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Location Aware Vertical Handover in a VLC/WLAN Hybrid Network

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ABSTRACT Visible light communication (VLC) has emerged as a promising technology for wireless communication as it offers higher data rates and secure data transmission along with providing indoor illumination. However, VLC is restricted by the line of sight (LoS) nature of the optical channel that consequently results in light path blockages. Therefore, an effective solution would be to combine VLC with a radio frequency (RF) system to form a hybrid VLC/RF network that would take into account the preferences of an end-user with the practicality of implementation. In such networks, an efficient vertical handover (VHO) technique is the most critical element as it ensures a seamless transition between the two networks. In this work, we propose a vertical handover technique that utilizes the user's location information to make a handover decision. We found that the frequency of light path blockages increases with the increasing number of users in a confined space, resulting in significant performance deterioration. This additional information is then utilized so that the VHO algorithm effectively selects the most feasible network. The proposed algorithm has been tested against the immediate vertical handover algorithm (I-VHO) and the dwell vertical handover algorithm (D-VHO) with two different dwell times. The average number of handovers, quality of experience (QoE), and packet loss have been set as performance metrics. We show from several simulation scenarios that the proposed method results in a fewer number of handovers while maintaining higher QoE and lower packet loss.

INDEX TERMS Handovers, indoor localization, optical communication, visible light communication, WLAN.

I. INTRODUCTION

Cisco's Visual Networking Index (VNI) predicts that by 2022, more web traffic will be generated across global networks than in all prior years combined up to the end of 2016 [1]; and it was noted that approximately 80% of the traffic will be generated in the indoor environments. This exponential rise in the demand for seamless mobile data connectivity is likely to exceed the available capacity in the coming years. Therefore, researchers all across the globe are trying to cater to this increasing traffic demand, specifically in indoor scenarios.

The RF-based wireless local area networks (WLANs) have gained massive popularity in the past years for indoor network connectivity. But as the demand for wireless connections rises, WLAN suffers from the limited spectrum and bandwidth shortage. Visible light communication has emerged as a strong candidate for wireless data transmission, which uses visible light to transmit data signals. The inherent advantages of VLC, such as higher capacity, larger bandwidth, higher security, etc. make them suitable for indoor applications. Along with these advantages, there are certain limitations imposed by VLC as well: VLC establishes a line of sight (LoS) link that is prone to disruptions due to environmental changes. Another challenge that VLC is facing is the limitation imposed by the size of the transmitter for uplink transmission.

An appropriate solution would then be to design a heterogeneous network embedded with the RF and VLC technologies where the two technologies would complement each other to give high quality of service (QoS). In such a hybrid wireless environment, a major challenge is to devise a vertical handover protocol that would provide ubiquitous connectivity by utilizing both RF and VLC networks.

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As previously mentioned VLC experiences intermittent link blockages, however, in an indoor scenario the immobile articles hardly contribute to link blockages because they are usually incurred by the random movement of active/inactive users, commonly known as shadowing [2]. The temporary link interruption does not generally require switching between different networks, however, if the frequency of these short-lived light-path blockages (LPBs) increases, the quality of communication significantly deteriorates. Additionally, the coverage area of VLC is smaller as compared to the coverage area of WLAN, and when the user walks out of the coverage area of the VLC AP the controller needs to handover the connection to WLAN and vice versa.

In this work, we set up a heterogeneous network comprising of VLC and WLAN access points. We observed that user mobility is highly relevant while making a handover decision. Based on this observation we proposed a location-aware vertical handover (LA-VHO) technique that is facilitated by an indoor localization algorithm to make the handover decision. Indoor localization is one of the most sought-after feature because it holds the capabilities to provide surveillance, navigation, and object tracking services. Global positioning system (GPS) has shown remarkable results for localization in the outdoors but it failed to supersede in the indoor environments due to the following reasons: firstly the signal power degrades as it interacts with obstacles in the indoor environment, and secondly, the accuracy of GPS in outdoor scenarios is 5m - 10m, which is further degraded in indoors resulting in poor localization. Recently, visible light positioning (VLP) has been getting attention as it features high positioning accuracy in an already existing infrastructure [3], [4]. There are many VLP algorithms proposed in the literature that have led to a rapid advancement in this area [5]–[9].

In this work, we utilized VLP to assist with the handover decision that would result in an increased performance while maintaining a lower number of handovers, which will be shown in the following sections. The main contributions of the work are summarized below:

- We performed a mathematical analysis to show the relationship between the blocking probability of an optical channel and an increasing number of users in an indoor scenario.
- Based on our analysis we devised a vertical handover technique that minimizes the number of handovers while maintaining an optimum QoE.
- We tested the proposed technique against the traditional VHO algorithms in two different indoor rooms: 5.6m × 5.6m × 3m and 8m × 8m × 3m with 4 and 9 overlapping VLC APs, respectively. Our results demonstrate that even in the worst-case scenarios the proposed technique outperforms the traditional algorithms.

II. RELATED WORKS

Vertical handover is the most critical element in a hybrid network, as it ensures continuous transmission. In this section, we present an overview of different vertical handover approaches that were previously investigated. Singhrova *et al.* proposed a multi-parameter-based vertical handover decision algorithm (VHDA), where they took inputs as fuzzy and employed neural networks for the training of decision vector [10]. Through simulations, they were able to demonstrate a decrease of vertical handovers by 16.5% as compared with those of the classic fuzzy methods. Reference [11] proposed an analytical Markov model that enhanced the modeling of vertical handover for integrated cellular/WLAN systems. The model prevents a handover hysteresis by differentiating requests originating in the cellular system and those being handed over from WLAN to the cellular system. Therefore once the calls are handed over from WLAN to cellular network, they are not allowed back to the WLAN which consequently resulted in an improved performance.

Liu *et al.* [12] introduced a QoE-driven VHO algorithm which was based on IEEE 802.21-Media Independent Handover (MIH). Their findings showed that compared to the bandwidth-based VHO algorithms, their algorithm made a rapid handover decision when the network condition deteriorated, and provided better QoE for video services. In [13] a vertical handover algorithm was investigated that made use of the potentiality of both hard and soft handovers, in a dual-mode configuration. They designed a system model through a multi-dimensional Markov chain by assuming a probabilistic approach as the handover decision metric and showed that soft VHO is preferred as compared to the traditional hard approach.

The aforementioned handover techniques are specific to the traditional RF/cellular integrated networks. Handovers in VLC, however, are considerably distinct as the directive nature of the optical channel limits the coverage area of a single VLC hotspot. Efforts have been made to devise algorithms that would allow smooth transitions in VLC/WLAN HetNets, some of which are discussed as follows: Wang *et al.* proposed a VHO scheme that aimed to reduce the switching cost without compromising system performance [14]. Their simulation results showed that they were able to achieve the same performance as that of I-VHO scheme while consuming approximately 50% of the VHO signaling cost. In [15] a dynamic scheme for the resource allocation problem of VLC/WLAN HetNets system is considered where they proposed a resource allocation algorithm in conjunction with optical power dynamic allocation. The goal of their proposed technique is to maximize best-effort service users' system throughput and individual fairness while guaranteeing the minimum rate requirement of delay-constrained service users. Their results showed improvement in the overall throughput of the system. Bao *et al.* proposed a hybrid VLC and orthogonal frequency division multiple access (OFDMA) network model and presented a protocol that combined with access, horizontal, and vertical handover mechanisms for a mobile terminal to resolve user mobility among different hot-spots and OFDMA systems. They were able to demonstrate significant improvements in the capacity performance

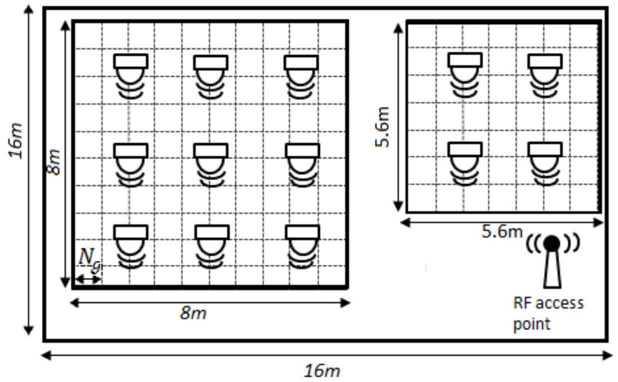

FIGURE 1. Layout of an indoor VWHnet.

of the hybrid system, rather than the OFDMA system [16]. Basnayaka *et al.* designed a VLC/RF hybrid system that dynamically assigned users to both VLC and RF systems depending on the user channel condition. They quantified the spectrum and power requirements for the RF system, whereas the VLC system resources were assumed to be fixed. Their results demonstrated that the hybrid network could achieve better per-user rate performance [17]. In [18] a mobility-aware load balancing (MALB) for hybrid RF/VLC system is considered in both single transmission (ST) and multiple transmission (MT) modes. In the ST mode, each user is served by only one access point. They formulated a joint optimization problem that balanced traffic loads between VLC and WLAN in the MT mode, where each user is simultaneously served by VLC and WLAN. Their results showed MALB-ST and MALB-MT could improve system throughput by up to 46% and 76%, respectively as compared to the traditional load balancing schemes. Another VHO scheme was proposed by [19] where the handover decision is made in order to enhance the QoE and reduce the handover cost of the user, by formulating the problem as a Markov decision process (MDP). They showed that their algorithm could achieve a relatively higher average QoE, lower handover failure probability, and fewer handovers when compared with the traditional handover schemes. It is well-known that the optical channel and the RF channel are fairly different from each other. Parameters, such as size of the indoor space, number of users and placement of furniture, etc, have a significant impact on the optical link as compared to the RF. The aforementioned studies aimed to establish a seamless wireless connection in a HetNet system by proposing VHO techniques that maximize the VLC network's usage and performance while minimizing handover costs. However, they do not address the major limiting factors of VLC i-e shadowing and light path blockages. The proposed VHO algorithm specifically addresses these two limitations of the optical channel which allows it to be easily incorporated in scenarios with recurring environmental variations; for example, in public spaces with varying user density, such as hospitals,

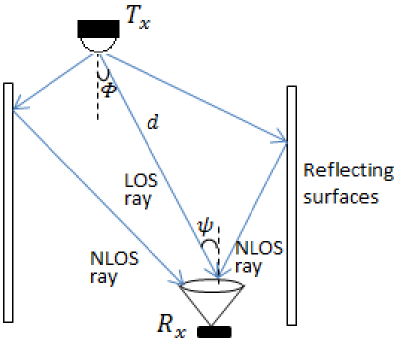

FIGURE 2. Geometry used for modeling the channel response.

libraries, shopping centers, etc. The details of the algorithm are presented in the subsequent sections.

III. SYSTEM MODEL

For this work, a 16m × 16m × 3m indoor environment layout has been considered and a VLC/WLAN hybrid network (VWHnet) has been created with a single 802.11ac WLAN access point (AP) and two separate rooms supported with multiple VLC access points, illustrated in Figure 1. The location of the WLAN AP is assumed to be stationary. Inorder to delve into the proposed algorithm, it is important to discuss the two channels that we would be dealing with, VLC channel and WLAN channel, the details of which are given in the following subsections.

A. VLC MODEL

For a VLC model two types of configurations are considered, a directed line of sight (LoS) and a non line of sight (nLOS) [20], [21], illustrated in Figure 2. The DC channel gain for the LoS configuration from AP to an end user is a straight line with low attenuation, and if the Euclidean distance between those two is denoted by d, the angles of irradiance and incidence are denoted by ϕ and ψ, respectively then the channel gain of the LoS path is expressed as:

$$H(0)_{LOS} = \frac{(m+1)A_r}{2\pi d^2} cos^m(\phi)O_g(\psi)cos(\psi) \tag{1}$$

where m is the order of Lambertian emission and is related to the LED semiangle at half-power $\Phi_{1,2}$ by $m = -ln2/(ln(cos\Phi_{1,2}))$, A_r is the active area of the photodetector, $g(\psi)$ is the optical concentrator gain and O_g is the optical filter gain. The received power then becomes:

$$P_{r_{LOS}} = H(0)_{LOS}P_t \tag{2}$$

where P_t is the transmitted power. We have only considered first reflections for the nLOS path as they have minor contributions in the indoor scenarios. The DC channel gain for the first reflection is then given as:

$$H(0)^{\alpha,u}_{nLOS} = \frac{I_o(\Phi_r)A_r}{(d_1 d_2)^2}\rho \quad dA_{wall} \\ \times cos(\alpha_{ir})cos(\beta_{ir})T_s(\psi))g(\psi)cos(\psi_r)$$

where $I_o(\Phi_r)$ is the transmitter radient intensity and is given as: ($\frac{(m+1)}{2\pi} cos^m(\Phi_r)$), the distance between the transmitter and reflection point is given as d_1 and the distance between the surface and photodiode is given as d_2. ρ is the reflectance factor, dA_{wall} is the reflective area of a portion of the region, the angle of irradiance to a reflective point is α_{ir} and the angle of irradiance to a receiver is β_{ir} and finally ψ_r is the angle of incidence from the reflective surface. The total received power of the VLC can then be defined as (3):

$$P_{VLCr} = (H(0)_{LOS} + H_{nLOS}(0)P_t \tag{3}$$

The signal to noise interference (SINR) can now finally be evaluated as:

$$SINR_V = \frac{R^2 P_{VLCr}}{\sigma^2_{shot} + \sigma^2_{thermal} + R^2 P^2_{rISI}} \tag{4}$$

R in eq. (4) is the photodetector's responsivity and σ^2_{shot} and $\sigma^2_{thermal}$ is the shot noise variance and thermal noise variance, respectively. And the P_{rISI} is the inter-symbol interference power of neighboring VLC access points.

B. WLAN MODEL

For the WLAN model, an 802.11ac access point is considered [22]. The received power (P_{wr}) from the AP to an end user, when they are d distance apart, is given as:

$$P_{wr}(d) = \mu_{RSS}(d) + S(\sigma, d) \tag{5}$$

Here $\mu_{RSS}(d)$ is the average received signal strength and is related to the path loss P_L(d) as $\mu_{RSS}(d) = \kappa - P_L(d)$, where κ includes transmitted power and transmitting/receiving antenna gain. $S(\sigma, d)$ represents shadowing effect, modelled as a Gaussian random variable with a standard deviation of σ_n.

Received signal strength (RSS) is the underlying factor that basically determines handover between the two different technologies. RSS in WLAN is the aggregation of two parts, depending on whether the end user is inside or outside the building. As we are only concerned with the indoor environment we focus on the indoor average signal strength, which is given as:

$$\mu_{RSS}(d) = C - 10 n_1 log_{10} d, d \in (0, d_d) \tag{6}$$

where $C = \kappa - 32.5 - log_{10} f$ (f is the operating frequency of the router) and d_d is the distance between the door and the router. The multipath propagation of a WLAN channel is found as:

$$H_{wlan} = \sqrt{\frac{K}{K+1}} e^{j\phi} + \sqrt{\frac{1}{K+1}} N_1 \tag{7}$$

K in equation (7) is the Ricean K-factor, ϕ is the angle of arrival and departure and N_1 is the Gaussian random variable with zero mean and unit variance. The WLAN channel gain can now be evaluated as:

$$G_{wlan} = \left|H^2_{wlan}\right| 10^{(P_{LF} d)/10} \tag{8}$$

where P_{LF} is the free space path loss. Now we can define the signal to noise ratio (SNR) of the WLAN link as follows:

$$SNR = \frac{G_{wlan} P_{wr}}{\omega_{wlan} B_{wlan}} \tag{9}$$

where ω_{wlan} is the power spectral density of noise at the end user and B_{wlan} is the bandwidth of the router.

IV. PROPOSED ALGORITHM

In this section we discuss the proposed algorithm in detail by considering an indoor scenario that is shown in Figure 1. The proposed algorithm is implemented by incorporating a location aware coordinator that connects all the access points with the internet using Ethernet wires or optical fibers. We start by exploring the effect of human traffic in indoor environments which is given in the following subsection:

A. LIGHT PATH BLOCKAGE

One significant difference between VLC and RF communications is that VLC waves have a shorter wavelength when compared with the size of a human body. Therefore, when VLC waves interact with a human body they cast a hard shadow (as photons cannot diffract nor do they penetrate a human body) resulting in a complete blockage of the signal. Suppose that a certain path (L) is established between the end-user and the transmitter. The probability that the path L would be blocked due to variations in the environment is termed as the blocking probability (P_b). The blocking probability of an end-to-end transmission link can be treated as a random variable X_E, where $E = 1, 2, ..L$ is the LOS and NLOS paths of photons. The blocking probability is then defined by setting the disjoint events of the photons arriving at the R_x via different paths to zero:

$$P_b = Pr[X_E = 0] \tag{10}$$

We model the human body as a cuboid object, same as [23], to calculate the number of blocked photons. The dimensions of the cuboid change according to the height and width of the human body. The Poisson process is used to represent the users, entering and leaving the room while being randomly distributed. In the 3-D reference system, the blocking probability is then calculated as:

$$P_b = \sum_{j=1}^{6} Pr[X_E = 0|b_j] \tag{11}$$

$$b_j = \begin{cases} 1 & \text{if } A_j \leq \alpha_j \\ 0 & \text{if } A_j > \alpha_j \end{cases} \quad \forall j = [1, 6] \tag{12}$$

$$A_j = A(P_{j,i}, F_{j1}, F_{j2}, F_{j3}, F_{j4}) \quad i = [1, 3] \quad j = [1, 6] \tag{13}$$

$$\alpha_j = A(F_{j1}, F_{j2}, F_{j3}, F_{j4}) \tag{14}$$

If a human body has six shadow surfaces, then $F_{j1}, F_{j2}, F_{j3}, F_{j4}$ are their four vertices. P_{ji} is the coordinate where photon path and human shadow surface interacts. A_j is the area of the pentagon that comprises the aforementioned vertices and the

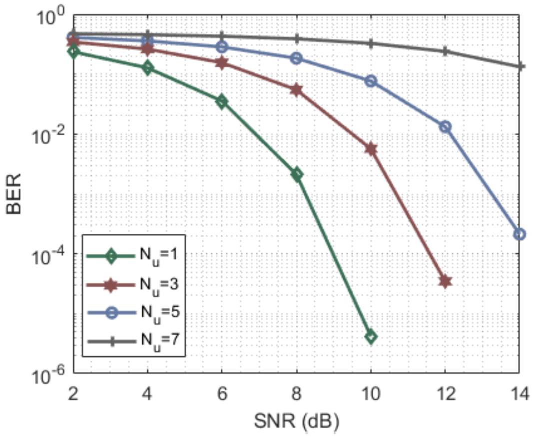

FIGURE 3. Performance of the system with varying N_u.

intersection point and α_j is the area of each of the six shadow surfaces.

For our study we have considered two rooms with VLC connections. The rooms have been partitioned into N_g grid points with equidistant lengths of 0.8m. The dimensions of the two rooms are 8m × 8m × 3m and 5.6m × 5.6m × 3m, with 100 and 49 gridpoints respectively. If N_u is the total number of active/nonactive users, then the blocking probability given in equation (11) becomes:

$$P_b = \sum_{j=1}^{6} Pr[X_E = 0|b_j]. \sum_{n=1}^{N_u} \frac{n}{N_g} \tag{15}$$

We simulated the aforementioned scenario in MATLAB to demonstrate the effect of shadowing on the VLC system's performance and its dependence on the number of users in an indoor environment. We setup a simulation environment that transmits a VLC waveform to an optical channel which is then detected at the receiver's end. We employed a direct current biased optical orthogonal frequency division multiplexing (DCO-OFDM) technique for the generation of VLC waveform, where the symbols were mapped to a 16-QAM constellation. 20MB data was transmitted and the SNR range is varied from 2dB to 14dB. In Figure 3 we present the performance of the system in terms of bit error rate (BER) as the number of people in the room (N_u) varies. It was found that as N_u increased from 1 to 7, the BER increased by 83.53%, averaged over all the signal to noise ratio (SNR) values.

B. COST FUNCTION BASED NETWORK SELECTION

The communication in a hybrid VLC/WLAN system can be defined as a state space given as follows:

$$S = \{(c, p, v), \quad c\epsilon C, \quad p\epsilon P, \quad v\epsilon V\} \tag{16}$$

where c is the condition of the VLC channel which can either be ON or OFF. The number of packets are shown as p of size P and v represents the mode of transmission which could either be 1, representing that the VLC is being used for data communication or 0, showing that WLAN is the preferred channel for data communication. Therefore at any given instant i, the state of the system can be expressed in terms of $i = \{c,p,v\}$.

The proposed network selection strategy suppresses multiple vertical handovers by defining function that divides the algorithm into two stages: in the first stage the end user is connected to either one of the technology based on the total number of end users in the indoor environment, where as in the second stage the end user selects the most suitable network depending on available bandwidth and SINR based on the cost function defined as:

$$c_h(i) = w_u.B(i) + w_s.R(i) \tag{17}$$

where $C_h(i)$ is the handover cost function at an instant i with weights w_u and w_s. In (17) the $B(i)$ represents the utilization of the network N_i at the time instant i such that $B(i) = b_{itotal}/b_{ia}$. Where b_{ia} is the available units of bandwidth at the network N_i and b_{itotal} is the total bandwidth. And the $S(i)$ in (17) is the inverse of the received signal strength of the network N_i. The weights w_u and w_s provide reference to $B(i)$ and $R(i)$ and are constrained as equation 18.

$$w_u + w_s = 1 \tag{18}$$

The algorithm is summarized as follows: first we have utilized an indoor localization algorithm to update the incriminating number of users. A threshold (ξ) is then set according to the minimum requirement of bit error rate. If the number of users (N_u) exceeds the set threshold then the WLAN is selected as the preferred network. If not, then the costs of the handovers is minimized to obtain the most suitable network for data communication. Q_{j-1} and Q_j are the average costs for iteration j-1 and j respectively. The weights are selected by minimizing the cost function. We have used gradient descend method to minimize Q_j. Gradient descend is one of the most popular optimization techniques that attempts to find a local minima of a function [24], [25]. The algorithm is repeated until the convergence criteria, given in line 14, is met.

Handover Algorithm

```
1. Input
2. S, $C_h$ and $N_u$.
3. Output
4. $Q_{j-1}, Q_j$
5. for each $i \epsilon S$ do
6. if $\sum_{k=1}^{N_u} \upsilon_k \geq \xi$ do
7. $a_j(i) = W$
8. else
9. $\delta = \infty$
10. while $\delta > e$
11. $Q_{j-1}(i) = w_u B(i) + w_s R(i)$
12. $Q_j(i) = argmin_{w_u,w_s} ||C_h(i) - Q_{j-1}(i)||_2$
13. end while
14. $\delta = ||Q_j(i) - Q_{j-1}(i)||$
15. $a_j(i) = Q_j(i)$
16. end for
17. end if
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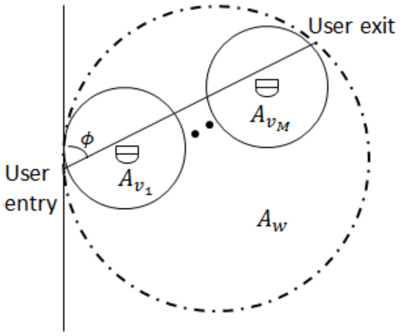


FIGURE 4. Illustration of VLC and WLAN cells as a user moves through the coverage areas.

V. THEORETICAL ANALYSIS

In this section we analyze the system's performance by theoretical models and mathematically derive the user's average dwell time (T_{AD}). Average dwell time is the average time a user stays in a particular cell and consequently stays connected to its respective AP. In this work, we have only considered vertical handovers and we attempted to account for the transition from VLC to RF and vice versa, therefore, the VLC coverage area is approximated as a single cell for evaluating T_{AD}.

We consider M VLC cells, each having an area A_v. The WLAN coverage area overlaps the VLC cells, with a total area of A_w, illustrated in Figure 4. We assume that when a user enters the VLC coverage area he proceeds to move along a straight line. In an indoor environment, the probability that a user would go through multiple turning points is rather unlikely, if not entirely implausible. For a larger M, the distance covered by the user is longer than the coverage area of an AP and hence users would go through several VLC APs until they turn. The given scenario is therefore a reasonable approximation for calculating T_{AD}.

We employ the fluid flow model [26] to obtain T_{AD}. The mobile users are assumed to be uniformly distributed throughout the area, and the end user can move in any direction with equal probability. Therefore the average outgoing rate of an area A_v is given as:

$$\mu_v = \frac{v l_v}{\pi A_v} \tag{19}$$

where A_v is the area of the VLC cells, l_v is the length of the perimeter of area A_v, and v is user's speed which would be measured by the indoor positioning systems. The radius of VLC cells is defined as R. In this case A_v is the area of the VLC cells given as:

$$A_v = \sum_{i=1}^{M} A_t \tag{20}$$

where,

$$A_t = \pi R_i^2$$

Similarly the perimeter of the VLC cells is given as:

$$l_v = \sum_{i=1}^{M} l_t \tag{21}$$

where,

$$l_t = 2\pi R_i$$

Thus, the T_{AD} has an expected value of μ_v, which can readily be obtained as:

$$T_{AD} = \frac{1}{\mu_v} \tag{22}$$

For M APs, T_{AD} simplifies to:

$$T_{AD} = \frac{\pi}{2v} \sum_{i=1}^{M} R_i \tag{23}$$

VI. SIMULATION RESULTS

In this section, we present the results of MATLAB simulations that are implemented to evaluate the performance of the proposed methods. Three baselines are considered: I-VHO and D-VHO with two different dwell times. We use the average quality of experience (QoE), average packet loss rate, and average handover rate as performance metrics. The simulation scenario is set up in a 16m × 16m × 3m building and VLC connections are available in two rooms with dimensions: 5.6m × 5.6m × 3m and 8m × 8m × 3m with 4 and 9 overlapping VLC APs, respectively. Each VLC hotspot has a coverage radius of 1.5m. The overlapping areas of VLC cells are regarded as out-of-VLC coverage due to the signal degradation caused by interference of existing optical signals. The coverage area of the RF AP covers the entire area of the building and can be accessed anywhere in the building. For an accurate and successful implementation of LA-VHO, real-time knowledge of the terminal location is mandatory. For this purpose, we have employed an indoor visible light communication localization system given in [27] to get terminal locations. Initially, a UE is connected via VLC and it undergoes random movement in a uniform random direction within 0 and 2π radians. The velocity of UE is obtained from the localization algorithm, which ranges from 0.2m/s to 1m/s [28]. As the end user moves around, it passes through regions of VLC and RF coverage areas. The simulation parameters are presented in Table 1. LA-VHO scheme is compared with the immediate and dwell-based vertical handover schemes [14]. In I-VHO, a vertical handover from VLC to RF is initiated whenever the VLC link is not strong enough to establish a connection. As soon as the VLC link is resumed, the controller performs a handover from RF to VLC. In the case of dwell-VHO, the controller waits for a specific period of time t_o before VHO decision. To make a fair comparison, we have used the same dwell times as of [29], i-e 0.5s and 1s. When the dwell time expires, the controller handovers the transmission mode to RF if the optical link is still blocked; otherwise, the transmission mode remains VLC.

TABLE 1. **Parameters used for the simulation and testing of LA-VHO algorithm.**

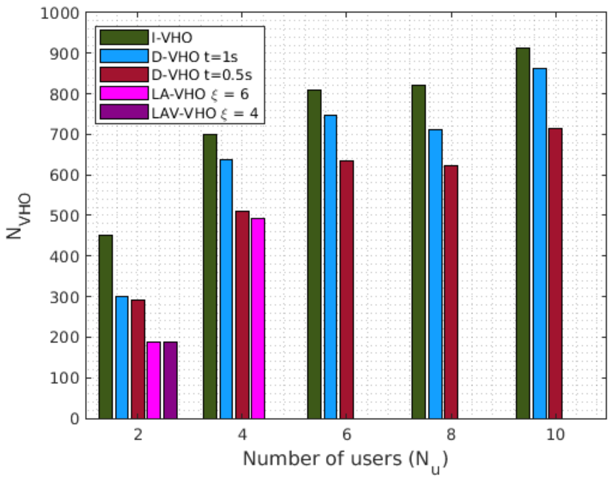
Parameter	Value
Room dimensions	5.6m x 5.6m x 3m, 8m x 8m x 3m
Number of VLC APs	4, 9
VLC coverage diameter	3m
User velocity	0.2m/s - 1m/s
LEDs semi angle at half power $\Phi_{1,2}$	60^o
Active area of the photodector A_r	10^{-4}
Gain of the optical filter O_g	1
Optical concentrator gain $g(\psi)$	1.5
User direction	0 - 2π
Number of users N_u	1 - 10 UEs
Dwell time t	05s, 1s
Total simulation time	2100s, 3800s
Total number of iterations N_i	1500

Akin to I-VHO, the controller switches from RF mode to VLC mode as soon as the optical link is revived.

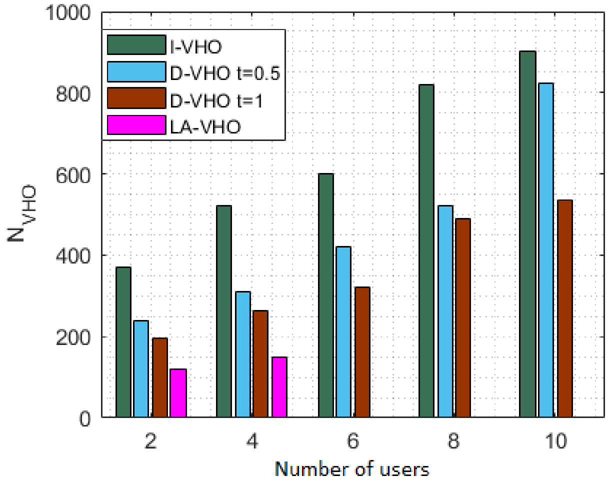
A. AVERAGE NUMBER OF HANDOVERS

We evaluate the average number of handovers (N_{VHO}), which is defined as the number of handovers averaged over the total number of iterations. It was discussed in the previous section that as N_u increases, the probability of VLC link blockage also rises, this effect is particularly prominent in smaller indoor spaces.

In the immediate vertical handover (I-VHO) scheme, a UE will immediately handover to WLAN when the optical link is blocked, which results in a significant rise in the N_{VHO} as the number of UEs increases. Therefore, I-VHO performs the worst in all scenarios. In the case of the smaller room with 4 VLC APs, when $N_u = 2$ D-VHO outperforms I-VHO by 33.3% and 36.8% for $t = 0.5s$ and $t = 1s$, respectively. The proposed technique outperforms I-VHO by 58.44%. However, when $N_u = 10$ the performance of D-VHO ($t = 0.5s$) is merely 6% better than I-VHO in contrast to D-VHO ($t = 1s$) which outperforms I-VHO by 21.7%. In the case of LA-VHO, when the number of users exceeds the set threshold it restricts users to WLAN only, therefore, N_{VHO} diminishes to zero and results in outperforming all the other handover techniques, as shown in Figure 5 (a).The same pattern is observed for the bigger room with 9 VLC APs, which is presented in Figure 5 (b). It was found that when $N_u = 2$, the dwell handover performs 35.14% and 47.03% better than I-VHO when $t = 0.5s$ and $t = 1s$, respectively; whereas the proposed method outperforms I-VHO by 67.57%. As N_u becomes ten, the performance of D-VHO is merely 19.89% and 29.33% better than I-VHO for $t = 0.5s$ and $t = 1s$, respectively. LA-VHO restricts users to be connected via WLAN and limits further handovers as long as N_u remains higher than the set threshold, consequently resulting in outperforming all the traditional algorithms. It was observed that LA-VHO resulted in 79% more handovers in the smaller room as compared to the bigger room when the same threshold criteria was used. In the same scenario, when the threshold was changed from $\xi = 6$ to $\xi = 4$ we see a significant decrease in N_{VHO}. Hence, the flexibility in the LA-VHO algorithm would allow implementing the technique according to the specifications of any indoor space.



(a) 4 VLC APs.



(b) 9 VLC APs

FIGURE 5. **Average number of handovers for different VHO schemes, as the number of UEs increases.**

B. QoE COMPARISON

Quality of experience (QoE) is a non-trivial performance metric as it describes the overall network performance from the user's perspective. When the VLC link is interrupted in a VLC/WLAN HetNet, the user experiences a serious QoE degradation. Therefore, the handover technique must minimize signal and delay costs to maximize the QoE. To estimate the average QoE, we determine whether the mobile terminal is transmitting via VLC or RF. The average QoE is then calculated as [19]:

$$A_{Q_e} = \frac{\sum_{r=1}^{N_i} \sum_{c=1}^{N_{c(r)}} [Q_e(c, r) \times T_{AD}(r)] - d_c}{\sum_{r=1}^{N_i} T_i(r)} \tag{24}$$

where A_{Q_e} is the average QoE for a particular VHO scheme, $Q_e(c, r)$ is the QoE during the c^{th} connection of iteration r, d_c is the delay cost of a VHO to establish the c^{th} connection. $T_{AD}(r)$ is the dwell time of the c^{th} connection in iteration r, the total number of connections in iteration r is given as $N_c(r)$ whereas $T_i(r)$ is the total time duration of iteration r, and N_i is the number of total iterations, which is 1500 in our case.

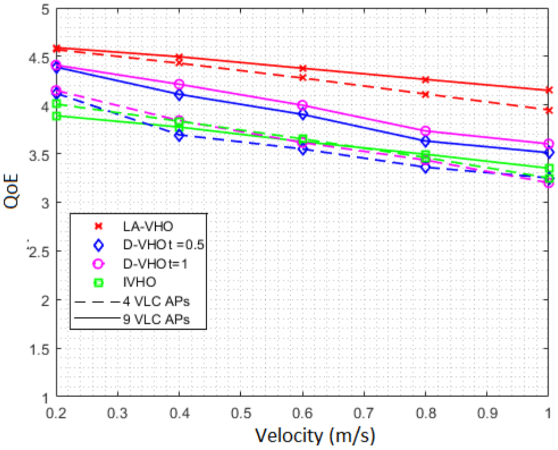
We evaluate how the number of users and a user's velocity impact QoE. It was observed that as the UE's velocity increases, he entered and exited the VLC'c coverage area rather frequently, therefore the average dwell time of a UE decreases which consequently resulted in a decrease of QoE. Among all handover techniques, I-VHO had the worst QoE performance this is because a handover is initiated as soon as the VLC link is blocked that eventually led to an undesirable ping-pong effect. The performance of D-VHO was slightly better than I-VHO, as it waits for the connection to be re-established, before handing it over to the available channels, which suppresses excessive handoffs. The performance of the proposed technique also degrades as the user's speed increases, this is because of the localization error incurred when the UE is moving too fast. However, the LA-VHO outperforms all other techniques as it has minimum delay cost; thereby resulting in an improved QoE, as shown in Figure 6 (a). We observed that the performance of the handover techniques in both rooms was almost the same, which makes sense because QoE remains unaffected by the number of VLC APs, regardless of how fast or slow the end user is moving.

We also evaluated QoE against the number of UEs. The increasing number of users increases the probability of light path blockages which in turn results in a higher number of handovers in the case of I-VHO and D-VHO. Meanwhile, in the case of LA-VHO, as N_u increases, the QoE first decreases and then starts to increase, since this method restricts users to be connected to WLAN, after N_u increases the threshold, also shown in Figure 6 (b). On average, for 9 VLC APs, QoE achieved by LA-VHO is 10.13%, 11.65% and 13.46% better than D-VHO ($t = 0.5s$), D-VHO ($t = 1s$) and I-VHO respectively.

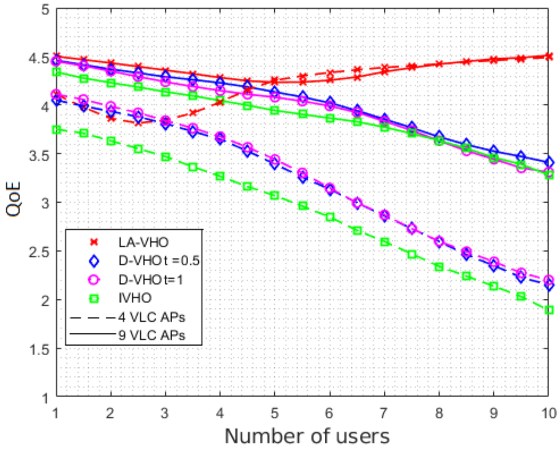
We observed that for a given N_u, a user experiences the worst QoE in the smaller room as compared to the bigger room. This is evident from equation (15) as well, since there is an inverse relationship between P_b and N_g. In this case, on average LA-VHO achieved 38.82%, 37.78%, and 52.77% better QoE performance as compared to D-VHO ($t = 0.5s$), D-VHO ($t = 1s$), and I-VHO respectively.

C. PACKET LOSS

We also evaluate the proposed method by comparing packet loss of different handover schemes; which is defined as the ratio of the number of dropped packets to the total number of sent packets. The impact of end user's velocity and the number of users in the indoor space on the packet loss is evaluated. We observed that the handover techniques behaved the same way in both rooms. The increase in velocity results in an increased frequency of VLC channel fluctuations. I-VHO exhibits minimum packet loss, as it initiates a handover immediately the optical link is blocked, ultimately resulting in fewer packet losses. The D-VHO, on the other hand performs inadequately and the performance is highly dependant on the dwell time; when the optical link is blocked the controller waits for a particular amount of time before initiating handover which resulted in higher packet loss. The performance of LA-VHO is almost the same as that of I-VHO, on average 11.31% and 9.45% improvement was noted in the case of 4 VLC APs and 9 VLC APs, respectively, which is also shown in Figure 7 (a).



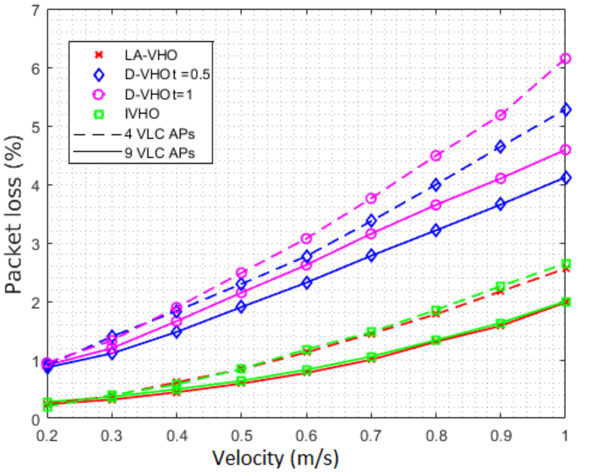
(a) The impact of UE's speed v on average QoE performance.



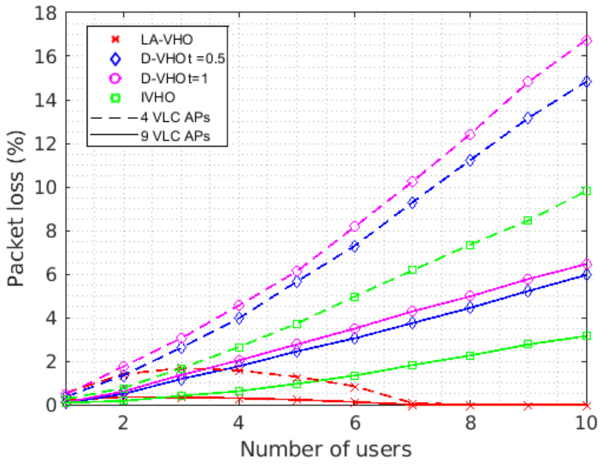
(b) The impact of number of users N on average QoE performance.

FIGURE 6. A comparison of different handover techniques with QoE as a performance metric.

Additionally, we investigated the impact of number of users on average packet loss, and observed that as N_u increases, the increase in optical path blockage resulted in higher packet loss, particularly in the case of D-VHO. LA-VHO outperforms all other techniques as it relies on the RF network when N_u becomes greater than the set threshold, thereby resulting in a drastic decrease of packet loss,



(a) The impact of UE's speed on average packet loss.



(b) The impact of number of users on average packet loss.

FIGURE 7. **A comparison of different handover techniques with packet loss as a performance metric.**

given in Figure 7 (b). In the smaller room with 4 VLC APs, LA-VHO performs 76.12% better than I-VHO, where as in room with 9 VLC APs LA-VHO results in 25.05% less packet loss as compared to the I-VHO. The significant difference in the former case can be explained by equation (15), where larger N_u resulted in an increased number of optical link blockages that prompted the coordinator to switch from VLC to WLAN and back to VLC leading to higher loss of packets when traditional VHO algorithms are employed.

VII. CONCLUSION

In this work, we have proposed a methodology that would allow VLC technology to seamlessly merge with the current infrastructure by forming a hybrid network (VWHnet) by proposing a location aware vertical handover technique. We tested the proposed technique in two different scenarios: 8m × 8m × 3m room with 9 overlapping VLC APs and 5.6m × 5.6m × 3m room with 4 overlapping VLC APs. Our simulation results highlight how different parameters effect an optical channel and we observed a remarkable improvement in the overall network performance when the proposed technique was implemented as compared to the traditional VHO techniques. The flexibility in the design of the proposed algorithm would allow it to be effectively implemented in indoor public areas with fluctuating user densities, such as museums, libraries, recreational spaces, etc. Therefore, in futuristic networks, VLC would become a smart location-based value-added service with higher data rates and enhanced performance.

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