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Optimization of MAC Frame Slots and Power in Hybrid VLC/RF Networks

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ABSTRACT Hybrid visible light communication and radio frequency (VLC/RF) networks provide combined benefits of both visible light and radio frequency technologies. This is an eminent technology for providing 5G services in an indoor environment. Because of small coverage range, multiple VLC cells co-exist in a close proximity. For efficiently utilizing resources of multiple VLC access points (VLC-APs), a different approach than conventional multi RF-APs based resource allocation schemes is required due to unique characteristics of light. In this paper, we provide an optimized solution for combined power and slot allocation in hybrid VLC/RF networks with the objective of maximizing sum rate for a downlink communication scenario. The resources are optimized on frame by frame basis, instead of per request basis. This frame-based optimization reduces the frequency of optimization and also improves the utilization of the resources. The non-convex problem of joint slot and power allocation is divided into less complex sub problems and solved iteratively. The performance of the joint slot and power allocation (JSPA) scheme has been analyzed for data rate and fairness factor for varying values of network size and minimum quality of service (QoS) requirements. The analysis exhibits on average more than 65% improvement in both fairness factor and average sum rate as compared to single VLC-AP based scheme (SV O RF), in which single VLC-AP is utilized for a user and RF-AP is utilized to offload traffic when VLC resources are not sufficient. Moreover, we propose a hybrid user-centeric and network-centeric (H-Uc/Nc) scheme for slot allocation which entails far less computational complexity. Although, H-Uc/Nc scheme performs inferior to optimized scheme, however, it exhibits much better performance than (SV O RF).

INDEX TERMS Hybrid VLC/RF networks, hybrid VLC/RF MAC layer, resource optimization.

I. INTRODUCTION

Visible light communication (VLC) provides a clean and energy efficient mean of communication. Already existing infrastructure of illumination in an indoor environment can be utilized for VLC, reducing both infrastructure and transmission energy cost [1], [2]. In an indoor environment, this technology is less prone to interference, thus can provide a high signal-to-interference-plus-noise ratio (SINR) to support high data rates with a large bandwidth [3]. However, inability of light to pass through opaque medium confined range and encourage line-of-sight (LoS) communication. Furthermore, to improve network coverage, RF-APs are proposed to be deployed along with VLC-APs [4]–[6]. An RF-AP provides high coverage probability with far less data rate than VLC. The combination of two technologies having complementary properties have attained a lot of focus these days. Hybrid VLC/RF networks are integral part of beyond 5G networks [7]. Due to LoS-based communication, multiple VLC-APs are deployed in an indoor area to further increase the available resources. To fully reap the benefits of ample resources of hybrid multiple VLC/RF network, it is essential to efficiently manage these resources. Recently, there is a lot of thrust in optimizing resources for hybrid VLC/RF networks. Many efforts have been made that focus on improving data rate at physical layer, considering the current slot or current tasks only [8]–[19]. The optimization of resources at medium access control (MAC) layer while satisfying the requirements of requesting users and increasing average network throughput is missing. Moreover, since most approaches focus on current instant, they allocate resources only from the best AP and attach single AP to a user.

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By looking at multiple time slots, it is possible to plan a better AP assignment strategy that will result into better utilization of the resources. Combining the slot allocation with power management will further improve the resource utilization. In our previous work [20], we propose a solution for uplink MAC layer slot allocation by considering resources of all VLC and RF APs together, namely multiple VLC-APS and RF-AP (MV + RF) scheme. We formulated and solved an optimization problem to optimally allocate these resources to users. In this paper, we extend our previous work by including power optimization for downlink communication. Our focus is to optimize MAC frame slot allocation and power optimization to improve the performance of network in time division multiple access (TDMA) mode while satisfying quality of service (QoS) requirements of each user. The joint problem of slot and power allocation is far more complex than the slot allocation problem alone. We solve the problem by subdividing the non-convex problem into less complex problems and used iterative approach to solve the complete problem. Moreover, we propose a simpler algorithm for slot allocation that follows hybrid user-centeric and network-centeric approach (H-Uc/Nc) and compare its performance with the optimized solution. The main contributions of this paper can be summarized as follows:

1) An optimization problem of joint slot and power allocation in hybrid VLC/RF networks has been formulated.
2) The non-convex optimization is sub-divided into less complex problems and sub-problems have been solved iteratively to find the solution of original complex problem.
3) For real time application of slot optimization, a simpler H-Uc/NC scheme has been proposed.
4) The performance of the network in terms of average sum rate and fairness has been evaluated for both optimized solution and H-Uc/Nc algorithm. Furthermore, we compare the performance of our proposed scheme with the classic approach of single VLC-AP and overload RF-AP based scheme (SV O RF).

The rest of the paper is organized as following. Section II overview significant schemes related to resource allocation in hybrid VLC/RF networks and in multi cell configurations. Section III presents the system model, followed by the description of optimization problem in Section IV. The proposed solution is evaluated in Section V, and we give our conclusion in section VI.

II. LITERATURE REVIEW

In literature, the efforts to optimize resources of multiple VLC-APs together is limited. Most of the existing schemes focus on optimizing resources between a single VLC-AP and an RF-AP. Here, we begin with some significant approaches for resource allocation in multiple APs scenarios in general. A brief overview of specific techniques for hybrid VLC-RF networks is presented later.

In [21], joint problem of frequency assignment and power allocation is solved for RF multicell network through an iterative algorithm. At first, the objective function is proposed as the weighted sum rate, where adaptive weights are selected to ensure fairness. Then the joint problem is divided into scheduling and power spectral density allocation. It is assumed that the interference is not affected by the user scheduling but power allocation. Moreover, joint scheduling is decomposed into cell based scheduling with fixed power allocation. Further, two methods are used for power spectral adaptation, Karush−Kuhn–Tucker (KKT) based method and Newton's method. The Newton s method converges faster as compared to KKT method.

Another important work for the selection of sub-carriers and power for energy harvesting enabled device to device (D2D) communication along with cellular communication is presented in [22]. The optimization problem is a nonlinear integer optimization problem that is hard to solve in real time. The problem is divided into two sub problems; the assignment of sub-carriers to cellular and D2D links and the selection of reusable links between D2D and cellular link. This selection is determined based on the minimum cross gain. After the sub-carrier selection, power is allocated with the objective of maximizing sum rate while satisfying minimum QoS, power and energy harvesting constraints. In [23] remote radio head (RRH) placement and resource allocation problem is solved for backhaul of moving cells. An algorithm is proposed for optimizing the placement of RRH. Based on the resultant network topology, a branch and bound based algorithm is used to optimize time and power resources with the objective of maximizing resource efficiency. Following is the discussion of the schemes pertinent to VLC and hybrid VLC/RF networks. An earlier work to combine resources of multiple APs is presented in [8]. In this work, it is proposed to shift all the processing to a central unit and VLC-APs act as simple transceivers. The SINR analysis of the proposed scheme exhibit better response due to better management of co-channel interference. In [9], power and bandwidth is optimized between a VLC-AP and an RF-AP to maximize energy efficiency. The convex-concave objective function is converted to a convex function and Dinkelbach type algorithm is used to find roots of convex objective function. Moreover, the effect of different parameters on the energy efficiency has been analyzed.

In [10], number of active VLC-APs and link to active APs are optimized to increase energy efficiency while satisfying the illumination requirements and user request. The NP-complete problem is divided into two sub problems. First problem deals with minimizing energy consumption by selecting optimum number of active VLC-APs. Second problem is to optimize link selection with the objective of minimizing energy while satisfying users' request. The first problem is solved using CPLEX and for second problem, the network is modeled as a weighted graph with edges representing connection between VLC-AP and user. An online policy with good competitive ratio has been designed for the selection of edges. The online policy works with pre-selected APs and does not consider channel response in the selection. Hence, there is a possibility that the selected APs might not be close to the users or do not have best channel response for the users.

A fuzzy logic based network assignment and link switching is proposed in [11] for a hybrid WiFi and optical camera based communication (OCC). The fuzzy rules are defined based on the SINR, data rate, instantaneous power and distance requirements. Different grades are defined based on user requirements and network assignment function (NAF) is calculated based on the fuzzification rules and user requirements for both OCC and LiFi networks. Users are assigned to the network with which they have better value of NAF. If NAF varies, a switching mechanism is proposed that is accomplished by the involvement of Gateway to find best AP to associate with, based on the NAF value. The network performance is compared with LiFi only network and result exhibit better performance in terms of outage probability and demand satisfaction factor (DCF), which is calculated based on the time resources allocated to the users. This scheme provides a solution for current time by selecting a single best AP for users and switching between OCC and RF-AP. Moreover, number of user connected to any AP are not considered in calculating the NAF, which might result into poor performance.

In [12], beam-forming vectors for RF and VLC are optimized for maximizing energy efficiency in multiple VLC-APs and RF-AP networks. The considered network consists of multiple VLC-APs in multiple rooms with a single VLC-AP per room as a result there is zero VLC interference. Each VLC-AP consists of multiple LEDs, likewise RF-AP consists of multiple (N_t) antennas. RF signals experience interference due to simultaneous RF transmission to other users. The objective function of the optimization problem is fractional. Moreover, QoS constraint is a non convex. The problem is converted to a convex problem by variable substitution and semi definite relaxation (SDR). Further, the relaxed problem is successively solved to obtain near optimal solution. In addition to electrical beam forming, mechanical beam forming scheme for increasing directness of the transmitter is proposed in [13]. In this technique, first the correct location of receiver is estimated based on the received SINR and then angle of the transmitter are adjusted in that direction. In uplink direction, due to fixed position of APs which can be broadcasted along with other beacon information, the implementation of this scheme is easier. Therefore, beam steering can be utilized in the uplink direction to direct the devices for better performance. Moreover, every device needs to direct beam once or twice based upon assigned resources which are informed at prior, so delay in beam steering can be coped with.

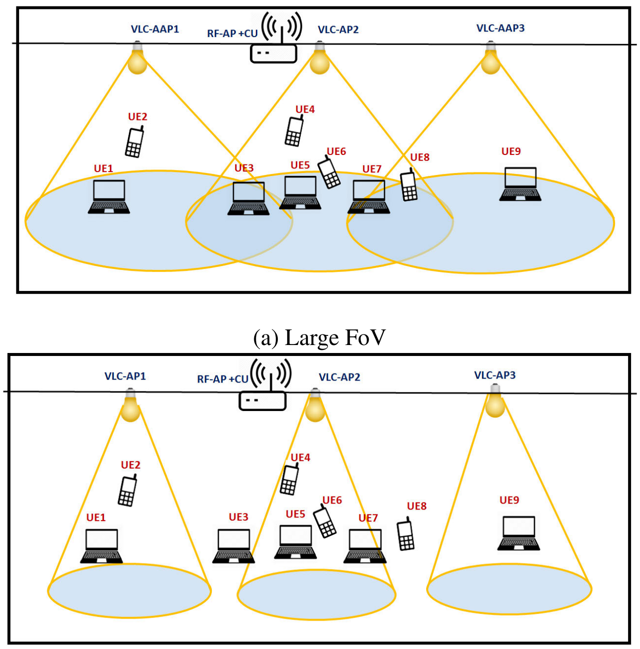
A complete protocol for queue length based packet scheduling in hybrid VLC/RF network has been proposed in [14]. The network consists of multiple VLC-APs and single RF-AP. As a packet of any node arrives at the gateway, it selects the mode of the packet, that is the AP by which this packet will be transmitted. A Lyapunov function is defined that depends on the queue length, the scheduling decision is made with the objective of minimizing drift of the Lyapunov. The proposed scheme is practically tested and evaluated. Main limitation of the proposed scheme is high scheduling frequency as scheduling is performed for every packet.

In [15], different cell formation strategies, unitary frequency reuse factor (UFF), two frequency reuse factor, combined transmission and with transmission vector have been discussed. In addition, an optimization problem for optimizing association and resources of associated users is solved for UFF based network. The multi-objective function is transformed to a single objective function of association and resources are assigned equally to all associated users of an AP. Moreover, the problem is decentralized, first user find best AP to associate with, namely demand vector, afterward network calculate the supply. The optimization problem is iteratively solved by using gradient decent method to find least difference in the demand and supply. Although, this paper discuss multiple VLC APs, however, no resource optimization is performed incorporating multiple resources. Moreover, allocating equal resources to every user, neither benefit for improving throughput of system nor for satisfying min QoS requirements of users.

In [16], the authors included the delay constraints in the objective function and optimized resource allocation with virtual cell structure and user association. However, there is no result indicating how delay requirements are fulfilled. Another approach to improve throughput is the position based cell structuring proposed in [17]. Further, in [19], resources are allocated in user centeric cellular network with nodes in the interference region serviced by combine transmission from all the APs in vicinity. A network graph is constructed for the network and weight of edges are calculated based on the ratio of node's throughput in a slot to the average throughput. The nodes with the highest priority are served first and then excluded from the graph. This procedure continues until all the nodes are served.

Another interesting work is presented in [18] for hybrid VLC/RF network. In this work, the authors proposed to optimize power allocation and AP assignment to improve average network capacity. The joint problem is divided into two sub problems; a) AP assignment, b) power optimization. First, the AP assignment is optimized iteratively and then corresponding power is optimized using Lagrange variables which are calculated by interpolating two equations instead of gradient descent method. Similar to the previous approaches, the AP assignment is optimized for current instant by assigning one-AP per user. The communication schemes, discussed earlier, that utilizes multiple VLC-APs, the optimization or decision frequency is very high resulting in a low efficiency of these schemes.

A kind of similar work to ours is presented in [6], in which the authors have proposed joint optimization of AP assignment and resource allocation. Two algorithm are proposed



(a) Large FoV

(b) Small FoV

FIGURE 1. **Downlink communication for a) high value of FoV B) small value of FoV.**

for maximizing β proportional fairness function without any constraint on the minimum QoS requirements. Joint optimization algorithm (JOA) is proposed to jointly select AP and time resources for maximizing β proportional fairness function. The derived optimization results are applicable to non-zero values of β. The separate optimization algorithm (SOA) algorithm assigns the best AP based on a threshold value and maximum SNR value. Then resources of APs are optimized with the objective of maximizing β proportional fairness function. They have selected one AP per user for entire duration of time. We, in contrast, considered optimization of discrete slot allocation and selection of more than one AP for a user during the MAC frame duration. Hence our work is of cross layer nature that consider both MAC and physical layer conditions. Our objective is to maximize average sum rate of network while satisfying minimum QoS constraints. Moreover, we have performed power optimization in addition to AP selection and slot allocation. We have taken the idea of a single VLC-AP and overload RF-AP (SV O RF) from SOA [6] and re-designed the SOA algorithm according to our objective and constraints. The adapted algorithm, namely (SV O RF), is discussed and compared in section V.

In the next section, we discuss the system model that has been considered in this work.

III. SYSTEM MODEL

The system under consideration consists of hybrid VLC/RF network with N_v VLC-APs and one RF-AP in an indoor environment as shown in Figure 1. All the APs are fixed in ceiling and connected to a central unit through an optical fiber connection. Each AP is following beacon enabled mode with L_f number of slots reserved for downlink communication. All the APs are synchronized, implies that all the frames of all APs overlap with each other entirely. A total of N users are assumed which are equipped with photo detectors and are uniformly distributed in the network. The users are considered to be static during entire frame time. Moreover, both VLC and RF channels are assumed to be unchanged for the time of superframe, hence the SINR remains the same during this period. By considering L_f resources per AP, there are $(N_v + 1) \times L_f$ resources to be allocated to N users. Each user has some minimum QoS requirements that must be satisfied. In this paper, our objective is to allocate resources from the joint resource block for downlink transmission scenario. There are N resource allocation matrix of dimension $(N_v + 1) \times L_f$ with binary entries, one for each user. Each matrix represents the slots that are allocated to the corresponding user. Moreover, the power of all APs must be optimized to improve the throughput by reducing interference. The solution is a a matrix indicating power values of all APs for all slots. Coverage area and interference in the VLC networks depend on the field of view (FoV) of the receiver [24]. A smaller FoV at the receiving end increases the directness of the VLC-AP transmission, consequently, connected users get the best throughput. However, it reduces the coverage probability of VLC network. As the FoV increases, the coverage probability of the VLC network increases at the cost of interference at the edge users. In this paper, we have considered two values of FoV for evaluating the proposed scheme.

A. MODEL FOR VLC COMMUNICATION

Physical channel characteristics of a VLC-AP is described by channel gain. The channel gain between user i and VLC-AP j is given as [6]:

$$h^v_{i,j} = \begin{cases} 0 & \phi > \Phi_F \\ \dfrac{(r+1)A_r}{2\pi d^2_{ij}} T_s(\phi) f(\phi) cos(\phi) cos^m(\Psi) & \phi \leq \Phi_F \end{cases} \quad (1)$$

where r represents Lambertian index which is given as $r = -1/log_2(cos(\phi_{1/2}))$. The $\phi_{1/2}$ is the angle where light intensity decreases to half of the maximum value. A_r represents the physical area of the receiver photo diode (PD), ϕ and Ψ represent incidence angle and irradiance angle, respectively. In this paper, we consider $\phi = \Psi$. The Φ_F is the half angle of FoV. $T_s(\phi)$ depicts the gain of an optical filter and $f(\phi)$ is the concentrator gain. The d_{ij} is the distance between i user and VLC-AP j.

For the downlink VLC transmission, SINR is given as:

$$SINR^v_{i,j,k} = \frac{(\gamma h^v_{i,j}\sqrt{(Pd_{i,j,k})})^2}{N^v_0 B_v + \sum_{l \neq j}(\gamma h^v_{i,l}\sqrt{Pd_{m,l,k}})^2}, \quad (2)$$

where $Pd_{i,j,k}$ is the power transmitted by AP j in slot k when communicating information to user i, $\sum_{l \neq j}(\gamma h_{i,l}\sqrt{Pd_{m,l,k}})^2$ is the sum of interference from all the other APs whose transmission reach at the receiver i, N^v_0 is power spectral density of noise for VLC communication. According to Shannon's capacity equation, maximum possible data rate for a user i connected to a single VLC-AP j is given by:

$$D_{i,j} = B_v log_2(1 + SINR^v_{i,j}), \tag{3}$$

where B_v is the bandwidth of the VLC AP. In case of multiple VLC-AP network, the effective data rate for user i is:

$$D^V_{i,eff} = \frac{\sum_j \sum_k s_{i,j,k} \times B_v log_2(1 + SINR^v_{i,j,k})}{L_f}, \tag{4}$$

where L_f is the total length of the frame and $s_{i,j,k}$ is a binary number. The value of $s_{i,j,k}$ is one if i user is connected to AP j in kth slot.

B. MODEL OF RF COMMUNICATION

A single RF-AP has been assumed to cover the whole indoor area with the total bandwidth supported B_{RF}. The RF communication model is considered as presented in [6]. The channel gain between user i and RF-AP is given as:

$$h_{i,RF} = \sqrt{10^{\frac{-Pl(d)}{10}}} h_0, \tag{5}$$

where h_0 is Rayleigh random variable with 2.64 dB variance and $Pl(d_0)$ represents a path loss at a distance d [6]. The path loss is calculated as follows:

$$Pl(d) = Pl(d_0) + 10ylog_{10}\frac{d}{d_0} + Z, \tag{6}$$

$Pl(d_0) = 47.9\ dB$ is the path loss at reference distance $d_0 = 1\ m$, $y = 1.6$ represents path loss exponent and Z represents shadowing factor which is modeled as a Gaussian random variable with zero mean and 1.8 dB standard deviation [6]. The SNR between user i and RF-AP is given as:

$$SNR_{i,RF,k} = \frac{Pd_{i,RF,k} h^2_{i,RF}}{B_{RF} N^{RF}_0}. \tag{7}$$

$Pd_{i,RF,k}$ is the downlink transmitted power to the user i, by RF-AP. In this paper, we consider only one RF-AP, with N_v VLC-APs, RF-AP becomes $N_v + 1$. B_{RF} is the bandwidth of RF-AP. The N^{RF}_0 is a Gaussian random variable representing noise power spectral density. The maximum achievable data rate for a user i serviced by RF-AP is:

$$D^{RF}_{i,eff} = \frac{\sum_k s_{i,Nv+1,k} \times B_{RF} log_2(1 + SNR_{i,RF,k})}{L_f} \tag{8}$$

IV. JOINT SLOT AND POWER ALLOCATION (JSPA) IN DOWNLINK DIRECTION

In hybrid VLC/RF networks, where multiple VLC-APs are deployed in a close proximity, interference can cause serious degradation in user performance in downlink direction.

$$\max_{s_{i,j,k}, Pd_{i,j,k}} \left(\sum_{i=1}^{N} \sum_{j=1}^{N_v} \sum_{k=1}^{L_f} \frac{s_{i,j,k} B_v log_2(1 + SINR^v_{i,j,k})}{L_f} + \sum_{i=1}^{N} \sum_{k=1}^{L_f} \frac{s_{i,N_v+1,k} B_{RF} log_2(1 + SNR_{i,RF,k})}{L_f} \right) \tag{9}$$

$$\text{subject.to } \frac{\sum_{j=1}^{N_v} \sum_{k=1}^{L_f} s_{i,j,k} B_v log_2(1 + SINR^v_{i,j,k})}{L_f} + \frac{\sum_{k=1}^{L_f} s_{i,N_v+1,k} B_{RF} log_2(1+SNR_{i,RF,k})}{L_f} \geq D_{th} \forall\ i \tag{10}$$

$$\sum_{i=1}^{N} \sum_{k=1}^{L_f} s_{i,j,k} \leq L_f \quad \forall\ j \tag{11}$$

$$\sum_{j=1}^{N_v+1} \sum_{k=1}^{L_f} s_{i,j,k} \leq L_f \quad \forall\ i \tag{12}$$

$$\sum_{i=1}^{N} s_{i,j,k} \leq 1 \quad \forall\ j, k \tag{13}$$

$$\sum_{j=1}^{N_v+1} s_{i,j,k} \leq 1 \quad \forall\ i, k \tag{14}$$

$$s_{i,j,k} \in \{0, 1\} \quad \forall i, j, k \tag{15}$$

$$Pd_{i,j,k} \leq P_{max} \quad \forall i, j, k \tag{16}$$

In the literature, mechanical beam steering is proposed for decreasing interference and directing transmission towards intended users. However, this technique is difficult and time consuming in downlink direction due to multiple users with diverse positions. Alternatively, in this work, we propose to control power in addition to slot allocation for increasing sum rate. The optimization problem is to find the best slot allocation and power allocation for downlink transmission in a hybrid VLC/RF network with the constraints on the minimum QoS requirements that should be satisfied for each user. The resulting optimization problem is presented in (9). The objective function describes the average sum rate for the whole MAC frame of length L_f and across all APs of hybrid VLC/RF network. Our objective is to select best values of $s_{i,j,k}$ and $Pd_{i,j,k}$, where $s_{i,j,k}$ is a binary variable indicating if user i is connected to AP j in slot k. $Pd_{i,j,k}$ is the value of power at which AP j is transmitting to user i in kth slot.

(10) ensures that minimum QoS requirements of each user are satisfied. (11) restricts that maximum allocated slots of every AP must be equal to or less than L_f. (12) maintains the limit on the total resources allocated to any user to be less than or equal to L_f. (13) ensures that one AP is connected to only one user in any given slot and (14) restricts that a user i is connected to only one AP in one slot. (15) restrict binary value of $s_{i,j,k}$ and maximum power limit of AP is imposed through (16). The solution of the optimization problem is N slot allocation matrices and one power allocation matrix. The dimension of slot matrices is $(N_v + 1) \times L_f$ and they indicate which user is connected to which AP in every slot of L_f. The solution of Power allocation is a matrix of dimension $(N_v + 1) \times L_f$ and it indicates power values for each AP in every slot of frame. Since, slot allocation matrix has binary values while power can take fractional values, therefore, this problem is a mix integers non-convex optimization problem. Due to non-convex nature of this problem, it is hard to

solve this problem optimally in a polynomial time. Therefore, an iterative approach is followed to solve the problem.

The solution to original problem is divided into three steps given below:

1) Calculation of number of slots considering a fixed power allocation, interference and scheduling.
2) Scheduling users in the slots with fixed allocated power and number of slots.
3) Optimizing power for a given slot, based on QoS requirements and interference caused by active users in that slot.

For optimal solution, these steps are repeated until convergence.

A. SLOT ALLOCATION

In this sub-problem, slots of all APs are allocated to users jointly with the objective of maximizing average network sum rate given the fixed values of power transmitted by APs and a chosen schedule. The optimization problem is presented in (17).

In this optimization problem, we aim to find best values of number of slots allocated to each user $sl_{i,j}$, where $sl_{i,j}$ is an integer variable rather than a binary number. The optimization problem is an integer linear problem (ILP) due to integer nature of the $sl_{i,j}$ which is hard to solve. The problem is relaxed to a linear problem by relaxing variable $sl_{i,j} \in \{0\ L_f\}$ to $sl_{i,j} \in [0\ L_f]$.

$$\max_{sl_{i,j}} \left(\sum_{i=1}^{N} \sum_{j=1}^{N_v} \frac{sl_{i,j} B_v log_2(1 + sinr_{i,j}^v)}{L_f} + \sum_{i=1}^{N} \frac{sl_{i,N_v+1} B_{RF} log_2(1 + snr_{i,RF})}{L_f} \right) \tag{17}$$

$$\text{subject.to} \quad \frac{\sum_{j=1}^{N_v} sl_{i,j} B_v log_2(1 + sinr_{i,j}^v)}{L_f} + \frac{sl_{i,N_v+1} B_{RF} log_2(1 + snr_{i,RF})}{L_f} \geq D_{th} \quad \forall\, i \tag{18}$$

$$\sum_{i=1}^{N} sl_{i,j} \leq L_f \qquad \forall\, j \tag{19}$$

$$\sum_{j=1}^{N_v+1} sl_{i,j} \leq L_f \qquad \forall\, i \tag{20}$$

$$sl_{i,j} \in \{0, L_f\} \quad \forall\, i, j \tag{21}$$

The $sinr_{i,j} = max(SINR_{i,j,k}^v)$, is the maximum signal-to-interference-plus-noise ratio between user i and j AP across all slots with $k \in 1, 2, .., L_f$. The problem is solved through CVX, which is a convex optimization tool in MATLAB. The corresponding algorithm for converting fractional solution of Sl to an integer solution is presented in algorithm 1.

The fractional solution of Sl is rounded off to the nearest integer solution, then data rate achieved by each user is calculated using the integer valued Sl in step 3. In step 4, it is checked if for every user, the minimum QoS requirements (D_{th}) are satisfied or not. If data rate achieved by some user i, is less than D_{th}, then the best AP j for user i is found, which is the column value of $max(SINR_{i,*})$. Then number of slots assigned to user i are increased by one. Best user $\acute{i}$, corresponding to AP j is found in step 6 and increased resources of user i are balanced by subtracting one from the resources assigned to the user $\acute{i}$. The condition in step 11 is to make certain that all resources of all APs are allocated. If an AP has some resources left unassigned due to rounding off,

Algorithm 1 Conversion of Fractional Solution Sl to Integer Solution

1: INPUT: $Sl_{N\times N_V+1}$, $SINR_{N\times N_v+1}$
2: $Sl_{N\times N_V+1} = Round(Sl_{N\times N_V+1})$
3: Calculate $D_i = \sum_{j=1}^{N_v+1} Sl_{i,j} log_2(1 + SINR_{i,j})\ \forall i \in \{1, 2, \ldots, N\}$
4: **if** for any i, $D_i < Dth$ **then**
5:     **for** each i for which $D_i < Dth$ **do**
6:         Find column value, j, corresponding to
7:         $max(SINR_{i,*})$
8:         Find row value, $\acute{i}$, corresponding to
9:         $max(SINR_{*,j})$
10:         Set $Sl_{i,j} = Sl_{i,j} + 1$ and $Sl_{\acute{i},j} = Sl_{\acute{i},j} - 1$
11:     **end for**
12: **end if**
13: **if** for any $j \in 1, 2, .., N_v + 1$, $\sum_{i=1}^{N} Sl_{i,j} < L_f$ **then**
14:     $\tilde{SINR} = SINR$
15:     **for** each j for which $\sum_{i=1}^{N} Sl_{i,j} < L_f$ **do**
16:         $slots_{unassign} = L_f - \sum_{i=1}^{N} Sl_{i,j}$
17:         **while** $slots_{unassign}$ **do**
18:             Find row value, i, corresponding to
19:             $max(\tilde{SINR}_{*,j})$
20:             Set $Sl_{i,j} = Sl_{i,j} + min(slots_{unassign}, L_f - \sum_{\check{j}=1}^{N_v+1} Sl_{i,\check{j}})$
21:             Set $slots_{unassign} = slots_{unassign} - min(slots_{unassign}, L_f - \sum_{\check{j}=1}^{N_v+1} Sl_{i,\check{j}})$
22:             Set $\tilde{SINR}_{i,j} = 0$
23:         **end while**
24:     **end for**
25: **end if**
26: **if** for any j, $\sum_{i=1}^{N} Sl_{i,j} > L_f$ **then**
27:     $\tilde{SINR} = SINR$
28:     **for** each such j **do**
29:         $slots_{extra} = \sum_{i=1}^{N} Sl_{i,j} - L_f$
30:         **while** $slots_{extra}$ && $\tilde{SINR}_{i,j}$ **do**
31:             Find row value, i, corresponding to $max(\tilde{SINR}_{*,j})$
32:             Set $Sl_{i,j} = Sl_{i,j} - min(slots_{extra}, Sl_{i,j}, \frac{\sum_{\check{j}=1}^{N_v+1} Sl_{i,\check{j}} log_2(1+SINR_{i,\check{j}})-d_{th}}{(log_2(1+SINR_{i,\check{j}}))})$
33:             $slots_{extra} = slots_{extra} - min(slots_{extra}, Sl_{i,j}, \frac{\sum_{\check{j}=1}^{N_v+1} Sl_{i,\check{j}} log_2(1+SINR_{i,\check{j}})-d_{th}}{(log_2(1+SINR_{i,\check{j}}))})$
34:             Set $\tilde{SINR}_{i,j} = 0$
35:         **end while**
36:     **end for**
37: **end if**

the best user with the maximum SINR value is found in step 18. The maximum unassigned slots are allocated to that user. $min(slots_{unassign}, L_f - \sum_{\breve{j}}^{N_v+1} Sl_{i,\breve{j}})$ ensures that maximum resource limit of user i is met. If maximum possible number of slots that can be assigned to user i are less than $slots_{unassign}$, then further nodes are checked until all the slots are assigned. In step 26 and onward, it is assured that no AP assign more than L_f slots. The condition in step 32 ensures that subtracted slots do not violate minimum QoS requirements of a user. Scheduler returns value of $s_{i,j,k}$ $\forall$ i, j, k given the values of $sl_{i,j}$ $\forall$ i, j.

B. A SIMPLIFIED HYBRID USER-CENTERIC/NETWORK-CENTERIC SCHEME FOR SLOT ALLOCATION (H-UC/NC)

The optimization based solution is computationally expensive. Therefore, here we present an SINR-based scheme that is a combination of user-centeric and network-centeric approach. This scheme considers slot resources of all APs jointly and allocate resources fulfilling min QoS requirements. The scheme is presented in algorithm 2. The algorithm starts by initializing an $SINR_{N\times(N_v+1)}$ matrix with SINR values for every possible pair of a user and an AP. If a user does not lie within the coverage range of an AP, the corresponding value of SINR is set to zero. A resource array (ra) of dimension of $N \times (N_v + 1)$ is initialized by zeros.

Algorithm 2 H-Uc/Nc

```
1:  Fill SINR_{N×Nv+1} with the values of SINR for every possible pair of a user and an AP.
2:  Set ra_{N×Nv+1} = [0]_{N×Nv+1} and Set Ds_{N×1} = D_th
3:  for i=1:1:N do
4:      while (D_s(i)) do
5:          find j̀ of max(SINR_{i,*})
6:          SINR_M = max(SINR_{i,*})
7:          sm_{i,j̀} = (L_f × Ds(i)) / (B log2(1+SINR_M))
8:          if Σ_{i=1}^{N} ra_{i,j̀} + sm_{i,j̀} ≤ L_f then
9:              ra_{i,j̀} = ra_{i,j̀} + sm_{i,j̀}
10:             D_s(i) = 0
11:         else
12:             sm_{i,j̀} = L_f − Σ_{i=1}^{N} ra_{i,j̀}
13:             ra_{i,j̀} = ra_{i,j̀} + sm_{i,j̀}
14:             D_s(i) = D_s(i) − (sm_{i,j̀} / L_f) log2(1 + SINR_{i,j̀})
15:             SINR_{*,j̀} = 0
16:         end if
17:     end while
18: end for
19: while Σ SINR_{i,j} > 0 do
20:     [a_{î,ĵ}] = max(SINR_{N×Nv+1})
21:     if [a_{î,ĵ}] > 0 then
22:         ra_{î,ĵ} = ra_{î,ĵ} + min((L_f − Σ_j ra_{î,j}), (L_f − Σ_i ra_{i,ĵ}))
23:         if Σ_j ra_{î,j} == L_f then
24:             SINR_{î,*} = 0
25:         end if
26:         if Σ_i ra_{i,ĵ} == L_f then
27:             SINR_{*,ĵ} = 0
28:         end if
29:     end if
30: end while
```

The minimum QoS vector $Ds_{N\times 1}$ is initialized with d_{th}. Based on the SINR values, best AP, represented by $\grave{j}$, is selected for each user. Corresponding number of slots $sm_{i,\grave{j}}$ are estimated that are required to fulfill minimum QoS requirements of a user i by using resources of $\grave{j}$ AP. It is checked if resource allocation limit of AP $\grave{j}$ holds by allocating $sm_{i,\grave{j}}$ resources. If condition is satisfied, then resource matrix ra is updated. In case, condition is not satisfied, then the available slots of AP $\grave{j}$ are allocated and remaining requirement of data rate is calculated. The number of slots that are allocated to a user i are updated in resource allocation matrix. If all the slots of any AP are allocated then all corresponding column entries in SINR matrix are set to zero. If minimum QoS requirements are not fulfilled then next best AP is selected until minimum QoS requirements are fulfilled. For allocating remaining slots, best SINR value is found, corresponding column value indicate the AP $\hat{j}$ and row indicate corresponding user $\hat{i}$. Resources of the $\hat{j}$ are allocated to the user $\hat{i}$ until either the limit of AP resource or the limit on user resources is reached. The resource matrix is updated accordingly. If limit of AP resource is reached i.e all resources (L_f) of AP are allocated then corresponding column entries are set to zero. Similarly, if the limit of user resources is reached that is user $\hat{i}$ is allocated maximum (L_f) resources then corresponding row entries in SINR matrix are set to zero. The selection of best SINR entry continues until all the entries of SINR matrix are set to zero. After allocation of all the resources, the slots are scheduled such that a user with minimum resources is scheduled first and constraints (13) and (14) are satisfied.

C. POWER OPTIMIZATION

For power optimization, it is assumed that an optimal number of slots and corresponding schedule has been selected. Now the problem is to determine optimal values of power for all APs for all the slots of frame. The power optimization problem is as follows:

$$\max_{Pd_{i,j,k}} \left(\sum_{k=1}^{L_f} \sum_{j=1}^{N_v} B_v \frac{log_2(1 + SINR^v_{i,j,k})}{L_f} + \frac{\sum_{k=1}^{L_f} B_{RF} \, log_2(1 + SNR_{i,RF,k})}{L_f} \right) \tag{22}$$

$$\text{subject.to} \quad \frac{\sum_{k=1}^{L_f} \sum_{j=1}^{N_v} B_v log_2(1 + SINR^v_{i,j,k})}{L_f} + \frac{\sum_{k=1}^{L_f} B_{RF} \, log_2(1+SNR_{i,RF,k})}{L_f} \geq D_{th} \quad \forall \, i \tag{23}$$

$$Pd_{i,j,k} \leq P_{max}, \quad \forall \, i, j \tag{24}$$

In the objective function and in constraints i represents the active user which is connected to AP j which is already determined after slot optimization and scheduling. (23) constraint ensures that power is allocated such that minimum QoS requirements are satisfied for each user. The constraint (24) prohibits allocated power to exceed maximum power limit for an AP. Since, our objective is to maximize average sum rate and there is only one RF-AP in the network which neither causes nor experience interference. Therefore, we have selected maximum power for RF-AP in all the slots. The optimization of power for VLC-APs depends on the active users and their channel gain, and is independent of the power in other slots. Hence, the problem can be divided into L_f sub problems, the decoupled problem is given as:

$$\max_{Pd_{i,j,k}} \left(\sum_{j=1}^{N_v} \frac{B_v log_2(1+SINR^v_{i,j,k})}{L_f} \right)$$

$$\text{subject.to} \frac{B_v log_2(1+SINR^v_{i,j,k})}{L_f} \geq Ds_{thi} \; \forall \; i, \quad (25)$$

$$Pd_{i,j,k} \leq P_{max}, \quad (26)$$

where first constraint ensures that minimum QoS (Ds_{thi}) is achieved by all the active nodes. This constraint is derived based on the earlier guess of SINR and every user's QoS requirements for the whole frame. The second constraint ensures that power constraints is satisfied for each AP. The Lagrangian of the sub problem is:

$$L(Pd_{i,j,k}, \lambda, \mu) = \sum_{j=1}^{N_v} \frac{B_v log_2(1+SINR^v_{i,j,k})}{L_f} + \sum_{j}^{N_V} \lambda_j(D_{si} - Ds_{thi}) + \mu_j(P_{max} - Pd_{i,j,k}), \quad (27)$$

where $\{\lambda_j = \lambda_1, \lambda_2, \ldots, \lambda_{N_v+1}\}$ and $\{\mu_j = \mu_1, \mu_2, \ldots, \mu_{N_v+1}\}$ are Lagrange multipliers associated with minimum QoS requirements and maximum power constraint respectively. $D_{si} = \frac{B_v log_2(1+SINR^v_{i,j,k})}{L_f}$ is the data rate achieved in given slot by user i when serviced by AP j. To determine the optimal power allocation for a fixed value of λ and μ, (27) is differentiated with respect to the power variable.

$$\frac{\partial L}{\partial Pd_{i,j,k}} = \sum_j \frac{\partial}{\partial Pd_{i,j,k}} \Big(\frac{(1+\lambda_j)}{L_f} \times B_v log_2\Big(1 + \frac{(\gamma h_{i,j}\sqrt{Pd_{i,j,k}})^2}{N_0 B + \sum_{l \neq j}(\gamma h_{i,l}\sqrt{Pd_{m,l,k}})^2}\Big) - \mu_j \quad (28)$$

Here $Pd_{i,j,k}$ represents power of AP j when it is transmitting to user i in kth slot. The above differential involves two kind of terms, the data rate term related to AP j, having $Pd_{i,j,k}$ in numerator and sum of data rate of other APs that experience interference from AP j, as a result having $Pd_{i,j,k}$ in denominator. Therefore, the differential of (28) is decomposed into following two parts:

$$\frac{\partial}{\partial Pd_{i,j,k}} \left(\frac{(1+\lambda_j)}{L_f} B_v log_2\Big(1+ \frac{(\gamma h_{i,j}\sqrt{Pd_{i,j,k}})^2}{N_0 B + \sum_{l \neq j}(\gamma h_{i,l}\sqrt{Pd_{m,l,k}})^2} \right)$$
$$= \frac{B_v(1+\lambda_j)}{L_f(1+SINR^v_{i,j,k})} \frac{(\gamma h_{i,j})^2}{N_0 B + \sum_{l \neq j}(\gamma h_{i,l}\sqrt{Pd_{m,l,k}})^2}$$
$$= \frac{B_v(1+\lambda_j)(\gamma h_{i,j})^2}{L_f(N_0 B + \sum_{l \neq j}(\gamma h_{i,l}\sqrt{Pd_{m,l,k}})^2 + (\gamma h_{i,j}\sqrt{Pd_{i,j,k}})^2)}, \quad (29)$$

where $h_{i,l}$ is the channel gain between user i and AP l which is transmitting information to user m in the current slot.

$$\frac{\partial}{\partial Pd_{i,j,k}} \Big(\sum_{l \neq j} \frac{B_v(1+\lambda_l)}{L_f} log_2\Big(1+ \frac{(\gamma h_{m,l}\sqrt{Pd_{m,l,k}})^2}{N_0 B + \sum_{\hat{l} \neq l}(\gamma h_{m\hat{l}}\sqrt{Pd_{\hat{m}\hat{l},k}})^2}\Big)\Big)$$
$$= \sum_l \frac{B_v(1+\lambda_l)}{L_f} \frac{(SINR^v_{m,l,k})^2}{L_f(1+SINR^v_{m,l,k})} \frac{-(\gamma h_{m,j})^2}{(\gamma h_{m,l}\sqrt{Pd_{m,l,k}})^2} \quad (30)$$

$\sum_{\hat{l} \neq l}(\gamma h_{m,\hat{l}}\sqrt{Pd_{m,l,k}})^2$ includes the interference caused by all the other APs including j AP, and $\hat{m}$ represents the user to which these APs are transmitting. The optimum value of power that maximize Lagrangian is found where derivative of Lagrangian function (28) is zero. This is deduced from the KKT conditions. KKT conditions provide us a method to solve a non-convex/non-concave optimization problem which includes non-equality constrains in addition to equality constraints by converting it to Lagrangian dual problem and applying KKT conditions. The optimal solution must satisfy all the KKT conditions. Further details on the KKT can be found in [25]. Applying KKT condition and setting (28) equal to zero, we get:

$$\frac{B_v(1+\lambda_j)(\gamma h_{i,j})^2}{L_f(N_0 B + \sum_{l \neq j}(\gamma h_{i,l}\sqrt{Pd_{m,l,k}})^2 + (\gamma h_{i,j}\sqrt{Pd_{i,j,k}})^2))} = \sum_l Sd_{l,j} + \mu_j, \quad (31)$$

where

$$Sd_{l,j} = \frac{B_v(1+\lambda_l)}{L_f} \frac{(SINR^v_{m,l,k})^2}{(1+SINR^v_{m,l,k})} \frac{(\gamma h_{i,j})^2}{(\gamma h_{m,l}\sqrt{Pd_{m,l,k}})^2}. \quad (32)$$

By considering $Sd_{l,j}$ constant, following power update equation is obtained.

$$Pd_{i,j,k} = \frac{B_v(1+\lambda_j)}{L_f(\sum_l Sd_{l,j} + \mu_j)} - \frac{(N_0 B + \sum_{l \neq j}(\gamma h_{i,l}\sqrt{Pd_{m,l,k}})^2)}{(\gamma h_{i,j})^2}. \quad (33)$$

The optimal solution must satisfy maximum power constraint,

$$Pd^*_{i,j,k} = min(Pd_{i,j,k}, P_{max}), \quad (34)$$

The corresponding Lagrange multipliers are determined by iterating following equation until convergence:

$$\lambda_j(u) = (\lambda_j(u-1) + \frac{\alpha_1}{\sqrt{(u)}}(D_{sj} - Ds_{thi}))^+, \quad (35)$$

TABLE 1. Simulation parameters.

Parameter	Value
Height of AP plane	3m
Transmit power of RF-AP transceiver P^{Rf}	20 dBm
RF bandwidth B_{RF}	40 MHz
RF Noise spectral density N_0^{RF}	10^{-19} W/Hz
Maximum transmit power of VLC-AP	2W
VLC Noise spectral density N_0^V	10^{-21} W/Hz
VLC bandwidth B_v	40 MHz
Physical area of photo detector A_pE	1 cm^2
Responsivity of photo detector γ	.53 A/W
half intensity angle $\phi_{1/2}$	$\pi/3$
Field of View (FoV) semi angle Φ_F	$\pi/2, 40°$
Refractive index RI	1.5

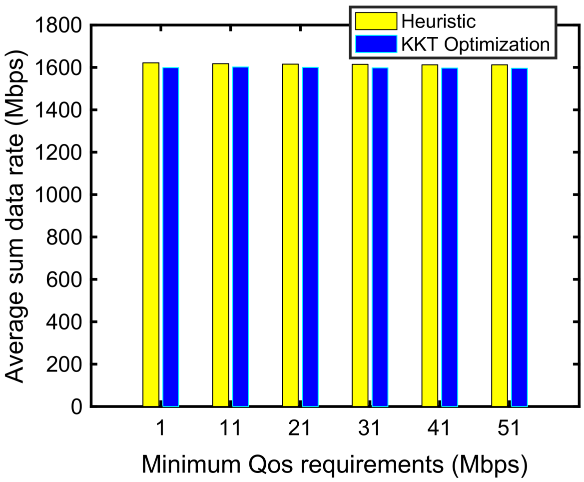


FIGURE 2. Comparison of average sum rate achieved by heuristically found optimum power value and the average sum rate achieved using KKT optimization.

$$\mu_j(u) = (\mu_j(u-1) + \frac{\alpha_2}{\sqrt(u)}(P_{max} - Pd_{i,j,k}))^+. \quad (36)$$

V. PERFORMANCE EVALUATION

In this section, we evaluate the performance of the proposed scheme that optimize joint slot and power allocation (JSPA) and compare its performance with (SV O RF) scheme in which single best VLC-AP is assigned to the users and RF-AP is utilized when some user is out of the range of all VLC-APs or the resources of a VLC-AP are not sufficient to fulfill minimum QoS requirements of its users. We use MATLAB and run several hundred iterations of monte carlo simulations for analyzing the average behavior. The values of simulation parameters are given in table 1 [18]. We start with the evaluation of power optimization. Minimum QoS requirement for a user for a single slot are calculated based on the corresponding overall minimum data rate requirements.

In heuristic approach, we discretized power values for all APs and evaluate average sum rate for all possible combination of power values for four APs. The combination of power values that satisfy QoS requirements of nodes and give maximum average sum rate are selected. The obtained sum data rates for various minimum QoS requirements are compared with the one achieved through KKT optimization in Figure 2. By changing minimum QoS, average sum rate decreases however, this change is very small. The response of KKT power optimization exhibits slightly inferior performance in average sum rate, however, it requires much less computation than heuristic approach that relies on brute force search for optimum solution.

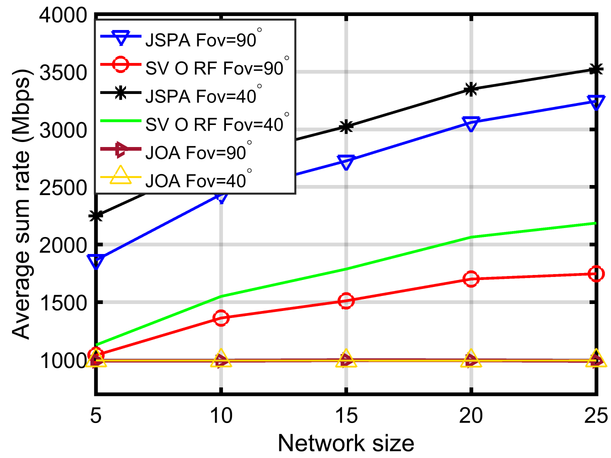


FIGURE 3. Average Sum rate (Mbps) vs. network size when minimum QoS requirements = 1 Mbps.

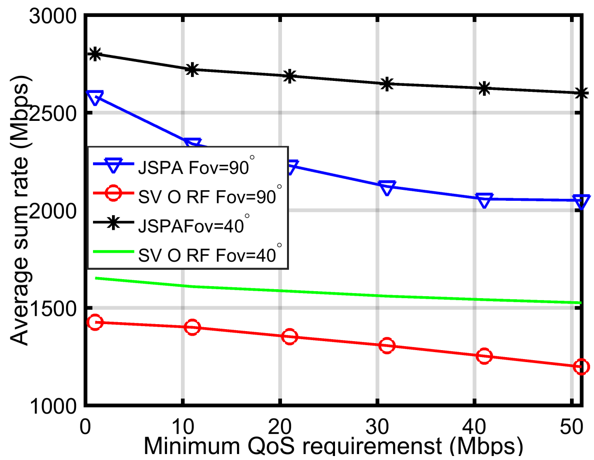


FIGURE 4. Average Sum rate (Mbps) vs. minimum QoS requirements when $N = 10$.

In Figure 3, average sum rate of a hybrid VLC/RF network under the application of the proposed scheme (JSPA), (SV O RF) scheme and JOA, is evaluated for various values of network size. We have considered two values of semi angle of FoV. As network size grows, the possibility of finding better channel conditions for every AP increases, hence the overall network performance improves as the network size grows for both schemes. Moreover, it can be observed that as FoV is reduced, the throughput increases for (SV O RF) scheme, since users interference range is reduced. It is known that small FoV result in lower coverage probability, however, due to availability of RF resources, users are able to utilize RF resources and therefore do not experience outage. The proposed scheme, due to better utilization of resources, performs better than (SV O RF) scheme. It can be observed that the proposed scheme performs better for both values of FoV providing on average 72% improvement. JOA [6] provides

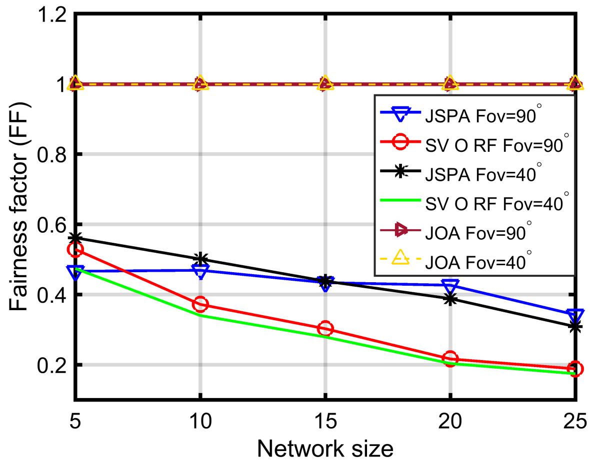


FIGURE 5. Fairness factor vs. network size when minimum Qos requirements =1 Mbps.

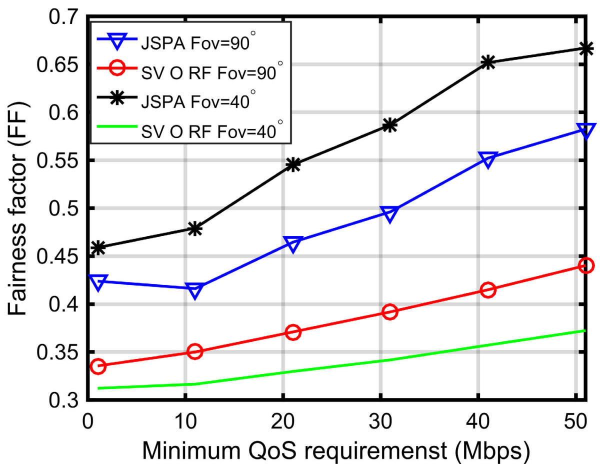


FIGURE 6. Fairness factor vs. minimum QoS requirements when $N = 10$.

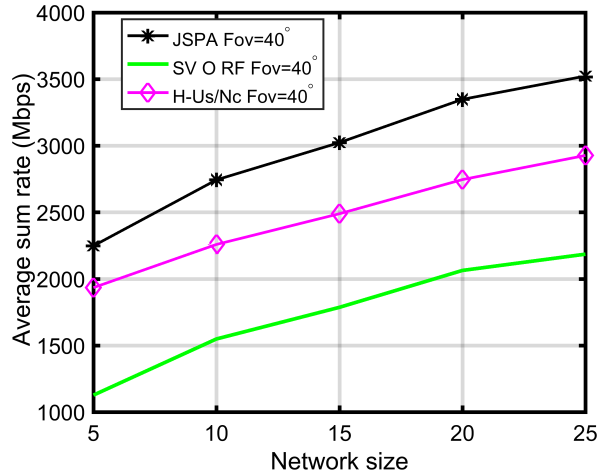


FIGURE 7. Comparison of average sum rate (Mbps) for varying values of network size when minimum QoS requirements = 1 Mbps.

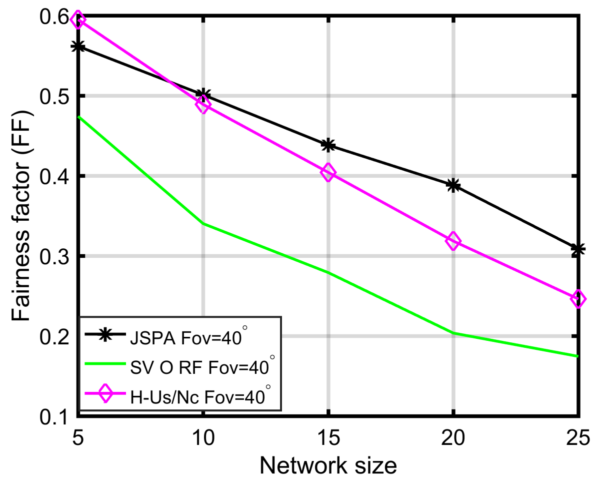


FIGURE 8. Comparison of fairness factor for varying values of network size, minimum QoS requirements = 1 Mbps.

far less average sum rate as compared to both (SV O RF) and JSPA. JSPA provides more than 200% better average sum rate as compared to JOA.

Figure 4 presents average sum rate performance of the two schemes for varying values of minimum Qos requirements. As the minimum QoS requirements increases, chances for exploiting good channel user decreases, as a result average sum rate of the network decreases with the increase in minimum QoS requirements. The performance of both (SV O RF) and (JSPA) schemes is better for smaller value of FoV. Moreover, the proposed scheme performs better than the (SV O RF) scheme by on average 69.7%. Since JOA [6] does not consider minimum QoS requirements in the objective function or constraints, therefore, it is not possible to evaluate the impact of varying values of minimum QoS requirements on the performance of JOA.

Fairness factor (FF) indicate the capacity fairness and is calculated as:

$$FF = \frac{(\sum_{i=1}^{N} D_i)^2}{N \sum_{i=1}^{N} (D_i)^2}, \tag{37}$$

where D_i is the data rate achieved by user i. The value of FF lies between 0 and 1, with 1 be the maximum possible value indicating that all the nodes are utilizing equal capacity or having same date rate. In Figure 5, fairness factor is evaluated for varying values of network size with fixed value of minimum QoS requirements of 1 Mbps. In contrast to the sum rate, FF decreases as network size increases. This is due to the fact that as network size grows, only few nodes which have best SINR values, exploit resources more and rest of the users only get resources that are sufficient for fulfilling their minimum QoS requirements. The proposed scheme, due to better utilization of resources for each user as compared to (SV O RF) scheme, performs better and 67.5% improvement is observed. JOA, in contrast, maintains fairness near to one for all values of network size. This is due to β proportional fairness function considered as the objective function in [6].

In Figure 6, FF is evaluated for varying values of minimum QoS requirements. As minimum QoS requirements increases, each user gets more resources to fulfill their minimum QoS requirements, as a result the difference of data rate among users decreases and consequently FF improves. The proposed scheme improves fairness by 66.9% on average as compared to (SV o RF).

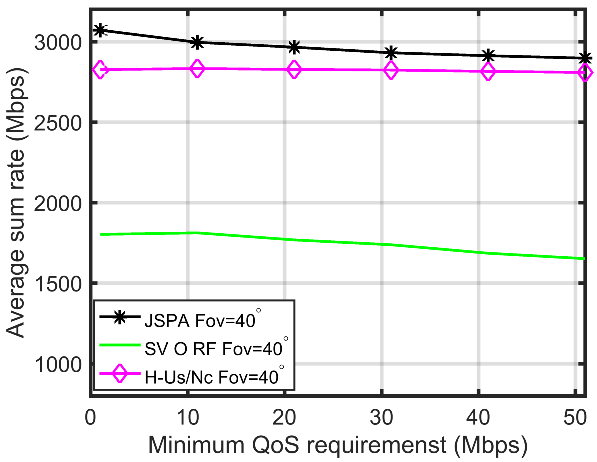


FIGURE 9. Comparison of average sum rate (Mbps) for varying values of minimum QoS requirements with $N = 13$.

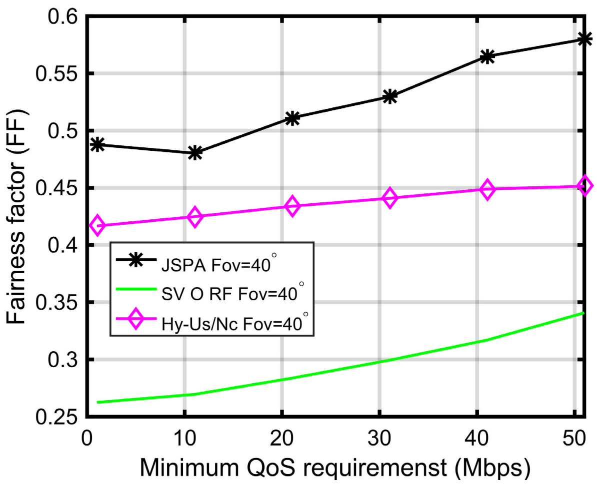


FIGURE 10. Comparison of fairness factor for varying values of minimum QoS requirements with $N = 13$.

In Figure 7 and Figure 8, the performance of the proposed scheme is compared with the H-Uc/Nc scheme for varying values of network size. Although, H-Uc/Nc scheme does not perform as good as the optimization-based scheme, however, its performance is much better than the (SV O RF) scheme. Moreover, for a given network size, the performance of H-Uc/Nc matches with the optimization based solution as the minimum QoS requirements are increased as depicted in Figure 9 and Figure 10.

Our analysis exhibits that there is a trade of between computation complexity and network performance. Based on the resource availability and application requirements, the corresponding scheme can be selected.

VI. CONCLUSION

The increasing needs of data amplify the importance of maximizing average sum rate of networks through optimization of resource allocation. In this paper, we have proposed a joint problem of MAC frame slots and power allocation in hybrid VLC/RF network. Due to the complexity of the problem, the problem is divided into sub problems and solved iteratively. The performance evaluation exhibits on average 70% improvement in average sum rate and on average67% improvement in fairness as compared to (SV O RF) scheme without power optimization. Moreover, we proposed a hybrid Uc/NC scheme for slot allocation which entails far less computational complexity. Although, the simplified scheme performs inferior to optimized scheme, however, its performance is much better than (SV O RF). In the future, we aim to include energy harvesting nodes of IoT and scheduling slots to meet their energy and delay requirements.

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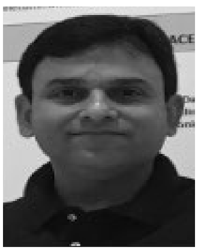

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