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RESEARCH ARTICLE

Enhanced Network Selection Algorithms for IoT-Home Environments With Hybrid VLC/RF Systems

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ABSTRACT The impending scarcity of the radio frequency (RF) spectrum has led to a boom in the development of complementary technologies such as visible light communication (VLC). Hybrid systems that complement both technologies have demonstrated numerous advantages in terms of data rate, bandwidth, and security. However, the successful operation of a hybrid VLC/RF network is highly dependent on the network selection process. In this paper, three network selection algorithms are proposed for hybrid VLC/RF systems in an indoor Internet of things (IoT)-home scenario. The proposed algorithms consider the signal-to-noise ratio (SNR), the available capacity of each network, the number of devices connected to each network, and the users' location within the scenario. Each algorithm analyzes the data load requirements of each mobile terminal and IoT device according to these metrics. Based on this evaluation, the network that offers the best benefit in terms of signal quality, capacity, and throughput is selected. The numerical results show that the VLC network presents higher SNR values, especially for users near its access points. In addition, a higher bandwidth, a higher connection capacity, and an improvement in the quality of service are perceived from these positions. The three proposed selection algorithms presented good overall performance of the hybrid system, with the Analytical Algorithm offering the best performance for connected users, superior to the Sequential Algorithm by an average of 15.9%. The network selection algorithms efficiently allocated the maximum number of users for the VLC network, improving overall system performance and reducing the RF network data load.

INDEX TERMS Hybrid networks, Internet of Things (IoT), radio frequency (RF), visible light communication (VLC).

I. INTRODUCTION

With the continued advancement of communication technologies, a potential innovation is emerging: the Internet of things (IoT). This trend is establishing a global network in which

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all types of devices will be connected to the Internet [1]. IoT consists of the convergence of data obtained from different smart devices to any existing internet infrastructure platform [2]. However, this wireless connectivity presents a major challenge due to the overload on the limited radio frequency (RF) spectrum caused by the exchange of data between smart devices. Allocating resources of the RF spectrum becomes even more complicated due to the large number of devices competing for its use [3].

Notably, the majority of IoT-connected devices are in indoor scenarios, such as homes, offices, and shopping malls. This makes optical wireless systems, such as visible light communication (VLC) technology, an excellent complementary option to RF networks to cope with the growing demand for smart devices [4]. In this context, VLC networks have gained popularity due to their advantages in terms of bandwidth, data transmission speed, and security. In addition, these networks are energy efficient and have minimal installation costs. However, the major limitation of VLC networks is that the devices connected require a direct line of sight between the transmitter and receiver to achieve an efficient connection. This is why in recent years hybrid networks composed of VLC and RF have emerged [5]. The authors in [6] propose a VLC/RF network to take advantage of the bandwidth, security and coverage benefits of this hybrid system. Here they develop a load balancing scheme that maximizes network performance and minimizes interference. On the other hand, a Communication Efficient Federated Learning scheme that minimizes communication cost (in terms of bandwidth used, amount of data transferred and latency) and improves system efficiency in hybrid VLC/RF networks is proposed in [7].

These hybrid networks can efficiently complement both networks, offering greater reliability, flexibility, and adaptability to different working conditions. The use of hybrid VLC/RF technologies in IoT systems offers significant advantages, such as wider coverage, higher data rates, increased reliability and security, and effective communications reach [8]. This combination of technologies makes it possible to take advantage of the best of each and overcome individual limitations, providing more complete and efficient solutions for IoT applications [9], [10]. However, using two communication technologies to serve multiple smart devices combined with the constant competition for resources between devices and the mobile terminals, represents a great challenge to efficiently allocate system resources. The development of network selection algorithms and vertical handover techniques allows to optimally allocate and manage the available resources in the electromagnetic spectrum [11]. The successful operation of a hybrid VLC/RF network is highly dependent on the network selection process with the best user benefit, which ensures communication effectiveness, scalability, security, and maximum efficiency. During this selection process, multiple factors must be carefully considered, including the inherent characteristics of the network technologies used [12]. In addition, there may be overlapping coverage areas between VLC and RF networks, which requires consideration of real-time performance fluctuations, user location and type of traffic. Bandwidth, latency, capacity and device density can also vary significantly between the two networks, requiring the use of algorithms to select the most appropriate network for optimal communication quality and user experience [13].

In this paper, our main contributions are:

- Three network selection algorithms are proposed, applicable in hybrid VLC/RF systems, and evaluated in an IoT-home scenario. The algorithms consider different system parameters and quality of service (QoS) requirements, such as the signal-to-noise ratio (SNR), the channel capacity of both RF and VLC networks, and the traffic load required by each user.
- The network selection algorithms improve the performance of the hybrid network, prioritizing the use of the VLC network to guarantee the QoS of the largest number of users and conveniently exploiting the advantages of the RF network to increase the number of smart devices connected to the hybrid network. In general, the selection of the VLC network is prioritized for most devices to ensure higher data rates and better system performance. In contrast, the RF network is used by users who cannot access the VLC network or require a lower traffic load. Thus, the proposed strategies attempt to make efficient use of the connection resources of both networks while guaranteeing the QoS required by the system users.
- The presentation of a study showing the trade-off resulting from the selection strategy used and the main parameters on which it depends is an important contribution. Thus, the timely identification of challenges latent for this type of system, such as user mobility and how to ensure optimal orientation in VLC links.

The paper is structured as follows: in Section II, we survey related works and frame network selection algorithms in the context of IoT in the home. In Section III, we design three network selection algorithms for the hybrid system. In Section IV, we perform a simulation evaluation of the proposed algorithms and present the numerical results. Finally, in Section V, we present the conclusions of the paper.

II. RELATED WORK

A considerable amount of work on VLC networks for IoT can be found in the literature. In [14], pixelated VLC back-scattering is proposed to overcome channel capacity limitations in IoT applications. To this end, multiple smaller VLC back-scatterers are integrated to generate multilevel signals, enabling the use of more advanced modulation schemes. The authors of [15] propose optimized algorithms to achieve the balance between uniform illumination and communication performance in a VLC network through joint lamp arrangement and power allocation for IoT applications in an indoor scenario. Recently, the cross-talk phenomenon in a real-time full-duplex VLC network was

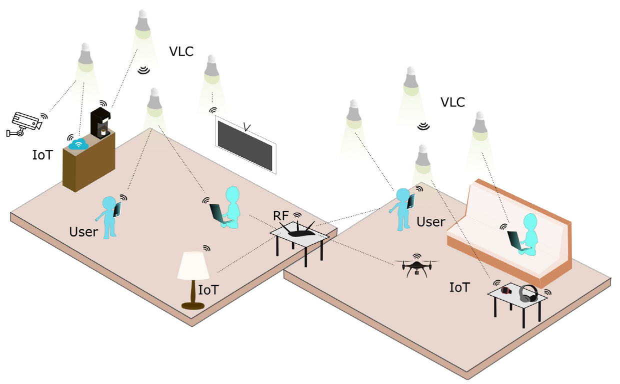

FIGURE 1. Hybrid VLC/RF network in IoT-home scenario.

studied in [16]. With the combination of a red light-emitting diode (LED) and an APD430A/M optical receiver, the authors achieved 100 Mbps Fast Ethernet transmission over a distance of 30 meters. In addition, they conducted an experiment on VLC-IoT networks where multiple terminal devices could access the VLC-IoT network at the same time. Through this experiment, the application field of traditional RF communications-based IoT was extended to VLC-IoT networks, making it possible to apply IoT in sensitive indoor scenarios. Moreover, the authors of [17] propose an optimized modulation of VLC signals based on authentication, which improves transmission security for indoor IoT applications. To do so, they modified multi-pulse position modulation to map digits and send particle data over a wider coverage.

Hybrid networks composed of VLC and RF technologies have also been proposed for indoor IoT applications. The authors in [9] investigate the outage performance of a hybrid VLC/RF system for IoT device connectivity. Here they propose the use of an aggregation agent acting as a relay node for bidirectional communication with IoT devices. In [18], a heterogeneous network based on RF and VLC is presented to manage quality of service (QoS) requirements in industrial IoT systems. Here, energy efficient uplink and downlink resource management algorithms were developed through a Markov process. In [19], a hybrid RF/VLC network architecture for IoT using low power and long range devices is proposed. The authors here achieved high interoperability between both technologies and homogeneous power supply through solar panels. In [20], a hybrid VLC/RF system is proposed to improve user service performance in an IoT system, based on simultaneous lightwave information and power transfer (SLIPT). The signal transmission is divided into two hops. In the first hop, the optical signal received from the VLC network at a relay device external to the network is separated into AC and DC components for information decoding and energy harvesting, respectively. The collected energy is then used to send the information through the RF network to the receiver.

In an IoT home scenario, there may be multiple smart devices connected from different locations, with different connection characteristics and different data load requirements. To achieve an efficient connection between IoT devices, mobile terminals, and the hybrid VLC/RF network, it is necessary to develop and implement network selection algorithms that ensure efficient resource utilization, improved quality of service, and better adaptation to the environment. Several network selection algorithms for hybrid VLC/RF systems have been proposed in the literature. In the works [21], [22] network selection algorithms are established in hybrid VLC/RF systems using cooperative non-orthogonal multiple access (CO-NOMA) techniques. In which two types of users are established: strong and weak users, strong users are served directly by the VLC network, while weak users can connect directly to the VLC network or can be served through the strong users by an RF link. Here the strong users can convert the light information and send it to the weak users via an RF link. For this purpose, in [21] an iterative strategy is established by taking into account the weighted sum rate for the whole network to determine the pairs of weak and strong users, the service link of each weak user and the power of each message. While in [22] a strategy based on the assignment of message and access point powers is established to determine the links serving each weak user. On the other hand, in [23] a joint optimization strategy based on deep Q-network learning algorithms in a hybrid VLC/RF network is presented. The authors use an action-value function, which allows training a newly arrived user team using the information of the environment before the arrival of a new user for a selection of the best network. In [24], a strategy for combined power and slot allocation in hybrid VLC/RF networks is proposed with the objective of maximizing the total data rate of the network. The non-convex problem of joint power and slot allocation is divided into less complex sub-problems and solved iteratively. The authors in [25] present a bidirectional selection handover algorithm taking into account the network load balance. For this purpose, the appropriate destination access point is first selected based on fuzzy analytic hierarchy and order preference techniques by similarity to the ideal solution. Then a set of users with higher priority to connect through the RF network is selected.

However, the network selection algorithms in hybrid VLC/RF systems previously proposed in the literature do not take into account the connection characteristics of IoT devices, nor the type of traffic offered by these devices. Moreover, these algorithms have a high complexity of execution and a high computational level. On the other hand, the algorithms proposed in [21] and [22], by dividing the users into strong and weak, the majority of the connections are established in the RF network. Considering the aforementioned parameters, namely connection and traffic properties of the devices, this paper presents three network selection algorithms applicable to hybrid VLC/RF systems and evaluates them in an IoT-home scenario, as shown in Figure 1. The three algorithms achieve optimized best network selection and elevate the throughput of the hybrid system very easily and with low computational overhead. For this purpose, three different network selection approaches are proposed, based on the proximity of the devices to each of the networks, the quality of the connection and the data load requested by each of the devices to the network. The comparison of these QoS parameters is done fairly without differentiating between user equipment and IoT devices. The hybrid model proposed in [26] was used to develop the algorithms, using a 20m^2 scenario with 4 VLC access points on the ceiling of the room and an RF access point in the center of the room. In this IoT-home scenario both the users' mobile terminals and the smart devices inside the house will be competing for the available channels of both networks.

III. SYSTEM MODEL

A hybrid system composed of VLC and RF networks operates in an indoor IoT-home scenario. The VLC network is composed by many access points located on the ceiling and the RF network has a central access point available for the whole scenario.

A. VLC CHANNEL MODEL

The VLC network link is directly dependent on the line-of-sight (LOS) between the transmitter and the receiver. $\iota = \log_2^{-1}(cos(\phi_{1/2}))$, is the Lambertian emission order that depends on the average angle at half illumination of the LED. The Euclidean distance of the path between the access point (AP) VLC and a user LOS is denoted by D_{LOS}. The angle of irradiance of the AP and the incidence are denoted by φ_{ir} and φ_{in}, respectively. A denotes the physical area of the photodetector; T_s is the gain of the optical filter at the receiver; and $g_c(\varphi_{in})$ is the gain of the optical concentrator used to focus the light onto the photodetector. From these parameters, the gain of the VLC channel with a LOS link is calculated as [27]:

$$H_{LOS} = \frac{(\iota+1)AT_s}{2\pi D_{LOS}^2} cos^{\iota}(\varphi_{ir}) g_c(\varphi_{in}) cos(\varphi_{in}), \tag{1}$$

with

$$g_c(\varphi_{in}) = \begin{cases} n^2 \sin^{-2}(\varphi_c) & \text{if } 0 \leq \varphi_{in} \leq \varphi_c, \\ 0 & \text{if } \varphi_{in} > \varphi_c, \end{cases} \tag{2}$$

where n denotes the refractive index and φ_c is the field of view (FOV) width from the receiver.

The light can reflect off any object or obstacle present on the scenario, as well as the surrounding walls. The channel gain in this type of link is called H_{NLOS}. For simplicity in calculations, only the first order of reflection is taken into account, which can be calculated by [28]:

$$H_{NLOS} = \int_{A_w} \frac{(\iota+1)AT_s\rho}{2(\pi D_1 D_2)^2} GA_w cos(w_1) cos(w_2), \tag{3}$$

with

$$G = cos^{\iota}(\varphi_{ir}) g_c(\varphi_{in}) cos(\varphi_{in}), \tag{4}$$

where ρ is the reflective factor of the object or wall; D_1 and D_2 represent the Euclidean distances from the NLOS link to the reflection point and from the reflection point to the receiver, respectively. The angle of irradiance and incidence between the reflection point and the receiver is represented by w_1 and w_2, respectively; A_w is a small area of reflection on the reflective object.

The total gain of the VLC channel is given by the contribution of the LOS gain and the NLOS gain as [26]:

$$H_{VLC} = H_{LOS} + H_{NLOS}. \tag{5}$$

The SNR after photodetection in the electrical domain (SNR_{VLC}) determined by the photodetector responsivity R, the received optical power and the shot and thermal noise variance, is given by [27]:

$$SNR_{VLC} = \frac{(RP_r)}{\sigma_{shot}^2 + \sigma_{thermal}^2}. \tag{6}$$

The *shot* and *thermal* noise variance are given by:

$$\sigma_{shot}^2 = 2qRP_rB + 2qI_BI_2B, \tag{7}$$

$$\sigma_{thermal}^2 = \frac{8\pi kT_k}{G_{ol}} C_{pd}AI_2B^2 + \frac{16\pi^2 kT_k\rho}{g_m} C_{pd}A^2I_3B^3. \tag{8}$$

The capacity of the VLC network is given by [26]:

$$C_{VLC} = \frac{B_{VLC}}{N_u} log_2(1 + SNR_{VLC}), \tag{9}$$

where N_u represents the number of users connected to the network and B_{VLC} represents the total bandwidth of the VLC AP. As users connect to a network AP, the total throughput available is reduced based on the amount of resources used by each user. This decreases the total available capacity of each network AP as the number of users served increases.

We assume in this work that all devices are oriented towards the VLC access points located on the ceiling. A random orientation of the devices within a VLC scenario would result in the loss of the LOS link between the transmitter and the receiver and increase the probability of blocking the VLC network. We consider this an important problem of VLC networks that should be studied in the near future.

B. RF CHANNEL MODEL

The RF link has the ability to transmit and receive data via radio waves in the electromagnetic spectrum. This technology allows wireless communication over long distances without the need for a direct line of sight between the transmitter and receiver. The RF link channel gain is given by [29]:

$$G_{RF} = |H_{RF}|^2 10^{\frac{-L(d_{rf})+\sigma}{10}}, \tag{10}$$

where H_{RF} describes the transfer function of the channel; $L(d_{rf})$ is the free space path loss and σ denotes the shadow fading. The path loss dependent distance can be calculated as:

$$L(d_{rf}) = \begin{cases} 20\log_{10}(f_c d_{rf}) - 147.5 & \text{if } d_{rf} \leq D_{ref}, \\ 20\log_{10}(f_c \frac{d_{rf}^{2.75}}{D_{ref}^{1.75}}) - 147.5 & \text{if } d_{rf} > D_{ref}, \end{cases} \tag{11}$$

where f_c is the carrier frequency and $d_{rf} = 10$m is the reference distance that we use.

The signal-to-noise ratio (SNR) is defined as [26]:

$$SNR_{RF} = \frac{G_{RF} P_{RF}}{N_{RF} B_{RF}}, \tag{12}$$

where N_{RF} is the power spectral density of the noise in the photodetector; P_{RF} and B_{RF} are the transmit power and bandwidth of the RF channel, respectively, and N_u is the number of users in RF network. The capacity of the RF network is given by [26]:

$$C_{RF} = \frac{B_{RF}}{N_u} log_2(1 + SNR_{RF}). \tag{13}$$

IV. ALGORITHM DESIGN

An indoor IoT-home scenario is considered in which the combination of VLC and RF technologies is used to serve both mobile terminals and smart devices within the scenario. Consequently, the coverage of both networks may vary for each user (mobile terminals and smart devices), as well as the data load requirements. For this reason, the proposed algorithms improve the network performance by selection based on the SNR and effective capacity values of each network and the data load requirements of each user. Here we assume that multiple users can be connected to a single AP based on time division multiplexing (TDM) technique, where different timeslots are allocated to each user in an AP.

The algorithms state that when a user initiates a network search, the system checks whether the device can successfully access the network. The SNR and effective capacity parameters of the connection through the VLC and RF networks are then calculated based on the user location and distance to the access points corresponding to each network.

A. SEQUENTIAL ALGORITHM

Algorithm IV-A prioritizes the connection of users through the VLC network sequentially. Here, users that require a data load above a certain data rate threshold (R_{th}) and meet the requirements for connecting to the VLC network are connected to the VLC network. Once the VLC network capacity is exhausted and all available channels are occupied, the remaining users will be connected to the RF network. Users not meeting the VLC connection requirements will connect directly to the RF network. Although this algorithm prioritizes the connection through the VLC network and guarantees that users requiring a data load greater than R_{th} can connect to the VLC network, it performs this process based on the users order of arrival, which does not guarantee that all users with a data load requirement greater than R_{th} will connect to this network. Some of the users with a high data load requirement may no longer be able to connect to the VLC network because the capacity offered by this network is fully occupied.

The VLC network connection requirements are the following:

- The SNR_{VLC} value must be greater than the SNR_{RF} value.
- The total capacity of the VLC network must be sufficient to serve the user.

The sequential algorithm is shown in Algorithm IV-A.

Algorithm 1 Sequential Algorithm

```
Create a variable Load with N random data load values, one for each user
Loop
For each user (i) a comparison of the values of SNR and the data load is performed, as follow
if SNR_VLC(i) > SNR_RF(i) and Load(i) ≥ R_th then
    if C_VLC > C_th then
        Select user (i) to connect to the VLC network
        C_VLC = C_VLC − C_th
    else
        Select user (i) to connect to the RF network
        C_RF = C_RF − C_th
    end if
else
    Select user (i) to connect to the RF network
    C_RF = C_RF − C_th
end if
end Loop =0
```

B. ANALYTICAL ALGORITHM

Algorithm IV-B presents the analytical algorithm. Unlike the algorithm IV-A, it analyzes and ranks the data load requirements of all users wishing to connect to the network, thus ensuring that all users with high data load requirements can connect to the VLC network. For this, users are ordered from the highest data load requirement to the lowest data load requirement. Users requiring a high data load are prioritized for connection through the VLC network because it provides higher bandwidth and higher data rates. Users requiring a low data load will connect directly to the RF network for greater coverage. In this way, users selected to connect to the VLC network, starting with the user requiring the highest data load, are screened to see if they meet the requirements for connecting to the VLC network. Users that meet the connection requirements will be connected to the VLC network and users that cannot connect to this network will be transferred to the RF network. This algorithm allows all users to be prioritized according to their data load, giving them a better chance to connect through the network that benefits them the most.

C. DIFFERENTIAL ALGORITHM

Algorithm IV-B presents the differential algorithm. It separates users wishing to connect to the hybrid system into three groups according to their differences in data load type. Three types of data loads are established here: (i) a fixed and high data load, (ii) a fixed and low data load, and (iii) a variable

Algorithm 2 Analytical Algorithm

Create a variable Load with N random data load values, one for each user
Loop
Select the N_H users that require the most data load, as follows
$Max_{value} = max(Load)$
Delete parameters: In each iteration, the selected user is deleted in order not to be selected again
end Loop
Loop
For each user (i) a comparison of the values of SNR and the data load is performed, as follow
if $SNR_{VLC}(i) > SNR_{RF}(i)$ and $i \in Max_{value}$ **then**
  if $C_{VLC} > C_{th}$ **then**
    Select user (i) to connect to the VLC network
    $C_{VLC} = C_{VLC} - C_{th}$
  else
    Select user (i) to connect to the RF network
    $C_{RF} = C_{RF} - C_{th}$
  end if
else
  Select user (i) to connect to the RF network
  $C_{RF} = C_{RF} - C_{th}$
end if
end Loop =0

Algorithm 3 Differential Algorithm

Create three groups of data load variables: fixed high load, fixed low load, and variable load
$Load_{high} \leftarrow N_H$ random data load values greater than R_{th}
$Load_{low} \leftarrow N_L$ random data load values less than R_{th}
$Load_{var} \leftarrow N_V$ random time-varying data load values
Randomly assign to each user a data load value corresponding to the three data load groups
Loop
For each user (i) a comparison of the values of SNR and the data load is performed, as follow
if $SNR_{VLC}(i) > SNR_{RF}(i)$ and ($i \in Load_{high}$ or $i \in Load_{var}$) **then**
  if $C_{VLC} > C_{th}$ **then**
    Select user (i) to connect to the VLC network
    $C_{VLC} = C_{VLC} - C_{th}$
  else
    Select user (i) to connect to the RF network
    $C_{RF} = C_{RF} - C_{th}$
  end if
else
  Select user (i) to connect to the RF network
  $C_{RF} = C_{RF} - C_{th}$
end if
end Loop =0

data load. Analysis of the difference between the types of data loads allows the separation of users requiring a fixed data load from users requiring a variable data load. This way, targeted and efficient attention can be given to each user, decreasing the overall transmission delay and increasing the overall throughput of the system.

Users who require a high fixed data load and meet the connection requirements of the VLC network will connect to the VLC network. Users who require a fixed but low data load will connect to the RF network. Two variants of this algorithm were designed. In variant 1, users requiring variable data load will be connected to the VLC network to obtain higher bandwidth and higher transmission speed. In variant 2, these users will be signed to the RF network to seek higher coverage and free up the available bandwidth in the VLC network for users with high data loads. All users who cannot access the VLC network because they do not meet the connection requirements will be transferred to the RF network.

This algorithm allows an analysis of the variability of the data load over time, allowing to obtain more realistic results that vary according to the data load of the applications being used by the users. The two variants of this algorithm also allow to analyze which network presents better benefits to these users even though their data load varies over time.

V. NUMERICAL RESULTS AND DISCUSSION

For the simulation of our network selection algorithms we used an indoor IoT-home of $20m^2$ with a height of 3m, where a hybrid VLC/RF network was deployed to connect all users. The hybrid network consists of 4 VLC access points (VLC-AP) evenly placed on the ceiling in a grid pattern, so that the entire room is illuminated, and an RF access point (RF-AP) located in the room center, so that all users can access this RF network. We assume an ideal scenario with static connections, where the VLC access points transmit information orthogonally in time to minimize interference. This type of scenario has been used by several works such as [6], [26], and [30]. This configuration minimizes interference between the different VLC-APs but promotes the appearance of uncovered zones in the VLC network, a drawback resolved by the network selection mechanism. Users who cannot access the VLC network or have a low SNR, for whatever reason, will be transferred to the RF network to be satisfactorily served. We simulated $N = 15$ users randomly placed inside the IoT-home, composed of mobile terminals and IoT devices, following a uniform distribution in the area. All devices are assumed to be facing the access points. The data load required by each user was randomly assigned using a Gaussian distribution. For the conditions of this scenario, we assume threshold values such as $R_{th} = 1$Mbps and $C_{th} = 2$Mbps. The parameters used in the simulation are shown in Table 1.

Figure 2 shows the SNR (dB) as a function of the distance from the users to the access points of the VLC and RF networks, respectively. It can be seen that the SNR of the VLC network is higher than the SNR of the RF network. This is mainly due to the nature of visible light wave transmission, which is less susceptible to interference and noise compared to radio waves. In both networks, users closer to the access points will perceive a higher SNR than users further away from the access points.

Figure 3 shows the achievable capacity that can be allocated to a single user by the VLC and RF networks, respectively, at each point in the scenario. This has been calculated using 9 and 13 with $N_u = 1$. It can be seen that higher network capacity can be obtained in the vicinity of the

TABLE 1. System parameters.

Indoor Scenario	Parameters
Length of room	20m^2
Height of room	3 m
Height of MT	0.85 m
BER target	10^{-5} [26]
VLC system	**Parameters**
Height of LED	2.5 m
Power of LED	20 w
Number of LED array	4
Position of the LED (x,y)	$(5,-5);(5,5);(-5,-5);(-5,5)$
Semi-angle at half power	70 deg [31]
Width of the field of view	60 deg [31]
Detector physical área of a PD	1cm^2
Refractive index of a lens at a PD	1.5
O/E conversion efficiency	0.53 A/W [11]
Available bandwidth	10 MHz [26]
Reflectance factor	0.8
Background current	$5.1 \cdot 10^{-3}$ A [11]
Open-loop voltage gain	10
Fixed capacitance of the PD per unit area	$1.12 \cdot 10^{-6}$ [11]
FET cannel noise factor	1.5
FET transconductance	$3 \cdot 10^{-2}$
Femtocell System	**Parameters**
Number of AP	1
Position of AP (x,y,Z)	$(0,0,2)$
Transmission power of the femtocell BS	0.02 W [26]
Indoor path-loss exponent	3 [26]
Indoor path-loss conctant	37 dB [26]
Available bandwidth	5 MHz [26]

access points of both networks. In addition, the VLC network can provide higher capacity within the scenario for the same number of users due to the higher offered SNR.

Figure 4 shows the available unallocated capacity of the VLC and RF systems as a function of the addition of new users. In all algorithms, the capacity provided by the VLC network is higher than the capacity provided by the RF network. In both networks, each user (mobile terminal or IoT device) is allocated only a portion of the total network capacity based on the SNR and the data load required by each user. For this reason, as the number of connected users in each network increases, the available unallocated capacity decreases. The Analytical, Sequential and Differential 1 network selection algorithms prioritize the connection of users through the VLC network, because the VLC network has a higher bandwidth than the RF network, these algorithms have a higher unallocated available capacity that allows them to serve more users through this network. On the other hand, Figure 5 shows the capacity allocated by the VLC and RF network as new users join the system. Here the total allocated capacity is shown, which represents the sum of the capacities of all users connected so far. The Analytic, Sequential and Differential V1 network selection algorithms prioritize the connection of users through the VLC network, so the 10 users connected to this network get a higher connection capacity. The remaining 5 users in the scenario are connected to the RF network and obtain a slightly lower connection capacity. On the other hand, Differential Algorithm V2 prioritizes the connection of users through the RF network, so this network divides its total capacity among 10 users (with variable data loads and low data loads), and the remaining 5 users are connected to the VLC network, thus obtaining a higher connection capacity.

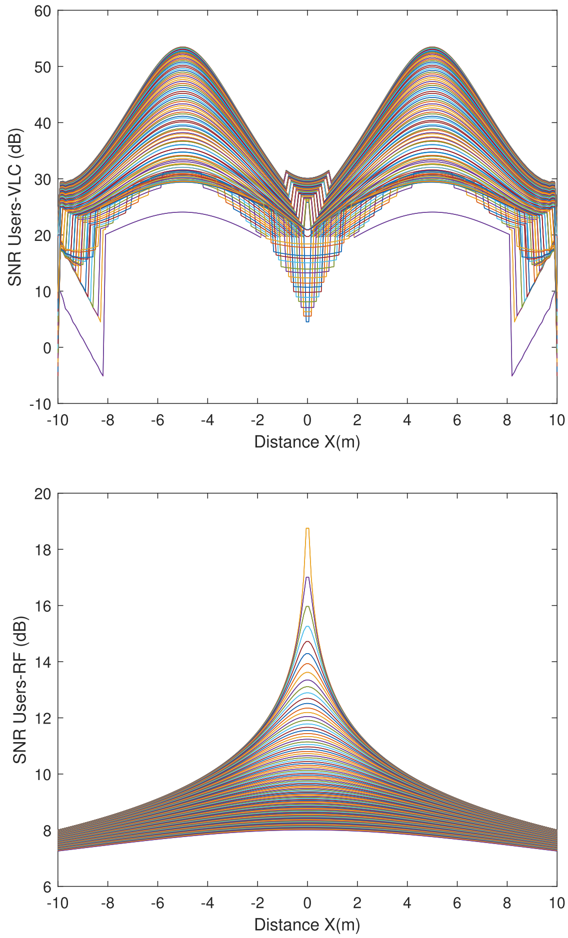

FIGURE 2. SNR Vs Distance from the user to the AP A) VLC Network; B) RF Network.

Figure 6 shows the throughput of the VLC and RF networks as a function of the number of users connected for the three selection algorithms proposed. The total throughput of the network is defined as the sum of the throughput of each user connected to the network, therefore, as the number of users increases so does the total throughput of the system. It can be seen that, in general, the throughput obtained by the users connected to the VLC network is higher than the throughput of the users connected to the RF network. For this reason, the Analytical, Sequential, and Differential V1 algorithms prioritize the connection of the mobile terminal or IoT device with the highest data throughput requirements through this network. The Analytic selection algorithm achieves the highest throughput values because it prioritizes the connection of users in order of highest to lowest data load requirements. This allows users with higher data load requirements to connect through the VLC network to take advantage of its high data rate and wide bandwidth. On the other hand, Differential Algorithm V2 obtains the lowest throughput values for the concurrent users. However, this is because this algorithm assigns users with varying data loads to the VLC network and these users can have both high and low data loads, reducing the overall throughput of the system.

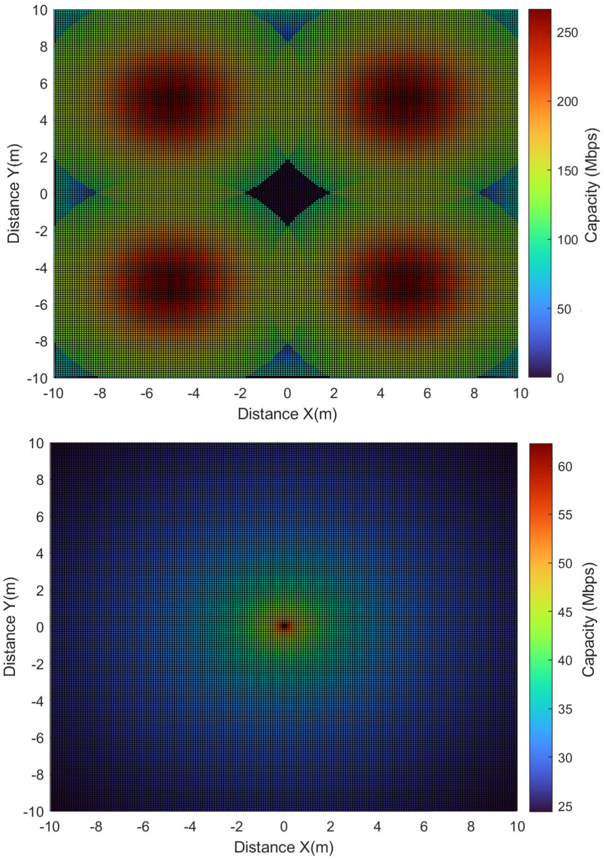

FIGURE 3. Heatmap of the VLC user capacity within the scenario A) VLC Network; B) RF Network.

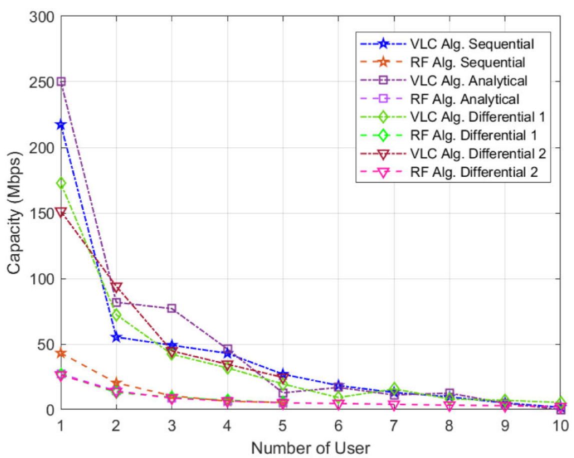

FIGURE 4. Unallocated Available Capacity of the VLC and RF systems based on the incorporation of new users. With $N = 15$, $R_{th} = 1$Mbps and $C_{th} = 2$Mbps.

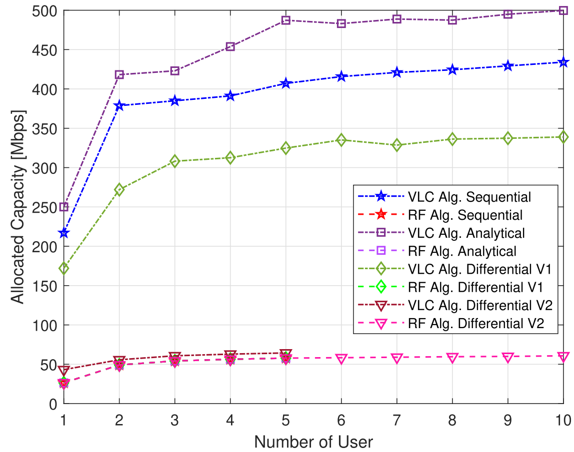

FIGURE 5. Allocated Capacity of the VLC and RF systems based on the incorporation of new users. With $N = 15$, $R_{th} = 1$Mbps and $C_{th} = 2$Mbps.

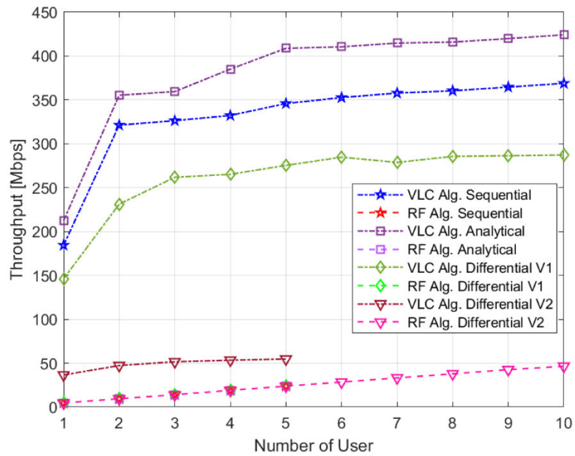

FIGURE 6. Network throughput of the VLC and RF systems per users. With $N = 15$, $R_{th} = 1$Mbps and $C_{th} = 2$Mbps.

Figure 7 shows the overall hybrid system performance for the Differential Algorithm as a function of time. This algorithm classifies and differentiates the users (mobile terminal or IoT device) into three groups according to their data load requirements. The first group can be composed of mobile terminals or smart devices such as Apple TV, Chrome-cast, Smart TV, and smart surveillance systems that use applications with a high fixed data load over time. The second group can be composed of sensor-based IoT devices such as smart devices for environmental monitoring, energy consumption measurement, monitoring and control of lighting, climate, and home security, among other devices that require a fixed but low data load. The last group can be composed of mobile terminals that are using applications such as social networks and instant messaging, as well as IoT devices such as home automation systems, smart activity tracking devices, and smart connected vehicles. All these devices and applications require a time-varying data load that depends on the amount of information being transmitted at any given time. Variant 1 of the Differential Algorithm assigns users with high or variable data load to the VLC network, this takes advantage of the high bandwidth and high data rate of this network and increases the overall throughput of the hybrid system. In the case of variant 2 of the Differential Algorithm, users with variable or low data load are assigned to the RF network, which reduces the overall throughput of the system even though it provides them with a larger coverage area and mobility. Variant 3 represents a case

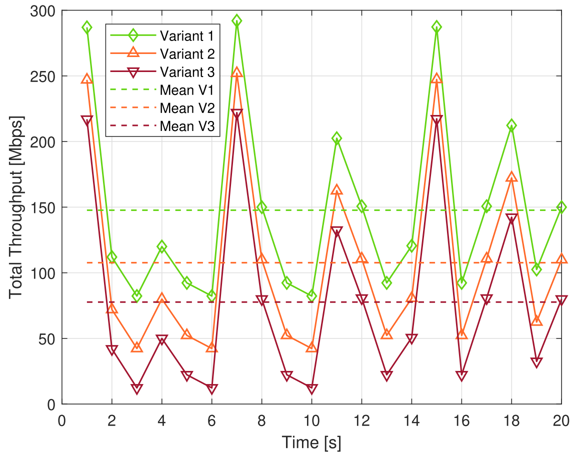

FIGURE 7. Total performance of the Differential Algorithm as a function of Time. With $N = 15$, $R_{th} = 1$Mbps and $C_{th} = 2$Mbps.

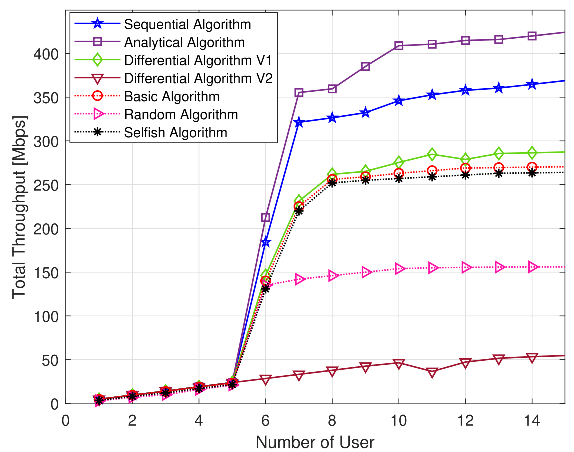

FIGURE 8. Comparison of the total throughput of the network selection algorithms. With $R_{th} = 1$Mbps and $C_{th} = 2$Mbps.

study of the Differential Algorithm where 60% of the variable data load users are assigned to the VLC network along with the high data load users and 40% of the variable data load users are assigned to the RF network along with the low data load users. To achieve optimal efficiency in the distribution of variable data load users and the performance of the hybrid system (Variant 3), it is necessary to perform an in-depth study of the percentage distribution of users based on the required data load, location, and possible user mobility over time. The dashed lines represent the average total throughput of each variant of the Differential Algorithm.

Figure 8 shows the comparison of the total throughput of the hybrid system between the three algorithms proposed in this work and three algorithms proposed in [25], [32], and [33], as a function of the number of users connected in a given time. We observe that the Analytical Algorithm outperforms all algorithms in terms of throughput, being superior to the Sequential Algorithm by an average of 15.9%. This is because the Analytical Algorithm establishes a priority order from highest to lowest user data load requirement and connects the users that need it most to the VLC network, while the Sequential Algorithm is limited by the order of requests. However, the Sequential Algorithm outperforms the Differential Algorithm by an average of 13.9% in Variant 1 since this algorithm is limited to serve 66% of the users that do not have a variable load. As can be perceived, up to 5 users, the benefits of the Basic Algorithm [25], [32] allow reaching approximately the performance of the Differential Algorithm in Variant 1 and both algorithms are very close to the Selfish Algorithm [32] selection of users. This is because both the Basic Algorithm and the Selfish Algorithm select the VLC network as the first choice due to its bandwidth and data rate benefits, which increases system performance initially at the cost of saturating the VLC network. Even though both algorithms (Basic and Selfish) have very similar behavior, the Basic algorithm outperforms the Selfish Algorithm by an average of 4.7%. The Basic Algorithm states that mobile terminals and IoT devices within the scenario will interact on a first-come, first-served basis prioritizing the connection through the VLC network. Once the VLC network can no longer serve more users, new requests will be connected through the RF network, as well as users that cannot connect to the VLC network because they do not meet the quality requirements. Although this algorithm gives priority to the VLC network and assigns the network selection taking into account the network capacity, it does not take into account the data of the user demand. On the other hand, the Selfish Algorithm shows the option where the user himself can selfishly select the preferred network for his connection, taking into account the signal strength displayed by his terminal device. In this case, we assume that the signal strength provided by the terminal device is only determined by the SNR of the network in question. Therefore, when selecting a network based on this information, the user does not take into account the actual capacity of the network or the number of users already connected to it. As a result of this most users selected the VLC network which has higher SNR and congestion in the system by demanding more capacity than the network could provide.

Finally, the poor performance of the Random Algorithm [32], [33] demonstrates the capability of the algorithms studied so far by showing that making a random decision will always have a worse average performance than the other algorithms, except for the Differential Algorithm in variant 2, which by assigning all variable traffic to the RF network causes deterioration of the hybrid system. This algorithm prioritizes the connection through the RF network, assigning users with low and variable data load to the RF network and once it saturates this system assigns the remaining users to the VLC network. In this way, end users may experience a slight improvement in system performance, but at the cost of a poor connection for most users. Therefore, this algorithm is not recommended for our scenario.

VI. CONCLUSION

This study proposes three different algorithms for selecting networks in a hybrid VLC/RF system, prioritizing the connection of users through the VLC network. The algorithms take into account factors such as SNR, capacity, and data load requirements of each user for the selection of the best network. These algorithms were simulated in an indoor IoT-Home scenario, where a hybrid VLC/RF network was deployed and 15 users between mobile terminals and IoT devices were considered. The results obtained showed that the VLC network presents higher SNR values, especially for users close to the VLC access points, in addition to a higher bandwidth that allows a higher connection capacity and an improvement in the quality of service. The three proposed selection algorithms showed a good overall performance for the hybrid system. However, the Analytic algorithm offered the best performance for connected users, as it prioritizes users based on their data load requirements. On the other hand, the Differential algorithm differentiates between users requiring fixed data loads and those with variable loads over time, allowing for the selection of the best network according to users' real-time needs. The results obtained show that these network selection algorithms enhance the overall system performance compared to random algorithms or user selection methods that disregard the different quality parameters of the connection. This ensures the selection of the best network for each user. All algorithms efficiently selected the maximum number of users for the VLC network, improving the overall system performance and reducing data load on the RF network.

Note that the numerical results are determined by the configuration parameters set, the current design of a simulator will allow us to explore new and multiple scenarios. In future work, we will propose an algorithm that can adapt the number of users to each technology based on the number of requests, their data load demands and their locations within the scenario. In addition, we will present a discrete event simulator for a hybrid VLC/RF scenario where these network selection algorithms can be evaluated taking into account external parameters such as interference and the probability of blocking due to high mobility within the scenario.

REFERENCES

[1] A. Koohang, C. S. Sargent, J. H. Nord, and J. Paliszkiewicz, "Internet of Things (IoT): From awareness to continued use," *Int. J. Inf. Manage.*, vol. 62, Feb. 2022, Art. no. 102442.

[2] A. Ćolaković, "IoT systems modeling and performance evaluation," *Comput. Sci. Rev.*, vol. 50, Nov. 2023, Art. no. 100598.

[3] T. Wang, F. Yang, J. Song, and Z. Han, "Dimming techniques of visible light communications for human-centric illumination networks: State-of-the-art, challenges, and trends," *IEEE Wireless Commun.*, vol. 27, no. 4, pp. 88–95, Aug. 2020.

[4] W.-C. Wu and G.-L. Chen, "Multiuser downlink communication for MIMO-VLC system using spatial modulation and optical orthogonal codes," *Phys. Commun.*, vol. 63, Apr. 2024, Art. no. 102264.

[5] X. Liu, S. Huang, K. Zhang, S. Maimaiti, G. Chuai, W. Gao, X. Chen, Y. Hou, and P. Zuo, "Joint resource allocation and drones relay selection for large-scale D2D communication underlaying hybrid VLC/RF IoT systems," *Drones*, vol. 7, no. 9, p. 589, Sep. 2023.

[6] A. Adnan-Qidan, M. Morales-Céspedes, and A. G. Armada, "Load balancing in hybrid VLC and RF networks based on blind interference alignment," *IEEE Access*, vol. 8, pp. 72512–72527, 2020.

[7] S. M. Sheikholeslami, A. Rasti-Meymandi, S. J. Seyed-Mohammadi, J. Abouei, and K. N. Plataniotis, "Communication-efficient federated learning for hybrid VLC/RF indoor systems," *IEEE Access*, vol. 10, pp. 126479–126493, 2022.

[8] L. Bravo Alvarez, S. Montejo-Sánchez, L. Rodríguez-López, C. Azurdia-Meza, and G. Saavedra, "A review of hybrid VLC/RF networks: Features, applications, and future directions," *Sensors*, vol. 23, no. 17, p. 7545, Aug. 2023.

[9] S. Ghosh and M.-S. Alouini, "On the performance optimization of two-way hybrid VLC/RF-based IoT system over cellular spectrum," *IEEE Internet Things J.*, vol. 9, no. 21, pp. 21204–21213, Nov. 2022.

[10] H. Liu, S. Yang, Y. Chen, X. Yuan, J. Chen, K. Chen, and H. Chen, "Resource allocation based on differentiated user services for indoor hybrid multi-color VLC/WiFi networks," *Opt. Commun.*, vol. 530, Mar. 2023, Art. no. 129072.

[11] A. Almehdhar, M. Obeed, A. Chaaban, and S. Zummo, "A hybrid VLC/RF cell-free massive MIMO system," in *Proc. IEEE Int. Conf. Commun.*, May 2022, pp. 1871–1876.

[12] X. Zhao and J. Sun, "Secure reconfigurable intelligent surface aided heterogeneous VLC–RF cooperative NOMA networks," *Opt. Commun.*, vol. 511, May 2022, Art. no. 127983.

[13] R. Abbas, "VLC systems using NOMA techniques: An overview," *Phys. Commun.*, vol. 60, Oct. 2023, Art. no. 102144.

[14] S. Shao, A. Khreishah, and H. Elgala, "Pixelated VLC-backscattering for self-charging indoor IoT devices," *IEEE Photon. Technol. Lett.*, vol. 29, no. 2, pp. 177–180, Jan. 15, 2017.

[15] F. Wang, F. Yang, C. Pan, J. Song, and Z. Han, "Joint illumination and communication optimization in indoor VLC for IoT applications," *IEEE Internet Things J.*, vol. 9, no. 21, pp. 20788–20800, Nov. 2022.

[16] H. Zhou, M. Zhang, and X. Ren, "Design and implementation of wireless optical access system for VLC-IoT networks," *J. Lightw. Technol.*, vol. 41, no. 8, pp. 2369–2380, Apr. 15, 2023.

[17] M. A. S. Sejan and W.-Y. Chung, "Secure VLC for wide-area indoor IoT connectivity," *IEEE Internet Things J.*, vol. 10, no. 1, pp. 180–193, Jan. 2023.

[18] H. Yang, A. Alphones, W.-D. Zhong, C. Chen, and X. Xie, "Learning-based energy-efficient resource management by heterogeneous RF/VLC for ultra-reliable low-latency industrial IoT networks," *IEEE Trans. Ind. Informat.*, vol. 16, no. 8, pp. 5565–5576, Aug. 2020.

[19] F. Delgado-Rajo, A. Melian-Segura, V. Guerra, R. Perez-Jimenez, and D. Sanchez-Rodriguez, "Hybrid RF/VLC network architecture for the Internet of Things," *Sensors*, vol. 20, no. 2, p. 478, Jan. 2020.

[20] H. Peng, Q. Li, A. Pandharipande, X. Ge, and J. Zhang, "End-to-end performance optimization of a dual-hop hybrid VLC/RF IoT system based on SLIPT," *IEEE Internet Things J.*, vol. 8, no. 24, pp. 17356–17371, Dec. 2021.

[21] M. Obeed, H. Dahrouj, A. M. Salhab, S. A. Zummo, and M.-S. Alouini, "User pairing, link selection, and power allocation for cooperative NOMA hybrid VLC/RF systems," *IEEE Trans. Wireless Commun.*, vol. 20, no. 3, pp. 1785–1800, Mar. 2021.

[22] M. Obeed, H. Dahrouj, A. M. Salhab, A. Chaaban, S. A. Zummo, and M.-S. Alouini, "Power allocation and link selection for multicell cooperative NOMA hybrid VLC/RF systems," *IEEE Commun. Lett.*, vol. 25, no. 2, pp. 560–564, Feb. 2021.

[23] S. Shrivastava, B. Chen, C. Chen, H. Wang, and M. Dai, "Deep Q-network learning based downlink resource allocation for hybrid RF/VLC systems," *IEEE Access*, vol. 8, pp. 149412–149434, 2020.

[24] M. Amjad, H. K. Qureshi, S. A. Hassan, A. Ahmad, and S. Jangsher, "Optimization of MAC frame slots and power in hybrid VLC/RF networks," *IEEE Access*, vol. 8, pp. 21653–21664, 2020.

[25] S. Huang, G. Chuai, and W. Gao, "Two-way selection handover algorithm for load balancing in hybrid VLC-RF networks," in *Proc. IEEE/CIC Int. Conf. Commun. China (ICCC)*, Jul. 2021, pp. 1065–1070.

[26] L. B. Alvarez, S. Montejo-Sánchez, N. Jara, L. Rodríguez-López, and G. Saavedra, "CSMA/CA protocol design in hybrid network of visible light communication and RF femtocell systems," *Opt. Commun.*, vol. 537, Jun. 2023, Art. no. 129434.

[27] K. G. Rallis, V. K. Papanikolaou, S. A. Tegos, A. A. Dowhuszko, P. D. Diamantoulakis, M.-A. Khalighi, and G. K. Karagiannidis, "RSMA inspired user cooperation in hybrid VLC/RF networks for coverage extension," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Mar. 2023, pp. 1–6.

[28] G. Pan, J. Ye, C. Zhang, J. An, H. Lei, Z. Ding, and M. S. Alouini, "Secure cooperative hybrid VLC-RF systems," *IEEE Trans. Wireless Commun.*, vol. 19, no. 11, pp. 7097–7107, Nov. 2020.

[29] W. Wu, S. Hu, D. Lin, and Z. Liu, "DSLN: Securing Internet of Things through RF fingerprint recognition in low-SNR settings," *IEEE Internet Things J.*, vol. 9, no. 5, pp. 3838–3849, Mar. 2022.

[30] J. Ding, I. Chih-Lin, K. Zhao, and S. Liu, "Exploring the Effect of optical beams on hybrid VLC/RF transmission characteristics," in *Proc. MDPI*, 2023, vol. 10, no. 2, p. 185.

[31] Y. Zeng, Y. Gong, J. Liu, S. Lin, Z. Han, R. Cao, K. Huang, and K. B. Letaief, "Multi-channel attentive feature fusion for radio frequency fingerprinting," *IEEE Trans. Wireless Commun.*, vol. 23, no. 5, pp. 4243–4254, May 2024.

[32] L. B. Alvarez, J. Nüñez-Kasaneva, S. Montejo-Sánchez, L. Rodríguez-López, and G. Saavedra, "Network selection in hybrid visible light communication-radiofrequency system," in *Proc. South Amer. Conf. Visible Light Commun. (SACVLC)*, 2023, pp. 23–28.

[33] S. Hashima, M. M. Fouda, S. Sakib, Z. Md. Fadlullah, K. Hatano, E. M. Mohamed, and X. Shen, "Energy-aware hybrid RF-VLC multiband selection in D2D communication: A stochastic multiarmed bandit approach," *IEEE Internet Things J.*, vol. 9, no. 18, pp. 18002–18014, Sep. 2022.

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