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Original scientific paper

Spectral Congestion Alleviation using RF Integrated Optical System with Optimization Based Dynamic Carrier Switching

S. MYTHILI*, M. KALAMANI

Abstract: With the rapid growth of wireless communication, congestion and interference in the RF spectrum have become significant challenges, leading to degraded quality of service (QoS). To address this issue, we propose an intelligent RF-integrated Optical System that dynamically switches user data transmission between RF and Visible Light Communication (VLC) based on real-time spectrum conditions. The core novelty of our approach lies in the application of the Wader Hunt Optimization (WaHO) algorithm, a bio-inspired metaheuristic method, for intelligent spectrum switching in hybrid RF-VLC Network. WaHO is utilized to continuously monitor RF spectrum usage, detecting interference and congestion patterns. When the RF spectrum is deemed unsuitable, the system autonomously redirects communication to the VLC spectrum, ensuring seamless data transmission. The key contributions include congestion aware spectrum switching and energy efficient hybrid communication. The experimental baseline of spectroscopic study investigates the real time interactions of different spectra and its interference when RF and Optical spectra are hybridized in wireless networks. The performance analysis of WaHO based dynamic spectral switching in RF integrated Optical System (RFiOS) proves that the enhanced data throughput is achieved and gives significant adaptability rating to next generation wireless networks.

Keywords: carrier switching; integrated network; optical; rf interference; visible light communication; wader hunt optimization

1 INTRODUCTION

The radio frequency (RF) channel spectrum is a critical component of wireless communication systems, characterized by various technologies and methodologies aimed at optimizing its use [4]. As of recent estimates, the number of mobile phone subscriptions globally has reached approximately 6 billion, indicating a significant penetration of mobile technology into daily life. The widespread use of mobile phones and other communication devices, which utilize radiofrequency (RF) electromagnetic fields (EMFs) for communication, has raised concerns regarding the spectrum congestion. This spectral congestion can affect the real time networks‘ timely communication [22]. Because of the rapid growth in communication technology and its usage, it led to increased research into the alternative spectrum use.

There are some advancements underscore the dynamic nature of RF channel spectrum management and its significance through various ways. The development of channel reservation and transmission schemes allows efficient access to shared RF spectrum, facilitating better coordination among users [23]. To maximize spectrum utilization, predictive models based on historical occupancy data have been proposed, employing machine learning techniques to forecast channel availability and improve resource allocation. Additionally, adaptive methods for ultra-narrowband IoT communications ensure that transmission rates align with real-time network conditions, thereby enhancing reliability and efficiency [18]. Even though it is efficient there are some factors in RF, affecting the data speed and channel access assignments.

With the growing demand for high-speed data and the limitations of available spectrum, there is a need to explore integrated communication solutions [5]. The convergence of RF and VLC technologies offers promising solutions for high-speed, reliable communication. The radio frequency spectrum, and Visible Light spectrum address different aspects of connectivity and capacity [6]. Integrating these technologies can optimize spectrum usage and improve overall network performance [26].

This paper investigates the feasibility of integrating RF and VLC, focusing on spectrum management, policy implications, and real-time implementation challenges. This research work is carried out with the base of spectral study and its integration feasibility.

Primary contributions of the research:

- This research highlights the interoperability phenomenon when two different spectra operate in an integrated mode of communication.
- This paper aims to provide a dynamic mode based carrier-switching methodology using Wader Hunt Optimization algorithm to suggest an alternative spectrum for communication.
- This study explores the benefits of using an alternative spectrum when the regular RF spectrum is congested.

The structure of the paper is in-lined with the following flow: The section 2 extracts the perception of RF spectrum study and use of Visible light frequency for communication. Section 3 demonstrates the methodological testing of RF and Optical spectrum and its integration capability. It also describes the WaHO configured RF integrated Optical system to limit the spectral congestion. Section 4 presents the optimization results of proposed Wader Hunt Optimization Algorithm used for dynamic carrier switching. Section 5 concludes the study by examining the effects of RFiOS in real time communication system.

2 BACKGROUND AND LITERATURE SURVEY

This section of study illuminates the background of RF network and comprehends the literature relevant to interference existing in RF network to propose the RF integrated Optical System (RFiOS).

The RF spectrum facilitates communication among multiple users through various methods of spectrum sharing and allocation [22]. In Cognitive Radio Networks, unlicensed users can dynamically access vacant spectrum slots, optimizing the use of underutilized frequencies typically reserved for primary users. This approach allows for efficient bandwidth allocation, enabling multiple users to transmit data simultaneously without interference, as users are classified into subsets based on channel strength and interference levels [21]. Additionally, multiuser distributed access methods enable secondary users to select channels based on real-time sensing and utility functions, ensuring equitable access to spectrum resources [15]. Time-sharing multiplex systems further enhance spectrum utilization by dividing RF channels into multiple time slots, allowing for synchronized data transmission across different users. Collectively, these strategies ensure that the RF spectrum can accommodate a growing number of users while maintaining communication quality and efficiency.

Radio frequency congestion occurs when multiple radio devices operate simultaneously within the same frequency band, leading to competition for limited spectrum resources. This is particularly evident in unlicensed bands, such as the 2.4 GHz spectrum, where devices like WiFi, Bluetooth, and ZigBee can create significant interference and congestion, especially in densely populated areas. Congestion can be exacerbated by the inability of devices to accurately assess the state of the network, as traditional methods may fail if packets do not reach their intended destinations. Moreover, in mesh networks, long-term congestion can arise from inefficient link utilization, necessitating network adjustments to alleviate bottlenecks. Techniques such as Dynamic Channel Assignment (DSA) and multipath routing have been proposed to detect and mitigate congestion, highlighting the need for adaptive strategies in managing spectrum use. Overall, the interplay of device density, spectrum limitations, and network management strategies plays a critical role in the emergence of radio frequency congestion [24, 25].

Additionally, spectral sensing techniques that combine temporal and frequency-based analyses can enhance the accuracy of identifying the number and types of transmitters in a given frequency band. This is particularly useful for frequency-hopping devices, where traditional methods may fall short. Furthermore, integrated photonic devices can facilitate simultaneous multichannel RF spectrum analysis, enabling the monitoring of multiple channels and thus providing a broader view of device activity in the spectrum [10]. Lastly, novel device detection methods that utilize RF fingerprints can adapt to new devices appearing in the spectrum, allowing for continuous monitoring and classification without prior knowledge of all device classes. Collectively, these techniques provide a robust framework for accurately assessing the number of devices utilizing the RF spectrum.

To calculate the number of RF devices using RF spectrum, several methodologies can be employed based on the analysis of received signals. One effective approach involves utilizing a radio frequency spectrum calculation device that measures the frequency spectrum of radio signals through I and Q signal processing, enhancing the observable band and minimizing DC component attenuation. Additionally, spectral sensing techniques can estimate the number of frequency-hopping interferers by analyzing temporal and frequency offsets, which improves the accuracy of RF fingerprinting. Moreover, employing a Probability Mixture Model (PMM) can help identify the number and characteristics of RF transmitters by fitting various probability density functions to RF power measurements in the environment [13]. Finally, an interferometry method using multiple receiving antennas can calculate phase differences to discern the number of electromagnetic transmitters [25]. These combined techniques provide a robust framework for accurately determining the number of RF devices operating within a given spectrum.

Still it defends for the timely communication based on the condition of application use. So as like Radio frequency spectrum the available spectrum which proves the data transmission capability is Visible Light Communication Spectrum [1]. Visible Light Communication (VLC) is emerging as a promising alternative to traditional radio frequency (RF) wireless communication, addressing spectrum scarcity and offering high data rates. VLC utilizes the visible light spectrum (375-780 nm) for data transmission, providing enhanced security and bandwidth compared to conventional wireless bulbs as transmitters and photodiodes as receivers, encoding data through intensity modulation and direct detection [12, 13, 18]. VLC can be implemented for various applications, including audio and data transmission systems [8]. Furthermore, combining VLC with RF in device-to-device (D2D) communication has shown potential to significantly improve system capacity, particularly in indoor scenarios [7, 11, 18]. As wireless data demands continue to grow, VLC presents an opportunity to unlock vast amounts of unused electromagnetic spectrum, potentially alleviating the impending RF spectrum crisis [17].

The standardization efforts to circumvent RF interference are purely based on logical partitioning of spectral use [19]. Even though it is devised well the interference occurrence is non-avoidable based on the surveys taken. So in order to make the timely communication feasible for the sensitive applications the spectral switching process is proposed to carry out the communication effectively.

3 PROPOSED WORK

A common misconception is that optical signals and radio frequency (RF) signals are not related [14]. Both optical and RF signals are part of the electromagnetic spectrum, with RF having longer wavelengths and lower frequencies than optical signals. In order to utilize the higher bandwidth available in optical spectrum and enhance security due to less interception among signals, the experimental analysis is carried out and its integrated properties are studied through the interaction of optical and RF using visible light spectroscopy.

3.1 RFiOS Behaviour Model Analysis

For the experimental analysis,a small dimension cuvette having a dimension of 45 × 12.5 ×12.5 mm made of a glass material which allows a range of 340-2500 nm wavelength and having a transmission rate of 83% is selected which allows RF waves to pass through it easily. The RF signal source is positioned close to the container containing the ferric ion thiocyanate solution to ensure minimal attenuation as they travel through the solution. Based on the specific characteristics of ferric ion thiocyanate complex the output power source of RF is tuned to make better penetration into the solution without causing unwanted heating or other side effects. Gentle agitation of the solution helps to ensure uniform distribution of the RF signal throughout the solution volume. This helps to maximize interaction between the RF waves and the complex molecules. Ferric Thiocyanate is obeying light and temperature [2]. The interaction analysis infers that the ferric thiocyanate solution is vibrated by increasing the temperature. Due to the increase in temperature the molecule gets vibrated and the non-bonding electrons are moved rapidly.

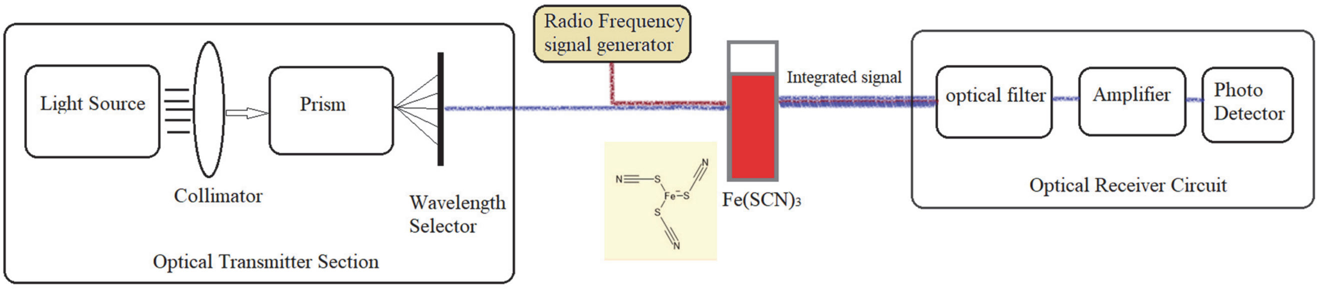

Figure 1 Absorbance detection set-up of proposed RF integrated optical system

Based on the Molecular collision theory of chemical reactions, frequency is directly proportional to average velocity of molecules. And average velocity is directly proportional to square root of temperature. With this it is proposed that frequency generated from the solution is proportional to square root of temperature. When temperature increases, the collision frequency increases and hence the fraction of effective collision increases. So these collisions lead to an increase in energy of the reactants.

Based on this notion, the RF Integrated Optical System is analysed with an experimental set up holding the transmitter and receiver section as a single unit in visible light spectroscopy as shown in Fig. 1. Extinction Coefficient (λ_{max}) is a factor which determines how strong the light absorbs at a particular wavelength [16]. Based on assessing the characteristic nature of spectroscopy it is identified that the Ferric Thiocyanate reacts well at 480 nm as shown in Fig. 2. With this base, the integrated interaction is analyzed with the visible light spectrum of 480 nm.

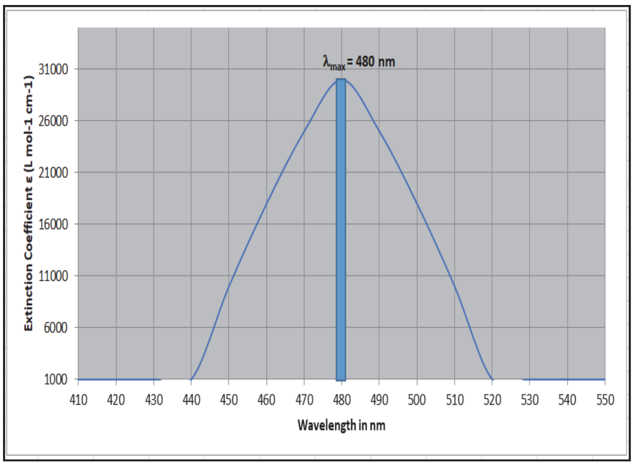

Figure 2 λ_{max} plot

As the chemical reactions depend on temperature, the system works significantly better at some temperatures than others. Initially when the temperature is raised, the non-bonding electrons of the complex are heated and vibrated. During this stage it interacts with light and causes molecular rotational vibration. At a high temperature of 40 °C the absorbance value is observed which ranges from 0.343 to 0.379 over the period of continual time measurement. When the temperature decreases gradually, it is observed that the absorbance increases gradually from 0.385 to 0.410. This experimental analysis concludes that at high temperature the energy of the solution is also high so there is no need for absorbance of light whereas when the temperature cools down the solution starts absorbing the energy for the molecular motion. If the absorbance is 38.5% then the remaining is considered as the transmittance. At room temperature the absorbance value is observed as 0.413 which means the integrated signal's transmittance value is 58.7. The rate at which it varies at 25 °C is shown in Fig. 3.

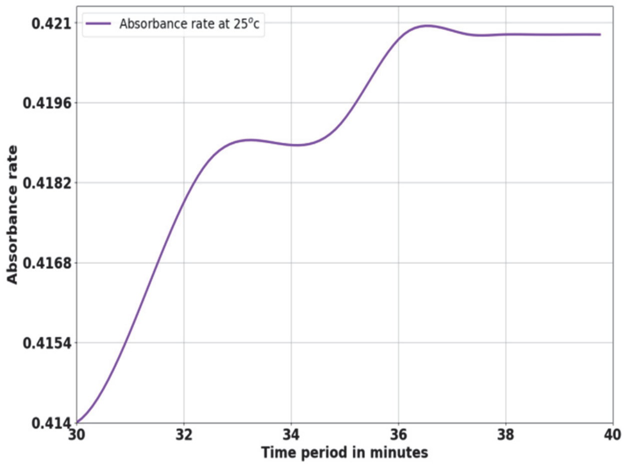

Figure 3 Absorbance rate of integrated system at room temperature

Based on the experimental analysis it is understood that the absorbance value does not change over a period of time at room temperature which indicates that the integrated signal is able to transmit and it does not negatively affect the signal propagation. Hence it is proven that the integrated communication paves a way for congestion free communication by switching the operating carrier from normal RF to RFiOS mode whenever the RF device faces the heavy data traffic.

A dynamic system is essential to switch the carrier, optimize the data handling and ensure seamless operations. So, Wader Hunt Optimization (WaHO) algorithm is proposed for effective spectral use. WaHO is a bio-inspired metaheuristic technique designed to optimize decision-making in complex environments.

3.2 Technical Framework

The RF spectrum is a limited resource, its demand is surpassing the availale bandwidth which leads to congestion and makes the network overloaded and increased traffic. RF interferences significantly impact communication reliability, by reducing SNR and packet error rate. Visible Light Communication (VLC) offers inherent immunity to RF interference, enabling dynamic offloading of traffic from RF to VLC in congested environments, making hybrid RF-VLC systems viable. The hybrid system acts as an augmentation layer on top of existing RF networks, enhancing localized performance by leveraging VLC. The proposed network model incorporates multi-node communication with multiple access points (APs) for RF and VLC, dynamically assigning users to APs based on real-time channel conditions. The system accounts for time-variant Signal-to-Noise Ratio (SNR) fluctuations to simulate real-world environments, ensuring dynamic spectral switching. Adaptive optimization is employed to solve the multi-objective optimization problem in real-time, implementing the Wader Hunt Optimization (WaHO) algorithm to continuously monitor network conditions, dynamically allocate spectral resources, and optimize user handovers between RF and VLC. Its main objective is to maximize data throughput and minimize latency by selecting the best spectrum (RF or VLC). Scaling the hybrid RF-VLC system requires efficient spectral allocation and congestion alleviation mechanisms, achieved through dynamic user allocation, distributed control architecture, and decentralized optimization, reducing reliance on a central controller and enabling horizontal scaling.

3.3 Dynamic Carrier Switching Operation

The process of switching RF-based devices to Visible Light Communication (VLC) or vice-versa using the Wader Hunt Optimization (WaHO) algorithm involves a series of steps that identify the optimal transition from RF communication to VLC, which is typically used to alleviate spectrum congestion, enhance security, and improve data rates. The given flowchart in figure 4 outlines the iterative process of spectrum sensing, evaluating alternatives, and switching using WaHO.

Step 1. System Initialization

- **Setup of Devices**: RF devices and VLC receivers (like LEDs and photodetectors) are initialized [20]. The network parameters for both RF and VLC (e.g., bandwidth, channel conditions, transmission power, interference levels) are set up [3].
- **Define Optimization Problem**: The transition from RF to VLC is formulated as an optimization problem, where WaHO is used to find the best possible channel or resource (either RF or VLC) to communicate under dynamic network conditions.

Step 2. Spectrum Sensing in RF and VLC

- **RF Spectrum Sensing**: The device senses the RF spectrum for available channels, interference levels, SINR, and other metrics to determine how well the RF link is performing.
- **VLC Spectrum Sensing**: Simultaneously, VLC channels are sensed by measuring light intensity, noise, potential obstacles, and flickering. VLC channels are influenced by factors like the quality of the light source (LED), distance from the light, and interference from ambient light.

Step 3. Initialize Wader Population (Candidate Solutions)

- **Waders in WaHO**: Each "wader" in WaHO represents a possible communication scenario. For example, one wader could represent an RF band, and another could represent a VLC band. The initialization step involves generating a population of waders, with each wader corresponding to a candidate spectrum (either RF or VLC).
- **Mixed Population**: The population can include both RF and VLC solutions, allowing for hybrid optimization.

Step 4. Fitness Evaluation of Waders

Fitness evaluation is a critical step in optimization algorithms where each candidate solution is assessed based on certain performance metrics [3, 27-29]. In the context of spectrum sensing and switching through the Wader Hunt Optimization (WaHO) algorithm, the fitness of each candidate solution (or "wader") is determined by evaluating how well a specific spectrum band performs under given network conditions.

- **Evaluate RF Channels**: For each RF candidate, evaluate metrics like SINR, data rate, energy consumption, and interference. High interference or low SINR decreases the fitness score of the RF solution.
- **Evaluate VLC Channels**: For VLC candidates, evaluate metrics like signal strength (light intensity), data rate, energy efficiency, obstacle presence, and delay. Higher data rates and better energy efficiency improve the fitness score of VLC solutions.
- **Fitness Function**: A fitness function is used to assess each wader (whether it is an RF or VLC candidate). The function considers:

i) **Signal-to-Interference-plus-Noise Ratio (SINR):** SINR values indicate better signal quality, lower interference, and noise. Higher SINR leads to a better fitness score because it ensures more reliable communication with less interference from other users.

ii) **Data Rate**: The data rate or throughput refers to the amount of data successfully transmitted over the network within a given time. It is influenced by the quality of the chosen spectrum. A spectrum band with higher data rate potential will result in a better fitness score as it maximizes network performance.

iii) **Energy Efficiency**: Energy efficiency measures how efficiently energy is used for communication in a given spectrum band. It is important for batteryoperated devices, such as IoT sensors and mobile devices. Spectrum bands with better energy efficiency will score higher in fitness evaluations, especially in energy-constrained networks.

iv) **Interference**: This metric measures the level of interference from other users (both licensed and unlicensed) operating on the same spectrum band. Lower interference levels increase the fitness score, as the spectrum will be more usable and stable for communication.

v) **Latency**: Latency refers to the time it takes for a signal to travel from the sender to the receiver. Some applications, such as real-time video or gaming, require low latency. Spectrum bands with lower latency will achieve higher fitness scores, as they are more suitable for delay-sensitive applications.

vi) **Bit Error Rate (BER):** BER measures the number of erroneous bits received over a communication link. This is an indicator of communication quality. Lower BER improves the fitness score, indicating more reliable communication.

vii) **Cost and Constraints**: The cost function aggregates multiple performance metrics, potentially incorporating network cost, monetary costs, or other constraints that penalize using certain spectrum bands. Lower overall cost (including spectrum usage, energy cost, and potential penalties) increases the fitness score.

The fitness function combines these metrics into a single value for each candidate spectrum band. It is formulated as follows.

$$Fitness = w_1 \cdot \frac{SINR}{Interference} + w_2 \cdot \frac{Data\,Rate}{Energy\,Consumption} - \\ -w_3 \cdot Latency - w_4 \cdot Bit\,Err$$

where w_1, w_2, w_3, w_4 are the weights assigned to different metrics based on the importance of communication.
The wader with the highest fitness score is selected as the optimal spectrum band for switching.

Adaptive Fitness:

The fitness function can be adjusted dynamically during operation to reflect changing network conditions or application requirements (e.g., during congestion, interference, or priority shifts).

Step 5. Wader Hunt Optimization Process

- **Position Update**: The wader positions (candidate channels) are updated iteratively based on WaHO. In WaHO, waders "hunt" by updating their positions based on the best-performing waders and the environment.
  - **RF to VLC Transition**: If the VLC candidates are found to have higher fitness scores (due to better data rates, lower interference, or energy efficiency), the algorithm encourages waders (devices) to transition from RF to VLC.
  - **VLC to RF Transition**: If conditions in VLC are unfavorable (e.g., high ambient light interference or obstacles blocking the light path), waders are moved back to RF bands with better conditions.

Step 6. Convergence Check

- The algorithm checks whether the solution has converged by assessing whether the fitness scores of the waders have stabilized (i.e., no significant improvements are found). Convergence indicates that the optimal spectrum (either RF or VLC) has been identified for communication.

Step 7. Optimal Spectrum Selection

- Once the algorithm converges, the wader with the highest fitness score is selected. If it corresponds to an RF band, the device stays on RF. If it corresponds to a VLC channel, the device switches to VLC communication.

Step 8. Switching to VLC

- The selected device switches its communication protocol from RF to VLC. The VLC transmitter (e.g., LED) begins transmitting data through visible light, and the VLC receiver (e.g., photodetector) starts receiving data. The VLC link operates under the selected optimal parameters (such as intensity, modulation type, etc.).

Step 9. Post-Switch Performance Evaluation

- After switching to VLC, the system evaluates the communication performance, monitoring parameters such as data rate, energy consumption, and delay. If performance degrades (due to environmental changes, for example), the device may switch back to RF using the WaHO algorithm again.

The Wader Hunt Optimization algorithm enables dynamic switching between RF and VLC by continuously sensing the performance of both communication systems and optimizing the selection of the best spectrum band by adapting to the flow as in Fig. 4.

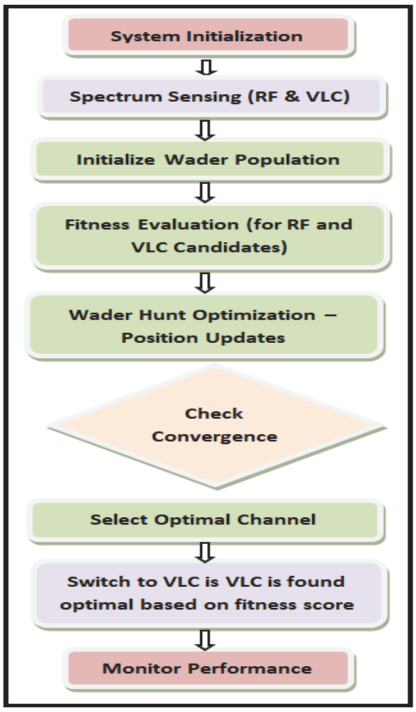

Figure 4 Operational flow of Wader Hunt Optimization Algorithm for dynamic switching

The WaHO algorithm dynamically balances the load between RF and VLC, leading to better utilization of both spectrums. The WaHO algorithm adapts the communication mode to prevailing conditions, ensuring efficient use of available resources while enhancing network performance in terms of data rate, energy efficiency, and interference reduction. The proposed working model flow representation is shown in Fig. 5. When the RF spectrum is congested or experiences high interference, the algorithm transitions suitable devices to VLC, thereby offloading traffic from RF spectrum. Light based communication can be more difficult to intercept than RF signals, which can penetrate walls. Therefore, VLC provides inherent security benefits due to the limited range and inability to pass through opaque objects.

WaHO can optimize for security by prioritizing VLC for sensitive data transmission. In case the VLC path is blocked the algorithm detects the degradation and dynamically switches the carrier back to RF spectrum for stable communication. As the density of devices in a network increases, WaHO can ensure scalability by optimally distributing communication between RF and VLC reducing bottlenecks and avoiding congestion in the RF spectrum. WaHO provides the seamless communication switching based on real time conditions and performance metrics.

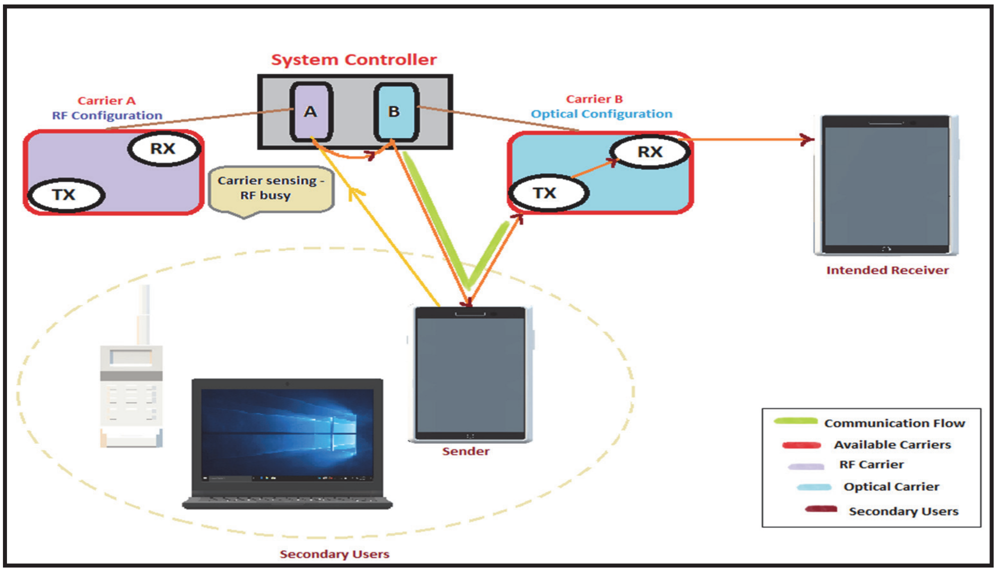

Figure 5 Proposed model with enabled dynamic switching configuration using WaHO

4 RESULTS

The simulation environment is developed in NS-3 with modifications for hybrid RF-VLC network modelling and dynamic spectral switching using WaHO. The setup includes RF access points, VLC transmitters, and hybrid user nodes with Random Waypoint mobility. Traffic varies from 1 Mbps to 100 Mbps. WaHO integrates with WiFi MAC and CSMA MAC for spectrum handovers, while FlowMonitor tracks throughput improvements before and after switching.The Cognitive Radio operates only in the RF domain and detects interference after channel occupancy whereas the proposed system uses dual-domain sensing with real-time congestion metrics to predict congestion beforehand and proactively assign channels. The following graphs can effectively display performance improvements of RFiOS through the key metrics such as throughput, Energy efficiency, Latency, SINR and Congestion Alleviation.

Throughput:

The throughput can vary widely based on several factors including the technology standard, frequency band and environmental conditions. The factors that influence the value of throughput include Signal strength, Interference, Number of connected devices, Coverage area, Channel congestion and Network configuration. From Fig. 6, it is observed that there is an improvement in network throughput when using the WaHO based channel switching algorithm for integrated RF-Optical compared against standalone RF network and standalone VLC network. The theoretical maximum throughput for the RF based WiFi communication is 600 Mbps and the real world throughput attained is in the range of 150-200 Mbps.

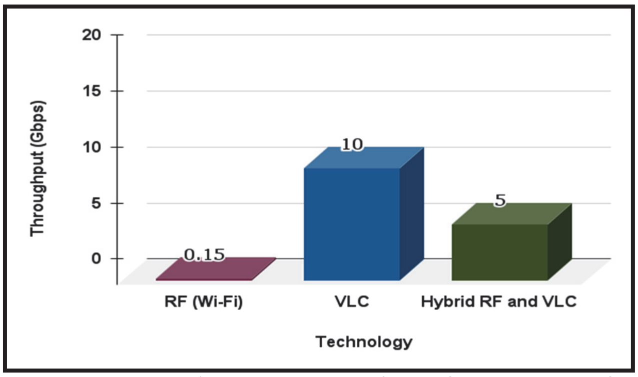

Figure 6 Throughput performance comparison of RF, VLC, and hybrid RF-VLC systems

The typical throughput of VLC system is 100 Gbps. But in experimental system it is attained as 10 Gbps. The decremented natures of practical values are obvious due to interference. When Radio frequency and Visible light communication are hybridized in a network, the overall throughputs are significantly increased by leveraging the strengths of both the technologies [9]. And also ensures interference free communication.

Energy Consumption:

RF systems generally consume 10-20 nJ/bit depending on the transmission conditions. VLC system consumes 1-10 nJ because VLC can leverage high frequency bands and direct light for more efficient data transmission. VLC is 50 to 80 % more efficient than RF due to its direct line of sight nature. The hybrid systems intelligently offload data to VLC when possible and achieve better energy efficiency as 5-15 nJ per bit than standalone RF and VLC networks. The proposed system is having a good reliability and energy efficiency when compared to standalone network. The Fig. 7 shows the VLC's efficiency while retaining the reliability of RF in hybrid model against the standalone model when number of devices increases.

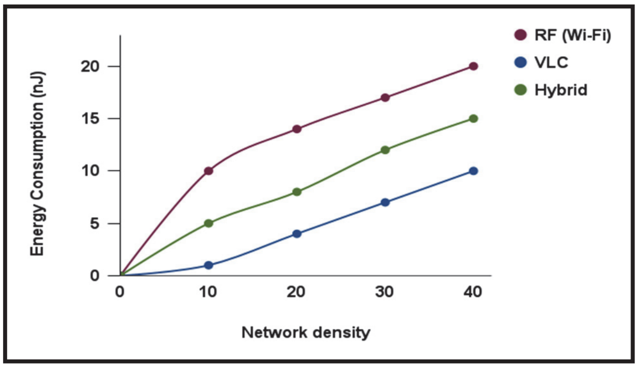

Figure 7 Energy consumption comparison of RF, VLC, and hybrid RF-VLC technologies

Latency

From Fig. 8, it is observed that Latency value increases with the number of devices due to congestion and resource sharing. Higher latency of around 10-50 ms in RF than VLC is due to the lower bandwidth and environmental factors.

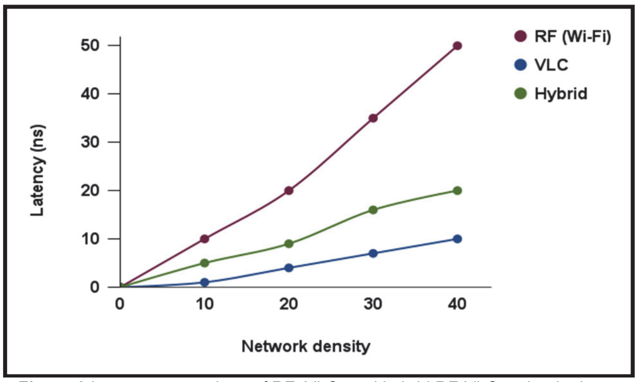

Figure 8 Latency comparison of RF, VLC, and hybrid RF-VLC technologies versus network density

VLC is typically 1-10 ms due to the direct line of sight communication. In hybrid model intelligent switching provides the latency of approximately 5-20 ms.

SINR

The proposed network performance heavily depends on network congestion, body movements, and environment. From Fig. 9, it is shown that RF is struggled with Multipath effects, body absorption and provides 5-25 dB as the SINR range. The VLC system offers higher SINR in the range of 20-40 dB due to interference. The hybrid RF and VLC shows the network ability by providing the SINR range as 10-30 dB even in the dynamic environment.

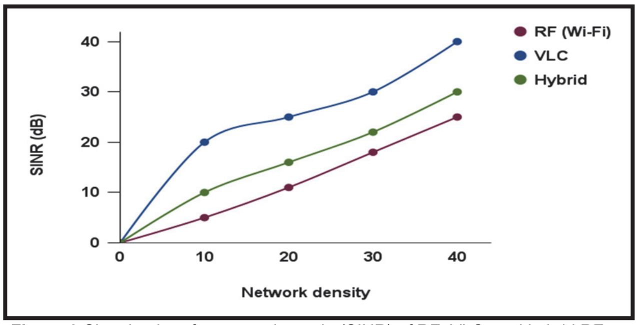

Figure 9 Signal to interference noise ratio (SINR) of RF, VLC, and hybrid RF-VLC technologies

Congestion Alleviation

It is observed through Fig. 10 that in RF, as the number of devices increases, congestion grows significantly in the range of 10-80%, leading to lower data rates and higher delays. Congestion increases more slowly in the range of 5% to 40% since VLC operate in less crowded spectrum. The hybrid systems alleviate the congestion better with lower range of 5% by intelligently balancing the load between RF and VLC.

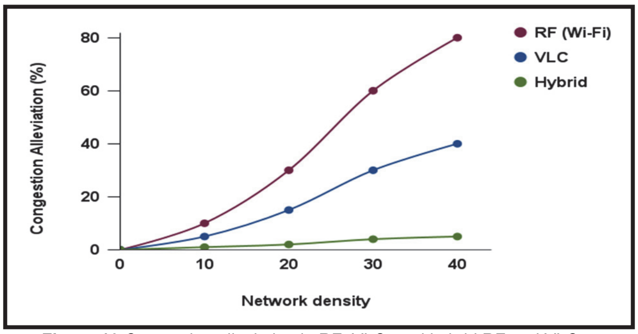

Figure 10 Congestion alleviation in RF, VLC, and hybrid RF and VLC technologies

Based on the analysis, WaHO based switching to Hybrid RF-VLC outperforms in terms of throughput and data rate; it also offers lower delay and interference and has a shorter optimization time for the data communication. Its working metrics and performance capabilities are assessed and shown in Tab. 1. The WaHO is suitable for Multi Objective Optimization in hybrid networks. The tuned search parameters help to achieve optimal performance. The other bio mimic algorithms such as Particle Swarm Optimization and Firefly show slower adaption to rapidly changing network conditions.

Table 1 Result of dynamic channel selection algorithm - WaHO

Metrics	WaHO algorithm
Channel Selection Efficiency / %	95
Optimization Time / s	30
Efficiency / %	95
Adaptability (Rating 1-10)	9
Real-Time Performance / s	2
Accuracy / %	98

The practical aspects of wireless networks are configured in different scenarios with sensor nodes and applied the WaHO algorithm for testing. The test bed results of different configuration with many interfered devices are shown in Tab. 2.

Table 2 Results of the WaHO algorithm for dynamic channel selection

Configuration	Channel	Throughput / Mbps	Delay / ms	Packet Loss / %
Config 1	RF Only	54.2	15.3	1.2
Config 1	VLC Only	112.5	8.1	0.5
Config 2	RF + VLC	78.9	12.0	0.9
Config 3	RF + VLC	85.7	10.2	0.8
Config 4	RF + VLC	92.3	9.5	0.6
Config 5	RF + VLC	97.4	8.7	0.4

Config 1 shows the performance of RF-only and VLC-only systems. VLC achieves higher throughput and lower delay compared to RF due to its high data rate capabilities and minimal interference.

Config 2 to **Config 5** illustrate various hybrid RF-VLC configurations optimized by the WaHO algorithm. As the configurations progress, there is an improvement in throughput and reduction in packet loss and delay, demonstrating the algorithm's effectiveness in optimizing channel selection.

The increasing trend in throughput and decreasing trends in delay and packet loss with different configurations highlight the algorithm's capacity to balance RF and VLC resources effectively. Table II summarizes the performance metrics obtained from running the WaHO algorithm for different configurations, showing how dynamic channel selection impacts the overall system performance. The hybrid architecture improves user density per cell by balancing the load between RF and VLC. It efficiently scales using RF macro cells and VLC femto cells, supporting over 1000 nodes with the help of decentralized network.

5 CONCLUSION

Through systematic experimentation and analysis this study sheds light on the multi-faceted utility of Radio Frequency Integrated Optical system. The RFiOS demonstrates significant advantages over standalone RF and VLC systems in various aspects including Bandwidth utilization, data transmission capability, Interference management and signal coverage. The results obtained using WaHO for switching between RF and VLC provided the enhanced network performance including higher throughput, improved energy efficiency, reduced congestion and better adaptability to dynamic conditions. However, these results are heavily dependent on the deployment environment and the effectiveness of hybrid infrastructure. By combining the strength of both RF and VLC technologies, the performance of RFiOS optimized the usual occurrence of interference with the accuracy of 98%. The computational complexity of the WaHO-based dynamic switching mechanism remains linear or near-linear in the number of agents and decision variables, ensuring low computational overhead while scaling to a large number of users. Integrating WaHO-based spectral switching within a hybrid RF-VLC system effectively mitigates interference and dynamically offloads traffic, ensuring robust and efficient spectral switching in dynamic environments, while VLC's natural compatibility with 6G THz networks (0.1-10 THz) enables ultra-high-speed, low-latency communication. For the real time implementation the challenges to be addressed are frequent handovers in a hybrid RF-VLC which may introduce the additional network latency. This can be structured with the proactive optimization algorithm scope.

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Contact information:

S. MYTHILI, Assistant Professor
(Corresponding Author)
Department of Electronics and Communication Engineering,
Bannari Amman Institute of Technology,
Erode, Tamil Nadu, India, 638 401
E-mail: mythilikarthikeyan911@gmail.com

M. KALAMANI, Professor
Department of Electronics and Communication Engineering,
KPR Institute of Engineering and Technology,
Coimbatore, Tamil Nadu, India, 641407
E-mail: kalamani.mece@gmail.com