Network Selection Algorithm using Stackelberg Game Theory

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B.Tech Project report

***Abstract*—To address the growing demand for high-speed, reliable, and cost-effective wireless communication, this paper proposes a novel Stackelberg game-based network selection framework for hybrid Radio Frequency (RF) and Visible Light Communication (VLC) systems. Traditional static or heuristic-based methods fail to account for dynamic factors such as pricing, resource allocation, and user preferences, often resulting in sub-optimal performance and revenue management. Our framework enables dynamic optimization of both provider strategies and user decisions by incorporating a comprehensive utility-based approach that considers data rate, cost, delay, energy efficiency, and reliability. The provider strategically adjusts pricing, bandwidth, and transmission power, while users select the optimal network accordingly. Leveraging the Lambertian model for VLC channel characterization, the system ensures accurate SNR and data rate estimation. Simulation results demonstrate that the proposed framework achieves improved network efficiency, load balancing, and user satisfaction, offering a scalable and adaptive solution for next-generation wireless networks.**

***Index Terms*—Hybrid RF-VLC Networks, Stackelberg Game Theory, Resource Allocation, Dynamic Pricing, Load Balancing, Next-Generation Wireless Networks.**

I. Introduction

With the rapid advancement of wireless communication technologies, the demand for high-speed, reliable, and energy-efficient connectivity has increased significantly. Traditional Radio Frequency (RF)-based communication networks, though widely deployed, face several challenges, including spectrum congestion, high energy consumption, and interference issues. We also cannot ignore the fact that the network bandwidth allocated for RF networks are usually limited. VLC can complement RF by providing high-speed, short-range communication with minimal interference. The integration of RF and VLC in a hybrid network allows for better utilization of overall network bandwidth by leveraging RF for long-range communication and VLC for short-range, high-capacity data transmission. However, determining the optimal network selection strategy for users while ensuring efficient resource allocation by providers presents a complex challenge that requires an intelligent and adaptive approach.

With the increasing demand for high-speed and reliable wireless communication, hybrid network solutions combining Radio Frequency (RF) and Visible Light Communication (VLC) have gained significant attention. Traditional network selection mechanisms typically rely on fixed threshold-based approaches or centralized decision-making systems that do not optimize overall network efficiency. To address these limitations, recent studies have explored intelligent and dynamic selection mechanisms for hybrid RF-VLC networks.

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Several works have investigated network selection strategies in hybrid RF-VLC environments. The study [1] proposes network selection algorithms specifically tailored for hybrid VLC/RF systems in IoT-enabled smart home environments. It emphasizes the importance of adaptive strategies that consider user requirements and environmental constraints. The study [2] provides a comprehensive review of hybrid VLC/RF networks, covering key architectural aspects, use cases, advantages, limitations, and open research challenges.

The study [3] proposed a dynamic network selection algorithm based on user requirements and network conditions to optimize network performance in hybrid RF-VLC systems. Their study demonstrated that an adaptive selection mechanism can significantly improve system throughput and user experience. Similarly, [4] analyzed the performance of hybrid RF-VLC systems under Quality of Service (QoS) constraints and emphasized the importance of efficient resource allocation strategies. The study showcased how VLC, when integrated with RF, enhances data transmission rates while maintaining reliability.

Machine learning-based approaches have also been applied to improve network selection decisions. [5] introduced a reinforcement learning-based network selection framework for hybrid RF-VLC systems. Their results highlighted the advantages of an AI-driven approach in optimizing user allocation between the two networks while reducing latency and power consumption. Furthermore, game theory models have been used to optimize resource management in wireless networks. [6] investigated the use of Stackelberg game theory for network selection, where the provider dynamically adjusts pricing and resource allocation strategies based on user demand, leading to efficient load balancing and cost optimization. Similarly, the study [7] formulates the resource allocation problem in heterogeneous D2D networks as a Stackelberg game between users and the network controller, optimizing power and spectrum resources. The study [8] proposes a Stackelberg game model to regulate power control in wireless mesh networks, improving network performance while managing interference and energy consumption, which supports our rationale for adopting Stackelberg games for power control and pricing strategy in our model.

These studies establish a strong foundation for hybrid RF-VLC network selection, but there is still a need for more comprehensive models that consider economic factors such as provider revenue, cost optimization, and user utility functions in the selection process. Our proposed approach builds upon these prior works by incorporating a Stackelberg game-based strategy to dynamically optimize pricing, power allocation, and bandwidth allocation while ensuring fair and efficient network utilization.

This research aims to optimize network resource utilization by dynamically allocating transmission power and bandwidth between RF and VLC networks to enhance overall efficiency and achieve effective load balancing. A user-centric network selection mechanism is developed, enabling users to choose between RF and VLC networks based on a comprehensive utility function that accounts for data rate, cost, delay, energy efficiency, and reliability. To align provider incentives with network performance, a dynamic pricing strategy is proposed, allowing providers to adjust the cost of RF and VLC services to maximize revenue while ensuring fair user distribution. The interaction between providers and users is modeled using Stackelberg game theory, wherein providers act as leaders optimizing pricing and resource allocation, and users respond as followers by selecting networks that maximize their individual utility.

II. Methodology

In this study, we introduce a network selection model based on Stackelberg game theory to optimize user association between Radio Frequency (RF) and Visible Light Communication (VLC) networks. The proposed framework comprises two primary entities: the provider and the users. The provider, acting as the leader in the Stackelberg game, strategically determines network pricing, power allocation, and bandwidth distribution across RF and VLC channels. Users, modeled as followers, make network selection decisions by evaluating a utility function that incorporates multiple performance metrics, including data rate, cost, delay, energy consumption, and reliability. The hierarchical decision-making structure of the Stackelberg game ensures that the provider's strategy anticipates user responses, thereby achieving an equilibrium that optimizes both network performance and provider objectives.

A. System Model

We consider a hybrid Radio Frequency (RF) and Visible Light Communication (VLC) network in which users dynamically select their access network based on a utility-driven decision process. The system model incorporates several key parameters to characterize network performance and user preferences.

The user (follower) optimizes his own $duty\_cycle$. Decreasing the $duty\_cycle$ reduces cost for both user and provider, but decreases the $quality\_of\_service$ of the user (say IOT device). This means, user's connectivity to the network gets hampered when we decrease the $duty\_cycle$ which is what given by $quality\_of\_service$.

The provider (leader) allocates transmission power and bandwidth to both RF and VLC channels, denoted by P_{RF}, P_{VLC}, B_{RF}, and B_{VLC}, respectively. The associated communication costs are represented by C_{RF} and C_{VLC}. Each user evaluates their utility for RF and VLC, denoted by U_{RF} and U_{VLC}, based on several performance metrics, including Signal-to-Noise Ratio (SNR), data rate (R), delay (D), and energy consumption (E).

In addition to the above, the model accounts for system-level parameters such as the number of users, the number of RF base stations, and the number of VLC access points. Constraints include the maximum transmission power and bandwidth available for both RF and VLC, as well as the noise power spectral density associated with each network. Cost modeling incorporates both fixed and variable components: a fixed cost for each network (in monetary units), a variable cost proportional to the data rate (in monetary units per Mbps), and an energy cost (in monetary units per Watt). Furthermore, circuit power consumption and operating frequency for both RF and VLC links are included to ensure realistic energy modeling and optimization.

B. Important Results that are used

We define the key results involved in the **RF and VLC network selection process** as follows:

1) Maximum Channel Capacity: The maximum achievable capacity for a given **bandwidth** B_{Max} and **transmit power** $P_{T_{Max}}$ is given by the **Shannon capacity formula**:

$$C_{\max} = B_{\text{Max}} \log_2 \left(1 + \frac{P_{T_{\text{Max}}}}{\text{Noise\_Density} \times B_{\text{Max}}}\right) \quad (1)$$

2) RF Signal Propagation:

1) **RF Path Loss (in dB):** The **path loss** for RF signals is given by:

$$PL_{\text{RF}}(d) = 20\log_{10}(f) + 35\log_{10}(d) + 20\log_{10}\left(\frac{4\pi}{c}\right) \quad (2)$$

Since the last term simplifies to **-147.5**, we rewrite it as:

$$PL_{\text{RF}}(d) = 20\log_{10}(f) + 35\log_{10}(d) - 147.5 \quad (3)$$

2) **RF Channel Gain:** The **channel gain** for RF can be computed using:

$$h_{\text{RF}} = 10^{\frac{-PL_{\text{RF}}(d)}{10}} \quad (4)$$

3) VLC Signal Propagation (Lambertian Model): For **Visible Light Communication (VLC)**, we use the **Lambertian emission model**.

1) **Lambertian Order of Emission (m):** Given a **half-power semi-angle** of $60°$, the Lambertian order is:

$$m = -\frac{\log_2(2)}{\log_2(\cos(60°))} = 1 \quad (5)$$

2) **VLC Channel Gain:** The **channel gain** for VLC communication is given by:

$$h_{\text{VLC}} = \frac{(m+1)A}{2\pi d^2}\cos^m(\phi)T_s(\psi)g(\psi)\cos(\psi) \quad (6)$$

where:

- A is the detector area.
- ϕ is the angle of incidence.
- $T_s(\psi)$ is the optical filter gain.
- $g(\psi)$ is the concentrator gain.
- ψ is the angle of irradiance.

- d is the transmitter-receiver distance.

Assuming $m = 1$ (as calculated earlier), the equation simplifies to:

$$h_{\text{VLC}} = \frac{2A}{2\pi d^2} \cos(\phi) T_s(\psi) g(\psi) \cos(\psi) \tag{7}$$

C. Utility functions

The utility function for the user (follower) is calculated using the algorithm stated in Algorithm 1. The utility function for the provider (leader) is calculated using the algorithm stated in Algorithm 2.

Algorithm 1 User Utility Function (Follower Strategy)

Require: Network parameters $(B, P_T, N_0, VC, \text{fixed cost}, \text{RF Circuit Power})$
Require: User preference weights $(w_1, w_2, w_3, w_4, beta)$
Ensure: Utility values for RF and VLC networks

for each network $n \in \{\text{RF, VLC}\}$ **do**

Compute **Channel Gain**:

$$h = \begin{cases} 10^{PL_{\text{dB}}(d)/10}, & \text{for RF} \\ \frac{(m+1)A}{2\pi d^2} \cos^m(\phi) T_s g(\psi) \cos(\psi), & \text{for VLC} \end{cases} \tag{8}$$

Compute **Signal-to-Noise Ratio (SNR)**:

$$SNR = \frac{P_T \cdot h}{N_0 \cdot B} \tag{9}$$

Compute **Data Rate** (in Mbps):

$$R = \frac{B \log_2(1 + SNR)}{10^6} \tag{10}$$

Compute **Total Cost**:

$$C = (\text{fixed cost} + VC \cdot R) \cdot \text{duty\_cycle} \tag{11}$$

Compute **Delay Components**:

$$D_{\text{prop}} = \frac{d}{c}, \quad D_{\text{trans}} = \frac{L}{R}, \quad D_{\text{queue}} = Q \tag{12}$$

Compute **Total Delay**:

$$D = D_{\text{prop}} + D_{\text{trans}} + D_{\text{queue}} \tag{13}$$

Compute **Reliability**:

$$\text{Reliability} = \min\left(1, 1 - e^{-SNR/2}\right) \tag{14}$$

Compute **QoS Term**:

$$\text{qos\_term} = \log(1 + beta \cdot \text{duty\_cycle}) \tag{15}$$

Compute **Utility Function**:

$$U = w_1 \cdot R - w_2 \cdot C - w_3 \cdot D + w_4 \cdot \text{Reliability} + w_4 \cdot \text{qos\_term} \tag{16}$$

end for
return $(U_{\text{RF}}, U_{\text{VLC}})$
=0

Algorithm 2 Provider Utility Function (Leader Strategy)

Require: List of users, pricing $(\text{rf\_price}, \text{vlc\_price})$
Require: Provider parameters $(\text{cost\_per\_rf\_bandwidth}, \text{cost\_per\_vlc\_bandwidth}, \text{VLC\_CIRCUIT\_PC}$
Ensure: Utility value for the provider

Compute **Number of Users** in each network:

$$n_{\text{RF}} = \sum_{\text{users connected to RF}} 1, \quad n_{\text{VLC}} = \sum_{\text{users connected to VLC}} 1 \tag{17}$$

Compute **Load Factor**:

$$RF_{\text{load}} = \begin{cases} \frac{n_{\text{RF}}}{\text{total users}}, & \text{if } n_{\text{RF}} > 0 \\ 0.1, & \text{otherwise} \end{cases} \tag{18}$$

$$VLC_{\text{load}} = \begin{cases} \frac{n_{\text{VLC}}}{\text{total users}}, & \text{if } n_{\text{VLC}} > 0 \\ 0.1, & \text{otherwise} \end{cases} \tag{19}$$

Compute **RF Energy Cost** and **VLC Energy Cost** based on duty cycle for each user:

$$\text{rf\_energy\_cost} = \sum_{\text{users connected to RF}} \text{rf\_cost\_per\_unit} \cdot \text{user.duty\_cycle} \tag{20}$$

$$\text{vlc\_energy\_cost} = \sum_{\text{users connected to VLC}} \text{vlc\_cost\_per\_unit} \cdot \text{user.duty\_cycle} \tag{21}$$

Compute **Provider RF Cost**:

$$\text{provider\_rf\_cost} = \frac{\text{rf\_bandwidth\_cost}}{\text{RF\_BANDWIDTH\_MAX}} + \frac{\text{rf\_energy\_cost}}{n_{\text{RF}}} \tag{22}$$

Compute **Provider VLC Cost**:

$$\text{provider\_vlc\_cost} = \frac{\text{vlc\_bandwidth\_cost}}{\text{VLC\_BANDWIDTH\_MAX}} + \frac{\text{vlc\_energy\_cost}}{n_{\text{VLC}}} \tag{23}$$

Compute **Revenue** from RF and VLC networks:

$$\text{RF Revenue} = n_{\text{RF}} \cdot \text{rf\_price} \tag{24}$$

$$\text{VLC Revenue} = n_{\text{VLC}} \cdot \text{vlc\_price} \tag{25}$$

Compute **Cost** for RF and VLC networks:

$$\text{RF Cost} = n_{\text{RF}} \cdot \text{provider\_rf\_cost} \tag{26}$$

$$\text{VLC Cost} = n_{\text{VLC}} \cdot \text{provider\_vlc\_cost} \tag{27}$$

Compute **Load Balance Penalty**:

$$\text{Load Balance Penalty} = \frac{1}{2} |n_{\text{RF}} - n_{\text{VLC}}| \tag{28}$$

Compute **Provider Utility**:

$$U_{\text{provider}} = (\text{RF Revenue} + \text{VLC Revenue}) - (\text{RF Cost} + \text{VLC Cost}) - \text{Load Balance Penalty} \tag{29}$$

return U_{provider}
=0

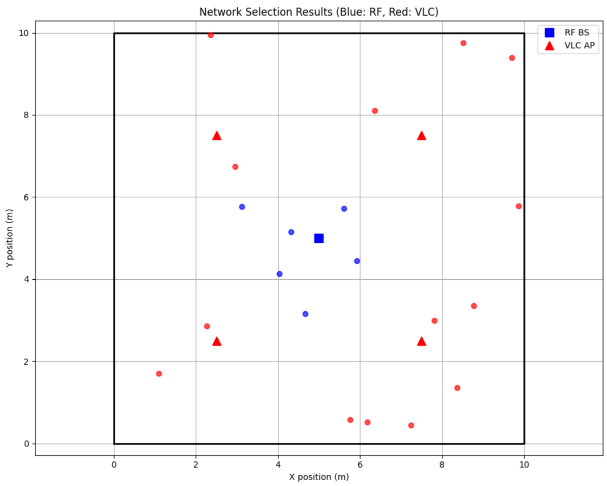

Fig. 1: Network Visualization Result

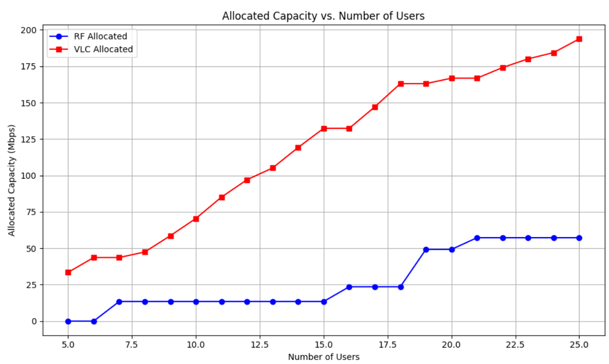

Fig. 2: Allocated Capacity to number of users

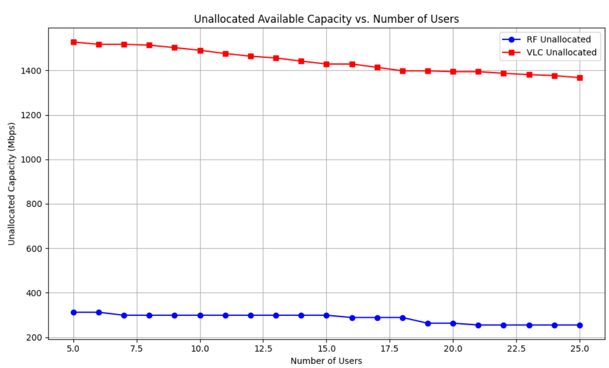

Fig. 3: Unallocated Capacity to number of users

D. Stackelberg Algorithm

The main algorithm for calculating the system parameters using the Stackelberg game theory algorithm is stated in Algorithm 3.

III. Results and Discussions

For our simulation, we took a room of size 10m by 10m, 20 users, 1 RF base station and 4 VLC access points placed symmetrically at the centre of 4 quarters of the room. The Table I refers to the additional parameters of the system.

Algorithm 3 Stackelberg Game Theory Algorithm for Network Selection

Require: Number of users N, provider strategy variables with bounds
Ensure: Optimal strategy variables and user network selection

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Step 1: Initialization
Initialize the provider with initial strategy variables and their bounds
Create N users with random positions and weight preference values
Step 2: Provider Strategy Initialization
Provider sets initial strategy variables within defined bounds
Step 3: Obtain Network Parameters
Retrieve strategy variables from the provider
Step 4: Finding the Stackelberg equilibrium
for Loop until convergence do
    Step 4.1: User Utility Maximization
    for each user i ∈ {1, 2, ..., N} do
        Maximize the user utility function to compute the optimal value for duty_cycle.
    end for
    Step 4.2: User Network Selection
    for each user i ∈ {1, 2, ..., N} do
        Compute the value for RF_Utility(U_RF and VLC_Utility(U_VLC
        if U_RF > U_VLC then
            User connects to RF network
        else
            User connects to VLC network
        end if
    end for
    Step 4.3: Provider Utility Calculation
    Compute provider's utility U_provider by substituting the duty_cycle for each user.
    Step 4.4: Optimization of Provider Strategy
    Maximize U_provider by adjusting strategy variables within bounds.
end for
Step 5: Recalculate User Utility with Optimized Strategy
for each user i ∈ {1, 2, ..., N} do
    Recalculate U_RF and U_VLC using the optimized parameters
end for
Step 6: User Final Network Selection
for each user i ∈ {1, 2, ..., N} do
    if U_RF > U_VLC then
        User connects to RF network
    else
        User connects to VLC network
    end if
end for
Step 7: Visualization of Results
Generate and analyze results for provider utility, user distribution, and network efficiency.
=0
```

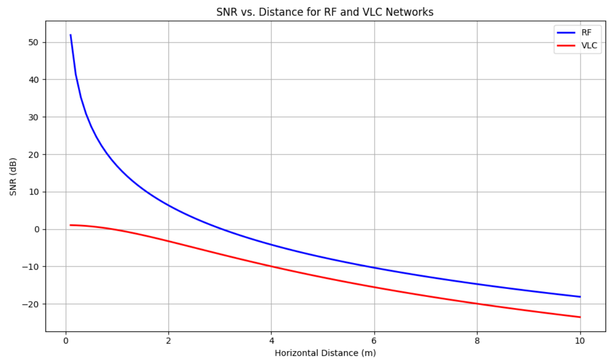

Fig. 4: SNR vs Distance

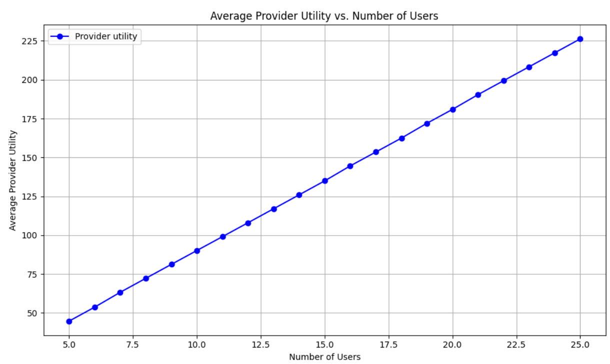

Fig. 5: Provider utility to number of users

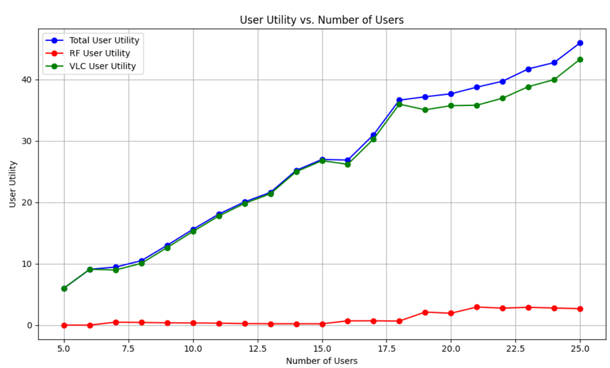

Fig. 6: User utility to number of users

Fig. 1 shows the state of the system after classification of the users to the appropriate networks. The black square represents the room. This figure has 20 users denoted by dots inside that room. The blue square denote the RF base station and the red triangles denote the VLC access points. The color of the dots (users) denotes the network to which they belong as stated in the legend.

Fig. 2 shows the relation between the total allocated capacity of the both networks and the number of users. It shows the increasing trend in the allocated capacity as the number of users increase. It also shows that the users are allocated mostly to VLC network as compared to RF network. This is because we have more number of VLC access points (4) as compared to the number of RF base stations (1). This is also because of

TABLE I: System Parameters for RF and VLC Networks

Parameter	**Symbol**	**Value**	**Unit**
	RF Network		
Max Transmit Power	$P_{\mathrm{RF}}^{\max}$	1.0	W
Max Bandwidth	$B_{\mathrm{RF}}^{\max}$	20×10^{6}	Hz
Noise Power Spectral Density	$N_{0,\mathrm{RF}}$	1×10^{-13}	W/Hz
Fixed Cost	$C_{\mathrm{RF}}^{\mathrm{fixed}}$	5.0	monetary units
Variable Cost Coefficient	α_{RF}	0.1	monetary/Mbps
Energy Cost Coefficient	β_{RF}	2.0	monetary/W
Circuit Power	$P_{\mathrm{RF}}^{\mathrm{circuit}}$	0.05	W
Carrier Frequency	f_{RF}	2.4×10^{9}	Hz
Max Capacity	$C_{\mathrm{RF}}^{\max}$	$\approx$ 66.44	Mbps
	VLC Network		
Max Transmit Power	$P_{\mathrm{VLC}}^{\max}$	0.5	W
Max Bandwidth	$B_{\mathrm{VLC}}^{\max}$	100×10^{6}	Hz
Noise Power Spectral Density	$N_{0,\mathrm{VLC}}$	1×10^{-14}	W/Hz
Fixed Cost	$C_{\mathrm{VLC}}^{\mathrm{fixed}}$	3.0	monetary units
Variable Cost Coefficient	α_{VLC}	0.05	monetary/Mbps
Energy Cost Coefficient	β_{VLC}	1.0	monetary/W
Circuit Power	$P_{\mathrm{VLC}}^{\mathrm{circuit}}$	0.05	W
Responsivity	$\mathcal{R}$	0.5	A/W
Max Capacity	$C_{\mathrm{VLC}}^{\max}$	$\approx$ 996.57	Mbps

the system parameters chosen which reflects almost real life scenario.

Fig. 3 shows the relation of the unallocated available capacity of both networks to the number of users. The unallocated available capacity for both the networks show a decreasing trend as the number of users increase. The trend is more steeply decreasing in case of VLC network because new users are mostly allocated to that network.

Fig. 4 shows the relation of the signal to noise ratio (SNR) to the distance for both the networks. The result show that the SNR decrease with increase in the number of users in the system. In case of RF network, as the distance is increased the radio waves (least energy in the electromagnetic spectrum) loses more energy and more noise gets added to the spectrum, thereby decreasing the SNR. In case of VLC network, as the distance increases, the line of sight communication becomes more and more difficult and more noise gets added to the system. It is also notable that the RF network decreases more steeply compared to VLC network in the starting (when distance start increasing).

Fig. 5 shows the relation between the optimized provider utility to the number of users. We see a linearly increasing trend with the increase in number of users. This shows that the utility function for the provider is a linear function of the number of users.

Fig. 6 shows the relation between the user utility to the number of users. We see an increasing trend in the total user utility as the number of users increases which shows a positive result in the working of our algorithm to the user satisfaction. We also note that the total utility of users in VLC network is higher than the utility of users in the RF network. This is due to the fact that more users are allocated to the VLC network as compared to the RF network as the number of users increases.

From figure 5 and figure 6, we can tell that our algorithm has a positive trend towards the satisfaction of both the provider and the user.

IV. Conclusions

This study presents a Stackelberg game-theoretic framework for optimizing network selection in hybrid RF-VLC environments. Unlike conventional static allocation methods and reinforcement learning-based techniques, our approach offers a mathematically interpretable and computationally efficient solution that balances the interests of both users and the network provider. By formulating utility functions that integrate multiple performance metrics—including data rate, cost, delay, energy consumption, and reliability—our method enables adaptive and efficient resource allocation.

Compared to RL-based techniques, which often require extensive training and computational resources, our game-theoretic approach provides faster convergence and enhanced explainability while maintaining near-optimal decision-making. Furthermore, by explicitly modeling the strategic interactions between the provider and users, the proposed framework achieves better load balancing, reduced congestion, and improved cost efficiency.

Experimental results demonstrate that this approach significantly enhances network performance and user satisfaction while ensuring optimal provider utility. Future research can focus on extending this model to multi-provider environments and exploring hybrid strategies that integrate both game-theoretic and reinforcement learning techniques for even greater adaptability in dynamic wireless communication networks.

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