Network Selection Algorithm using Stackelberg Game Theory

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Outline

Problem Statement

- Next-generation wireless networks must efficiently allocate resources between Radio Frequency (RF) and Visible Light Communication (VLC) networks.
- Users have different preferences (e.g., data rate, cost, delay, reliability), making network selection a complex decision-making problem.
- Service providers need to optimize their strategies to maximize revenue while maintaining load balance and user satisfaction. Main Reference Paper: [1]

Objective

- Design the utility functions for the user and provider(RF and VLC).
- Develop a Stackelberg game-theoretic framework for optimal network selection in a hybrid RF-VLC environment, ensuring efficient resource allocation for both users and service providers. Here the users act as the follower while the providers act as the leader.
- Find the optimal strategy variables/system parameters and visualize the results.

Literature Review

- Núñez-Kasaneva *et al.* proposed an adaptive network selection algorithm based on user requirements and network conditions to enhance performance in hybrid RF-VLC systems. Their study demonstrated improved system throughput and user experience [2].

- Obeed *et al.* introduced a reinforcement learning-based framework for network selection in 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 [3].

- Chen *et al.* applied Stackelberg game theory for dynamic pricing in wireless network virtualization. Their work optimized resource allocation and load balancing by adjusting network provider pricing strategies, ensuring efficient utilization of hybrid RF-VLC systems [4].

System Model

RF Path Loss Model [5]

- Signal attenuation follows:

$$PL(d) = PL(d_0) + 10n\log_{10}(d/d_0) + X_\sigma$$

where: d = distance, n = path loss exponent, X_σ = shadowing effect.

VLC Lambertian Model [6]

- Received power in VLC is given by:

$$P_r = P_t \frac{(m+1)A}{2\pi d^2} \cos^{m+1}(\phi) T_s(\psi) g(\psi)$$

where:

- P_t = transmitted power, m = Lambertian order, A = detector area, d = distance, ϕ = angle of incidence, ψ = receiver field-of-view angle, $T_s(\psi)$, $g(\psi)$ = optical filter gain and concentrator gain.

Stackelberg Game-Based Network Selection

Players in the Game

- **Network Provider (Leader)**: Sets resource prices, transmission power and allocates bandwidth. It considers revenue, cost and load balance penalty to calculate its utility.
- **Users (Followers)**: Sets the $duty\_cycle$ for each user and choose the network offering the best utility based on data rate, cost, delay and reliability.

Stackelberg Equilibrium

- The leader anticipates the best response from the follower and chooses the strategy variables to maximize his utility.
- The follower uses the optimized strategy variables from provider to maximize his utility function by optimizing a separate set of variables.
- The above steps are repeated over and over until convergence and Stackelberg equilibrium/Nash equilibrium is reached.

Stackelberg Game-Based Network Selection

Algorithm

1. Initialize the network parameters (strategy variables optimized by provider). (Leader moves first).
2. Maximize the user utility function for all users given the network parameters with respect to duty cycle for each user. (Leader anticipating the best response from the follower).
3. Maximize the provider's utility function with respect to the network parameters (price, transmission power, bandwidth, etc.) given the optimized duty cycle for each user.
4. Goto step-2 until convergence (difference between strategy variables of current and previous iteration is less than some threshold) is not reached.

User Utility Function

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

$$C = \text{fixed cost} + VC \cdot R \tag{11}$$

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 $(U_{\text{RF}}, U_{\text{VLC}})$

Figure 1: References: [7] [8]

Provider Utility Function

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

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

2: Compute **Load Factor**:

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

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

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

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

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

4: Compute **Provider RF Cost**:

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

5: Compute **Provider VLC Cost**:

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

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

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

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

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

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

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

8: Compute **Load Balance Penalty**:

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

9: Compute **Provider Utility**:

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

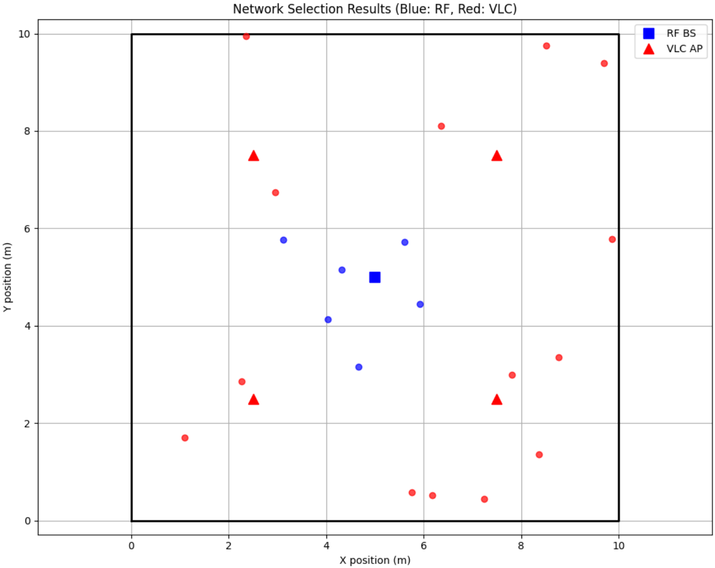
System Parameters

TABLE I: System Parameters for RF and VLC Networks

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

Figure 3: System Parameters

Results and Inferences



Results and Inferences

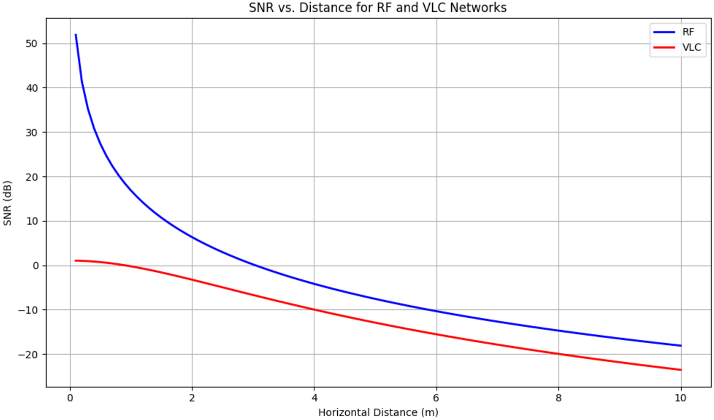


Figure 5: SNR vs Distance plot

Results and Inferences

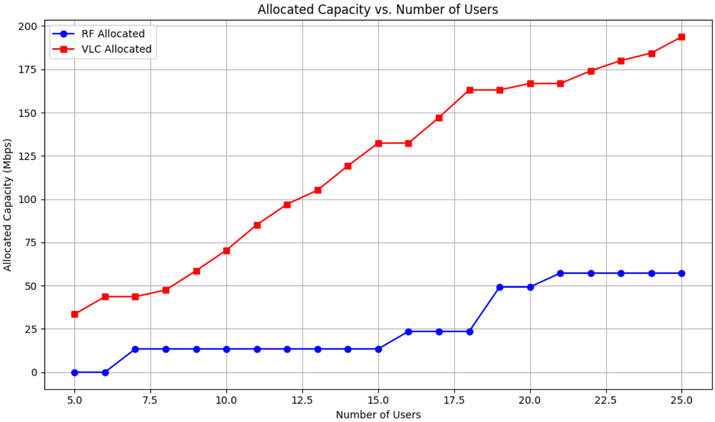


Figure 6: Allocated capacity to number of users

Results and Inferences

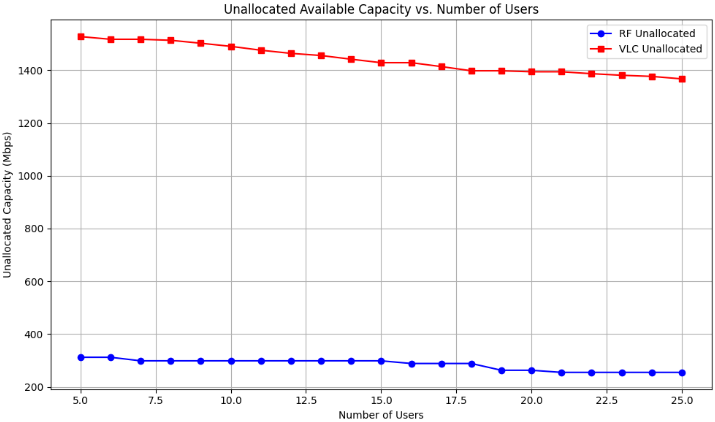


Figure 7: Unallocated capacity to number of users

Results and Inferences

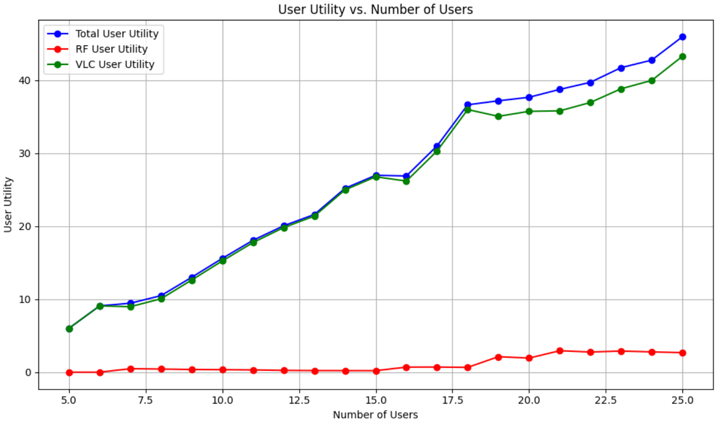


Figure 8: User Utility to number of users

Results and Inferences

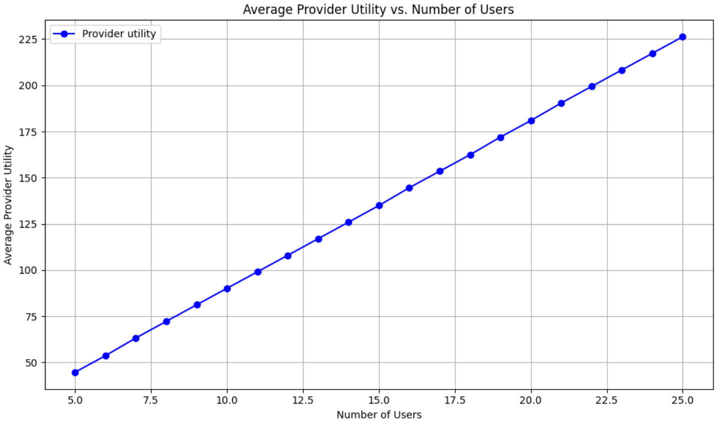


Figure 9: Provider Utility to number of users

Results and Inferences

Inferences

- Users are effectively classified into RF or VLC networks based on utility, with most users preferring VLC because of favorable parameters and greater availability of access points.
- Allocated capacity of both networks increase with the number of users, while unallocated capacity decrease, indicating efficient resource utilization.
- VLC network handles higher user loads, leading to better utilization and higher user utility compared to RF.
- Signal-to-noise ratio (SNR) decreases with distance for both networks, with RF degrading faster due to higher attenuation.
- Both provider and combined user utilities show a consistently increasing trend with more users—highlighting the effectiveness of the proposed Stackelberg-based optimization algorithm.

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Scalable Dashboard

Purpose and significance

Nutanix requires a dashboard for monitoring and analyzing Large-Scale Disaster Recovery Operations. Current challenges include:

- Inadequate Analysis Capabilities: Existing tools lack the analysis needed to identify trends, correlate metrics, and pinpoint bottlenecks.
- Multi-Persona Requirements: Different stakeholders, such as managers, developers, and QA engineers, have varying information needs. A single, static dashboard may not effectively cater to these diverse requirements.

Objectives

- Develop a Real-Time DR Monitoring Dashboard: Create a dashboard that provides real-time visibility into key DR metrics, including RPJ progress, resource utilization, enabling proactive identification of performance bottlenecks and faster troubleshooting.
- Enable In-Depth Performance Analysis: Facilitate detailed analysis of DR performance through interactive visualizations, build-to-build comparisons, release-to-release benchmarking, and microbenchmarking of individual recovery tasks within RPJs.

Architecture

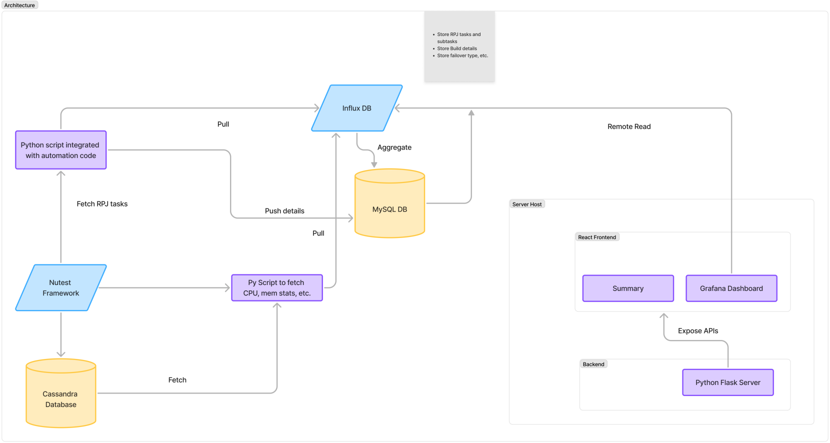

Figure 10: Architecture

Scalable Dashboard

Progress

- Completed data collection script for polling different subtask types during different kinds of failovers and computed stats on the metadata.
- Integration of the data collection script with the Nutest framework is almost done with a few changes in progress.
- Script for manipulating data and writing data to InfluxDB, basic template for react template, flask backend is done.

Challenges faced

- Real time data handling for ongoing RPJs, required us to collect the metadata before it gets garbage collected from the Cassandra database.
- Associating a unique identifier(PR UUID/RPJ UUID) to the collected metadata proved to be a challenge.
- Encoded entity list from the API used for getting metadata from the Cassandra DB.