Li-Wi: An Upper Layer Hybrid VLC-WiFi Network Handover Solution

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Abstract

Visible light communications (VLC) as a wireless communication technology complementing the radio frequency-based wireless fidelity (WiFi). The hybrid VLC/WiFi, offers the best of both worlds, which are of particular interested in vehicular VLC (V-VLC) that have not yet been explored yet. In this paper, we propose an upper layer hybrid VLC-WiFi network handover solution known as "Li-Wi" to address the handover issues in V-VLC due to the mobility, shadowing, and obstacles. Li-Wi utilizes the benefits of high data rates and link availability of VLC and WiFi, respectively. It offers robust connectivity with lower handover outage duration (T_{hod}) and a high network throughput. Based on experimental evaluation results using a small-scale prototype, we demonstrate the advantage of the proposed approach. Our experiments reveal that, in an indoor vehicular network Li-Wi is highly efficient in minimizing (T_{hod}) to 0.03 and 0.06 s for horizontal and vertical handovers, respectively.

Keywords: Visible light communication, Horizontal handover, Vertical handover, Outage duration, Link aggregation, Frequency diversity, MPTCP, Data link layer, Transport layer

1. Introduction

In a mobile network handover takes place when the user is transferred from one access point (AP) to another AP without experiencing loss of connectivity. Achieving a reduced network outage duration during handover in an indoor industrial vehicular visible light communication (V-VLC) network is essential and very critical, specially in indoor scenarios such as industrial and logistic plants with automatic guided vehicles (AGV) moving around. In V-VLC networks to ensure a smooth handover it is essential to adopt techniques to achieve the minimum handover outage duration (T_{hod}) [1]. In V-VLC network, horizontal handover is carried out within the VLC network, and an AGV is disassociated from a light AP (LAP) and it is associated to the next available LAP in the same network in an industry environment. However, there are some cases where (T_{hod}) is longer than expected and therefore the high demand for a complementary alternative wireless technology to the radio frequency (RF)-based systems [2].

To guarantee coverage in V-VLC networks many APs can be used, which can result in continuous dis-connectivity between AGVs as the clients and their associated APs due to frequent handovers. Since, VLC technology is a short-range optical wireless technology providing line of sight (LOS) links, VLC-based indoor vehicular communications may experience regular link failures due to shadowing, obstacle, and mobility resulting in frequent handovers [3]. Therefore, in such cases there is the need for fast failure detection and a back-up link (i.e., WiFi) to ensure continuity (i.e., link availability all the times). Note, vertical handover occurs when there is no longer links between the AGV and all available LAPs and the connection is made with an external AP via a different network. In this work, we use a WiFi network.

Several works have addressed the mobility and handover challenges in the physical [4, 5] and upper layers [6, 7, 8]. However, not much works have been reported on the upper layers specifically on the Transport and Data link layers for VLC networks. Multipath transmission control protocol (MPTCP) has been designed at the Transport layer to improve network throughput and resource utilization by means of simultaneous use of several sub-flows [9]. A scheduler defined for MPTCP allows transmission of packets on the specific sub-flow [10]. Among all MPTCP schedulers, Default and Redundant are much relevant in the case of mobility and therefore handovers in mobile networks. In addition, link aggregation or Ethernet bonding is a method introduced at Data link layer, which combines several network connections in parallel in a single virtual

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bonded interface. Among different modes of the link aggregation method, the mode known as active-backup offers redundancy during blocked VLC link and provides load balancing as well as linear scaling of the bandwidth, thus improving the link reliability [6]. Moreover, introducing frequency division multiple access (FDMA) is a possible option for diversity to avoid conflicts in the channel access procedure during the handover.

In this paper, we propose a hybrid handover solution in a two dimensional (2D) network in an industrial environment and address mobility and handover challenges both in Data link and Transport layers. The proposed transmission scheme called as Li-Wi, which relies on two network technologies of VLC and WiFi, provides a combined architecture using MPTCP in the Transport layer and the link aggregation method in the Data link Layer on top of VLC and WiFi networks. We configure each AGV to act as a client establishing connection links with APs rather using VLC or WiFi or both. In this way, we provide both up-link and down-link via VLC or WiFi or both and choose the best connectivity with reduced T_{hod}. Additionally, we provide robustness to the indoor industrial vehicular network using WiFi. We assume that, an AGV establishes a link primarily through a VLC network and then switches to WiFi when it is experiencing blocking and/or shadowing. Thus, a Li-Wi-based network offers significant reduced T_{hod} in both cases of horizontal and vertical mobile handovers. The main contributions can be summarized as follows:

- Developed an upper layer handover technique for indoor industrial vehicular communication networks based on Li-Wi;
- Assessed the effect of link aggregation method and MPTCP in the Data link and Transport layers, respectively separately and together as a combined solution in hybrid indoor vehicular network where VLC and WiFi act as a primary and backup links, respectively; and
- Demonstrated how using Li-Wi horizontal and vertical handover latencies in an indoor vehicular hybrid network is reduced, which leads to improved network coverage, reliability, and robustness.

The remainder of this paper is organized as follows. Section 2 summarizes the existing related approaches. Section 3 details the potential problems in vehicular networks, and the motivation behind Li-Wi. Moreover, it presents an overall comparison results for Li-Wi and reported V-VLC handover techniques. Section 4 presents the Li-Wi network architecture in details. Section 5 describes four different hybrid[1] handover experiment setups. Section 6 describes how efficiently plan the VLC cell sizes in this hybrid network. Section 7 demonstrates the implementation of several handover techniques in hybrid real-world case studies including Li-Wi. Finally, Section 8 concludes the paper.

[1]In this work, a hybrid network is indicated as an indoor vehicular network connecting over VLC and WiFi.

2. Related Work

The feasibility of a hybrid VLC and RF system has been experimentally validated in [11, 12, 13] and several solutions have been proposed to deal with challenges in handover in indoor environments [14, 15, 4, 16, 17, 18, 19]. A handover mechanism, which improved management and acknowledgement frames on the MAC layer, were designed in [14]. A VLC-WiFi testbed was designed based on software defined radio and the measurements on users created blocking by developing multiple decision algorithms for flawless handover timing by considering a practical scenario. A physical layer approach has been presented in [13], which exploited the ability COTS WiFi chips to perform diversity combining from multiple receive antennas. they combined a VLC and an RF channel and offered robustness against signal blockage and external interference in optical and RF channels.

There are several handover solutions proposed for the hybrid networks. In [15], a prediction-based vertical handover (PVHO) mechanism was proposed and evaluated with the aim of providing a seamless handover between VLC and the standardized scheme for convoy-based applications. The proposed scheme was validated using an NS3 network simulator. Its performance was evaluated in terms of the packet delivery ratio (PDR) and the dynamic prediction redundancy period. The results obtained showed a PDR improvement of up to 20% in dense traffic scenario and PVHO reaching a 100% prediction success rate, thus permitting sufficient redundancy time for seamless handovers in certain scenarios.

In [4], an efficient inter-system handover scheme for the hybrid VLC-WiFi system with the channel adaptive dwell vertical handover (CAD-VHO) scheme was presented as an improvement to the static D-VHO scheme. The proposed scheme was adaptive to the rate and the extent of blocking of the line-of-sight VLC link due to the users' mobility and other objects. Simulation results showed that, the proposed CAD-VHO scheme decreased the number of VHOs by up to 80%. While in [16], a hybrid VLC-WiFi system was designed and implemented with results showing a reduced packet loss rate with the increasing bias voltage level. Also reported was the total handover latency value of 2.75 s from WiFi to VLC and VLC to WiFi.

In [17], a vertical handover algorithm for a hybrid VLC-Femto system in an apartment was proposed, which utilized the analytic hierarchy process (AHP) and cooperative game (CG) to deal with multi-attribute decision making process for use under different traffic types. Note, multiple attributes considered in [17] included dynamic network parameters, and actual traffic preferences. Results obtained from comparison of the average vertical handover for different schemes showed that, the proposed AHP-CG offered improved performance in terms of the reduced average vertical handover by to 18% compared with the AHP scheme providing a reduction in the average vertical handover by to 18%.

Vertical network handovers between LiFi and RF links were simulated in [18] for different scenarios such as blocking and random orientation of LiFi receivers (Rxs). Additionally, a load balancing scheme was proposed for a hybrid LiFi-RF network, which is based on the evolutionary game theory. The results showed that, the scheme greatly improved the user satisfaction level with reduced computational complexity compared with state-of-the-art load balancing techniques. In addition, it was shown that optimal orientation of the LiFi Rxs with the number of blocking in hybrid networks led to maximized quality of service for the end users. In [19] a novel method of handover skipping was investigated, which enabled handovers between two non-adjacent APs in a LiFi network. The proposed method was based on reference signal received power (RSRP), which combined it with its rate of change to determine the handover target. Compared with the proposed and standard handover schemes, and the conventional handover skipping method the proposed method offered reduced handover rates by up to 29% and 17%, and improve throughput by up to 66% and 26%, respectively.

In this work, we go beyond the simulation based experiments and experimentally implement the proposed Li-Wi architecture, which addresses not only the vertical handover as mentioned in the literature review, but also the horizontal handover issue in a hybrid indoor network. We proposed solutions utilizing the benefits of techniques in both MAC and transport layer with the aim of decreasing the handover latency and improving the network robustness by utilizing the backup WiFi technology when the VLC link is not available. By doing so, Li-Wi offers reduced T_{hod}, increased data rates, and flexibility when deployed in indoor environments.

3. Problem Statement

One of the main challenges in V-VLC networks is to provide a robust network with high data rates and low handover delays. Considering a high degree of mobility, the network will experience frequent handovers due to mobility, shadowing and obstacle, thus the need for an efficient handover technique. For a V-VLC network with no handover, we measured T_{hod} to be 15 s, which is too long for the link with handover using the same prototype and architecture in [6].

One possible solution is applying frequency diversity in order to avoid conflicts of channel access during handover. In this way, the receivers (Rx) can receive signals

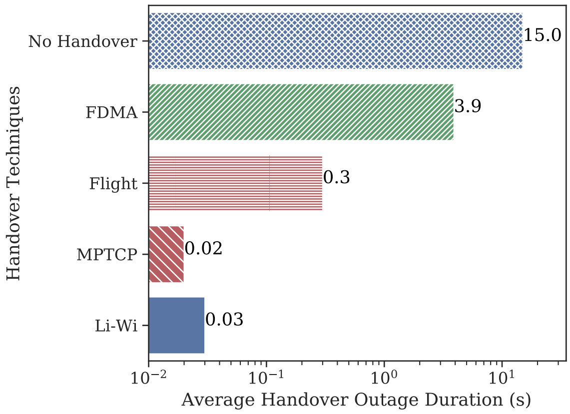

Figure 1: Comparison of horizontal handover outage duration for different handover methods.

on multiple channels with different carrier frequencies [20]. In order to implement frequency diversity, we assign non-overlapping frequency ranges using the OSRAM provided software to each corresponding LCs and LAPs pair to establish VLC links, accordingly. In this way, only the LAPs and LCs which are configured on the same frequency range can establish a VLC connection. In this work, we have emulated frequency division multiple access (FDMA) within V-VLC network and repeated the experiment 10 times. As depicted in Figure 1, the results present that, the average T_{hod} using only FDMA is 3.9 s, which is lower by 11 s compared when we do not apply any handover solution.

In previous work [6], we proposed an architecture known as Flight that addressed handover challenge in the Data link layer in a V-VLC network with linear mobility. We also considered each AGV being equipped with two light clients (LC) and there ceiling-based LAPs configured using two different frequency ranges. We analysed Flight performance under different connections including shadowing and mobility using different channel selection methods [20], and showed the least T_{hod} of 0.3 s.

In [7], we presented a flexible Transport layer protocol architecture for handover in a V-VLC network, where MPTCP was used to optimize both the network throughput and latency. In addition, we studied and evaluated in detail how different MPTCP schedulers and modules offered higher throughputs and lower T_{hod}.

Note that, there are pros and cons when dealing with mobility and handover at Data link and Transport layers. The main advantages of the link aggregation adopted in [6, 20] are relatively easy to set up with no need for additional devices with the optimized T_{hod} of up to 0.3 s compared to tens of seconds using no handover technique. However, it only addressed handover for AGVs with linear mobility in any direction. In [7], the handover issue was at the Transport layer addressed with lower optimized T_{hod} compared with the previous method. Moreover, the method was less complex with no modifications to packet routing and transmission at the Data link and Network lay-

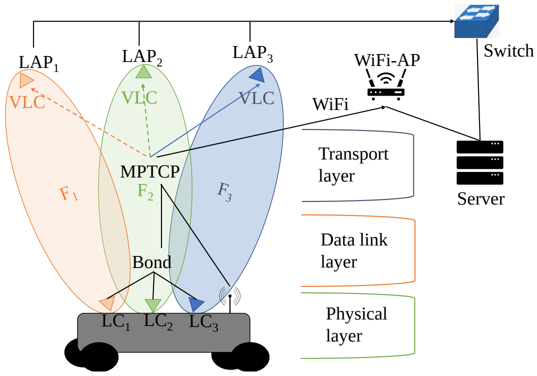

Figure 2: Li-Wi architectural design.

ers. However, there is a trade off in using different types of MPTCP schedulers. For example, The redundant scheduler led to a lower network throughput at the cost of bandwidth but reduced T_{hod} considerably. Therefore, depending on the specific use case scenario, a specific MPTCP scheduler should be selected irrespective of the throughput or T_{hod} being highest or lowest, respectively.

In addition to the mentioned handover solutions, there remains one main concern on what happens if the VLC network becomes inaccessible or there is a network hole with no coverage by LAPs (i.e., in a warehouse-based network area)? A possible answer might be, to adopt handover techniques over the Data link and Transport layers, as well as use a second wireless technology as a backup. In this way, the network remains connected even if it experiences disconnections in VLC or WiFi links due to the lack of network coverage.

Therefore, the main motivation in this work is to propose a hybrid Li-Wi wireless technology for the industrial indoor vehicular network, which provides a seamless handover under mobility challenge at both Data link and Transport layers. In this paper, we present Li-Wi, which is built upon our previous works, as a hybrid solution using multiple VLC and a single WiFi links to enhance hybrid network reliability and robustness. Figure 1 presents an overall comparison of achieved T_{hod} during a horizontal handover using ***(i)*** no handover technique; ***(ii)*** FDMA; ***(iii)*** Flight [6]; ***(iv)*** MPTCP [7]; and ***(v)*** Li-Wi. As shown in Figure 1, Li-Wi offers T_{hod} of 0.03 s for the horizontal handover using the MPTCP redundant scheduler, which quite similar as MPTCP described in [7]. However, the main advantage of Li-Wi is that, it ***(i)*** provides an improved network coverage utilizing the second wireless technology as the backup link in case of lost connectivity; and ***(ii)*** offering AGV with four wireless links, thus ensuring smooth handover at any given times and directions in a 2D environment, see more on this in Section 7.

4. Li-Wi Network Architecture

In this section, we introduce the designed hybrid system and the network architecture in Physical, Data link, and

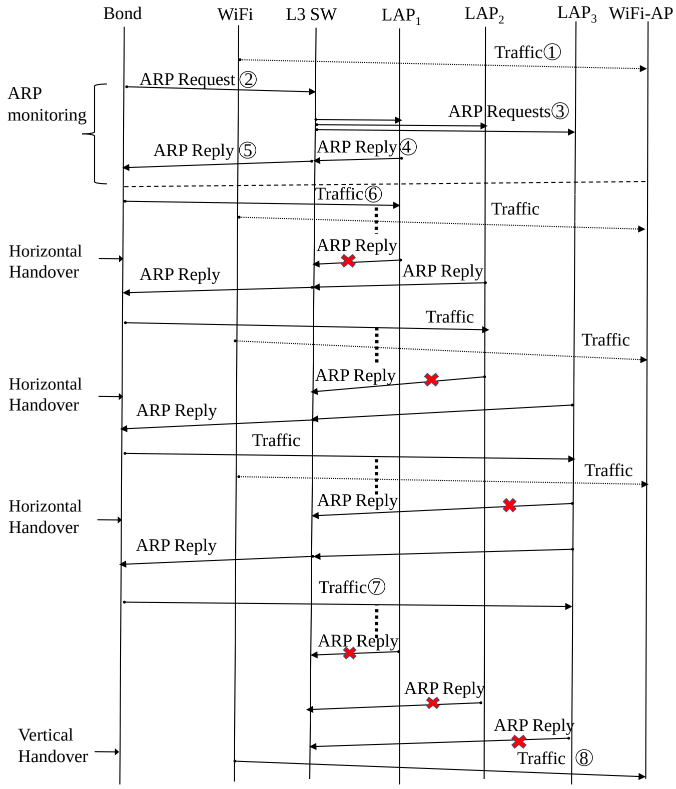

Figure 3: Packet flow diagram of Li-Wi

Transport layers as shown in Figure 2. The Li-Wi system, which is intended for the variable outage duration handover in indoor industrial vehicular networks, comprises of three cells with LAPs and LCs and separate WiFi interfaces. The Li-Wi includes FDMA, link aggregation (Ethernet bonding), and MPTCP, with the packet flow diagram depicted in Figure 3. As shown in Figure 3 the follow diagram is composed of: ***(i)*** ARP monitoring – a channel access procedure for the packet exchange, where the Bond interface request to establish a VLC connection via a specific LAP. ***(ii)*** Horizontal handover - when no reply is received from the current associated LAP and the Bond interface switches in other LAPs to maintain the VLC connection. ***(iii)*** Vertical handover – when VLC link is no longer available and WiFi is used instead. Note, the WiFi interface in MPTCP Redundant scheduler uses the WiFi link in parallel with the VLC link ①, whereas in Default scheduler only the WiFi link is utilized i.e., vertical handover ⑧.

As shown in the Figure 3, during channel monitoring, the Bond interface broadcast ARP request ② continuously to L3 SW, which is then forwards to all LAP i.e., ③. The LAP with highest speed and a duplex link sends an ARP reply first to SW ④ and then to the Bond interface ⑤. Finally, the Bond interface transmit the traffic packet ⑥ to LAP_1.

4.1. The Physical layer

As shown in Figure 2, the LAPs are located to ensure seamless coverage in the VLC network using FDMA with

Parameter	**Value**
Frequency band F_1	2-29 MHz
Frequency band F_2	29-59 MHz
Frequency band F_3	59-94 MHz
Distance between LCs and LAPs	1 m
Photodiode's field of view	60 degree
Bandwidth of LED	80 MHz [21]
Room dimension	5 x 4 x 2.7 m^3
Transmit power of LED	630 mW
Photosensitive area of PD	150 mm^2
PD's High sensitivity	0.63 A/W ,(λ=850 nm)
PD's Cut-off frequency	30-50 MHz
Number of LEDs	5
Number of PDs	4

Table 1: Experiment settings and parameters

three non-overlapping frequency bands of F_1, F_2 and, F_3. The reason behind choosing the three different frequency ranges is to apply FDMA and transmitting the same information over all three VLC links using frequency diversity. The proposed approach divides the available VLC baseband frequency spectrum into three non-overlapping frequency bands such that each LAP and LC supports only one of the such non-overlapping frequency bands. Therefore, every time the AGV turns in a 2D movement [20], it can continue transmitting the same information utilizing one of the established VLC link configured on one of the specified frequency range. It is also mentionable that both VLC and WiFi links are bidirectional and support both uplink and downlink.

On the server side, All LAPs are connected to a server with Linux Operating system via a layer three switch (SW). Here, we have used OFDM VLC-based transceiver (OSRAM devices) for both LCs and LAPs to provide a real-time bidirectional communications at the average data rate of 100 Mbps over a transmission distance of 10 m. Each LC is composed of five off the shelf high-power LEDs (OSRAM SFH 4715 AS) with 60 degree half angles and four optical Rxs (i.e., large-area silicon photodiodes (PD) (Hamamatsu S6968) and trans-impedance amplifiers). In addition, WiFi is used to provide a link to the server. Table 1 shows the key experimental parameters adopted in this work. Figure 4 demonstrates our indoor Li-Wi setup using VLC transceivers and WiFi devices. As shown in Figure 4, three LCs and a WiFi interface are connected to the mini-PC on the client side. And three LAPs and a WiFi-AP are connected to the server. The communication between the client and server is possible using VLC and WiFi configured as a primary and the backup, respectively.

4.2. The Data link layer

The LC interfaces are configured as a logical Ethernet bonding interface called Bond using the link aggregation

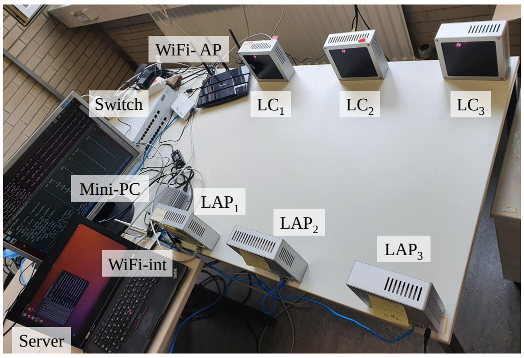

Figure 4: Experimental indoor Li-Wi setup

method at the Data link layer, see Figure 2. Note, in Bond one of the LC interfaces is configured to be the active mode while the others are in the backup mode. To monitor the link failure during handover, we have used an ARP monitoring tool, where the Bond interface sends a request to the ARP target, which is defined as SW in this work, in parallel and over the predetermined intervals to establish the VLC link for packets transmission. The active LC will continue transmission if it receives the ARP request. However, with no ARP requests during the handover LC will use the backup interface for packet transmission provided the ARP request is received. Similarly, while AGV is using the backup interface for packet transmission, and on receiving no ARP request from a LAP via the backup link, LC will switch to the second backup or the active interface until it receives the ARP request.

4.3. The Transport layer

In the Transport layer of the Li-Wi architecture, MPTCP 0.95 with the full mesh path manager, which is a Linux kernel, is installed on Ubuntu 18.04 both on the server and client. TCP connection is established via two sub-flows between Bond and WiFi interfaces, see Figure 2. We have used two MPTCP schedulers as Default and Redundant, where the latter is for transmitting data traffics over available sub-flows. This results in the lowest latency at the cost of the transmission bandwidth. On the other hand, the Default scheduler transmits data on the sub-flow with the lowest round trip time (RTT) until its congestion-window is full. Following this, traffic transmission is proceeded via the other sub-flow with the next highest RTT value.

5. Handover options supported by Li-Wi

In this section, we consider four handover options supported by Li-Wi.

5.1. Link aggregations

In this architecture, we consider a link aggregation using VLC and WiFi which are used to connect AGV to the server. In the proposed hybrid system, V-VLC is

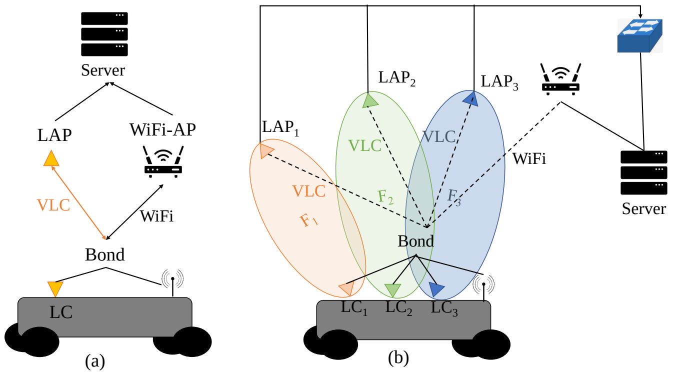

Figure 5: Link aggregation between VLC and WiFi use case scenarios

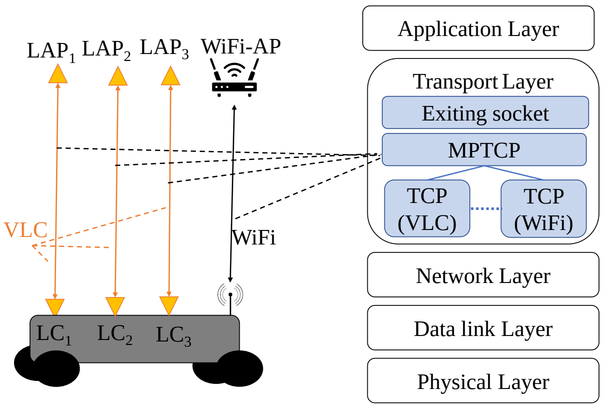

Figure 6: MPTCP between VLC and WiFi use case scenarios

considered as the main communications network, where VLC and WiFi are configured as the primary and backup links, respectively using the active-backup mode. Initially, each AGV is equipped with LC and a WiFi interface with a logical Bond interface, see Figure 5(a). To establish a link between the server and AGV the Bond interface using ARP will monitor VLC and RF links and select one for packet transmission. As shown in Figure 5(b), using three LCs and a WiFi interface an extended and more complex model is proposed to deal with handover in a 2D movement. The main goal for this technique is to reduce T_{hod} when VLC links experience blocking and therefore the use of WiFi as a backup link to maintain network connectivity.

5.2. MPTCP

In this architecture, we address the hybrid handover only in the Transport layer using MPTCP. As in Figure 6, MPTCP provides four TCP connection links for packet transmission using the chosen MPTCP schedulers between the Network and Application layers. Note, MPTCP is aware of several TCP paths and correctly adjusts the congestion control on each path based on changing network conditions. Note, the exiting sockets have an option to control the creation and the removal of sub-flows during the lifetime of a Multipath TCP connection.

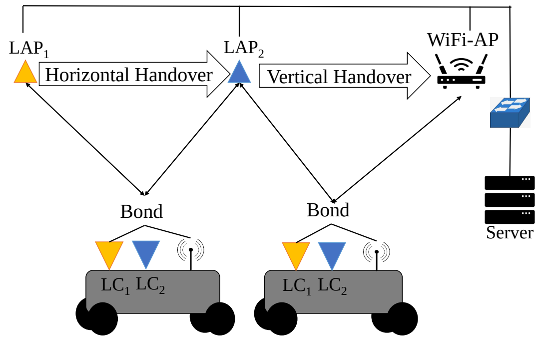

Figure 7: Horizontal and vertical handovers presentations.

5.3. Li-Wi with handovers

In this architecture, initially, we evaluate the performance of Li-Wi, see Figure 2, by measuring T_{hod} during vertical handover. As shown in Figure 7, vertical handover is established once the existing link between the Bond interface and LAP_2 is disconnected and is replaced with a new WiFi link.

As shown in Figure 7, in this architecture, the AGV experiences both horizontal and vertical handovers and we evaluate the system performance using Li-Wi as depicted in Figure 2. In this work, we consider the horizontal handover when AGV experiences link failure within VLC network and handover occurs in the same network. Besides, vertical handover occurs when the AGV has no longer the VLC link and the traffic data is switched to WiFi link.

6. Cell Planning

One of the main challenges in indoor V-VLC network is the high mobility, which contributes to frequent handovers, which is leads to increased latency, increased processing, and higher resources. Thus, the need to address this issue there is the need to adopt cell planning to provide acceptable coverage. Since, the main aim of the paper is utilizing VLC technology as a primary communication technique, we focused on providing mathematical model only on VLC to provide an acceptable network coverage within the V-VLC network.
RF is even more complicated to model in industrial settings as presented in [22]. In [22], an architecture for more realistic assessment of protocol performance aspects in industrial automation environments is provided. They utilized a toolkit consisting of a planning tool to model the environment including walls, machinery, and other obstacles, as well as the location of the communicating devices,such as the base station and the sensor nodes. Therefore, the designer could annotate application characteristics and performance demands. In [22], they also presented a simulation model which integrated to verify whether the application demands are satisfied and for which protocol configuration. Moreover, in [23] and [24], they proposed network planning approaches considering the principles of the shortest hops,

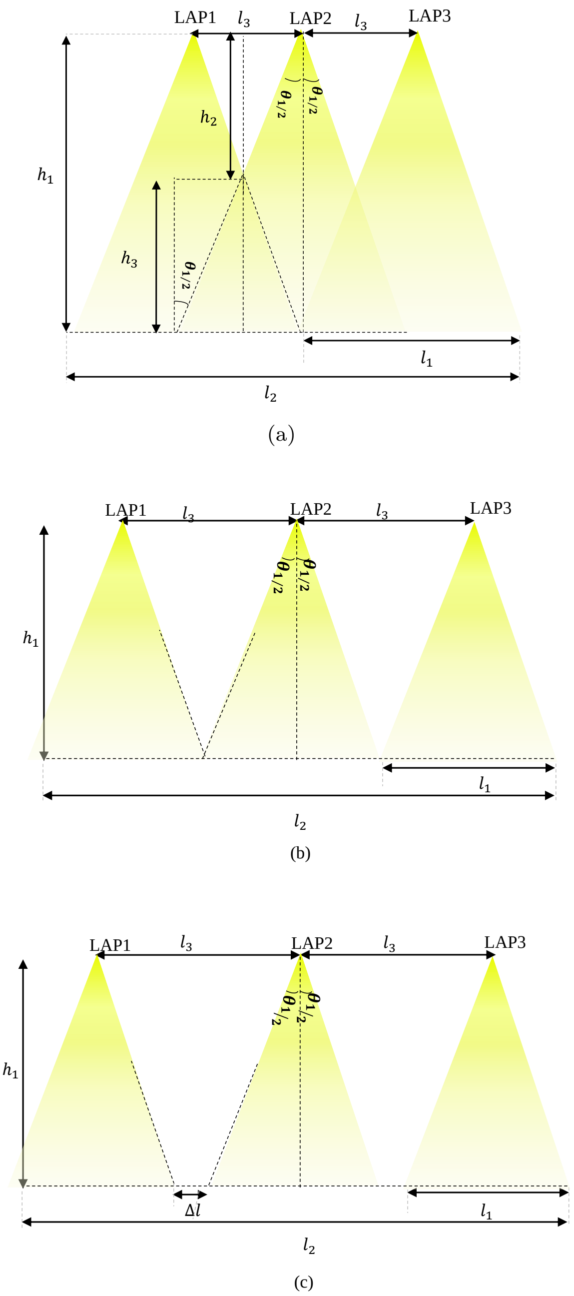

Figure 8: Illumination profiles with: (a) overlapping, (b) non-overlapping with no illumination gaps, and (c) non-overlapping with illumination gaps scenarios.

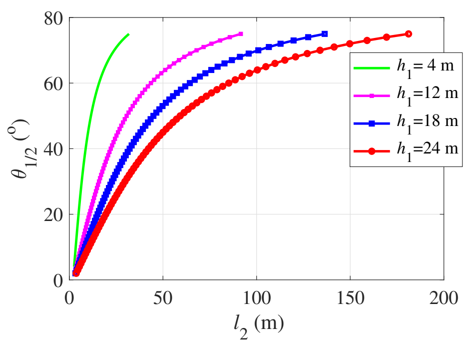

Figure 9: LAP's FOV as a function of half power angle for a range of vertical link spans.

the least routers and balance of the shortest hops and the least routers, respectively. they also implemented the proposed algorithms to generate the network deployment for a given factory layout.

In this work, we provide insights into VLC cell planning and carry out analysis to determine the optimum distances between LAPs based on LAP and channel parameters. The radiation characteristics of a light source defines its spatial intensity distribution and the coverage field of view (FoV). The radiation pattern of each light source, the distances between the light sources and the vertical link span will determine the overlapping illumination regions as depicted in Figure 8(a). The height from the LAPs to the overlapping light intersection is given as:

$$h_2 = \frac{l_3}{2\tan(\theta_{1/2})} \tag{1}$$

where l_3 is the distance between the LAPs, $\theta_{1/2}$ is the half power angle of LAPs, and l_1 is the beam length of a single LAP expressed as:

$$l_1 = 2h_1 \tan(\theta_{1/2}) \tag{2}$$

where h_1 is the height of LAP from the floor.

The coverage length is given as:

$$l_2 = l_3(n-1) + 2h_1\tan(\theta_{1/2}) = l_3(n-1) + l_1 \tag{3}$$

where n represents the number of LAPs.

Note, for overlapping illumination areas we have:

$$h_3 = h_1 - h_2 = h_1 - \frac{l_3}{2\tan(\theta_{1/2})} \tag{4}$$

Figure 8(b) and Figure 8(c) depicts LAPS with no overlapping illumination areas. For Figure 8(c), with n number of LAPs the total path length is:

$$l_n = nl_1 + \Delta l \tag{5}$$

where Δl is the separation gap between illumination regions, where the network will experience more frequent and unwanted handovers. Note that, beam forming optics can be used to change the optical illumination pattern depending on the room size and shapes as well as the network coverage requirements. Using (2), we obtain $\theta_{1/2}$, as a function of the l_2 for a range of h_1, where $l_3 = 1$m , and $n = 3$ is presented in Figure 9, which show logarithmic profiles. As shown in Figure 9, for a given $\theta_{1/2}$, e.g., 50°, l_2 is increased by 19, ∼33, and ∼48 m for h_1 of 12, 18, and 24 m, respectively compared with h_1 of 4 m.

The overlapping area between two LAPs (given by the area between two intersecting circles[2]) can be expressed as:

$$\begin{aligned} A_{ovl} =& 2\left(\left(h_1\tan(\theta_{1/2})\right)^2 \cos^{-1}\left(\frac{l_0}{h_1\tan(\theta_{1/2})}\right) - \right. \\ & \left. l_0\sqrt{\left(h_1\tan(\theta_{1/2})\right)^2 - {l_0}^2}\right) \end{aligned} \tag{6}$$

[2]https://diego.assencio.com

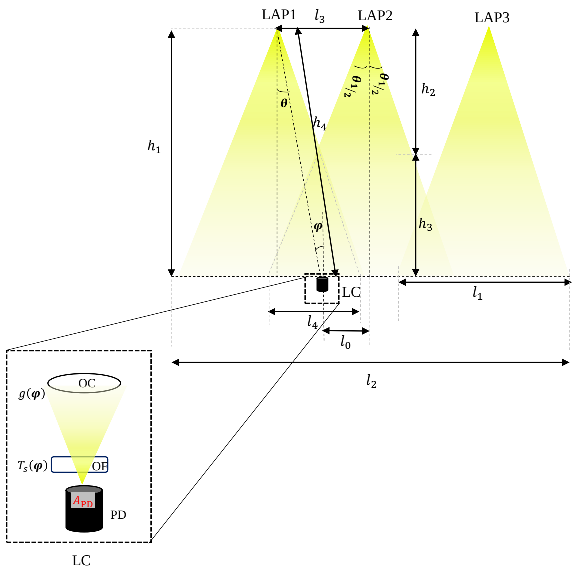

Figure 10: Configuration of an indoor V-VLC system.

where l_0 is the horizontal distance from the centre of the LAP to the centre of the overlapping area. The total illumination area for the non-overlapping and overlapping beam cases with n number of LAPs can be expressed, respectively as:

$$\begin{aligned} A_{n-ovl} &= n\pi\Big(h_1\tan(\theta_{1/2})\Big)^2, \\ A_{w-ovl} &= n\pi\Big(h_1\tan(\theta_{1/2})\Big)^2 - (n-1)A_{ovl} \end{aligned} \tag{7}$$

Note that the LAPs and LCs are pointing to the floor and ceiling, respectively, with no vertical/horizontal tilting angle. For the VLC link, the received optical power is given as:

$$P_R = \begin{cases} \frac{(m+1)P_T A_{PD}}{2\pi h_4^2}\cos^m(\theta)T_s(\varphi)g(\varphi)\cos(\varphi), & 0 \leq \varphi \leq \xi \\ 0, & \varphi > \xi \end{cases} \tag{8}$$

where P_T is the transmit optical power, A_{PD} is the active area of the PD, $T_s(\varphi)$ and $g(\varphi)$, are the gains of the optical filter (OF) and the optical concentrator (OC), respectively. θ denotes the irradiance angle, φ is the incidence angle, ξ is angular FOV (AFOV) semi-angle of the receiver, h_4 is the distance between the LAP and LC, and m represents Lambertian order of emission for the LAP, which is given by [25]:

$$m = -\frac{\ln 2}{\ln\Big(\cos(\theta_{1/2})\Big)} \tag{9}$$

Lambertian radiant intensity is expressed as [25]:

$$R(\phi) = \frac{(m+1)}{2\pi}\cos^m(\theta) \tag{10}$$

Note, with sufficient light coverage within a room full availability of the LOS path with no blocking, the overall system's latency depends on the handover implementation as the AGV moves between cells. Figure 10 depicts the configuration for an indoor V-VLC system with overlapping illuminations regions, 3 Laps, and a single LC. In the overlapping areas, the handover time is given by:

$$t_{han} \leq \frac{h_1\tan(\varphi)}{S_{AGV}} - t_{sm}, \varphi \leq \xi \tag{11}$$

where $h_1\tan(\varphi) = l_4$ (for $\varphi = \theta$), t_{sm} is the time safety margin and S_{AGV} is the speed of AGV.

7. Experimental Evaluation

An experimental prototype of the proposed Li-Wi system is implemented and its performance evaluated. We have used 3 LAPs - LCs pairs with a 1 m distance between each LC and LAP. In addition, we have used ***(i)*** a WiFi USB antenna and a WiFi-AP for WiFi connection; ***(ii)*** a mini-Pc with the Linux-Ubuntu operation system as a client equipped with 3-LC and one WiFi antenna; and ***(iii)*** 3-LAP and a WiFi-AP, which are connected to a server via a configurable layer three SW. As it shown in Figure 2, a logical Bond interface is configured on top of 3-LC in the Data link layer, and in the Transport layer the Bond interface and WiFi link providing sub-flows in MPTCP is connect to the server. We have also separately, implemented the handover options supported by Li-Wi as ***(i)*** link aggregation between VLC and WiFi; and ***(ii)*** MPTCP between VLC and WiFi, which are explained in details in Section 5. We evaluate each experiment and compare it with the LiWi system using Redundant (LiWi-Red) and Default (LiWi-Def) schedulers. Note, each test is repeated 10 times per scenario and the average values are taken as outlined in the followings.

7.1. Link aggregations between VLC and WiFi

As was described in subsection 5.1, this is the case in a hybrid network where there is a link aggregation (Link Agg) between VLC and WiFi interfaces. Table 2 presents the measured T_{hod} for three values of ARP for UDP and TCP and using a simple scenario where the Bond interface is configured on only a single LC with the WiFi interface installed on AGV. As it is shown in Table 2, the minimum and maximum T_{hod} of 0.15 and 0.91 s are observed for UDP and TCP packet transmission with ARP of 50 and 200 ms, respectively.

Next, we included two more LCs and a configuring Link aggregation on top of 3-LCs and a WiFi interface, thus introducing complexity to the system. Figure 11 shows the measured average throughput for the TCP traffic and for ARPs of 50, 100, and, 200 ms. As illustrated, for all three cases, the average throughput has almost reduced from ∼49 to ∼37 Mbps as a result of the vertical handover between VLC and WiFi. Note, vertical handovers between

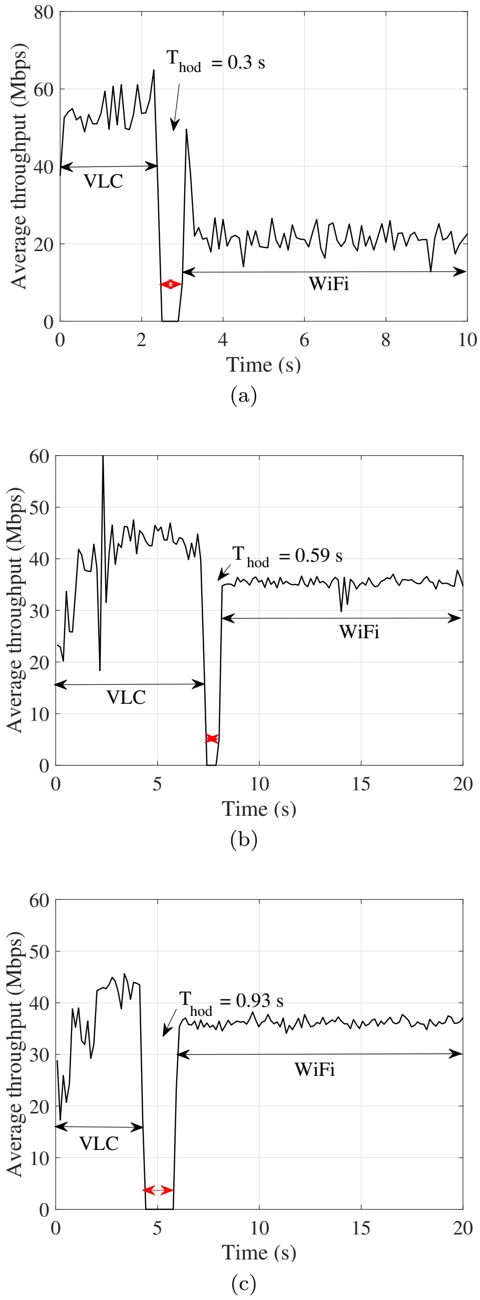

Figure 11: The average throughput between 3-VLC and a wifi interface in case of link aggregation for ARPs of: (a) 50, (b), 100, and, (c) 200 ms.

ARP interval (ms) $T_{hod}(s)$	***50***	***100***	***200***
UDP	0.15	0.25	0.7
TCP	0.3	0.7	0.91

Table 2: $T_{\rm hod}$ vs. ARP interval values Link aggregations between VLC and WiFi architecture using TCP and UDP.

Handover type $T_{hod}(s)$	***Horizontal***	***Vertical***
Default	0.34	1.5
Redundant	0.2	0.85

Table 3: $T_{\rm hod}$ values using MPTCP between VLC and WiFi interfaces.

WiFi and VLC also result in almost the same values of $T_{\rm hod}$ for each specific ARP intervals. In addition, the results show that for TCP $T_{\rm hod}$ values are in the same range as the previous case, where the Bond interface was configured on top of only 2 interfaces. Therefore, increasing the number of interfaces does not increase $T_{\rm hod}$, but it addresses the handover challenge in AGV with 2D movements, which is a great benefit, and decreases $T_{\rm hod}$ considerably compared with the case with no handover.

7.2. MPTCP between VLC and WiFi

Here, we emulate the architecture showed in Figure 6, which is described in subsection 5.2, and evaluate $T_{\rm hod}$ for the case of AGV experiencing link failures due to mobility. We apply two different MPTCP schedulers of Redundant (MPTCP-Red) and Default (MPTCP-Def) for addressing the mobility issue in a hybrid network. Table 3 presents the achieved values for $T_{\rm hod}$ for horizontal and vertical handovers, where the lowest and highest $T_{\rm hod}$ of 0.2 and 1.5 are observed for Redundant and Default with horizontal and vertical handovers, respectively.

However, the network throughput using the Redundant scheduler is 25 Mbps compared with 55 Mbps for the Default. This is because of the bandwidth penalty to achieve improved latency. Thus, the trade-off between latency and bandwidth.

7.3. Li-Wi performance with handovers

We emulate and evaluate the main proposed Li-Wi architecture configured on both the Data link and Transport layers. We use the ARP interval of 100 ms for monitoring the link via the Bond interface and apply both Redundant and Default schedulers for MPTCP between the Bond and WiFi connection links. In this experimental set-up, we analyse $T_{\rm hod}$ for the case where AGV only experiences a vertical handover. As shown in Figure 12, using both link aggregation and MPTCP during the vertical handover $T_{\rm hod}$ observed are 0.06 and 0.3 s for Redundant and Default schedulers, respectively. Note, the average network throughput for the Redundant scheduler is decreased to 28 Mbps from ~50 Mbps for the Default scheduler for the VLC link, see Figure 12, with no network disconnection and smooth vertical handover. Following switching from VLC to WiFi, the average throughput of 20 Mbps is achieved for both schedulers. Thus, the trade-off between the average throughput and $T_{\rm hod}$ depending on the network's demand priority.

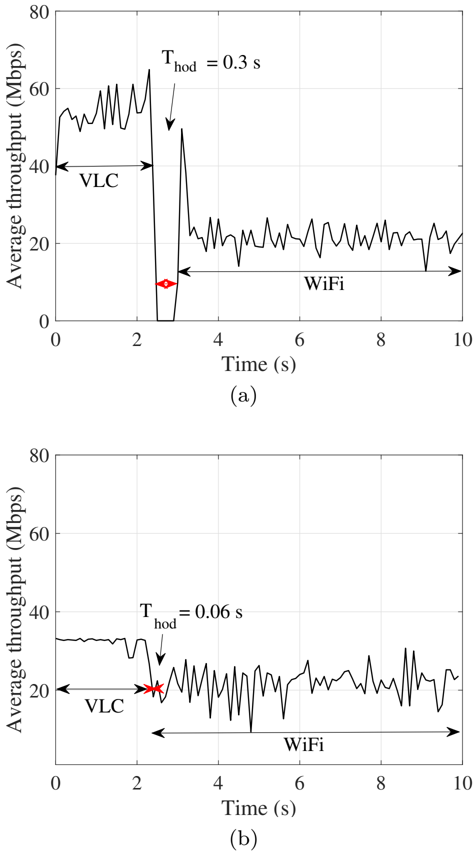

Figure 12: Li-Wi performance applied on a hybrid architecture experiencing only vertical handover using (a) Default (b) Redundant schedulers.

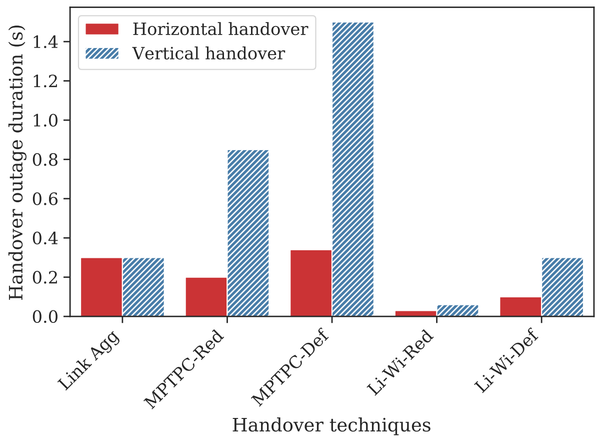

Figure 13: Performance comparison between proposed handover techniques.

Handover type $T_{hod}(s)$	***Horizontal***	***Vertical***
Default	0.1	0.3
Redundant	0.03	0.06

Table 4: T_{hod} values using Li-Wi during horizontal and vertical handovers.

Next, we emulate and analyse the performance of Li-Wi when AGV is experiencing both horizontal and vertical handovers. Using Li-Wi, as shown in Table 4 the minimum and maximum T_{hod} of 0.03 and 0.3 are observed for horizontal and vertical handovers using Default and Redundant schedulers, respectively.

Finally, we compare the performance of Li-Wi with horizontal and vertical handovers in terms of T_{hod} with the other handover techniques proposed in the Data link and Transport layers as depicted in . Figure 13. As shown, using the Redundant scheduler Li-Wi offers the lowest T_{hod} of 0.03 and 0.06 s for horizontal and vertical handovers, respectively compared with LinkAgg, MPTPC-Def, MPTPC-Red and LiWi-Def.

8. Conclusion

This paper presented a hybrid handover solution known as Li-Wi in the Data link and Transport layers based on the frequency diversity, link aggregation and MPTCP tool for the hybrid networks. Li-Wi utilized the link aggregation method in the VLC network to provide an efficient channel selection method using the three different frequency ranges, therefore it provided smooth horizontal and vertical handovers with the minimum T_{hod} of 0.03 s for the horizontal handover. This is a considerable improvement compared with the 15 s in case of the link with no handover. Additionally, MPTCP was used over the Bond and WiFi interface in the Transport layer, thus ensuring network connectivity in case of VLC link failure. Therefore, it provided a hybrid network to offer robustness with the minimum vertical handover delay of 0.06 s within the network. We also experimentally, implemented and evaluated two other handover options for the hybrid network, which were performed separately at the Data link and Transport layers with the achieved minimum T_{hod} of 0.2 s and 0.35 s using MPTCP and link aggregation only, respectively. Finally, we illustrated that Li-Wi as a combined solution offered improved performance compared with VLC or WiFi. Li-Wi not only reduced the handover delay in both cases of horizontal and vertical handovers but also provided robustness in the network by using the WiFi as the backup link. The future work will focus on a real mobile testbed not only in an indoor environment but also in an outdoor scenario where new MPTCP schedulers and channel selection methods can be considered. In addition, the hybrid VLC and other RF wireless techniques (i.e., millimetre waves and LTE) will be considered.

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