Algorithmic and System Approaches for a Stable LiFi-RF HetNet Under Transient Channel Conditions

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***Abstract*—A LiFi-RF heterogeneous network can provide additional capacity to standalone wireless technologies due to their non-interfering nature. However, due to the properties of the short-range LiFi channel, the network is prone to transient channel variations that result in frequent, unnecessary handovers. This handover process creates an overhead and can result in the loss of connection. To ensure a stable connection for all users, a low complexity resource allocation algorithm, that considers the loss due to handovers, is proposed to minimize the number of handovers. This algorithmic approach is evaluated with simulations. For scenarios with unavoidable handovers, a system approach to manage vertical handovers is proposed to minimize the vertical handoff overhead and to offer a seamless interface switch, thereby resulting in a stable network. This protocol is implemented in hardware and the results show a negligible overhead.**

***Index Terms*—LiFi, stability, HetNet, hardware measurement, vertical handover**

I. INTRODUCTION

The global data transmission is expected to increase at the rate of 50%, annually, in the next 15 years [1]. This results in a demand on the network to provide high capacity per user. To satisfy this growing demand, the trend is to move to Light-Fidelity (LiFi), operating on the visible light and infra-red spectrum having a spectrum size 2600 times that of the Radio Frequency (RF) spectrum [2]. Since a LiFi system does not interfere with existing RF systems, a LiFi-RF Heterogeneous Network (HetNet) can provide an aggregate capacity greater than the standalone technologies. But this short-range, ultra-dense LiFi network induces frequent horizontal and vertical handoffs for mobile users. Such frequent handoffs increase the probability of link failure and may cause packet losses and delays, which result in poor user experience. During a handoff procedure, the users exchange signaling information with a central controller. This is termed as the handoff overhead and results in a disruption of data communication especially, during a vertical handover where the wireless interface has to be switched. There has been a significant amount of research that analyzes the impact of handoffs on RF HetNets. A survey [3] was carried out to compare the available load balancing schemes that consider the impact of handoffs in a heterogeneous LTE network. However, the handoff process in a LiFi-RF HetNet differs from a pure RF HetNet in that the handoffs are not only caused by mobile users but also due to Line of Sight (LOS) blockages and receiver orientation changes. Due to rapid link changes caused by transient blockages or changes in user device orientation, frequent unnecessary handoffs would be prompted. The effect of random receiver orientation on the handoff performance of a LiFi-RF HetNet was analyzed in [4]. These unnecessary handoffs affect the stability of the system. Hence, in this work, we propose approaches to provide a stable LiFi-RF HetNet that offer link stability in the presence of transient channel changes.

A. Related Work

In [5], the authors use the users' trajectory information to skip unnecessary handoffs along the trajectory. They, however, do not consider using this information to skip handoffs of the stationary users that are affected by transient blockages. There is also a body of work that focuses on designing load balancing algorithms that consider handoffs like in [6], where the algorithm performs Access Point (AP) assignment and resource allocation maximizing the sum throughput of the network, considering the data rate loss due to handoffs. This algorithm has the disadvantage of high computational complexity and is assumed to be performed in a central controller. To reduce processing overhead, a heuristic algorithm for load balancing based on evolutionary game theory was introduced in [7]. This algorithm analyzes the effect of light path blockages but does not incorporate it in the algorithm. The authors in [8], propose a low complexity fuzzy logic-based scheme to handle AP allocation considering handoffs. They, however, do not optimize the wireless resource allocation.

In the presence of mobile users, handoffs cannot always be avoided. Therefore, methods have to be developed to minimize the overhead while performing handoffs, to ensure the stability of the system. The authors, in [9] and [10], propose soft handover methods that reduce the overhead in horizontal handoffs between LiFi APs. However, vertical handovers are not considered. Vertical handoffs incur a larger overhead due to the wireless interface switch that has to be performed [11].

B. Contribution

In this paper, we propose methods to ensure a stable LiFi-RF network in the presence of transient channel conditions caused by light path blockages, instantaneous receiver orientation changes, and mobility. We propose a low-complexity, iterative, game theory-based algorithm that performs AP allocation and wireless resource allocation, taking into consideration the loss of stability due to handoffs. This algorithm can be performed in a centralized controller or in a distributed manner in systems where the two wireless technologies have different operators. We evaluate this algorithm under different transient channel conditions using extensive simulations. Additionally, we propose a system approach to handle unavoidable vertical handoffs to provide a seamless interface switch. This approach has been implemented on hardware in a LiFi-WiFi HetNet setup and evaluated with measurements.

C. Organization

The rest of the paper is organized as follows. Section II introduces the system model considered in this paper. The algorithmic approach is given and evaluated in Section III. Section IV provides the system approach and its evaluations and Section V concludes the paper.

II. SYSTEM MODEL

A. Network Architecture

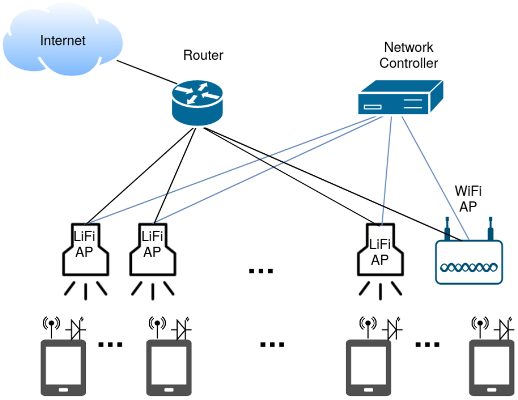

Fig. 1: Centralized architecture of a LiFi-RF HetNet

In this paper, we consider an indoor heterogeneous LiFi-WiFi network architecture with N_l LiFi APs and N_r WiFi APs as represented in Fig. 1. The LiFi APs are Light Emitting Diodes (LEDs) mounted at a certain height above the user plane and facing downwards. All LiFi APs operate at the same frequency which results in users in the overlapping area, experiencing co-channel interference. The set of all LiFi APs is represented by C_L. The WiFi APs are located at the same height as the LiFi APs. The set of all WiFi APs is represented by C_R. In this paper, we only consider a single RF AP but when more RF APs are considered, inter-cell interference exists. To avoid this, different RF APs can be assumed to operate on different non-overlapping frequency channels. There are a total of N_u users in the system and they are equipped with LiFi photodiode receivers and WiFi receivers. But each user can be served by only one AP at a given time. Both LiFi and WiFi APs use a TDMA system to serve multiple users. All LiFi and WiFi APs are connected to a central network controller, through a link, which is assumed to provide error-free communication with a negligible delay. The controller collects wireless channel state information of all users in the network and has an overview of the load on each AP. The channel state information for both LiFi and WiFi links is assumed to be constant for a short duration called a state. Since the controller has global information, it can run a centralized resource allocation algorithm and communicate its decision to the users. The algorithm is repeated at regular intervals since the channel state information is assumed to fluctuate from state to state. The time interval between two consecutive states is denoted by T_s.

B. Channel Models

The channel model for LiFi and WiFi are the same as described in [7]. For the sake of brevity, the models are not detailed here.

C. Blockage Model

The signal from LiFi APs can easily be blocked by opaque objects. Therefore, it is important to consider the blockage of light when modeling a realistic system. In this paper, we model the occurrence of blockages using a Bernoulli distribution. The probability that a user μ is blocked in a state is given by,

$$Pr_\mu = \begin{cases} p, \mu \text{ blocked}, \\ 1-p, \mu \text{ not blocked}, \end{cases} \tag{1}$$

where p is user's blocking probability. This model is apt for modelling transient blockages. In addition, a second method is proposed to model correlated blockages. In this model, it is assumed that a user blocked in the previous time step is more likely to be blocked in the current time step. The blocking probability of user μ is given by,

$$Pr_\mu^t = \begin{cases} \Pr[\mu \text{ blocked at time } t \,|\, \mu \text{ not blocked at time } t-1] = q \\ \Pr[\mu \text{ blocked at time } t \,|\, \mu \text{ blocked at time } t-1] = p \end{cases} \tag{2}$$

where $p > q$.

D. Network Topology

In this paper, an aircraft cabin topology and an indoor conference room topology are considered, as these are typical application areas of a LiFi-RF HetNet. The indoor conference room topology comprises a lattice LiFi AP placement, with one WiFi AP in the center of the room and randomly positioned mobile users. The area of the room is 6x6 m^2. A medium-sized aircraft topology is also used for simulations, e.g. Boeing 737. The dimensions are as given in [12]. LiFi APs are assumed to be integrated into the reading light in the middle of each row on the left and right side of the aisle. One WiFi AP is positioned at the same height as the LiFi AP.

III. ALGORITHMIC APPROACH

In this section, the proposed algorithmic approach to resource allocation that considers the handoff overhead, for the goal of providing a stable connection, is detailed and extensively evaluated with simulations. The proposed algorithm is based on Evolutionary Game Theory (EGT) and is similar in approach to the algorithm in [7] but with a different goal of providing stability under transient channel changes. EGT is especially well-suited for resource allocation tasks since it models the user behavior into a game where the users compete for shared resources. An evolutionary equilibrium is reached upon the convergence of the algorithm, where the users reach stable status [13]. Evolutionary games are well suitable for being implemented in a distributed fashion. With minimum signaling, this can be achieved in a client-driven system. However, in this paper, we consider this algorithm running at the central controller. In this way, the controller has global knowledge of the network and communicates its decision to the users after convergence of the algorithm.

A. Algorithm Setup

The Evolutionary game theory-based algorithm is performed to allocate the users to the APs. The algorithm has the following components.

- *Players:* The users in the network are called players.
- *Population:* Every user is assigned to an AP. Population U_α is the set of users allocated to the same AP denoted as α. The number of users assigned to the same AP α is given by N_α.
- *Strategy:* A player can select the LiFi or WiFi AP that can serve this player.
- *Payoff:* In EGT, players adapt their strategy at each iteration with the goal of improving their payoff. So the payoff has to be designed to achieve the goal of minimizing handoff delays while maximizing user throughput or data rate. Therefore, the payoff function is the user throughput weighted by a function of the loss incurred due to horizontal handoffs or interface switches (vertical handoffs). The weighted throughput payoff function is defined as,

$$F_{\mu,\alpha} = y_{\mu,\alpha} R_{\mu,\alpha} w_{\alpha',\alpha} \tag{3}$$

where $y_{\mu,\alpha}$ is the proportion of time resources assigned to user μ by AP α, $R_{\mu,\alpha}$ is the achievable link data rate between user μ and AP α; $w_{\alpha',\alpha}$ is the weighting factor when moving user connection from α' to α; The weighting factor is defined as a function of the delay incurred due to AP switches. Specifically, $w_{\alpha',\alpha}$ can be defined as,

$$w_{\alpha',\alpha} = \begin{cases} 1 - \frac{T_{\text{loss}}}{T_s}, & \alpha \neq \alpha' \\ 1, & \text{otherwise.} \end{cases} \tag{4}$$

where T_{loss} is the time loss incurred due to performing the handoff procedure, and T_s is the time intervals between states. This implies, that the weighting factor decreases as time loss increases. So, the allocation that results in an AP switch will have a lower weight and will be avoided when maximizing the payoff function.

B. Access Point Association and Resource Allocation

With the game set up as mentioned before, the algorithm is now run to find the AP association that maximizes the payoff for all users. The user adapts its strategy of AP association by using the average payoff of players connected to the same AP and global average payoff of all players as input. The average payoff of players in the ith iteration served by AP α is,

$$\bar{F_\alpha}^{i} = \frac{1}{N_\alpha} \sum_{\mu \in U_\alpha} F^i_{\mu,\alpha}, \tag{5}$$

where $F^i_{\mu,\alpha}$ is the payoff of user μ that is connected to the AP α. The global average payoff is,

$$\bar{F}^i = \frac{1}{N_u} \sum_{\alpha \in C_L \cup C_R} N_\alpha \bar{F_\alpha}^{i}. \tag{6}$$

A user is more likely to switch its association to another AP (mutate) if it has lower payoff values compared to the global average. This switching probability is calculated as,

$$p^i_{\mu,\alpha} = \begin{cases} 1 - \frac{F_{\mu,\alpha}{}^{(i-1)}}{\bar{F}^{(i-1)}}, & F^{(i-1)}_{\mu,\alpha} < \bar{F}^{(i-1)} \\ 0, & \text{otherwise.} \end{cases} \tag{7}$$

After the AP selection has been performed, the AP then allocates wireless resources to the users according to the proportional fairness rule. For a fixed AP assignment, the optimal resource proportion $y_{\mu,\alpha}$ for a user μ associated to AP α, considering proportional fairness, has been proved in [14] to be,

$$y_{\mu,\alpha} = \frac{1}{N_\alpha} \tag{8}$$

This implies that users are served in a proportionally fair manner when they equally share the resources of the Access point that they are connected to.

C. Algorithm Implementation

The algorithm is summarized in Alg. 1. The controller collects the wireless channel statistics from the users. This is assumed to be constant within one state. Initially, the users are allocated randomly to APs. In each iteration, the user selects a new AP with the probability given in Eq. 7. The larger the difference between the user's payoff and the global average, the more likely the user is to switch APs. Once the AP is selected, the wireless resources are allocated according to Eq. 8. The algorithm is then repeated for multiple iterations until convergence. In this state, no user can increase its payoff without decreasing another user's payoff. This algorithm can be carried out entirely at the controller and the final decision after convergence can be communicated back to the network. The algorithm is then repeated for multiple iterations until convergence. The algorithm converges when no users switch their access points anymore i.e. the evolutionary equilibrium is achieved. The complexity of the algorithm is proportional to the product of the total number of users and APs. The

Algorithm 1 Handoff-Aware Game Theory-Based Algorithm for Access Point and Resource Allocation

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The users report their channel statistics to the controller.
Initialization: $i = 0$. A random AP $\alpha$ is assigned to user $\mu$. Each AP allocates equal time resources to the connected users. The controller calculates average payoff $\bar{F}^0_{\mu,\alpha}$ for each user $\mu$ as in Eq. (5) and the global average payoff $\bar{F}^0$ as in Eq. (6).
repeat
    for each user $\mu$ do
        The controller calculates the AP switching probability $p^i_{\mu,\alpha}$ as in Eq. (7).
        With this probability the user $\mu$ is assigned to the AP that offers the maximum payoff $F_{\mu,\alpha}$.
    end for
    for each each AP $\alpha$ do
        Allocate the wireless resource for each user as $y_{\mu,\alpha} = \frac{1}{N_\alpha}$. The controller stores the number of users that are connected to each AP as $N_\alpha$.
    end for
    $i \longleftarrow i + 1$
until no user $\mu$ changes strategy
The controller communicates the user to AP association to the APs and the APs perform the re-association.
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complexity is given as, $O(N_u(N_L + N_R)I)$. Here, I is the number of iterations until convergence. The algorithm has a fast convergence as can be observed in Fig. 2. This is the result of 500 repetitions and it can be observed that the payoff function converges before the 15th iteration.

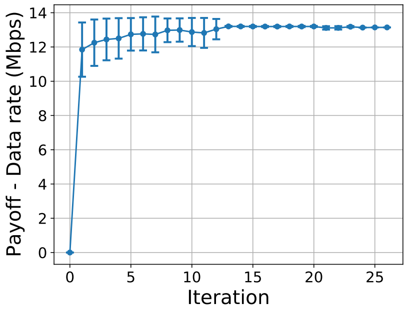


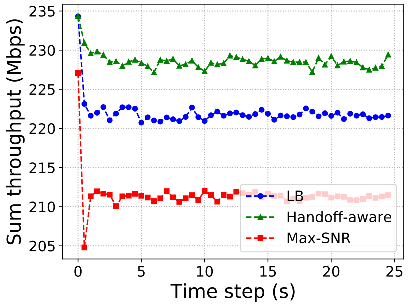
Fig. 2: Algorithm convergence

D. Numerical Simulations

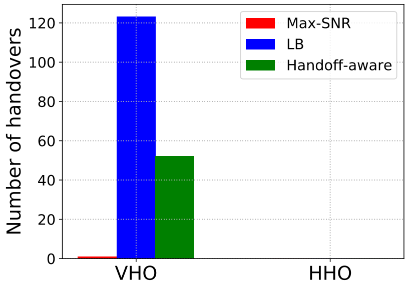
The algorithm has been evaluated with extensive simulations (source code at https://gitlab.com/lifi-network-management/stability-aware-lifi) and a selection of the results are presented. The simulations are performed for the aircraft and conference room scenarios for different blockage models, receiver orientations and user speeds. Influence of user mobility is studied only for the room topology. Random Way Point (RWP) mobility model is widely used in research [15] and is well suited for this scenario with slow moving users. The blockage model with no block is named as Model0, the correlated blockage defined by Eq. (2) as Model1 and the transient blockage defined by Eq. (1) as Model2. The results are compared with the maximum downlink SNR (Max-SNR) allocation because currently existing devices use this strategy. For a fairer comparison, we also include our algorithmic approach without considering the loss function. So we compare our algorithm (handoff-aware) with the algorithm with $w_{\alpha',\alpha} = 1$ in Eq. (3). We call this the Load Balancing (LB) algorithm. The simulation parameters are summarized in Table I. The Fig. 3a shows the sum throughput of all users over time for the conference room topology when the blocking model is Model2 with a probability of 0.05. This shows a network with transient blockages. Under these conditions we see that our algorithm outperforms the other

TABLE I: Simulation Parameters

Parameter	**Abbreviation**	**Value**
Optical power of a LiFi AP	P_{opt}	1 W
Half power beam width	$\theta_{1/2}$	60°
Physical area of received PD	A_p	$10^{-4}m^2$
FoV of the receiver	FoV	60°
Noise spectral density of LiFi links	N_L	$10^{-21}\ A^2/Hz$
WiFi AP transmit power	P_R	20 dBm
Noise power of RF	σ	-57 dBm
Time of interest	T_S	500 ms
Loss due to horizontal handover	T_{loss}	200 ms
Loss due to vertical handover	T_{loss}	300 ms

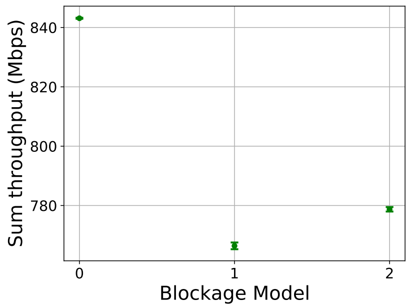


(a) Sum throughput over time

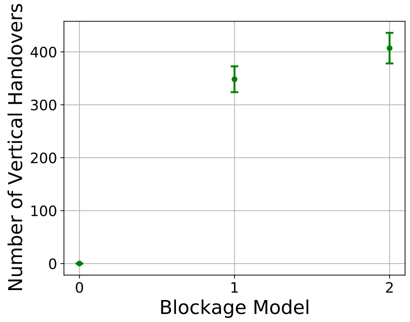


(b) Number of horizontal and vertical handovers

Fig. 3: Comparison of results for conference room topology with 24 users, receiver elevation 0° with Model2 blockage

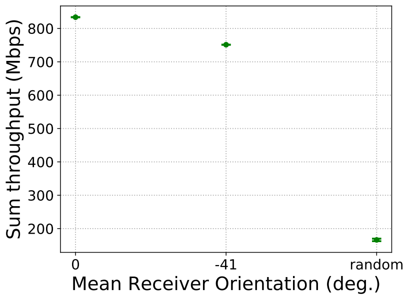


(a) Sum throughput

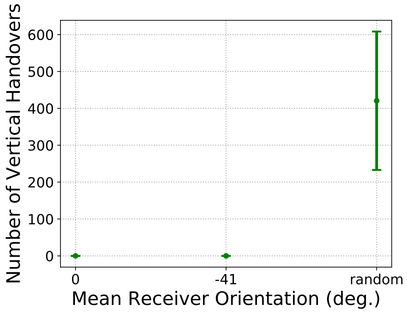


(b) Number of vertical handovers

Fig. 4: Comparison of results for aircraft topology with 9 rows, receiver elevation of 0° for varying blockage models



(a) Sum throughput



(b) Number of vertical handovers

Fig. 5: Comparison of results for aircraft topology with 9 rows, Model0 block and receiver elevation of 0°, $-41^\circ \pm 10^\circ$, and random orientations

two. This is due to the significant reduction in number of vertical handovers as seen in Fig. 3b. Although the Max-SNR performs much less handovers, this results in a significant loss in throughput. We then evaluate the effect of different parameters on the performance of the system.

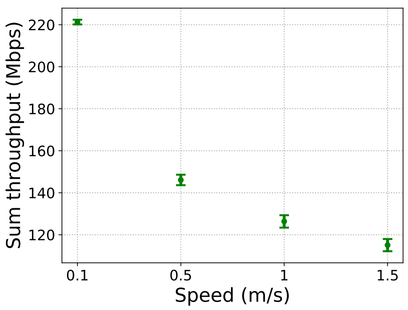
1) Varying Blockages: Fig. 4 shows the effect of varying blockage models on the mean sum throughput and number of vertical handoffs for an aircraft topology. The blocking probability for the transient blockage model is set to be 0.1 and the probabilities for the correlated blockage model are 0.1 and 0.7 where 0.7 is the probability that the light path is blocked in the current time step given that it was blocked in the previous time step. We observe that the number of handoffs increases when the light path is blocked. The number of handoffs for the correlated blockage model is lower than for transient blockage since the user is forced to switch to WiFi if the light path is blocked for multiple time steps. In this case the sum throughput is also lowered because the user is forced to stay connected to the access point offering a worse data rate.

2) Varying Orientations: Fig. 5 shows the effect of varying receiver elevations. The elevation of -41° is the typical elevation of a handheld device [16]. We see that ± 10° variation does not impact the handover situation. But we observe that for random receiver orientations the sum throughput drops drastically. This is because in most cases the LOS path is out of the Field of View (FOV) of the receiver.

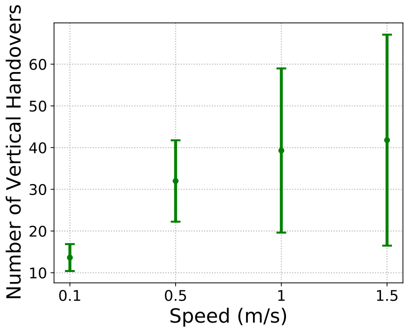
3) Varying Speeds: Fig. 6 shows the effect of varying user speeds. We see that the number of handoffs increases with speed and the number of handoffs are large. In cases like these, the handoffs cannot be avoided and it becomes even more important to reduce the overhead caused by the handoff procedure.

IV. SYSTEM APPROACH

In this section, we detail the proposed system approach to reducing the handoff overhead when the handoffs are unavoidable. In Section III-D3, we see that when the users are mobile the unavoidable handoffs are large. We also know that the overhead due to vertical handoffs is much larger due to the interface switch. A delay of more than 42 ms can negatively affect real-time applications [17]. This motivates the need for a protocol for interface switching to minimize handoff overhead and provide seamless connectivity, thereby, ensuring a stable network. The design of such an approach is challenging when we consider a network where the APs are not open for control. This could happen in situations where the two technologies have different operators. Our approach is based on the idea of assigning the same IP address to both LiFi and WiFi interfaces on user devices and changing the routes between the source and the destination at the user device and in the downlink so that traffic goes through the desired interface. Since the routes are changed on the network layer, Transmission Control Protocol (TCP), continues sending the data to the destination and does not reset the connection, thus providing seamless connectivity. Multipath TCP (MPTCP) [18] is also an option to provide seamless connectivity where the data flow is split



(a) Sum throughput



(b) Number of vertical handovers

Fig. 6: Comparison of results for conference room topology with 24 users, Model0 block and receiver elevation of 0° for varying user speeds

between the two wireless paths and the user is served by the two technologies simultaneously. In this paper, we only consider the situation where the user devices do not support MPTCP because many devices like the devices on-board an aircraft do not currently support this. We also aimed to provide an approach that can readily be integrated with all user devices currently existing.

A. Protocol for Vertical Handoffs

In order to manage the handoffs, a central controller communicates with agents running in the user and on the downlink. The agents establish a connection with the controller by exchanging Hello messages on startup. The users are assigned the same IP on both LiFi and WiFi interfaces. The agents then wait for the handoff instruction. Upon receiving a handoff instruction the agent on the user device selects a new route through the different interface but with the same destination. The downlink is also simultaneously switched to the new interface. Since the user IP remains the same after the switch the downlink data traffic is switched without the need for a TCP re-connection. The vertical handover protocol is presented in Alg. 2.

B. Hardware Setup

The hardware setup considered for this approach is as follows. One LiFi-XL [19] AP and a WiFi AP serve a user which is an APU2E4 board [20] fitted with a LiFi receiver dongle and a WLE200NX WiFi network card. The WiFi AP runs as a container in another APU2E4 board. The downlink agent also runs as a separate container on the same physical device. The measurement setup is shown in Fig. 7 where the vertical distance between an AP and the user is 1 m, and the elevation angle of the user device is 0°. A TCP iPerf server is set up at the user device and continuously receives data. iPerf is configured to have a constant packet rate and Nagle's algorithm is disabled. To collect handover data, the controller enforces a handover every 3 seconds. The incoming and outgoing packets on each interface are analyzed using Wireshark [21]. The overhead is calculated as the time between the last packet on the old interface and the first packet on the new interface after the switch.

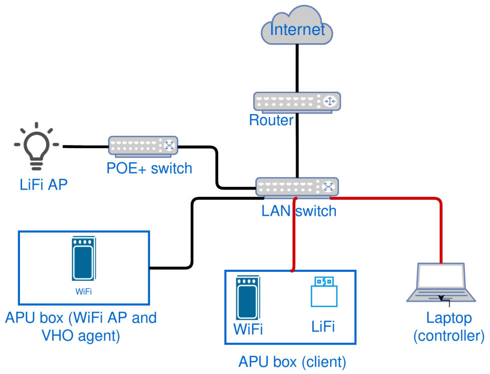


Fig. 7: Measurement setup with a controller, LiFi and WiFi AP and a user

C. Measurement Results

Fig. 8 presents the mean and the standard deviation of the vertical handover overhead measured for different bandwidths.

Algorithm 2 Vertical Handover Protocol

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Initial configuration: The same IP address is configured on the LiFi and WiFi interfaces at the user device. A different IP address is configured on the LiFi and WiFi APs downlink.
The controller has an Ethernet connection to the agents to communicate control information.
The user agent and downlink agent connect to the controller.
repeat
    if the user / downlink agent receives a command from the controller to make a handover to LiFi or WiFi then
        The user / downlink agent replaces the current route in the routing table with the desired interface name for LiFi or WiFi
    else
        The user / downlink agent continues waiting for a command from the controller
    end if
until stop
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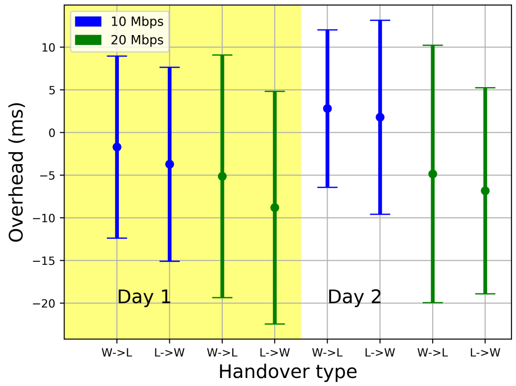

Fig. 8: Vertical handoff overhead from WiFi (W) to LiFi (L) interface and from LiFi (L) to WiFi (W) interface

600 WiFi to LiFi and 600 LiFi to WiFi measurements are obtained. The same measurements are performed on another day to exclude any environmental errors. From the results, we see that the overhead is negligible because TCP re-connections are not observed. Negative values for overhead are measured due to TCP queuing at the old interface. When an upper-layer application sends data, the packets are first copied to a kernel write queue. Then, the kernel copies the packets from the write queue to the network interface controller, and finally sends them. TCP queues packets to the driver's queue (write buffer) and the packets are transmitted sequentially. There is a queue per interface, in our case, one for LiFi and one for WiFi. During a handover, the interfaces are switched. The queue of the new interface is empty, hence, the first packet can immediately be transmitted while other packets can still be waiting in the old interface's queue. In this case, the handover overhead is negative. To sum up, with this vertical handover technique, measured vertical handover overhead does not require TCP re-connections, and this ensures the stability of a LiFi-RF network in case of unavoidable handovers.

V. CONCLUSION

In this paper, first, a low complexity algorithm for resource allocation has been proposed that considers the loss in data rate due to handoff overhead and in doing so, aims to provide stability in a LiFi-RF heterogeneous network. The algorithm has been extensively evaluated with simulations and it can be concluded that the algorithm offers a significant improvement in sum throughput over conventional resource allocation methods under transient channel variations. The effects of varying blockage probabilities, receiver orientations, and user speeds were analyzed. The results show that in cases of LOS blockages with longer duration and user mobility, there are unavoidable handoffs. To minimize the overhead due to unavoidable handoffs we propose a system approach to managing vertical handoffs as they incur a large overhead. The proposed protocol has been implemented on a hardware setup and evaluated with measurements. The results of this measurement show that the vertical handoff overhead can be negligible, thus avoiding TCP re-connections, and this results in a stable network.

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