, in 2013 and 2018, respectively.

He currently works as a Research Assistant with the Department of Electromagnetic Field, CTU in Prague, where he is also a member of the Wireless and Fiber Optics Group. He leads the research in the field of visible light communications (VLC) focusing on optical systems design and modeling, including inorganic and organic devices and digital signal processing techniques. He is the author of one book chapter and over 30 journals and conference papers. He was on internships at the Ben-Gurion University of Negev, Beersheba, Israel, in 2013, Northumbria University, Newcastle upon Tyne, U.K., in 2014, and University College London, London, U.K., in 2018.

STANISLAV ZVANOVEC received the M.Sc. and Ph.D. degrees from the Faculty of Electrical Engineering, Czech Technical University (CTU) in Prague, in 2002 and 2006, respectively. He currently works as a Full Professor and the Deputy Head of the Department of Electromagnetic Field and the Chairperson of a Ph.D. Branch with CTU. He is the author of two books and the coauthor of the recent book *Visible Light Communications: Theory and Applications*, several book chapters, and more than 250 journals and conference papers. His current research interests include free space optical and fiber optical systems, visible light communications, OLED, RF over optics, and electromagnetic wave propagation issues for millimeter wave band.