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Wireless Handover solutions in Vehicular Visible Light Communications

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Wireless Handover solutions in Vehicular Visible Light Communications

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Abstract

A vast number of research works demonstrated the high potential of Visible Light Communications (VLC) as a complementary wireless communication technology that can be widely used in vehicular VLC (V-VLC) networks. V-VLC utilizes visible light spectrum to provide communication connections among vehicles. To guarantee coverage in V-VLC networks many Access Points (AP) can be used, which can result in intermittent connectivity between vehicles as the clients and their associated AP and lead to many handovers. In VLC-based vehicular communications the link may experience regular link failures due to shadowing, obstacle, and mobility in contrast to RF-based networks. Therefore, one of the main challenges of V-VLC is the frequent handover which causes outages and network disruption, evidently.
In this thesis I introduce V-VLC network scenarios, where there are Automated Guided Vehicles (AGV) moving linearly and in two dimensional (2D) around the warehouse in an indoor environment and each AGV is equipped with several Light Clients (LC). The installed LC stablish VLC link connections with their corresponding Light Access points (LAP) which are installed on ceiling. Each pair of LC and LAP is assigned to non-overlapped frequency bands using Frequency Division Multiple Access (FDMA) technique. Therefore, each LC can establish a VLC link with its corresponding LAP.
This Ph.D. thesis aims enhancing the reliability and robustness of the indoor vehicular network communications by reducing the handover latency in the vehicular network. In this thesis, I propose handover solutions at different network layers using different wireless technologies. Note, in all proposed solutions, VLC acts as a primary connection link.

To address the frequent link failures during handover in the V-VLC network, I propose Flexible Light Communications (Flight) and Frequency Diversity and Link Aggregation (FDLA) architectures which make use of link aggregation method and FDMA in data link layer to switch between available LAP in case of handover during mobility or the link blockage in linear and 2D movements, respectively. Applying Flight and FDLA solutions decrease the handover delay from 15 s to 0.3, and 0.2

s, respectively compared with no handover technique. Moreover, in the transport layer I utilize the advantage of Multipath-Transmission Control Protocol (MPTCP) to provide network redundancy and load balancing during handover and minimize the number of packet lost caused by connection lose. This solution minimizes the handover delay up to 0.02 s. Additionally, to add robustness and increase network reliability and coverage, I propose Li-Wi, a system which utilizes the benefits of high data rates and link availability of VLC and Wireless Fidelity (WiFi), respectively. Li-Wi solution minimizes the handover latency significantly up to 0.03 s.

The main contributions of this thesis can be summarized as ***(i)*** Developed several upper layer handover solutions for indoor V-VLC networks,***(ii)*** Assessed the effect of link aggregation and MPTCP methods in the data link and transport layers, respectively separately and together as a combined architecture in a hybrid vehicular network where VLC and WiFi act as a primary and backup links, respectively, and ***(iii)*** Demonstrated how applying proposed solutions decrease network latency in both horizontal and vertical handovers in a V-VLC network, which lead to provide an improved network in terms of coverage, reliability and robustness.

Kurzfassung

Eine erhebliche Anzahl von Forschungsarbeiten hat das hohe Potenzial von Visible Light Communications (VLC) als komplementäre drahtlose Kommunikationstechnologie aufgezeigt, die in Fahrzeug-VLC-Netzwerken (V-VLC) breit eingesetzt werden kann. V-VLC nutzt das sichtbare Lichtspektrum, um Kommunikationsverbindungen zwischen Fahrzeugen herzustellen. Um die Abdeckung in V-VLC-Netzwerken zu gewährleisten, müssen viele Access Points (AP) verwendet werden, was zu einer intermittierenden Konnektivität zwischen den Fahrzeugen als Client und ihren zugehörigen AP‘s führt und viele Handover zur Folge hat. In der VLC-basierten Fahrzeugkommunikation kann es, im Gegensatz zu RF-basierten Netzwerken, zu regelmäßigen Verbindungsausfällen aufgrund von Abschattungen, Hindernissen und Mobilität kommen. Daher ist eine der größten Herausforderungen von V-VLC der häufige Handover, das zu Ausfällen und Netzwerkstörungen führt.
In dieser Arbeit stelle ich V-VLC-Netzwerk-Szenarien vor, in denen es Automated Guided Vehicles (AGV) gibt, die sich linear und in 2D im Inneren einer Lagerhalle bewegen und jedes AGV mit mehreren Light Clients (LC) ausgestattet ist. Die installierten LCs stellen VLC-Link-Verbindungen mit ihren entsprechenden LAPs her, die an der Decke installiert sind. Jedes Paar von LC und LAP wird unter Verwendung der FDMA-Technik nicht überlappenden Frequenzbändern zugeordnet. Daher kann jeder LC eine VLC-Verbindung mit seinem entsprechenden LAP herstellen.
Diese Doktorarbeit zielt darauf ab, die Zuverlässigkeit und Robustheit der Kommunikation in Indoor-Fahrzeugnetzen zu verbessern, indem die Handover Latenzzeit im Netzwerk reduziert wird. In dieser Arbeit schlage ich Handover-Lösungen auf verschiedenen Netzwerkschichten unter Verwendung verschiedener drahtloser Technologien vor. Dabei ist zu beachten, dass in allen vorgeschlagenen Lösungen VLC als primärer Verbindungslink fungiert.

Um die häufigen Verbindungsausfälle während des Handovers im V-VLC-Netzwerk zu adressieren, schlage ich Flexible Light Communications (Flight) und Frequency Diversity and Link Aggregation (FDLA) Architekturen vor, die die Link Aggregation Methode und Frequency Division Multiple Access (FDMA) in der Datenverbin-

dungsschicht nutzen, um zwischen verfügbaren Light Access Points (LAP) im Falle eines Handovers während der Mobilität oder der Verbindungsblockade in linearen und zweidimensionalen (2D) Bewegungen zu wechseln. Die Anwendung der Flight- und FDLA-Lösungen verringert die Handover-Verzögerung von 15 s um 0,3 bzw. 0,2 s im Vergleich zu keiner Handover-Technik. Darüber hinaus nutze ich in der Transportschicht den Vorteil des Multipath-Transmission Control Protocol (MPTCP), um Netzwerk-Redundanz und Lastausgleich während des Handovers zu gewährleisten und die Anzahl der Paketverluste aufgrund von Verbindungsverlusten zu minimieren. Diese Lösung minimiert die Handover-Verzögerung um bis zu 0,02 s. Um zusätzlich die Stabilität hinsichtlich Netzwerkzuverlässigkeit und –abdeckung zu erhöhen, , schlage ich die Verwendung von Li-Wi vor. Li-Wi ist ein System, das die Vorteile der hohen Datenraten und Link-Verfügbarkeit von VLC bzw. Wireless Fidelity (WiFi) nutzt. Die Li-Wi-Lösung minimiert die Handover-Latenzzeit signifikant um bis zu 0,03 s.

Die Hauptbeiträge dieser Arbeit lassen sich wie folgt zusammenfassen: (i) Entwicklung verschiedener Handover-Lösungen für V-VLC-Netzwerke in Innenräumen, (ii) Bewertung der Auswirkungen von Link-Aggregation und MPTCP-Methoden in den Datenverbindungs- und Transportschichten, jeweils separat und zusammen als kombinierte Architektur in einem hybriden Fahrzeugnetzwerk, in dem VLC und Wi-Fi als primäre bzw. Backup-Links fungieren, und (iii) Demonstration, wie die Anwendung der vorgeschlagenen Lösungen die Netzwerk-Latenz sowohl bei horizontalen als auch bei vertikalen Handovern in einem V-VLC-Netzwerk verringert, was zu einem verbesserten Netzwerk in Bezug auf Abdeckung, Zuverlässigkeit und Stabilität führt.

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Chapter 1

Introduction

Wireless communications, in their many flavors constitute a popular alternative to wired networks, especially in mobile and dynamic scenarios. Improving mobile network management in terms of coverage and reliable connectivity is one of the main research challenges in vehicular networks [1]. Existing vehicular techniques, such as the IEEE standard, 802.11p and 3rd Generation Partnership Project (3GPP) [2] are based on high-power Radio Frequency (RF) transmission to cover long distances up to several kilometers. The limited bandwidth is however shared among many vehicles. In emergency cases, only narrowband information can be exchanged in each link [2].

Visible Light Communications (VLC) has been introduced as a complementary technology to RF communications for vehicular environments [3]. VLC which uses the visible spectrum between 375 and 780 nm [4], is a short-range wireless communication technology that is gaining momentum in research and industry for indoor and outdoor environments [5]. With VLC, the Light Emitting Diode (LED) [6], [7] normally employed for lighting is modulated with the desired information (e.g., using such modulation schemes [8]–[11] as On-Off Keying (OOK), or Orthogonal Frequency Division Multiplexing (OFDM) [12], [13]) at a sufficiently high speed to make the light flickering invisible to the human eyes [14] [15]. Some of the well-known benefits of VLC are defined as [16], it introduces no interference to RF cellular networks, and not being affected by the RF induced electromagnetic interference [17]. Moreover, it has a high energy efficiency as a green technology. VLC provides a high security to networks since light is confined within a room [4]. Additionally, it provides a heigh deployment density and increases network capacity thanks to its very large spectrum [18]. VLC has a large bandwidth; therefore, it implies good spatial resolution and it is considered as a cost efficient technology [19]. Although VLC provides short range connectivity which is shared by a small number of vehicles [20], but there are several open research challenges, specifically applicable to Medium Access Control (MAC) and upper layers of VLC [21]–[23]. For instance, though LEDs in vehicles are rapidly gaining VLC capabilities, the LED links are notorious for being unreliable: shadowing, blockage, mobility, and external light, can disrupt the vehicular networks connectivity easily and additionally, it suffers the spatial diversity [24]–[26].

In general, VLC is still considered as a technology to use in indoor Intelligent Transportation System (ITS) networks [27] as well as outdoor environments [28]–[30]. This thesis concentrates on addressing handover issues in indoor vehicular network environments for Vehicle-to-Infrastructure (V2I) where the primary and backup network communications are considered as VLC and WiFi, respectively.

1.1 VLC for indoor vehicular networks

Using Automated Guided Vehicles (AGV) for industrial automation improves efficiency, decreases energy consumption, and increases financial benefit for the company [31], [32]. An AGV is basically a mobile robot. It can navigate in a given geographical area typically by using markers e.g., on the floor or at the ceiling [31]. AGVs can be used both in indoor and outdoor vehicular network environments [33]. Common indoor environments are industry buildings, manufacturing halls and warehouses [33]. The AGVs can communicate using wired and wireless technologies or a combination of both depending on the application scenario and the implementation.

While remote control and traffic management require communication between the vehicles and the infrastructure V2I, robotic control for cooperative driving may

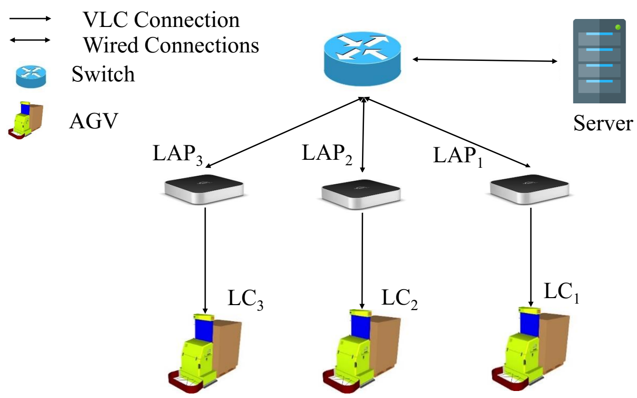


FIGURE 1.1 – VLC network topology for a vehicular network.

be based on Vehicle-to-Vehicle (V2V) communication. Therefore, both V2V [34], [35] and V2I communications are required. Handover mechanism is the essential requirement for most of the mobile communication. In V2I communication, the handover between Access Points (AP) must be seamless without any loss of data and minimum delay [36], especially for time-critical messages. One of the reasons behind choosing VLC technique for AGV communications might be that VLC is inherently more secure than other wireless communications [4], it can be considered as the superior technique to provide reliable communication for the AGV and making a vehicular VLC (V-VLC). This is due to the visible light being confined within a room and therefore, access is only possible by being within the illumination range [1]. Besides, there will be no interference with RF cellular networks, which also prevents jamming, and more capacity to its very large spectrum [4]. In addition, VLC provides a high bandwidth with capability of high data rate exchange within the network. Therefore, VLC is supposed to be a desire technique for providing a secure and fast communication in a highly mobile network such as AGVs [37] in a V-VLC network.

Figure 1.1 shows a basic V-VLC network topology as a starting point for providing VLC for AGV in an indoor industrial environment. Each AGV can be equipped with Light Clients (LC). The VLC Clients connects to the ceiling-mounted Light Access points (LAP), which in turn connect to a remote server via a wired backbone network. The AGV is controlled and monitored by the remote server. The basic structure should also allow direct communication between AGV.
Considering that LAP have limited wireless coverage, a dense grid of LAP is required to provide a seamless wireless coverage in V-VLC network. Given that, V-VLC is very robust against jamming attacks, it offers a smaller interference domain and uses a large spectrum for vehicular communication networks [37]. In industrial networks, real-time information transmission is considered as a high demand to communicate regarding possible collisions, congestion, traffic signal violations, emergency brakes and locations [37], [38]. This information is required to monitor the traffic and following, improve energy and cost efficiencies within V-VLC environments. Currently, technologies that could be adopted for V2I communications are in their early stages and researchers are exploring V-VLC networks and data link layer, which are introducing new challenges [1].

1.2 Handover in indoor vehicular networks

In a vehicular network a handover occurs once the transmission is transferred from one AP to another one without losing connectivity [1]. In a V-VLC network a smooth handover requires a technique where the least handover outage duration (T_{hod}) can

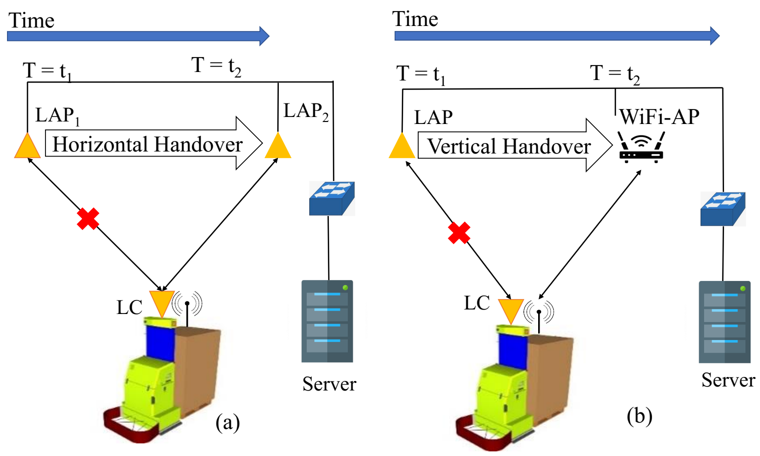


FIGURE 1.2 – Horizontal and vertical handovers in a vehicular network.

be achieved [39]. In this thesis, I refer to a horizontal handover when the handover takes place within the same network. In an industrial V-VLC network, it means an AGV disassociates from an LAP and associate to the next available LAP in the same network. However, in V-VLC networks there are some cases where T_{hod} takes longer than expected and there is a high demand for a substitute connectivity as a complementary wireless link. Here to this end, I introduce vertical handover, where an AGV loses its connectivity internally with all available LAPs and it connects to an AP from an external network. Therefore, a fast detection of link failure is significant in V-VLC network to establish a link connection with the least T_{hod} [1].
It is presented in Figure 1.2(a); horizontal handover occurs once the VLC link between LC and LAP_1 disconnects and a new VLC link establishes between the LC and LAP_2. Figure 1.2(b) presents an AGV experiences vertical handover once the already established link between LC and LAP disconnects and a Wireless Fidelity (WiFi) connection link establishes between WiFi antenna installed on AGV and AP. One of the main problems in V-VLC networks is how to minimize the T_{hod} during handovers. This means to reduce the time duration between the client switches links between access points. I discuss initially specific case of horizontal handovers considering mobility of AGV over a given path. A mobile device connects to the first VLC link on entering the first LAP coverage area and continues moving towards the next LAP coverage area. On entering the overlapping region, handover is initiated, and a new VLC link is established with the second LAP. In the case of shadowing, where the VLC Line-of-Sight (LOS) path experiences link failure (permanent or temporarily), handover is also initiated connecting AGV to the first available LAP. Therefore, to decrease the T_{hod}, the times required to detect link failure and to establish a new connection must be minimized. Two significant causes of V-VLC

handovers are mobility and shadowing/obstacle [40]. In mobility case, a complete link failure occurs due to connection lose. However, in case of shadowing, V-VLC faces with a sudden link blockage in most cases temporarily and experiences a link blockage [39]. Therefore, in a V-VLC network, not only it is important to detect the link failure as soon as possible but selecting between available channels and their methods are significant as well [39].

1.3 Hybrid network architecture

To guarantee coverage in a V-VLC network, there is a high demand to use many AP, and this causes a continuous dis-connectivity between AGV as clients and their associated AP, due to frequent handovers. Therefore, a fast detection of link failure is necessary in V-VLC networks [1]. Although VLC provides high data rates for vehicular connectivity, but it experiences frequent handovers which take place during link blockage, and mobility [41]. Therefore, it may not be considered as robust as RF networks but a complementary solution technique to WiFi networks [42], [43]. In addition, in industrial networks using an additional robust link connection like WiFi is critical, where V-VLC experiences failure. A fast detection of link failure is therefore necessary to trigger the vertical handover from VLC to a WiFi link [42].
In this thesis, I propose, evaluate and implement handover solutions separately on the data link and the transport layer and together as a combined solution in a two dimensional (2D) hybrid network using VLC and WiFi to tackle handover challenges in an indoor vehicular network environment [44]. As it is shown in Figure 1.3, it provides a combined architecture using Multipath-Transmission Control Protocol (MPTCP) in transport layer and Link aggregation method in data link Layer on top

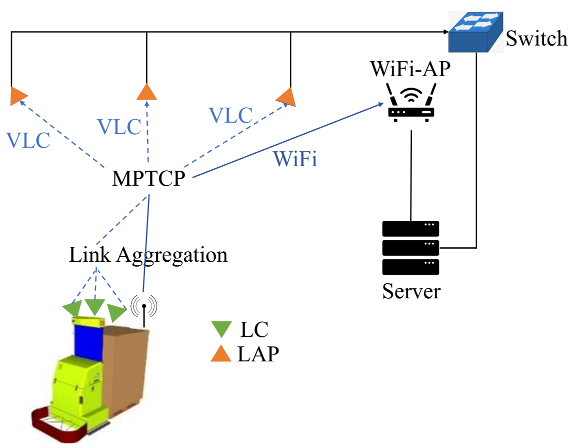


FIGURE 1.3 – Hybrid network architecture.

of VLC and WiFi networks.
Several works have addressed the mobility and handover challenges in the physical layer [45], [46] and upper layers [1], [21], [39], [47] for VLC networks. In addition there are several research works proposing hybrid handover solutions by making use of different wireless technologies [45], [48]–[53]. However, there is not a vast investigation on the upper layers specifically on Transport and data link layers for a hybrid VLC-WiFi indoor vehicular network [44].
As presented in Figure 1.3, I configure each AGV to act as a client establishing connection links with AP working rather using VLC, WiFi or both networks. In this way, I provide both up-link and down-link networks to work on either VLC, WiFi or both and choose the best connectivity among available links to decrease T_{hod} in this hybrid network. I make use of MPTCP to improve network throughput and the resource utilization by means of simultaneous use of several VLC and WiFi sub-flows [54]. In addition, I utilize link aggregation method in data link layer to combine several VLC network connections in parallel into a single virtual bonded interface. I also apply a Bonding mode called active-backup which improves the link reliability [1], [39] during VLC link blockage. In such a hybrid network, using WiFi connection as a backup link provides robustness to the vehicular network. Therefore, initially an AGV establishes its connection primarily through a VLC network and switches to WiFi alternatively, only when it experiences a VLC connection lost. As a result, a significant decrement of T_{hod} in both cases of horizontal and vertical handovers is achieved within an indoor vehicular network [44].

1.4 Summarizing the Contributions

Having described the scope of research in this Ph.D. undertaking, I now present the main contributions of this thesis.
As the first contribution of this Ph.D. thesis, I tackle handover issue in data link layer, introducing a low-latency handover system based on link aggregation or Ethernet bonding which decreases the handover delays, considerably. By means of experiments, I emulate and evaluate indoor mobile network scenarios using VLC technology. This solution has improved the network performance and can be utilized in industrial indoor scenarios where there is a high chance of frequent mobility, shadowing and link breakage within the network environment [1].
As the second contribution, I analyze Ethernet bonding schemes using different interface reselection methods [39]. The results show that using "failure" interface selection method instead of "always" method reduces the VLC handover outage duration by 62% and 44% in bonding schemes for Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) network traffics, respectively. Addition-

ally, I present that, the “failure” interface selection method has a greater impact in decreasing the outage duration during the possible handovers caused by shadowing within the network.

As the third contribution, I continue extending the architectural design to enable V-VLC to decrease handover delay in a 2D indoor industrial environments [55]. I configure VLC devices to establish links using the predefined frequency bands and aggregate Ethernet links on the client side. Therefore, in a V-VLC network and at any given time and direction, my proposal selects the best link established between the client and the server in both up- and down-link with the minimum handover delay times. I investigate and evaluate the performance of the proposed system using three different use case scenarios and traffic types to gain a better understanding of the mobility and handover in V-VLC networks. To this end, I develop a small-scale prototype and experimentally evaluate its performance for a variety of scenarios and compare the results with other handover techniques. I also assess the configuration options in more detail, focusing on different network traffic types and various address resolution protocol intervals. The measurement results demonstrate the advantages of my approach for low-outage duration handovers in V-VLC. The proposed approach can decrease the handover outage duration in a 2D network to about 0.2 s, which is considerably lower compared to previous solutions.

As the fourth contribution, I propose a novel architecture in transport layer, using MPTCP for a V-VLC network to improve the performance in terms of T_{hod} and throughout. Moreover, two relevant MPTCP schedulers and an MPTCP tool are selected to analyze V-VLC performance during the handover [47]. The results show that the proposed system offers low-outage duration handover of 24 ms and high data throughput of 125 Mbps using “Redundant“ and “Default“ schedulers, respectively.

As the fifth and final contribution, I propose a hybrid handover solution called Li-Wi in a 2D network for an industrial environment and tackle mobility and V-VLC handover challenges both in data link and transport layers [44]. I configure each AGV to act as a client establishing connection links with APs working rather using VLC or WiFi networks. Additionally, I add robustness to the V-VLC network using WiFi connections. Therefore, I consider an AGV establishes its connection initially through a VLC network and switch to WiFi alternatively, only when it experiences a VLC connection lost. In Li-Wi [44], I utilize the benefits of high data rate transmission of VLC and the reliable connectivity of WiFi to provide robust connectivity with a low handover outage duration and a high network throughput. Based on experimental evaluation results using a small-scale prototype, I demonstrate the advantage of my approach. The experiments reveal that Li-Wi is highly efficient minimizing T_{hod} to 0.03 s and 0.06 s for horizontal and vertical handovers in an indoor vehicular network, respectively.

1.5 Structure of the Thesis

Within the scope of this Ph.D. dissertation, I propose and develop handover techniques in upper layers using VLC as a primary and WiFi as a backup network, with the aim to reduce V-VLC handover outage duration and increase network reliability and robustness in an indoor vehicular network.

I propose an initial handover solution using only VLC in data link layer which works for AGV with linear movements in an indoor environment, called Flexible Light Communications (Flight) [1]. Flight decreases the handover outage duration considerably compared to when there is no handover technique is used. To improve the outage duration in very frequent handovers caused by shadow, I analyze interface bonding schemes using different primary interface reselection methods and show how it has a greater impact in decreasing the outage duration during the possible handovers caused by shadowing within the network [39].

Later, I extend the Flight architecture increasing VLC transmitters per each AGV [55] to decrease handover delay also in two-dimensional (2D) V-VLC network.

I also proposed a network architecture to address handover issue for V-VLC network utilizing MPTCP in the transport layer on VLC network for the first time. The proposal provides low-outage duration handover and high data throughput using different MPTCP schedulers and tools [47].

Finally, to provide a more reliable and robust vehicular network and minimize the handover outage duration even further, I propose a hybrid handover solution called Li-Wi [44] as a combined version of mentioned proposals and using WiFi as a backup network to VLC in indoor vehicular network environments. Li-Wi achieves a considerably low handover latency for both handover cases of vertical and horizontal. Moreover, it provides a more reliable vehicular network use of link availability of WiFi connection. Following, it presents the organization of the thesis including 6 chapters.

After introducing the thesis's scope and its main contribution in Chapter 2, I present the first handover solution technique in data link layer for V-VLC networks in Chapter 2 [1]. Firstly, it explains how VLC can be used in vehicular communications network and what are the challenges it faces with. Later, related works are well described. After, I introduce our proposed network architecture called Flight and explain how it performs using VLC links. Moreover, I cover channel selection method descriptions and their difference in case of handover due to shadowing and mobility use cases [39]. In addition, I present the experimental results which are based on real test-bed implementations to demonstrate Flight network performance using different network traffic, in case of mobility and shadowing.

Chapter 3 covers a novel frequency diversity and link aggregation solution for handover in a 2D indoor vehicular VLC network called FDLA [55]. Initially, I introduce the related work by explaining the handover techniques generally in wireless networks. I compare the proposed system's performance with the state of the art. Later, I address problem definition and what our proposed system aims to do. Moreover, I describe FDLA network architecture in details and define three scenarios where our V-VLC network experiences a single VLC link failure, two VLC link lost concurrently and change of direction and lose of two VLC link connections, respectively. In addition, I explain FDLA system concept and show practical experimental results for each mentioned use case scenarios.

Chapter 4 describes a flexible transport layer protocol architecture for handover in vehicular VLC networks [47]. First, it overviews the related works and specifies the main motivation behind this work. Later, it well describes how to perform MPTCP in a V-VLC network. And I show the experimental results that how MPTCP tackles mobility issue in transport layer using different schedulers and tools.

Chapter 5 introduces an upper layer hybrid VLC-WiFi network handover solution called Li-Wi [44]. firstly, I overview the related work and problem statement with a hybrid network as a vehicular network using both VLC and WiFi technologies. Later, I describe Li-Wi network architecture in three layers of Physical, data link and transport. After, I demonstrate architecture of different network experiments using aggregation method, MPTCP and Li-Wi addressing vertical and horizontal handovers. I also, cover cell planning which is required to plan our V-VLC network, efficiently. Within cell planning, I analyze the light coverage profile, calculate the effective cell size, and light density per cell and analyze time for handover. After, I show experimental results for each test-bed setup and compare them with Li-Wi performance in a hybrid network.

Finally, in Chapter 6, I conclude the thesis and present the future works.

1.6 Publications

The research results derived during this Ph.D. study have been submitted and published in scientific journals and presented in a series of international conferences. This section lists the peer-reviewed publications which I have worked on during my Ph.D. thesis.

1.6.1 Publications This Thesis is Based On

Specifically, this thesis is based on the technical content presented in the following publications:

1. E. Alizadeh Jarchlo, S. M. Kouhini, H. Doroud, G. Maierbacher, M. Jung, B. Siessegger, Z. Ghassemlooy, A. Zubow, and G. Caire, "Flight: A Flexible Light

Communications network architecture for indoor environments," in *15th International Conference on Telecommunications (ConTEL 2019)*, Graz, Austria: IEEE, Jul. 2019. DOI: 10.1109/contel.2019.8848541

In this publication I present a flexible network architecture for indoor environments named flexible light (Flight), which is designed for VLC to tackle existing mobility and handover challenges in the network environment.

2. E. Alizadeh Jarchlo, S. M. Kouhini, H. Doroud, E. Eso, P. Gawłowicz, M. Zhang, B. Siessegger, M. Jung, Z. Ghassemlooy, G. Caire, and A. Zubow, "Analyzing Interface Bonding Schemes for VLC with Mobility and Shadowing," in *12th IEEE/IET International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP 2020)*, Virtual Conference: IEEE, Jul. 2020. DOI: 10.1109/CSNDSP49049.2020.9249515

   In this paper I aim to improve the outage duration in handover caused by mobility and shadow for VLC networks. I analyze interface bonding schemes using two different primary interface reselection methods.

3. E. Alizadeh Jarchlo, P. Gawłowicz, H. Doroud, B. Siessegger, M. Jung, G. Caire, A. Zubow, and Z. Ghassemlooy, "A Flexible Transport Layer Protocol Architecture for Handover in a Vehicular VLC Network," in *12th IEEE/IET International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP 2020)*, Virtual Conference: IEEE, Jul. 2020. DOI: 10.1109/CSNDSP49049.2020.9249575

   I propose a novel architecture using MPTCP for a vehicular visible light communications (VLC) network to improve the performance in terms of network outage duration and throughout.

4. E. Alizadeh Jarchlo, E. Eso, H. Doroud, A. Zubow, F. Dressler, Z. Ghassemlooy, B. Siessegger, and G. Caire, "FDLA: A Novel Frequency Diversity and Link Aggregation Solution for Handover in an Indoor Vehicular VLC Network," *IEEE Transactions on Network and Service Management*, 2021. DOI: 10.1109/TNSM.2021.3075476

   In this publication I propose a frequency diversity and link aggregation solution, which is a technique in data link layer to tackle handover challenge in indoor V-VLC networks. The proposed idea can decrease the handover outage duration in a two-dimensional network considerably lower compared to previous solutions.

5. E. Alizadeh Jarchlo, E. Eso, H. Doroud, B. Siessegger, Z. Ghassemlooy, G. Caire, and F. Dressler, "Li-Wi: An Upper Layer Hybrid VLC-WiFi Network Han-

dover Solution," *Elsevier Ad Hoc Networks*, vol. 124, p. 102 705, Jan. 2022. DOI: 10.1016/j.adhoc.2021.102705

For this publication I propose an upper layer hybrid VLC-WiFi network handover solution known as "Li-Wi" to address the handover issues in V-VLC network. Li-Wi is highly efficient in minimizing handover outage duration in a hybrid vehicular network for both horizontal and vertical handovers.

1.6.2 Additional Publications

During my Ph.D. studies I further co-authored the following peer-reviewed papers:

6. E. Alizadeh Jarchlo, X. Tang, H. Doroud, V. P. G. Jimenez, B. Lin, P. Casari, and Z. Ghassemlooy, "Li-Tect: 3-D Monitoring and Shape Detection Using Visible Light Sensors," *IEEE Sensors Journal*, vol. 19, no. 3, pp. 940–949, Feb. 2019. DOI: 10.1109/jsen.2018.2879398

7. P. Gawlowicz, E. Alizadeh Jarchlo, and A. Zubow, "Bringing MIMO to VLC using COTS WiFi," in *IEEE International Conference on Communications (ICC 2020), IEEE Workshop on Optical Wireless Communications (OWC 2020)*, Virtual Conference: IEEE, Jun. 2020. DOI: 10.1109/ICCWorkshops49005.2020.9145232

8. P. Gawłowicz, E. Alizadeh Jarchlo, and A. Zubow, "Practical MIMO for Visible Light Communication," arXiv, cs.NI 2002.00808, Feb. 2020

9. P. Gawlowicz, E. Alizadeh Jarchlo, and A. Zubow, "WiFi over VLC using COTS Devices," in *39th IEEE International Conference on Computer Communications (INFOCOM 2020), IEEE Workshop on Computer and Networking Experimental Research using Testbeds (CNERT 2020)*, Virtual Conference: IEEE, Jul. 2020. DOI: 10.1109/INFOCOMWKSHPS50562.2020.9163042

10. P. Gawlowicz, E. Alizadeh Jarchlo, and A. Zubow, "WoV: WiFi-based VLC testbed," arXiv, cs.NI 2001.08489, Jan. 2020

11. S. M. Kouhini, E. Alizadeh Jarchlo, R. Ferreira, S. Khademi, G. Maierbacher, B. Siessegger, D. Schulz, J. Hilt, P. Hellwig, and V. Jungnickel, "Use of Plastic Optical Fibers for Distributed MIMO in Li-Fi Systems," in *IEEE Global LIFI Congress (GLC 2019)*, Paris, France: IEEE, Jun. 2019. DOI: 10.1109/GLC.2019.8864130

12. H. B. Eldeeb, E. Eso, E. Alizadeh Jarchlo, S. Zvanovec, M. Uysal, Z. Ghassemlooy, and J. Sathian, "Vehicular VLC: A Ray Tracing Study Based on Measured Radiation Patterns of Commercial Taillights," *IEEE Photonics Technology Letters*, Mar. 2021. DOI: 10.1109/LPT.2021.3065233

13. E. Eso, E. Alizadeh Jarchlo, Z. Ghassemlooy, S. Zvanovec, F. Dressler, and J. Sathian, “Performance Analysis of Indoor Vehicular VLC Links for Autonomous Driving,” in *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC 2021), Workshop on Optical Wireless Technology for Enhanced Connectivity in 6G (OWTEC 2021)*, to appear, Virtual Conference: IEEE, Sep. 2021

Chapter 2

Flight: A Flexible Light Communications network architecture for indoor environments

This chapter introduces my proposed early network architecture to address handover issue in vehicular VLC (V-VLC) network environment. This chapter briefly overviews related approaches using light and Radio Frequency (RF) techniques. I also present the proposed network architecture in VLC systems and the practical experimental results and finally, I conclude the chapter.

2.1 Using VLC in an indoor vehicular network

One of the main processes in industries is the automation, which has gone through radical changes by the introduction of robots, and Automated Guided Vehicles (AGV) to improve efficiency and quality of products and services decrease energy consumption and increase the revenue (i.e., the profit margins) [33]. The AGV can communicate using wired and wireless technologies [62] based on the demands of a company and the processes involved. Compared to wired technologies, a wireless transmission offers improved mobility and simplified scalability within the process environment [1]. Visible Light Communications (VLC) is one possible wireless technology, which can be effectively utilized for establishing robust communications for AGV-to-AGV communications within industrial enthronements at a low cost and high-flexibility [1].

Due to the high mobility of AGV in an indoor industrial environment, there is a strong possibility for the communication links to being lost due to shadowing, obstacle, and possible handovers within the wireless network [1]. Therefore, there is a need for networks with high levels reliability and low latency to provide a robust network with high rates (i.e., throughput) [63] to address the mentioned problems. In [64], to achieve 100mm path accuracy, it is demanded for an overall latency of 50 ms, including the processing latency. Considering that Light Access points (LAP) have a limited transmission range and there is a high demand for VLC transceivers to stay aligned to maintain the connectivity, a highly dense LAP grid is required to provide a seamless coverage in an indoor environment. However, there will be frequent handovers taking place in an indoor environment, which results in network disruptions up to several seconds during the handover process. This work proposes a flexible network architecture, which reduces the handover latency to a few hundreds of milliseconds, thus leading to improved quality of services [1].

2.2 Related works

Several research works focused on the handover in VLC mobile networks have been reported. In [65] a simulation-based handover management approach has been proposed based on the received signal intensity, for both overlapping and non-overlapping lighting scenarios. It was based on the buffer size adjustment, handover initiation before breaking the connection and finding a new neighboring cell before exiting the serving light cell.

In [66] a handover procedure was proposed based on a pre-handover scheme that relies on position estimation obtained by visible light positioning and motion tracking with Kalman filters. In [67] power and frequency-based horizontal handover methods were proposed to reduce data rate fluctuations as the mobile device moves from one cell to another. The statistical distribution of the received data rate was also studied using computer simulations. In [68] a handover algorithm was proposed with the aim of extending the transmission bandwidth by minimizing the multipath induced dispersion of the VLC channel. For a multi-cell network, the algorithm deactivates those cells that do not cover the mobile user to decrease the overall root mean square delay spread. In [69] an implementation of a hybrid communications system supporting vertical handover between VLC and RF was presented. The hybrid system can efficiently monitor its primary VLC link and quickly switch to the RF link whenever the primary link is failed. Decision-making and link-monitoring schemes in between network and data-link layers were also defined to enable efficient handover.

In this chapter, I make use of VLC transceivers, which benefit from aggregation/networking features in a typical indoor network, where the out-of-band handover is achieved for different handover latencies, as required by an application. Moreover, I have implemented the proposed scheme using VLC for both uplink [70] and down-

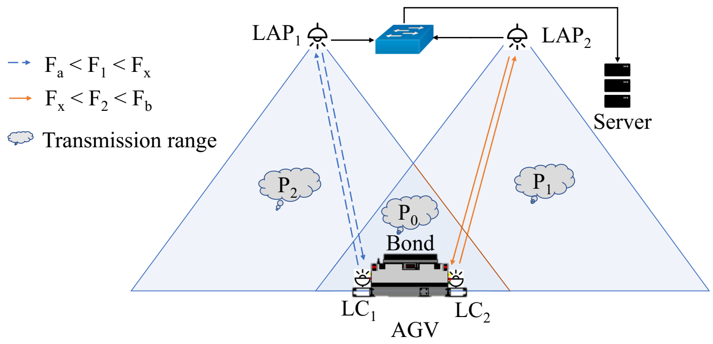


FIGURE 2.1 – Flight network architecture [1].

link.

2.3 Flight network architecture

A Flexible Light Communications network architecture for indoor environments called Flight network architecture is shown in Figure 2.1 [1] , which provides V-VLC for an indoor industrial network environment. An AGV has both windows and Linux machines installed on the mini-PC which is located on it. Additionally, it is equipped with two VLC transceivers, which act as Light Clients (LC). LC connect to the ceiling-mounted LAP, which in turn connect to a server (with a Linux operation system) via a configurable switch and a wired backbone network. P_1 and P_2 are the transmission ranges for LAP_1 and LAP_2, respectively. And P_0 is the mutual transmission range between the two LAP. As it is shown, there are two full-duplex links between the AGV's LC and LAP which are configured on two different frequency ranges as F_1 and F_2. The AGV can move linearly entering in P_1, passing through P_0 and exiting from P_2 area. Finally, the logical bond interface is configured on top of the two Ethernet interfaces of LC, which provides VLC network for the AGV to connect to the server.

Given that the cell sizes in VLC networks are much smaller than the RF-based cellular systems, the required number of densely deployed indoor LAPs is therefore high, thus the need for an efficient mobility management procedure. In this work, I propose a simple and flexible practical solution which facilitates the use of VLC devices and a software solution configured based hardware. To this end, I have adopted Frequency Division Multiple Access (FDMA) and Linux network bonding feature, which are described in the following subsections.

2.3.1 FDMA in VLC network

Assuming the VLC spectrum is with the range of F_a (MHz) to F_b (MHz) and a frequency F_x lies between F_a and F_b, the first and second frequency bands of F_1 and F_2 are defined as F_a - F_x and F_x - F_b. For each LC, the corresponding LAP and the other pair are configured to operate at F_1 and F_2 frequency bands, respectively. LAP_2 and LC_2 are configured to perform between 4 to 52 MHz, which are F_a and F_x, respectively. And LAP_1 and LC_1 perform between 52 to 96 MHz, which 96 is F_b in this scenario. It is also mentionable that we configured LAPs and LCs to perform on that specific frequency ranges using a provided software designed to modify the devices configurations.
Therefore, once the AGV enters the P_1 area, LC_2 connects to LAP_2 on F_2 frequency band and once the AGV arrives at P_0 , there will be two parallel VLC active links between the LCs and corresponding LAPs as shown in Figure 2.1 [1]. Finally, when the AGV continues towards to P_2 area, the link between LC_2 and LAP_2 breaks and only the link between LC_1 and LAP_1 on F_1 frequency band remains active.

2.3.2 Link aggregation in VLC

In order to improve the network outage during handover, link aggregation is implemented at the Ethernet interface level of the AGV and the Datalink layer at LCs. Link aggregation, or Ethernet bonding, is about combining several network connections in parallel into a single virtual bonded interface. Depends on the mode chosen for the bonded interface, it offers redundancy in the case of link blocking or load balancing and linear scaling of bandwidth, thus improving link reliability. Different modes of link aggregations are explained below [1][1]:

- Mode 0 - balance-rr: Transmits packets in a sequential order from the first available slave through to the last. This mode provides load balancing and fault tolerance.

- Mode 1 - active-backup: Only one slave in the bond is active. A different slave becomes active if, and only if, the active slave fails. This mode provides fault tolerance.

- Mode 2 - Here bitwise XOR operation of the source and destination Medium Access Control (MAC) addresses are carried out to provide load balancing and fault tolerance.

- Mode 3 - broadcast: Transmits everything on all slave interfaces which provides fault tolerance.

[1] http://knowledgebase.45drives.com/kb/implementing-network-bonding-on-centos-7/

- Mode 4 - 802.3ad: Creates aggregation groups, which share the same speed and duplex settings. Utilizes all slaves in the active aggregator according to the 802.3ad specification.
- Mode 5 - balance-tlb: The outgoing traffic is distributed according to the current load (computed relative to the speed) on each slave. Incoming traffic is received by the current slave. If the receiving slave fails, another slave takes over the MAC address of the failed receiving slave.
- Mode 6 - balance-alb: It is like mode 5 but the received load balancing is achieved by Address Resolution Protocol (ARP) negotiation. The bonding driver intercepts the ARP Replies sent by the local system on their way out.

In this work, I have adopted the active-backup mode to avoid network disruption due to link blockage once shadowing. In this case, only one of the links of the AGV is active. In the case of link unavailability, the second LC link will be used. The reason behind choosing this mode, is that active-backup mode provides the network fault tolerance.
The used VLC devices have the potential of offering real-time bidirectional communications at 100 Mbit/s over a transmission distance of 10 m. The VLC devices have been developed for a separate project in OSRAM, which is based on Orthogonal Frequency Division Multiplexing (OFDM) [71], [72] and G.hn standard [73]. The analogue board has been customized to provide a high optical transmit power and high sensitivity using off-the-shelf high-power LEDs (OSRAM SFH 4715 AS) and large-area silicon photodiodes (Photo-Detector (PD), Hamamatsu S6968).

2.4 Channel selection method description

Using Linux network bonding method, I consider two methods to detect the path failure and reselect the active link in the bonding setup. In this approach, I can specify how the active link is selected as a primary interface and in case of its failure how the bond interface switches to the slave link. In the first method, which is based on the default values in network bonding, the defined primary link is always the active link. This is called “always” in this work, which refers to the slave link being active when the primary link is down. Note that, when the primary link becomes available the bond interface selects it always as a new active link. In the second method, named “failure” in this work, the primary slave becomes the active slave only if the current active slave fails.
There are pros and cons with two methods outlined before. Depending on the V-VLC network setup and architecture and the defined ARP interval value, the two methods

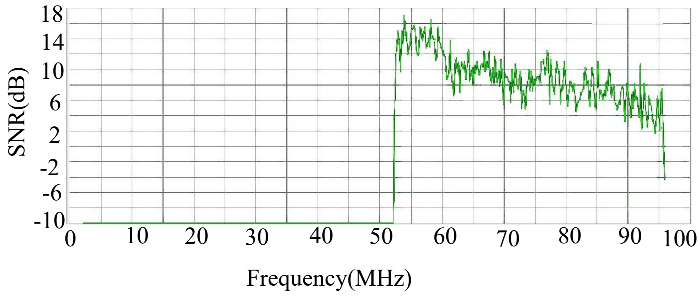
may or may not improve the throughput. In case of using the "always", the bond interface has the advantage of monitoring the primary link and making it the active link. Therefore, no need to measure the link's parameters on a continuous base. In this case, depending on the failure time length of the primary link, one can flip between the predefined primary and slave links. For longer primary failure time, the link switching within the V-VLC network is reduced. The other significant advantage is no path bouncing that might occur in the network using small ARP interval values. However, the major disadvantage is when the primary link experiences blocking due to shadowing and, where the link is no longer available for a short period. In this case, the primary reselection procedure takes place twice within a very short time duration, which may result in lost packets. The "failure" method has an advantage of bouncing avoidance between primary and current slave interface and with no planned switching to the primary link once it comes up. This helps to provide a more robust VLC connection. The disadvantage is when the quality of the current salve becomes poor, and it will not switch until the current slave is not yet disconnected.

2.5 Experimental Results

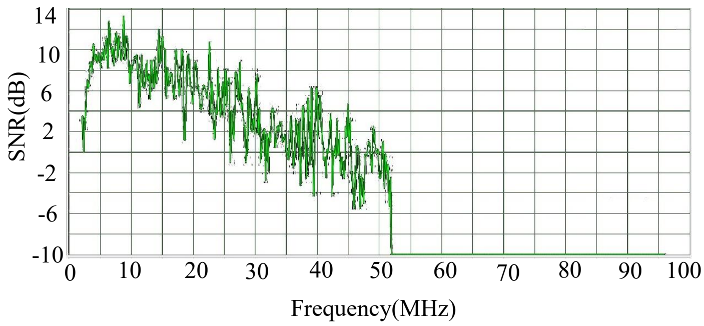
In this section, I demonstrate the experimental results of Flight architecture in a linear scenario and evaluate the handover duration using two methods of "always" and "failure" for the primary interface selection during V-VLC handover.

2.5.1 Flight performance

The proposed system architecture is experimentally implemented by developing a prototype to validate its performance. A linear scenario using a bi-directional full duplex link has been emulated where the handover time and the system throughput are evaluated once an AGV passes through two LAP transmission ranges. The prototype units are configured to work in the same network subnet as 192.168.10.x. The purpose of this network setup is to provide a flexible robust connectivity between the AGV and the server regardless of the device's mobility and handovers between LAP. Link aggregation has been configured on a mini-PC installed on the AGV. Within this setup, I configured a bond logical interface on top of two physical Ethernet interfaces of the PC, which are connected to LC using Ethernet cables. An active-backup mode was chosen in the bonding configuration during experimental investigation. The link between LC_1 and LAP_1 was chosen to be in the active mode and the link between LC_2 and LAP_2 was configured to work as a backup mode. In case of failure of the active link, the bond interface switches on the backup link and continues functioning seamlessly.



(a)



(b)

FIGURE 2.2 – SNR for the link connection between (a) LC_1 and LAP_1, (b) LC_2 and LAP_2 [1].

Link monitoring for the bond interface was enabled through ARP monitoring, which was enabled at different frequencies, therefore different handover latencies were experienced. The logical bond interface polls the ARP target every *T* millisecond and waits for the ARP replies through its physically configured Ethernet interfaces at the bond interface. Based on successful acknowledgement from ARP, the bond interface decides on which physical Ethernet interface should be used to send or receive information. Since, the bond interface is configured in the active-backup mode, it uses the active link to send/receive traffic if the active link transmits the acknowledgement from ARP. When the active link does not provide acknowledgement from ARP, the bond interface sends/receives traffic at the backup link provided the backup link provides acknowledgement from the ARP.

Figure 2.2a and Figure 2.2b [1] show the signal-to-noise ratio (SNR) performance for connection links between LC_1 and LAP_1 and LC_2 and LAP_2, respectively [1]. In this setup LAP and LC were in a distance of half a meter away from each other.

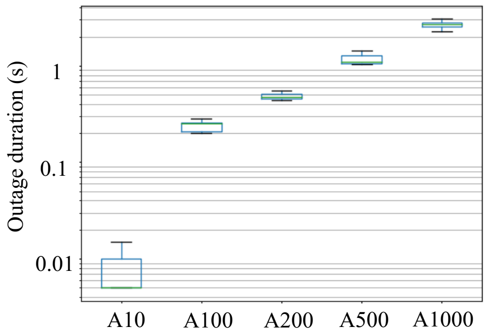


FIGURE 2.3 – UDP Outage duration due to handover. A10, A100, A200, A500 and A1000 show the used ARP intervals as 10, 100, 200, 500 and 1000, respectively [1].

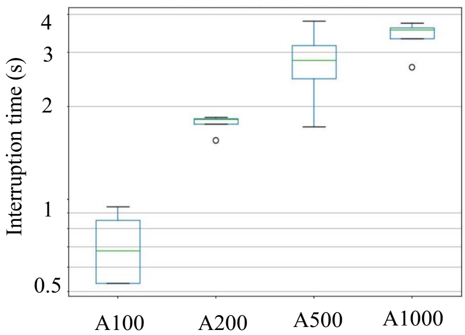


FIGURE 2.4 – ICMP interruption time due to handover. A10, A100, A200, A500 and A1000 show the used ARP intervals as 10, 100, 200, 500 and 1000, respectively [1].

The reason to show this figure is to demonstrate that there is no conflict between the assigned frequency ranges for the links and two independent active connection links are established while an AGV is located within the mutual transmission range of two LAP.
Three network traffic types; Transmission Control Protocol (TCP), User Datagram Protocol (UDP) and Internet Control Message Protocol (ICMP) are chosen to evaluate the performance of the proposed network architecture for both uplink and downlink in an indoor environment. Figure 2.3 [1], presents the measured outage duration for each set of ARP intervals for UDP packets, which obtained using the

Internet Performance Working Group (Iperf) tool. The server machine is configured as an Iperf server using the following command:

```
$iperf -s -u -i 0.005
```

and the mini-PC installed on the AGV is configured as an Iperf client using the command below:

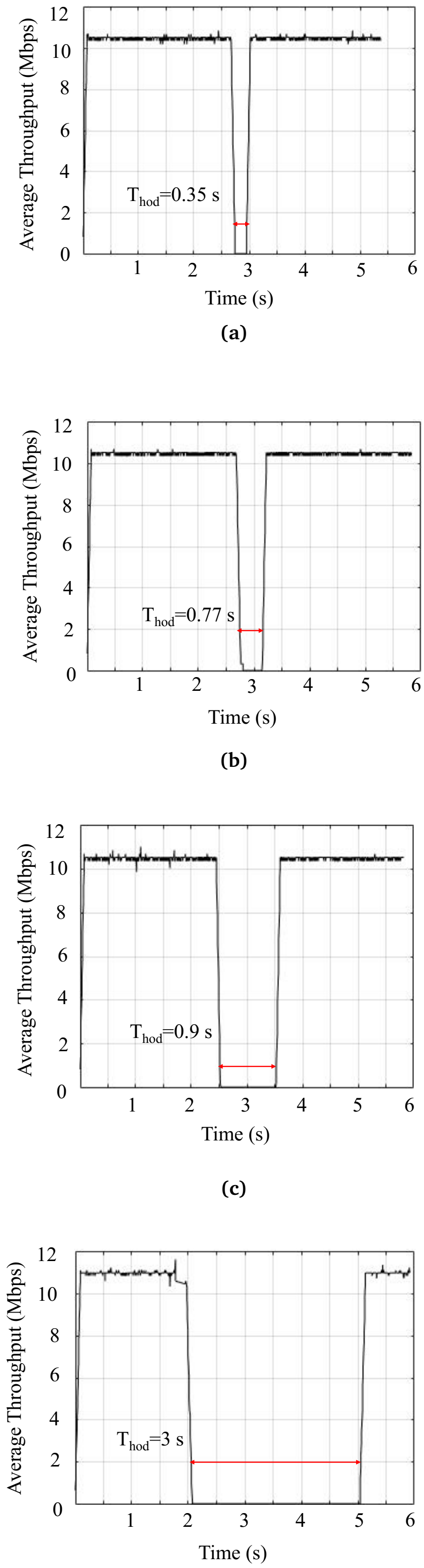
```
$ iperf -c 192.168.10.2 -u
```

where *-s* means to run in server mode, *-u* specifies using UDP packets rather than TCP, *-i* means pauses between periodic bandwidth reports in seconds and *-c* is to run in client mode. In this setup, there is an uplink transmitting packets from the AGV (Linux machine) to the server with the interval of 5 ms at 10 Mbit/sec.
As a result, the outage duration T_{hod} achieved using ARP interval equals to 10 ms decreases the handover latency considerably to less than a hundred of milliseconds. Obviously, increasing the ARP interval values causes the higher outage duration in the network.
Figure 2.4 [1] depicts the measured interruption time for the ICMP traffic. Interruption time is the time difference between the last received Packet Internet Groper (Ping) prior to handover and the first Ping request following handover. The size of ICMP packets is 100 bytes, and they are transmitted every 5 ms from server to the AGV (windows machine) using downlink using the following command:

```
$ fping 192.168.10.40 -t5 -n500 -T -s100
```

where *-t* means time interval between two Ping in milliseconds, *-n* means the number of Ping to send to each host, *-T* shows the timestamp with each reply and *-s* specifies the amount of data in byte. As it is shown in Figure 2.4 [1], using ARP interval of 100 ms decreases the interruption time for Ping to less than 1 second and by increasing the ARP intervals, the interruption time grows considerably. The experiment has been repeated for five times and as Figure 2.4 and Figure 2.3 [1] show, each box presents the min, max, mid, first and third quarters of the obtained results to prove that the achieved results are not randomly obtained.

Figure 2.5 [1] presents the average throughput and T_{hod} for four UDP traffics while using different ARP intervals. The same command setup is configured as utilized in Figure 2.3 [1]. As it is shown, the network throughput in Figure 2.5a, Figure 2.5b, Figure 2.5c and Figure 2.5d [1] are almost the same before and after the handover takes place. However, the T_{hod} which are shown as gaps in the graphs



(a)

(b)

(c)

(d)

FIGURE 2.5 – UDP average throughput vs. time. (a), (b), (c) and (d) use ARP intervals 0.1, 0.2, 0.5 and 1 seconds, and perform handover at t= 2.69, 2.60, 2.46 and 1.99 second respectively [1].

Table 2.1 – T_{hod} vs. ARP interval values using TCP [1].

ARP interval (ms)	***100***	***200***	***500***	***1000***
$T_{hod}(s)$	0.52	1.1	3	3.3

are increasing due to ARP interval increments.

Table 2.1 shows the TCP T_{hod} for the same ARP intervals as in Figure 2.5 [1] and for the UDP traffic. The experimental measurement results are obtained using Iperf tool. In this setup, the AGV (Linux machine) is configured as an Iperf client since the server machine is configured to work as a Iperf server. It is mentionable that in section, we repeated each experiment 10 times in order to achieve an average for throughput vs time for our V-VLC network. In order to configure the network, the following commands are used for Iperf client and server mode, respectively:

```
$ iperf -c 192.168.10.2 -w65535 -t6 -b 10m
```

and `$ iperf -s -i 0.005 -w65535`

where the *-w* is TCP window size, *-t* is the time to listen for new traffic connections, receive/transmit traffic and *-b* sets target bandwidth to n bits/sec.
As shown in Table 2.1, the achieved T_{hod} using ARP 100 ms is much lower than once I send less frequent ARP requests to the ARP target. Therefore, transmitting ARP request every 100 ms gives us the lowest value for T_{hod} .
As the results illustrate the proposed network architecture improves the network robustness and decreases the T_{hod} during the handover. Thus, leading to improved network stability for uplink and downlink. However, to achieve the reasonably low outage duration based on the project's demand, it is needed to use a rather lower ARP intervals.

2.5.2 Analyzing Flight in shadowing and Mobility scenarios

As outlined earlier, in V-VLC networks the handover is due to the mobility and shadowing. In this work [39], I consider both possible link blockage scenarios and using an experimental prototype evaluate the handover duration for the two methods of "always" and "failure".
It is worth mentioning that, in all experiments I implement the Flight architecture as presented in Figure 2.1 [39] and consider the ARP monitoring method for detecting the VLC link failure. ARP is chosen since it performs based on communications

Table 2.2 – Experimental parameters [39]

Parameter	Value
ARP interval	100 ms
Pauses between periodic bandwidth	5 ms
ICMP packet size	100 bytes
Number of ICMP packet for transmission	1000
LC_1 and LAP_1 frequency range	4-52 MHz
LC_2 and LAP_2 frequency range	52-96 MHz
LC's field of view	60 degrees
Distance between LCs and LAPs	50 cm

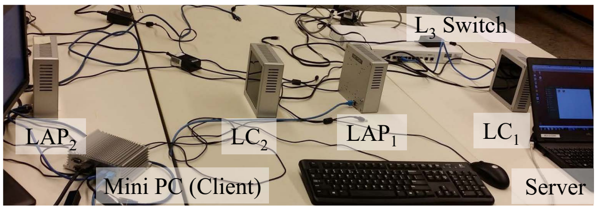
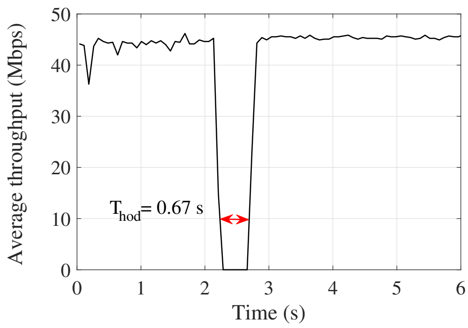


FIGURE **2.6** – Flight prototype [39]

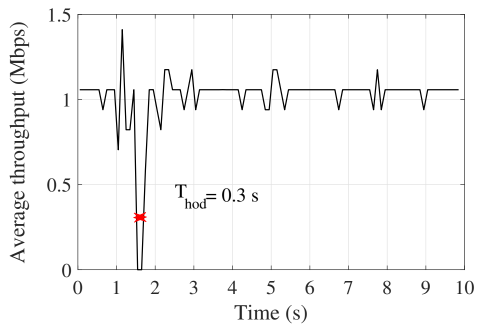
to the predefined ARP target and can detect the link failure even if the link is beyond the nearest connected switch. The variable parameters are ***(i)*** a method of interface selection while bonding; ***(ii)*** mobility and shadowing use case scenarios; and ***(iii)*** transmitting three different network traffics as TCP, UDP and ICMP. Each experiment is repeated ten times to ensure consistency. Table 2.2 presents the key experimental parameters. In addition, Figure 2.6 [39] demonstrates the Flight prototype which is composed of a pair of OSRAM VLC units operating at F_1 frequency band as a LAP and LC in the V-VLC network.

2.5.3 Channel selection in mobility

In these experiments, I have used the topology shown in Figure 2.1 [39]. We emulate a complete link failure due to mobility by a manual link blockage. We consider two selection methods for the primary interface as "failure" and "always" for the bonding configuration.
Experiment 1 - "always": To evaluate and measure the network throughput for unicast and broadcast transmissions for the uplink (i.e., AGV and the remote server), both TCP and UDP packets are generated and transmitted, separately. The average throughput for TCP, UDP and T_{hod}s are shown in Figure 2.7 [39]. Note that, the drop in the throughput is due to handover. For TCP it will take 0.67 s to establish



(a) TCP



(b) UDP

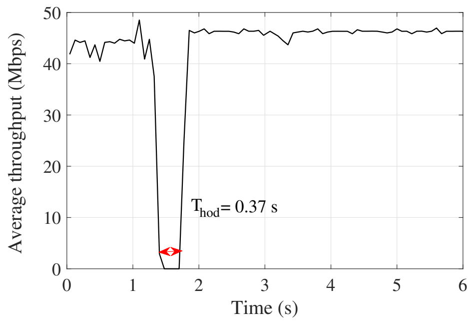
FIGURE 2.7 – "Always" Channel selection method in mobility use case [39].

a new VLC link with the next available LAP. Whereas for UDP, it will take 0.3 s for the bond interface to switch over the slave backup link and establish a new VLC connection via the next LAP.

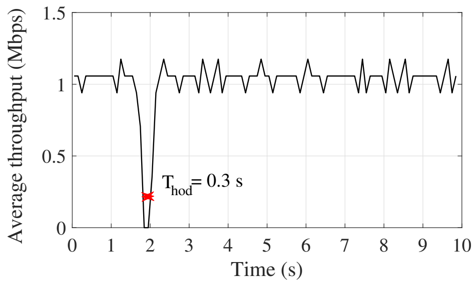
Experiment 2 - “failure”: Here, the bonding configuration is setup to use “failure” as the primary interface reselection method. As shown in Figure 2.8 [39], both schemes display the same throughput profiles. This is because with AGV moving between different LAPs coverage areas the primary connection is lost and therefore there is no option for the AGV to reconnect to the first primary interface. Note, the T_{hod} stays almost the same in case of UDP when using the “always” channel selection method. However, we observe an improvement for achieved T_{hod} in case of using TCP traffic type using “failure”.

2.5.4 Channel selection in shadow

In this subsection, I consider shadowing to evaluate the performance of the two channel selection methods considering the handover. We emulate shadowing by



(a) TCP

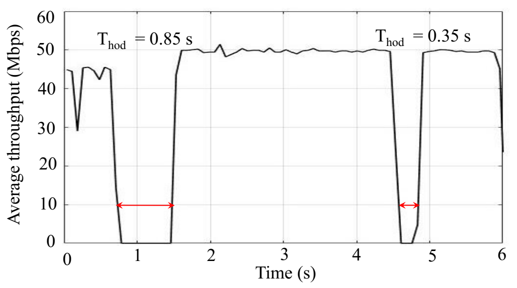


(b) UDP

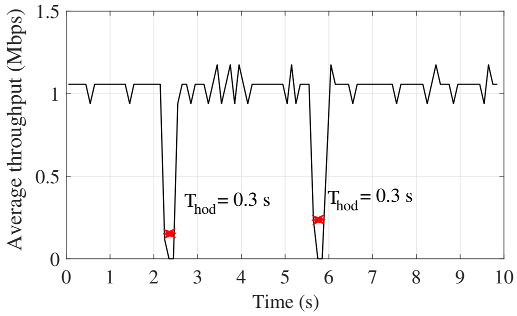
FIGURE 2.8 – "Failure" Channel selection method in mobility use case [39].

blocking the link temporarily for a couple of seconds.

Experiment 3: Here, I show that, under shadowing-imposed link blockage, which last for a very short time, the default channel selection method of "always" does not perform well. This is because, with shadowing the bond interface connectivity via the primary link is lost and the slave link is used as the backup VLC link. However, shadowing may not last long and therefore the primary link will once again become available. Note, the bond interface will need to flip back to the primary interface, which is the default link for the "always" channel selection method. In this case, the V-VLC network will experience two link losses with increased handover delay time. Figure 2.9 [39] shows the link throughput during handover under shadowing using "always" channel selection method for TCP and UDP packets transmissions while AGV is connected to the remote server. Note, for TCP the throughput is for the uplink (i.e., AGV to the remote server). AS shown in Figure 2.9 [39], there are two notches in the throughput. This is because ***(i)*** for TCP the channel selection method was set to "always", which results in connection loss during the handover. Therefore, I observe an increased value as 1.34 s for the T_{hod}. And ***(ii)*** for UDP, the interface selection happening twice due to shadowing and the handover network outage increases up to 0.6 s in total due to the extra channel switching in the V-VLC network.



(a) TCP



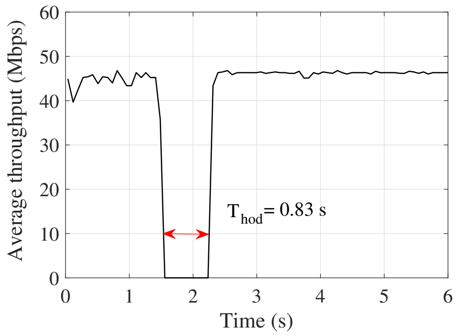
(b) UDP

FIGURE 2.9 – "Always" Channel selection method in shadow use case [39].

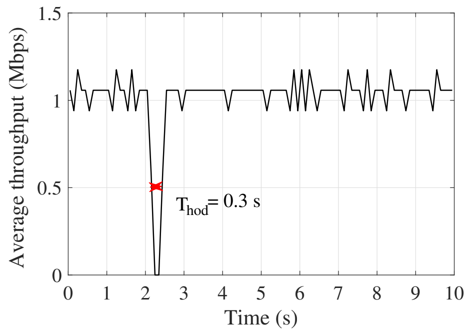
Experiment 4: This investigates the shadowing effects in order to block the V-VLC link using the "failure" channel selection method configured on top of the bond interface on AGV. Figure 2.10a [39] the TCP traffic is transmitted, and shadow caused a handover which occurs after the first second of the measurement. Using a "failure" channel selection method improves the handover network outage in comparison using "always" method. It decreases the TCP handover network outage up to 0.83 s which is almost two times less than when "always" method as a default method was used. Moreover, in Figure 2.10b [39] an impact of "failure" primary reselection method has been shown in a shadow use case during UDP traffic transmission. As it is shown the throughput turns to zero once shadow occurs and the bond interface dose not switch to the primary link right after it becomes available, and it leads to the handover network outage improvement to 0.3 s.

2.5.5 V-VLC link quality in both shadow and mobility use cases

To monitor and check the VLC link quality during the handover caused by shadow and mobility in the V-VLC network environment, I evaluate the link quality via Fast



(a) TCP



(b) UDP

FIGURE **2.10** – "Failure" Channel selection method in shadow use case [39].

Ping (Fping) tool transmitting ICMP traffic between the remote server and the client machine installed on the AGV for the VLC network monitoring.
Experiment 5: This experiment uses the Fping tool to count the number of packets lost in both use cases of shadowing and mobility during the handover in V-VLC environment. As shown in Table 2.3, the type of interface selection method does not have a significant impact on the mobility use case, however it directly has a critical impact on the shadowing use case scenario. The average number of packets lost

Table 2.3 – Number of the packet lost Vs handover causes [39].

	Shadow		**Mobility**	
Number of Packet lost	***Always***	***Failure***	***Always***	***Failure***
Average	15.66	9.83	2.4	2.4
Minimum	7	2	1	1
Maximum	18	16	6	5

during the VLC handover under shadowing using the “always” interface selection method increases to more than 15, however, using a “failure” method it reduces up to 10. In addition, there is a considerable difference in the minimum number of packets lost under mobility and shadowing. In shadowing, using the “failure” and “always” methods the number of packets lost are reduced and increased to 2 and 7, respectively.

2.6 Conclusion

In this chapter I provided a solution named Flight, a flexible and efficient network architecture in VLC network. This work has been performed to decrease the outage duration during the possible handovers within the network both in uplink and downlink. The solution included two main sections as use of FDMA and link aggregation in only pure VLC network. I presented real-world experiments using VLC devices to prove the network performance while applying the proposed network architecture. This solution has improved the network performance and can be utilized in industrial indoor scenarios where there is a high chance of frequent mobility, shadowing and link breakage within the network environment.

Additionally, I provided analyzes results for mobility and shadowing use cases based on the Flight VLC network architecture and studied the impact of two main interface selection methods in network bonding schemes. I showed that, the “failure” interface selection method has a greater impact in decreasing the outage duration during the possible handovers caused by shadowing within the network. Therefore, it is a significant factor to use a “failure” channel selection method in place of default value of the bonding scheme for both scenarios, especially under shadowing.

Chapter 3

FDLA: A Novel Frequency Diversity and Link Aggregation Solution for Handover in an Indoor Vehicular VLC Network

In this chapter, I extend Flight architecture to tackle handover problem in two dimensional (2D) indoor vehicular network environment [55]. I configure each pair of Visible Light Sensors (VLS) to establish links using one of the three predefined frequency bands and aggregate Ethernet links on the client side. Therefore, in a vehicular VLC (V-VLC) network and at any given time and direction, I select the best link established between the client and the server in both up- and down-link with the minimum handover delay times. I investigate and evaluate the performance of the proposed FDLA system using three different use case scenarios and traffic types to gain a better understanding of the mobility and handover in V-VLC networks.
This chapter also briefly describes an overview of the existing related approaches and details the potential problems, which arise due to handover in a V-VLC network, and the motivation for the proposed FDLA system. It also presents the proposed solution for handover in details and describes three different V-VLC network scenarios. It describes the approaches adopted in designing the system architecture in detail and demonstrates the implementation of the algorithm in real-world case studies.

3.1 Related work

A growing number of research works on the handover in Visible Light Communications (VLC) and wireless mobile networks have been reported in the literature, which are mostly focused on proposing schemes to achieve a smooth handover with decreasing data rate fluctuation and increasing transmission bandwidth [67], [66].

In addition, in [1], [39] and [47], I proposed and evaluated new architectural designs, aiming at handover delay decrement and VLC network throughput increment.

3.1.1 Handover techniques in wireless networks

In [65], mobility in VLC were investigated and a simulation-based handover approach was proposed to achieve seamless connectivity for two different indoor scenarios consisting of non-overlapping and overlapping lightings based on the received signal intensities. The proposed scheme was based on the buffer size adjustment, initiation of handover before disconnection and establishing new connections with the neighboring cell prior to leaving the serving light cell. Moreover, the statistical distribution of received data rates by means of simulations as well as frequency- and power-based horizontal handover methods were proposed in [67] for reducing data rate fluctuations as MUs moving between cells.
In [68], an optimal Lambertian order and a handover algorithm were proposed to increase the transmission bandwidth in a VLC system by reducing the multipath induced dispersion. This was achieved using an algorithm, where in a multicell network cells not covering the MU were deactivated to decrease the overall root mean square delay spread. Also, in [66], a handover procedure was proposed based on a pre-handover scheme, which was based on the position estimation using visible light positioning and motion tracking with Kalman filters.
In [69], a hybrid communications system supporting vertical handover between radio frequency (RF) and VLC links was proposed, where with no access to the primary VLC link the Radio Frequency (RF) link was used. To ensure efficient handover, link monitoring and decision-making schemes were defined between the data link and the network layer.
In [74], a cognitive indoor VLC system using multiple access points (APs), which served primary and secondary users using orthogonal frequency division multiple access (OFDMA), was presented. The OFDMA-based [75] network was defined in terms of the physical area and the number of allocated subcarriers for the regions of primary and secondary MUs. A light-based cell design with cognitive constraints was proposed to assure sufficient illumination, handover, and mobility requirements. Consequently, a realistic scenario was investigated to evaluate the performance of the proposed scheme using Monte Carlo simulations. The results obtained showed that, using the optimum value for the mobility parameter the desired requirements could be realized, while still attaining within the cell a high level of spectral efficiency.
In [76], an algorithm called BIGAP was proposed with the purpose of providing both improved network performance and seamless mobility in the RF domain. The proposed algorithm was designed based on various channel assignment to the co-

located APs using the available RF spectrum. Note, dynamic selection of the operating frequencies was carried out by BIGAP, which is compatible with IEEE-802.11, forcing the client to change APs. BIGAP improved T_{hod} significantly with frequent and seamless handover supporting efficient load balancing within the network. This approach is like FDLA, since both use different channel frequencies. In contrast to BIGAP, where there is the need for a single network interface, FDLA requires multiple VLC interfaces.

In this work, I use prototype devices provided by OSRAM, where neighboring LAPs and clients are assigned different frequencies and a logical bond interface on the client side is adopted to select the VLC link any time as part of the VLC network. In FDLA link selectivity is based on the speed and the availability of duplex links with the aim of improving T_{hod} during handover and maintaining the highest data rates in the V-VLC network.

3.1.2 Comparison to the state of the art

Note, that to the best of authors knowledge this work is the first to evaluate T_{hod} in a V-VLC network with two dimensions movements, considering possible scenarios where an Automated Guided Vehicles (AGV) experiences link failure during handover. Previously, in [39] and [1], I initially proposed the idea of using link aggregation on top of multiple VLC clients for AGV and frequency division for neighboring LAPs and their corresponding LCs. In addition, I analyzed an interface bonding scheme using only two different primary interfaces and evaluated T_{hod} for the AGV with a linear movement [1], [39] [55].

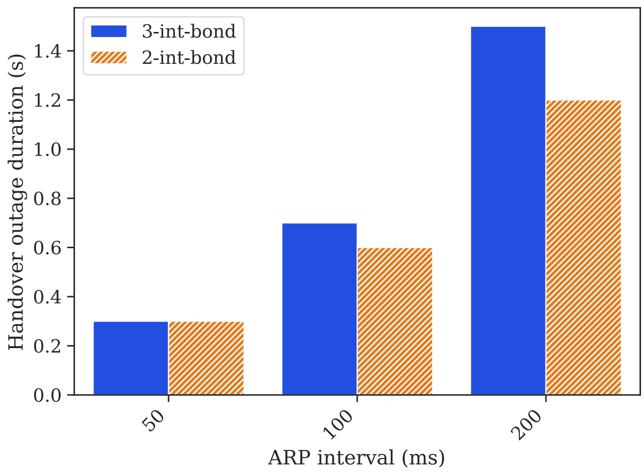


FIGURE 3.1 – Comparison of Transmission Control Protocol (TCP) handover outage duration for the cases with two and three primary interfaces [55].

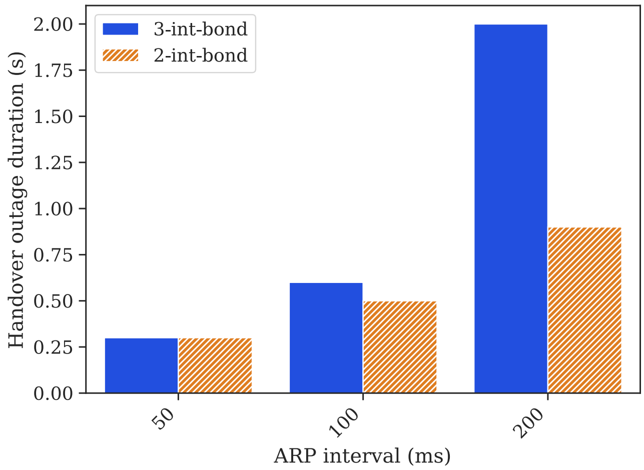


FIGURE 3.2 – Comparison of UDP handover outage duration for the cases with two and three primary interfaces [55].

Figure 3.1 and 3.2 [55] present comparisons of achieved T_{hod} for the V-VLC network cases using two and three primary interfaces for Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) packet transmissions, respectively. As it is presented the values of T_{hod} for the case with only two primary interfaces, are slightly lower than the case where an AGV client is equipped with three VLC interfaces in most of cases. The reason for this is that detecting the available link to switch will take longer for the case where the number of interfaces is more than two. However, the achieved T_{hod} is still much lower compared with the case where there is no handover technique is used.

3.2 Problem statement

VLC networks provide secure and high data rate connectivity in indoor applications where there is a high demand for network reliability with low handover delay, i.e., low T_{hod}. However, in situations with a high degree of mobility the network experience frequent handovers between the LAPs due to shadowing (i.e., blind spots) and blocking particularly in VLC. In indoor industrial environments with many LAPs, data transmission between Light Clients (LC) and a remote server situated far from the V-VLC network may experience link failures due to ongoing handovers between the LCs and LAPs

In some cases, T_{hod} can be as high as tens of seconds, which is not desirable in VLC networks. To address this and deal with high mobility, one possible solution would be to adopt frequency diversity to avoid channel access conflicts during handover, where the receivers (Rxs) can receive signals on multiple channels with different carrier frequencies.

For the system with frequency diversity, I should assign unique frequencies to ***(i)*** two LCs per AGV each with its; and ***(ii)*** LAPs installed on the ceiling to establish links with the corresponding available LCs. In this work, I have emulated Frequency Division Multiple Access (FDMA) using two pairs of LSs and repeated the experiment 10 times. As depicted in Figure 3.3 [55], for UDP packet transmission results show that, the average T_{hod} for FDMA is 3.9 s, which is lower by 11 s compared with no handover. This is since, following a link failure it will take a couple of seconds for the LC to monitor the existing channels and establish a new link using a free channel.

For FDLA I have shown two T_{hod} values as 3 and 0.2 s for ARP intervals 200 and 50 ms respectively, see Figure 3.3 [55]. As it is presented, the achieved values are much lower than the case with no handover.

3.3 FDLA network architecture

Following, I present the designed V-VLC communication system and the potential network architecture that can be realized. The network architecture includes an AGV with three LSs installed on it. The number of LSs can be more to increase the coverage, however, three is the minimum number to support 2D movements of vehicles within the network environment. Each of the LS of the AGV acts as a LC which is configured on one of the defined three non-overlapped frequency ranges. If we consider a cell including three LAPs which are installed on the ceiling and each of them is configured to establish links on one of the three non-overlapped

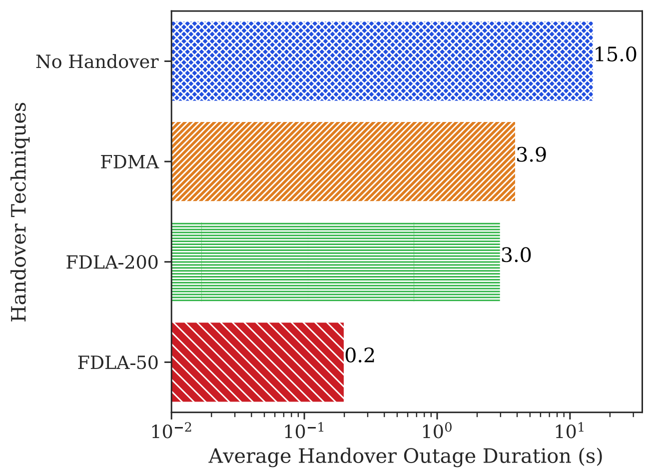


FIGURE 3.3 – Outage duration for selected VLC handover techniques [55].

frequency ranges to make three pairs with LCs. As Figure 3.4 [55] presents a possible cell architecture with the green link between LC_1 and LAP_1 is configured to establish links in frequency range F_1 (MHz). Units LC_2 and LAP_2 are configured on F_2 (MHz). LC_3 and LAP_3 are the last pair which work on the F_3 (MHz) frequency range. Therefore, there is no conflict between the assigned frequency ranges for the links and it leads to establish three independent active connection links within the network. The values for frequencies F_x, F_a, F_y and F_b are explained in Table 3.1. As Figure 3.4 [55] shows there are three transmission ranges presented in yellow ellipses for each pair of LSs and it creates five coverage areas which two of them are mutual between two LSs pair like A_x and A_y. In this system LAPs are connected to a layer three switch and then to a remote server.

Each AGV is equipped with a mini-PC and an indoor VLC mobile client system which is described in following subsections.

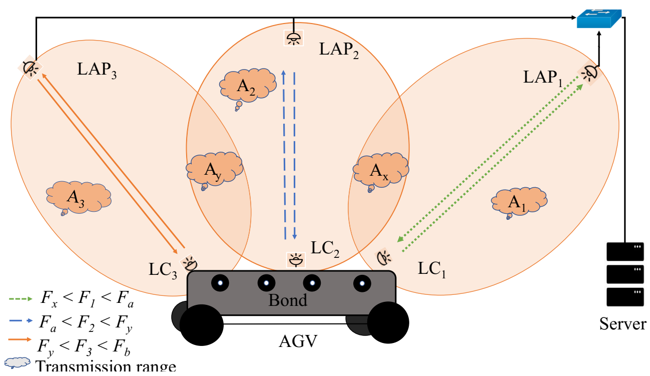


FIGURE 3.4 – FDLA network architecture [55].

Table 3.1 – Experimental parameters [55]

Parameter	Value
LC_1 and LAP_1 frequency range (f1)	2-29 MHz
LC_2 and LAP_2 frequency range (f2)	29-59 MHz
LC_3 and LAP_3 frequency range (f3)	59-94 MHz
Distance between LCs and LAPs	2 m
Link blockage duration time for shadowing/obstacle	3 s
Field of view (FoV)	60 degrees
Average throughput between LAP and LC	90 Mbps
Room dimension	5 x 4 x 2.7 m^3
Distance between LAPs	1 m
Bandwidth	100 MHz
Transmission power of LED	630 mW
Effective active area of photodiode	150 mm^2
Number of LEDs in a VLC COTS	5
Number of photodiodes in a VLC COTS	4

3.3.1 Light Sensors (LS)

The Light sensors are used in this works are COTS VLC devices provided by OSRAM. They provide an average real-time bidirectional communication at 90 Mbit/s over a transmission distance of 10 m. The LSs are developed based on Orthogonal Frequency Division Multiplexing (OFDM) and G.hn standard [73]. They are equipped with five off-the-shelf high-power LEDs (OSRAM SFH 4715 AS) and four large-area silicon photodiodes (Photo-Detector (PD), Hamamatsu S6968). The field of view for each LS is 60 degrees half angel and the operation distance is 0.2 - 10 meter. The transmission power of LEDs is 630 mW and the effective area of photodiodes are 150 mm^2.

3.3.2 Indoor Mobile Client (IMC)

In this work, I consider an independent interconnection of the Indoor Mobile Client (IMC) and a single or multiple LS(s). An independent interconnection of IMC with three LSs can be seen in Figure 3.5 [55], where the standard Ethernet interface is used to connect each LS to the IMC's standard physical communication interface (Ethernet). This independent interconnection ensures that an LS connects to IMC's existing wired communication interface easily without requiring a custom software/hardware integration at neither in IMC or in LC. This novel architecture assumes that an IMC already has multiple standard wired network interfaces such as Ethernet for enabling the IMC's data communication to reach the next network hop (Switch or Router). Therefore, when the IMC is interconnected to LS as in Figure 3.5 [55], the resulting system is capable of VLC-based wireless communication. A future IMC may not require other protocol interfaces to exist between the LS and the IMC Application layer, since an IMC can be designed with in-built LS capabilities at the Physical Layer (PHY) and data link layers of the communication interface.

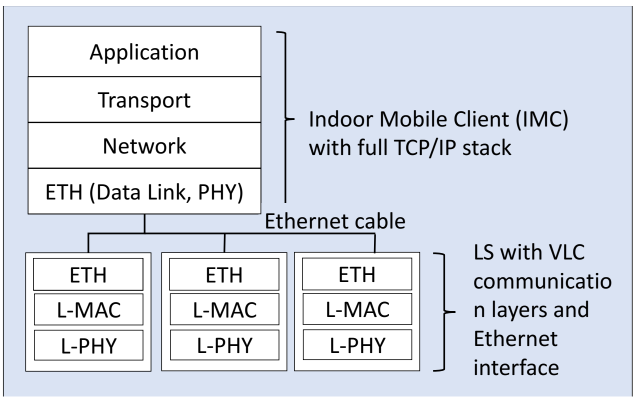


FIGURE 3.5 – Indoor VLC mobile client diagram [55].

3.3.3 Definition of three use-case scenarios

This chapter considers three critical most often scenarios which an AGV can lose its connectivity due to handover caused by mobility and I present how the handover issues can be solved with FDLA as a flexible and modular VLC handover solution. In the following subsections, I describe three different scenarios shown in Figure 3.6 [55] which are implemented in real-life experiments.

3.3.4 Scenario 1: A single VLC link blockage in a linear direction.

Scenario 1 indicates an AGV continues riding on a linear movement in each direction any given time instance, such that at the LAPs can provide seamless VLC coverage for the IMC along its mobility path within a 2D indoor space. Due to AGV's moving, shown in case number 1 in Figure 3.6 [55], VLC handover between the IMC and LAPs occur as an IMC moves from a Light Access points (LAP)'s coverage region through a different coverage region at T = t1. Imagine an AGV is moving from P1 to P2 area shown in Figure 3.4 [55]. Once the AGV enters the P1 area, LC_1 connects to LAP_1 on F_1 frequency band and once the AGV arrives at Px, there will be two parallel VLC active links between the LCs and corresponding LAPs. Finally, when the AGV continues towards to P2 area, the link between LC_1 and LAP_1 breaks and only the link between LC_2 and LAP_2 on F_2 frequency band remains active.

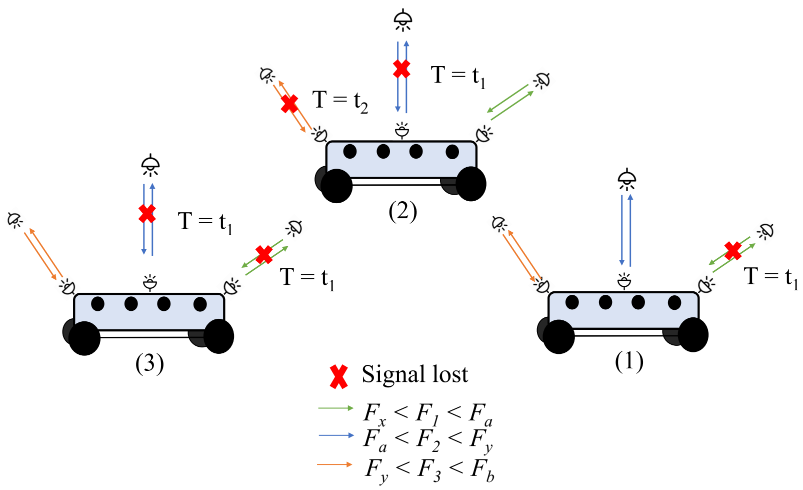


FIGURE 3.6 – three Different scenarios: (1), (2) and (3) present scenario 1 with a single link broken at T= t1, scenario 2 with two links broken at T= t1 and scenario 3 with two links broken at T= t1 and T = t2, respectively [55].

3.3.5 Scenario 2: Lose of two VLC link connections concurrently.

In scenario 2 which is demonstrated in case number 2 in Figure 3.6 [55], defines when an AGV loses two VLC link connections simultaneously due to shadowing and/or a moving turn in an 2D indoor space. In this case an AGV enters P3 coverage area at T = t1 and loses the connection in P1 and P2 coverage areas. Therefore, at last the IMC and an LAP establishes a connection between LC_3 and LAP_3 on F_3.

3.3.6 Scenario 3: Change of direction and lose of two VLC link connections, respectively.

The last scenario as presented in case number 3 in Figure 3.6 [55], an AGV turns in a way that loses two VLC links at time T= t1 and T= t2, respectively. In this case the AGV is heading from P1 to P3 area through P2 coverage area. At first, AGV enters and the same happens as scenario 1 until it arrives by P2 coverage area at T= t1. Therefore, there is a VLC link connection established between LC_2 and LAP_2 on F_2 frequency band and it continues towards P3. Before the AGV enters the P3 area at T= t2, there will be two parallel VLC active links between the LCs and corresponding LAPs. Eventually, when the AGV keeps riding towards to P3 area, the link between LC_2 and LAP_2 breaks and only the link between LC_3 and LAP_3 on F_3 frequency band remains active.

3.4 FDLA system concept

FDLA is a flexible network architecture which is mainly developed based on frequency diversity and link aggregation method. This is a novel solution which is built up on VLC for the first time in 2D V-VLC network environment. FDLA is proposed to tackle the early mentioned problems during VLC handover with decreasing the outage duration and increasing the network reliability, robustness and improving the network coverage in V-VLC. FDLA is designed to well-perform under different conditions and use-case scenarios. The two main phases of FDLA are described separately in the following.

3.4.1 Frequency diversity

Using frequency diversity technique, I extend the coverage three LSs and avoid frequent loss of connectivity which might happen due to shadowing, obstacles, mobility, and handover within the network. Moreover, FDMA is configured on each node with three non-overlapping frequency ranges. The proposed frequency division mechanism in this chapter divides the available VLC baseband frequency spectrum into multiple non-overlapping frequency bands such that each LAP and LC supports only one of such non-overlapping frequency bands. Such a frequency division mechanism ensures that when an IMC crosses through a coverage region of three LAPs, there will always be three parallel and non-interfering VLC communication links between each of the three LCs in the ILMC and each of the different LAPs providing parallel VLC coverage in the overlapping coverage region.

For example, assuming one of the LCs of IMC should be configured to operate at F_1 frequency band and the second LC at F_2 and the third LC at F_3 frequency band. In parallel, LAPs should strictly be configured with either of F_1, F_2 and F_3, such that when the IMC crosses through the coverage region of three LAPs, there will be three parallel VLC links between the IMC and the LAPs in the overlapping coverage region. In Figure 3.7 [55], each pair of LAP and its corresponding LC is configured with a non-overlapping frequency band. On the ILMC side, LUE1 is configured with F_1 and LUE2 is configured with F_2. The figure presents the aerial view of LAP coverage plan providing seamless VLC coverage for the IMC mobility scenarios with only three non-overlapping frequency groups (F_1, F_2, and F_3) shown in different colors.

3.4.2 Link Aggregation

To facilitate variable-outage duration handover, network (Ethernet) bonding is implemented at the Ethernet interface of the IMC's data link layer within the system installed on an AGV. In this work, link aggregation or Ethernet bonding is com-

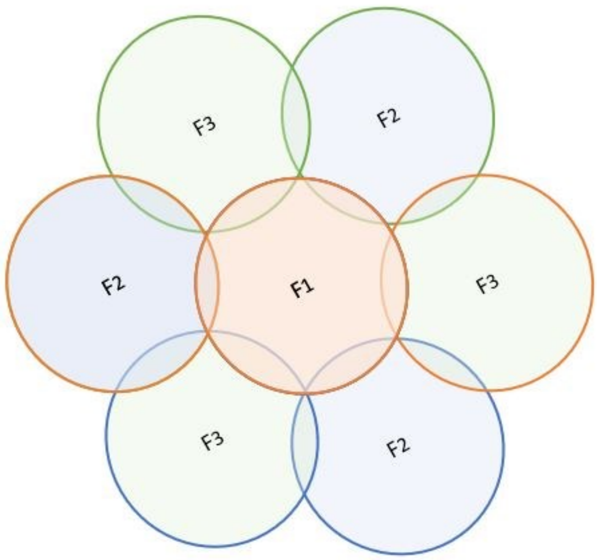


FIGURE 3.7 – Aerial view of LAP coverage plan providing seamless LiFi coverage for the General ILMC mobility scenario with only three non-overlapping frequency groups (F_1, F_2 and F_3).

bining of various VLC network connections in parallel into a single logical interface called a Bond interface. Among 7 different types of network bonding, I have chosen active-backup mode 1 for the bonded interface. The reason behind this decision is that this mode offers redundancy once a VLC link blocks and it provides load balancing and linear scaling of bandwidth, thus it improves VLC link reliability in the system.

To enable Ethernet Bonding, the IMC is configured with a logical Ethernet Bond interface which aggregates three physical Ethernet interfaces in the IMC. Each of the physical Ethernet interface in IMC is connected to each of the LSs. Then in Active-Backup bonding mode one of the three Ethernet interfaces acts as 'Active' and the two others as 'Backup's. To monitor the VLC connectivity in the network, I use ARP monitoring technique for the logical Ethernet Bond interface to monitor which of the three Ethernet links are active at any given time. VLC connection monitoring is enabled through ARP monitoring at a predefined ARP frequency with a preconfigured ARP target as the switch WAN address. The reason for this is the closer the ARP target to the IMC, the faster round-trip outage duration receives from the ARP target via the receiving ARP replies.

The working principle of ARP monitoring based on active-backup Ethernet bonding is as follows: the Bond interfaces polls the ARP target every configured interval and waits for the ARP replies through its physically configured Ethernet interfaces. Based on successful ARP replies, the logical Ethernet Bond interface decides as to which physical Ethernet interface should be used to send or receive traffic. The logical interface uses the 'Active' physical link to send/receive traffic if the 'Active' link provides the ARP replies, regardless of whether the 'Backup' link is providing ARP replies or not; when the 'Active' link does not provide ARP replies, the logical Ethernet Bond interface sends/receives traffic at the 'Backup' link if the 'Backup' link provides the ARP replies.

3.4.3 Channel Optimization

In this work I use a 'better' value in case of failure of the primary slave for the primary-reselect-policy configuration. In means that the best link based on the speed and duplex is chosen continuously while receiving ARP replies in the network. Therefore, I get sure that I always use the best connection link to communicate over it. However, it is worth mentioning that achieving the best throughput in this solution depends directly on a significant factor called ARP frequency. In this research work I use three different ARP frequencies to send ARP requests to the ARP target and I realize that there is an interesting trade-off between using a channel aware system and higher ARP frequency on the system, simultaneously. It is Obvious that increasing ARP frequency leads to detect the VLC link failure faster.

However, on the other side if I build a channel aware system and I apply a very high frequency value for ARP monitoring, then it leads the system to get overloaded and the receiver becomes saturated. As a result, I face with a path bouncing among the VLC connection links which increases the outage duration during the handover in V-VLC. Therefore, the highest frequent ARP interval value I transmit is every 50 ms which has been achieved after observing and analyzing different ARP intervals ranges from 20 to 200 ms.

Figure 3.8 [55] presents the view of the interaction between LAP and the AGV client moving from P_3 to P_1 passing through three LAPs' network coverage. At the client system installed on the AGV, Ethernet light interface 1 (ELI_1) is assigned with F_1, ELI_2 is assigned with F_2 and ELI_3 is assigned with F_3. At P_3 position, ARP reply is received only at ELI_1, which is used for data communication by Ethernet bond interface (EBI). At P_2 and P_1, ARP replies are received at ELI_2 and ELI_3 respectively; so only the ELI_2 and ELI_3 are respectively selected for data communication by EBI at P_2 and P_1 transmission ranges. To enable variable-outage duration handover, at P_y, even though ARP replies are received at ELI_1 and ELI_2, the higher priority interface ELI_1 is used for communication by EBI; similarly, at P_x, even though ARP replies are received at ELI_2 and ELI_3, the higher priority interface ELI_2 is used for communication by EBI. Priorities between ELI_1, ELI_2 and ELI_3 are manually configurable at EBI.

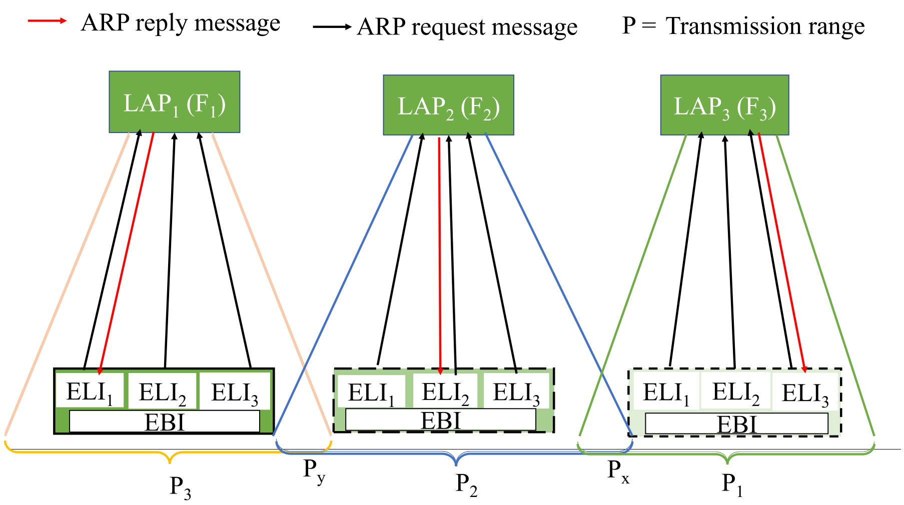


FIGURE 3.8 – The view of the interaction between LAP and the AGV client moving from P_3 to P_1 passing through three LAPs' network coverage [55].

3.5 Practical experimental results

The proposed FDLA system is experimentally implemented into a prototype in order to validate its performance. As Figure 3.9 [55] presents six LSs in three pairs of clients and access points. The distance between each pair is 1 meter and the distance between each LC and LAP is 2 meters in a room with dimension 5 x 4 x 2.7 m^3 as specified in Table 3.1 [55]. There is a mini- PC with Linux-Ubuntu operation system machine which works as a client. It is connected to three LCs using Ethernet cables to build an IMC system. From the other side, there are three LAPs which are connected to a remote server machine via a configurable switch. We configure the LSs with different values of the frequency bands shown in Table 3.1 [55].

A bond interface has been built on the mini-PC on the client side and it controls the traffics over three physical Ethernet interfaces on VLC devices. ARP monitoring is also configured on top of the bond interface using Linux Netplan tool. Therefore, based on the defined ARP intervals, at any specific time, the bond interface sends an ARP broadcast message to everyone with a target as a switch IP address. For the receivers on the network, the request means if anybody knows the Medium Access Control (MAC) address of the device with this specific IP address. Then the ARP target receives that packet through the VLC link, and it would have to reply that this interface with the requested IP address is available and here is its MAC address. That reply specifies that the host is available and is ready to respond to the queries. In other words, this monitoring method tries to determine the MAC address of a specified host by its IP address. Therefore, If the obtained MAC address is equal to the specified one, the check is considered passed and it means that the link is available to transfer the traffic with. Of course, the bond interface looks for the second reserved interface, in case the current primary link gets lost. Following subsections present the achieved experimental results using three different traffic types as TCP, UDP and Internet Control Message Protocol (ICMP) implemented on given real-case scenarios. It is worth mentioning that I repeat each test for 10 times for each scenario.

3.5.1 VLC handover in a linear movement in V-VLC network

As it is described before in subsection 3.3.4 [55], this is the most usual scenario in V-VLC that an AGV moves in a linear direction, and it loses connectivity due to its fast movement. Therefore, VLC handover occurs and the AGV as a client dissociates from its current LAP and requires associating with the next LAP which approaches its coverage area. As it has been shown in Figure 3.3 [55] without using any handover solution, the outage duration during VLC handover takes up

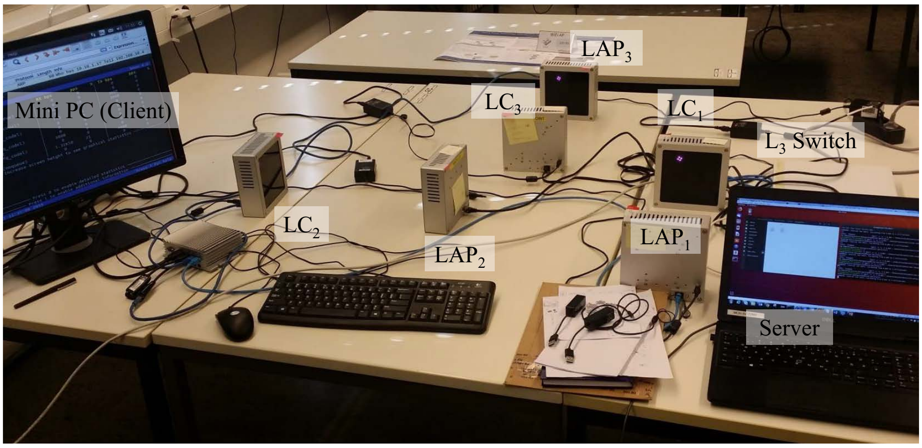


FIGURE 3.9 – Experimental indoor VLC setup [55].

to 15 seconds. However, using FDLA on the V-VLC network, decreases the outage duration value incredibly up to 20 ms.

In this experimental setup, I use Iperf tools to measure the network performance actively. Iperf is a network tool which has two functionalities as server and client and can create data streams to do network throughput measurement between two ends or even both directions. Iperf output presents a time-stamped report containing the data transferred and the measured throughput. The data traffic type can be either TCP or UDP. In the first setup I transfer the UDP packets from the remote server to client using a downlink. We repeat the test under the same condition for three different ARP frequency values to analyze each link's quality and measure the outage duration based on the achieved time-stamped. In this experiment the UDP stream transferred with the default bandwidth as 1 Mbit/sec.

As the Figure 3.10 [55] demonstrates, the outage duration achieved using ARP intervals 100 and 50, are reasonably meet the threshold value shown in Figure 3.3 [55] specially when the ARP interval has been set to 50 ms.

In this experiment, I use TCP streams. We create the traffic between client and the remote server machine and use an uplink to communicate between the AGV and the corresponding LAPs in the network. In this setup the VLC T_{hod} is measured using Iperf tool as before, however the T_{hod} is measured on the uplink. The setup proves that FDLA can be applied both on uplink and downlink in V-VLC successfully. One of the most frequently used traffic types in V-VLC is unicast packets. It is very critical for industries to use a low latency but reliable unicast traffic to and from controllers. In order to minimize the number of packet lost during this setup, I applied FDLA using different ARP frequency values to analyze and evaluate the achieved results.

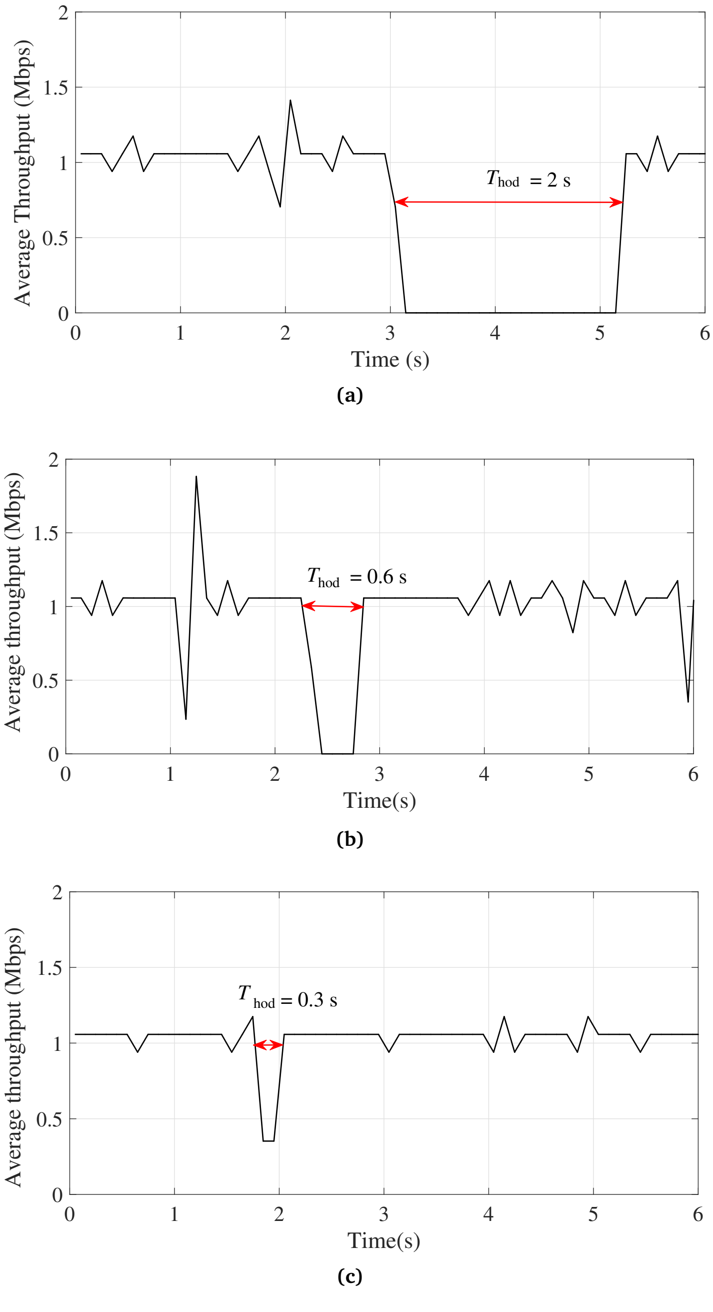


FIGURE 3.10 – The UDP average throughput for ARP intervals of (a) 200, (b) 100 and, (c) 50 ms for scenario 1 with a single link failure [55].

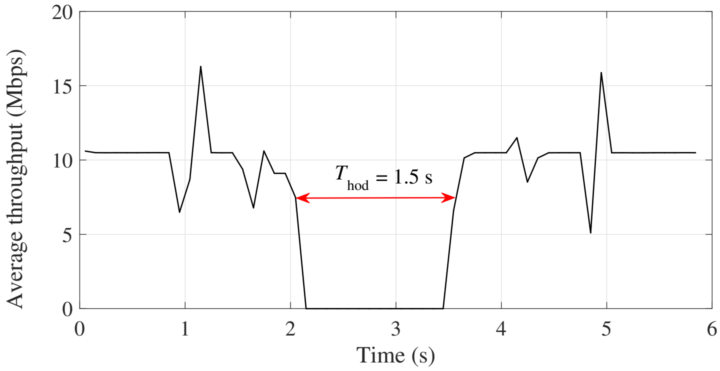
The results in Figure 3.11 [55] present the outage duration measurement for different ARP intervals, running every experiment for 10 times, and averaging the outage duration over the measurement time. As the Figure 3.11c [55] shows the T_{hod} with ARP interval value of 50, decreases the VLC T_{hod} to 30 ms, which is sufficiently low to be able to meet our outage duration requirements in V-VLC networks. Moreover, as it is shown, the higher ARP intervals, I achieve larger T_{hod} values. Therefore, the performance started to decrease when the ARP interval values get higher than 100 ms and the reason behind is as shown in the Figure 3.11a [55] the ARP monitoring does not occur very often, so this obviously affects the link broken detection procedure negatively once the handover takes place in V-VLC.

To monitor V-VLC network reliability, I conduct a set of experiments using Fast Ping (Fping) tools. The type of the traffic in this setup is ICMP. Fping is a network monitoring tool like Fping to send ICMP echo probes to network hosts. Fping provides us the facility to define several important parameters to set as a time interval between two Packet Internet Groper (Ping) in millisecond, number of Ping to send to each host and the amount of data in byte. In this setup, I create and transmit 500 ICMP packets from the client to the remote server every 5 ms. The data packet size is considered as 100 bytes. We measure interruption time of FDLA for three different ARP frequency values as 50, 100 and 200 ms. The interruption time is determined by the time delta between last received Ping reply before handover has taken place and the first successfully answered Ping request after the handover has taken place. Each measurement is repeated for 10 times. As the Figure 3.12 [55] presents using ARP request interval of 200 ms leads the network experience a large interruption time and following an increased number of packet lost and less reliable network.

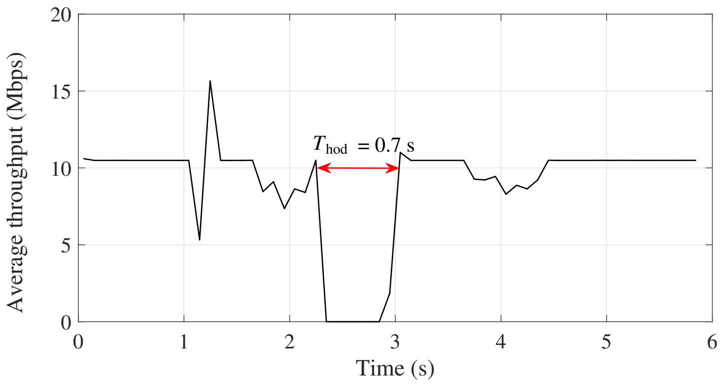
3.5.2 VLC handover in 2D movement in V-VLC network

In this experimental setup, I emulate and evaluate the extreme case where an AGV loses two VLC link connectivity synchronously. This can be due to an obstacle, shadowing or a U-turn movement in a two dimensions environment. We analyze the FDLA performance in a very extreme case and observe how the V-VLC network performs in this scenario well explained in subsection 3.3.5. Following I use different type of traffic types of transmission in this scenario using different values of the parameter of the ARP interval.

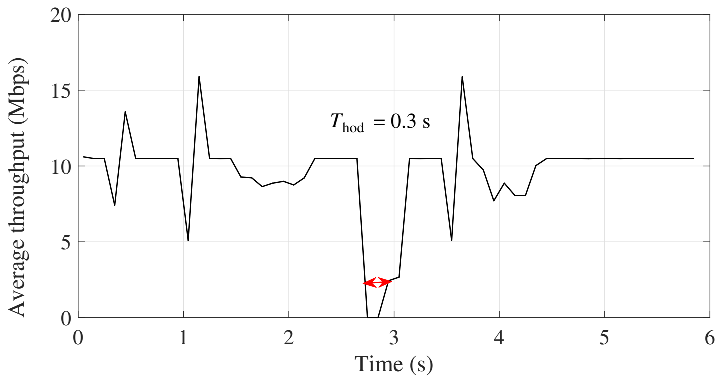
Using the Iperf tool I have created and transmitted UDP traffic and use the UDP stream for updating the AGVs continuously with the key information such as AGVs current location, next position, and route path. Note, the V-VLC network should be highly reliable and flexible specially for extreme cases, see subsection 3.3.6. Therefore, I have emulated the scenario and measured the average data throughput for



(a)



(b)



(c)

FIGURE 3.11 – TCP Average throughput vs. time for interval (a) 200, (b) 100 and, (c) 50ms for scenario 1 with single link broken [55].

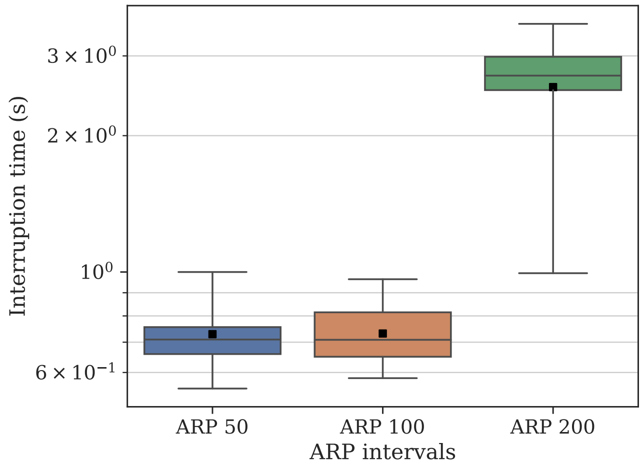


FIGURE 3.12 – Interruption time vs. ARP intervals in scenario 1 [55].

Table 3.2 – T_{hod} vs. ARP interval values in scenario 2, using TCP and UDP [55].

ARP interval (ms) $T_{hod}(s)$	***50***	***100***	***200***
UDP	0.3	0.5	2.5
TCP	0.2	0.8	3

ARP intervals of 200, 100 and 50 ms for scenario 2 with two simultaneous links, see Table 3.2 [55]. T_{hod} values shown are 2.5, 0.5 and 0.3 s for ARP of 200, 100 and, 50 ms, respectively, where the latter offers the best T_{hod}, which is the same as the threshold value given in Figure 3.3 [55]. To send information to a specific destination I have used the TCP traffic for unicast transmission and evaluated the V-VLC network performance with FDLA. Table 3.2 [55] depicts the TCP average throughput for ARP intervals of 200, 100 and 50 ms for scenario 2 for the case with two simultaneous link failures. As it is shown, the lowest handover delay time of 0.2 s is achieved for TCP.

Table 3.3 – T_{hod} vs. ARP interval values in scenario 3, using TCP and UDP [55].

	Handover 1			**Handover 2**		
ARP interval (ms) $T_{hod}(s)$	***50***	***100***	***200***	***50***	***100***	***200***
UDP	0.3	0.5	2.5	0.3	0.4	1.6
TCP	0.4	0.6	1.55	0.3	0.8	1.7

Table 3.4 – Number of the packet lost vs. ARP interval values in the 3 scenarios [55].

Statistics		**Scenario 1**	
Packet Delivery percentage	***ARP 50***	***ARP 100***	***ARP 200***
Average (%)	99.8	99.8	99.44
Minimum (%)	99.8	99.8	99.2
Maximum (%)	99.8	99.8	99.8
Statistics		**Scenario 2**	
Packet Delivery percentage	***ARP 50***	***ARP 100***	***ARP 200***
Average (%)	99.62	99.76	99.44
Minimum (%)	99	99.4	99
Maximum (%)	100	99.8	99.6
Statistics		**Scenario 3**	
Packet Delivery percentage	***ARP 50***	***ARP 100***	***ARP 200***
Average (%)	99.64	99.36	98.86
Minimum (%)	99.2	98.2	98
Maximum (%)	99.8	99.6	99.2

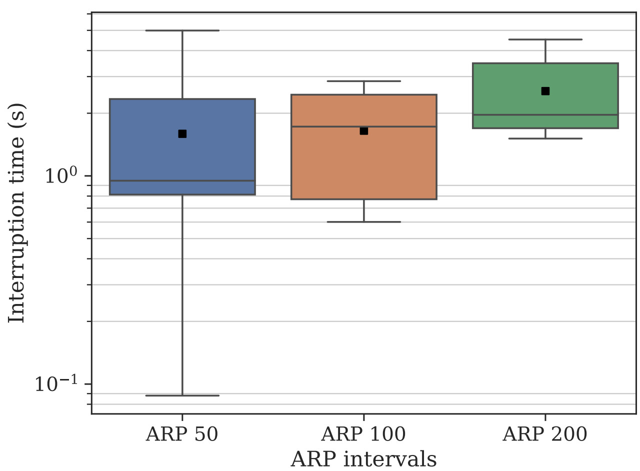


FIGURE 3.13 – Interruption time vs. ARP intervals in scenario2 [55]

Here, I evaluate the VLC network performance using the Fping monitoring tool. Note that, for the case of AGV experiencing two simultaneous link failures all failed links are re-connected. 500 ICMP packets are transmitted from the client to the remote server. Figure 3.13 [55] depicts T_{int} as a function of ARP intervals for scenario 2, where the lowest T_{int} is observed for APR interval of 50 ms. However, the network experiences a large gap between the minimum and maximum interruption times, and this makes the average value stays far from the median number.

3.5.3 VLC handover in a two dimensions V-VLC network: Lose of two VLC connections asynchronously

In V-VLC network, AGVs require to move between the parallel defined paths. In this case, there is a very high possibility for an AGV to lose its connectivity from the reachable LAPs one after the other, respectively. As it is well described before in subsection 3.3.6, losing VLC connection links one after another, for the AGV is a very significant challenge. It is very critical for V-VLC network to recover as quick as possible after each broken link. That is why I emulated the scenario basically and applied FDLA to tackle the VLC handover challenge in two dimensions scenarios.

3.5.3.1 UDP stream

In this experimental setup, I analyze how FDLA achieves the network connection following each handover between LAPs. This might be due to AGV not being able to utilize the two VLC links when making a U-turn or experiencing shadowing/blocking.

Here, I consider two V-VLC network handovers as presented in Table 3.3 [55]. Transmitting UDP, I achieve the shortest handover delay as 0.3 s during first and second handovers, once ARP interval is configured as 50 ms, respectively. The use of ARP interval value of 100 ms results in achieving T_{hod} values of 0.4 and 0.5 s with two handovers.

3.5.3.2 TCP stream

We measure and analyze T_{hod} once AGV transfers unicast packets to the remote server. The client starts transferring TCP packets to a destination as the remote server and meanwhile at $T = t_1$ and t_2, two VLC link connections break and the BI, which is installed on the client machine, immediately re-establishes the link with the third available link on the LAP on the third frequency range. Table 3.3 presents T_{hod} using the TCP packet transmission for three different ARP interval values. Based on how fast BI transmits the ARP request, it detects the failed link and establishes a new connection. Therefore, in ARP interval 200 and 100 ms the number of the packet lost increases due to not frequent ARP request transmission. However, for the ARP interval of 50 ms, T_{hod} is within the range of 0.3 to 0.4 s since the channel is monitored more often.

3.5.3.3 ICMP stream

Here, I analyze FDLA reliability performance and measure the total packet delivery for transmitting 500 ICMP packet every 5 ms. Table 3.4 [55] presents minimum, maximum, and average packet delivery in a network for three scenarios. As shown, in scenarios 2 and 3 with two failed VLC links, FDLA offers the highest packet delivery of 99.5%.

3.6 Conclusion

This chapter presented a handover solution in data link layer based on frequency diversity and link aggregation for V-VLC network called FDLA. The proposed system tackled the V-VLC handover challenge by decreasing the handover outage duration time once an AGV loses connectivity within a network environment. To provide an efficient channel selection method while using multiple VLC channels with different frequencies, FDLA used link aggregation techniques over VLC data link layer. This way, the V-VLC handover took place smoothly by detecting the broken links and establishing the new link among within a short period which met the handover delay threshold demanded in industries. Moreover, FDLA solved the channel selection problem among multiple bonded interfaces by choosing the best available link based on links properties as speed and duplex.

By means of implementation, three most often scenarios were described and emulated, where an AGV experiences one or more links broken at the same or different given times. The experimental results showed the performance of FDLA in comparison with methods using no handover technique and FDMA in the defined scenarios, how FDLA decreased the handover outage duration time using different ARP intervals up to tens of milliseconds instead of couple of seconds.

Chapter 4

A flexible transport layer protocol architecture for handover in a vehicular VLC network

In this chapter, I concentrate on transport layer, using Multipath-Transmission Control Protocol (MPTCP) to address mobility issue in vehicular VLC (V-VLC) network [47]. I consider Automated Guided Vehicles (AGV) travelling along a given path. Initially, a vehicle is connected to the first Light Access points (LAP). While moving and entering the overlapping coverage area between two cells, handover is initiated, and a new Visible Light Communications (VLC) link is established with the second LAP. In case of shadowing or existence of obstacles, handover initiates when there is no Line-of-Sight (LOS) path, and therefore, a new connection link is established via the next available LAP. In both cases, the V-VLC network will experience decrement in the network outage during the handover. In addition, this chapter summarizes related research works for the use of MPTCP in various types of networks. It presents the motivation behind this research. I also describe the proposed architecture to use MPTCP in a VLC network and present the implementation results for mobility and shadowing use case scenarios in a V-VLC network.

4.1 Related works

Different approaches have been proposed to use MPTCP in various networks such as millimetre Wave (mmW), long term evolution (LTE), Wireless Fidelity (WiFi) and hybrid networks (VLC-WiFi and WiFi-cellular). In [77], it was shown that how mmW-based mobile networks could be affected by the most widely used transport protocols and demonstrated the throughput-latency trade-off when MPTCP is used across various links, such as LTE. In [78], an experimental investigation of MPTCP

in dual-band 60 GHz/5 GHz Wireless Local Area Network (WLAN) was reported, where uncoupled and different coupled congestion control algorithms were considered and compared with the aim of improving the throughput over a single path Transmission Control Protocol (TCP). The results showed that, a significant throughput improvement for the case of uncoupled congestion control, achieving a throughput roughly equal to the sum of the SPTCP throughputs over WiFi and 60 GHz cellular links. Besides, in the case of coupled congestion control, the throughput was lower as the algorithms fail to fully utilize the capacity of both paths simultaneous.
In [54] the use of MPTCP in WiFi and cellular networks using a smart-phone interfaces was reported, where the device used more than one interface simultaneously. They evaluated the performance Internet Protocol (IP) reachability over real world networks and conducted experimental tests over multiple paths with differing loss rates and round-trip latencies in order to assess the effect of primary path selection and issues related to selecting the under-performing paths. Finally, in [79] and [80] MPTCP in hybrid networks including VLC were investigated. In [79], a novel decoupled TCP extension protocol for a VLC hybrid network was proposed, where decoupling operation to TCP transmission overcomes the limitation of regular TCP by allowing the users full utilization of network resources by the users. Based on Linux-kernel, they showed higher throughputs for MultiPath DETCP (MP-DETCP) compared with Decoupled TCP (DETCP) for different downlink packet loss ratios. Moreover, in [80], a practical hybrid WiFi-VLC system was proposed, there was no need for a separate VLC uplink with aggregated WiFi and VLC downlinks and sharing the WiFi uplink. The link aggregation was achieved using Linux bonding and Medium Access Control (MAC) address redirection. The system throughput for the WiFi only (i.e., one WiFi downlink) and asymmetric (i.e., one VLC downlink) links were compared under a congested WiFi environment. The results demonstrated that, the proposed system offered an aggregated downlink bandwidth, which is approximately the sum of the downlink capacities of the WiFi-only and asymmetric systems. In addition, a trade-off between bandwidth utilization and latency was outlined.

In this chapter, I propose a novel transport layer architecture, which uses MPTCP in a VLC network, for the first time, which is flexible, robust and offers seamless handover between a vehicle and a server. We provide both uplink and downlink using VLC networks. Moreover, the proposed architecture offers lower latency of 0.024 seconds and higher throughput of 125 Mbps, respectively. The next section describes the use of MPTCP in a VLC network in detail.

The main motivation behind this chapter is to address existing challenges in a V-VLC network including mobility, shadowing or obstacles, which will block the LOS

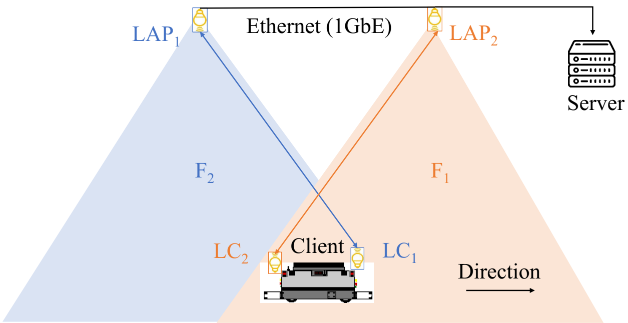


FIGURE 4.1 – VLC with MPTCP [47].

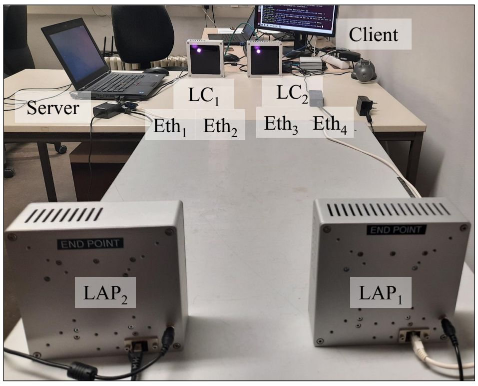


FIGURE 4.2 – MPTCP architectural design prototype in VLC [47].

path between the transmitter and receiver, thus leading to increased packet losses and reduced network reliability. In addition, the network throughput is critical. To offer a reliable V-VLC network with the required throughput, the outage duration during handover needs to be reduced. In this chapter, I consider the transport layer of VLC with two different MPTCP schedulers and an MPTCP tool to investigate their impact on the VLC performance by considering Mobility (i.e., handover) and shadowing/obstacle.

4.2 VLC WITH MPTCP

MPTCP is a Linux kernel, which is installed on Ubuntu 18.04 both on server and client systems. Here, MPTCP version 0.95 with full mesh path manager is adopted, which creates a full mesh of sub-flows among all available VLC network interfaces. A TCP connection is established over two sub-flows as shown in blue and orange colors in Figure 4.1 [47] using Default and Redundant schedulers. In addition, I

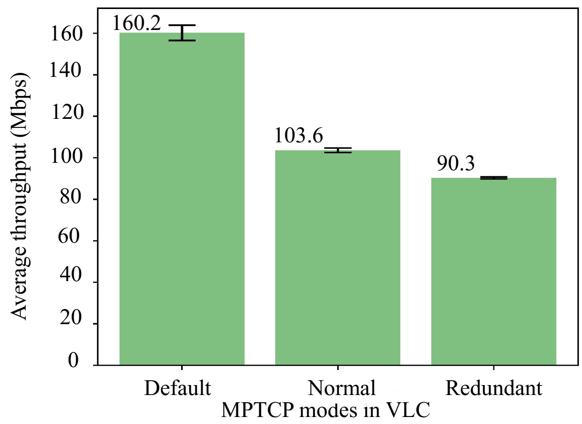


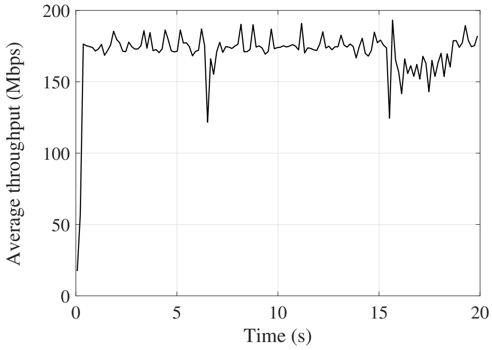
FIGURE 4.3 – Average throughput of MPTCP in VLC links using "Default", "Redundant" and backup-mode MPTCP tool [47].

Table 4.1 – Experimental parameters [47]

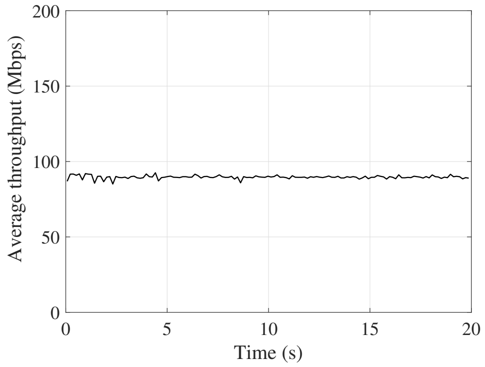
Parameter	**Value**
LC_1 and LAP_1 frequency range (f1)	4-52 MHz
LC_2 and LAP_2 frequency range (f2)	52-96 MHz
Distance between LCs and LAPs	2 m
Link blockage duration time for shadowing/obstacle	3 s
Field of view (FoV) of photodiodes	60 degrees
Average throughput between LAP_1 and LC_1	90 Mbps
Average throughput between LAP_2 and LC_2	110 Mbps
Room dimension	5 x 4 x 2.7 m^3
Distance between LAPs	1 m
Bandwidth	100 MHz
Transmission power of LED	630 mW
Effective active area of photodiode	150 mm^2
Number of LEDs in a VLC COTS	5
Number of photodiodes in a VLC COTS	4

use an MPTCP tool called the backup mode with a TCP sub-flow for each interface and with one of the interfaces being configured in the backup mode. By doing this, if the current sub-flow experiences a failure, then the backup interface is selected as the backup for establishing TCP.

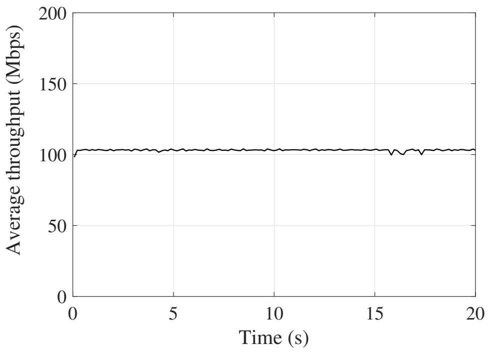
Figure 4.2 [47] shows the experimental prototype for the proposed system as a proof of concept. Two pairs of LAPs and LCs, which are configured using two different frequency ranges of 4-52 MHz and 52-96 MHz for MC1-LAP_1 and MC2-LAP_2, respectively. Note, ***(i)*** there are two parallel active and non-overlapping VLC links between the client and the server; and ***(ii)*** VLC transceivers are connected to the clients and server using Ethernet links. In this work, I analyze the performance of



(a) MPTCP performance in VLC using "Default" scheduler.



(b) MPTCP performance in VLC using "Redundant" scheduler.



(c) MPTCP performance in VLC using Backup mode tool.

FIGURE 4.4 – MPTCP performance in VLC without any link blockage [47].

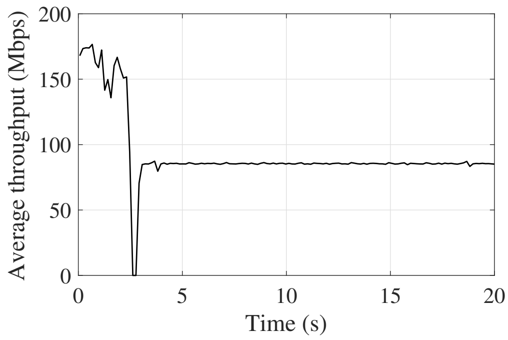
VLC with MPTCP under the handover, which is initiated by or shadowing and temporary link blockage. For initialization, first I established TCP over two VLC links, see Figure 4.3 [47], to evaluate the performance of VLC links in a network environment with no link blockage. Table 4.1 shows the key experimental parameters

adopted in this work.
Figure 4.3 [47] presents the average throughput for VLC with MPTCP links for the three cases of Default and Redundant schedulers and backup tool with no handover. As shown, using Default offers the highest possible throughput of 160.2 Mbps. Figure 4.4 [47] depicted the throughput for the three cases. As can be seen, for Default a higher throughput (i.e., an average of 160 Mbps) is achieved for the TCP link between client and server, this is because data is transmitted over both VLC links. For the Redundant scheduler, see Figure 4.4b [47], the throughput is lower (i.e., an average of 90 Mbps) with reduced variability. Figure 4.4c [47] presents the impact of this method on TCP established over VLC network. As it is shown, For the backup scheduler, the achieved average throughput is marginally higher than Redundant. And shows a smooth flow over only a single sub-flow since the second sub flow is configured as the backup only in case of the primary sub flow's failure.

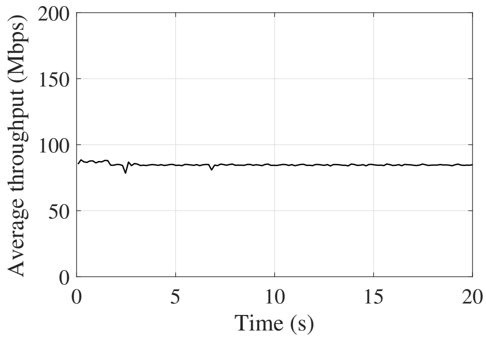
4.3 Experimental results

The proposed transport layer VLC architecture is experimentally implemented using the VLC prototype to validate the performance of MPTCP. To emulate the mobility, I introduced a permanent link blocking on the simplex link between a client and the server. To emulate shadowing/obstacle, a temporary link blockage on the single VLC link was introduced for about 3 s. The VLC links were configured as two different subnets as in 192.168.10.x and 192.168.20.y. The client and the server machine with Ethernet interfaces are configured to use Ubuntu 18.04. The VLC devices operating at two different transmission frequency bands of 4-52 MHz and 52-96 MHz are connected to both sides via Ethernet cables.
I have carried out experimental investigation for the two schedulers and a MPTCP tool, where each measurement is carried out for 10 times to ensure consistency. In the Default scheduler, the scheduler transmits the traffic data considering the Round Trip Time (RTT) and congestion control window size, whereas in the Redundant scheduler the traffic is broadcasted over all available sub-flows regardless of path's characteristics. As was stated before, the latter reduced latency. In the backup mode, a single VLC link is configured as the backup to ensure connectivity during link failure.

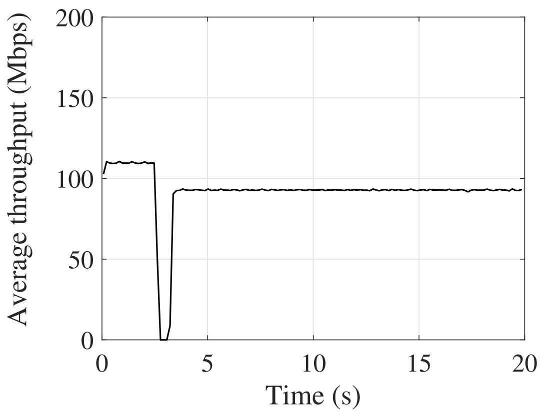
Experiment 1 - The Default scheduler: To evaluate and measure the network throughput via the uplink between the client and the server, I have used Internet Performance Working Group (Iperf) tools both on server and client systems. For the mobility use case, the initial throughput is 170 Mbps and is reduced to 85 Mbps due to mobility induced link blockage. On receiving no acknowledgement back



(a) Mobility use case using "Default" scheduler.



(b) Mobility use case using "Redundant" scheduler.

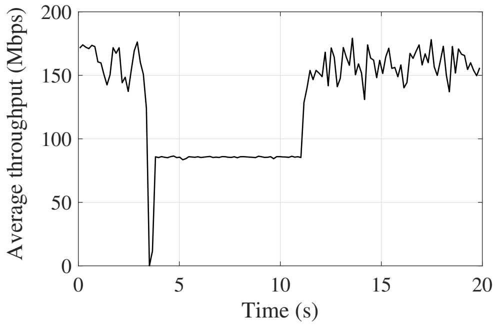


(c) Mobility use case using Backup mode tool.

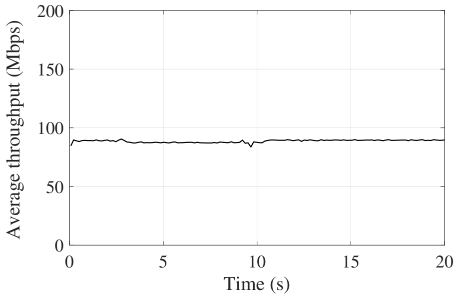
FIGURE 4.5 – MPTCP performance in VLC with link blockage due to mobility in "Default","Redundant" and Backup modes [47].

from the receiver the data traffic will be transmit over the second link with an average throughput of 90 Mbps. In the case of throughput dropping to zero, the data packet is buffered in a queue (i.e., packets in flight) for re-transmission over the first available sub-flow.

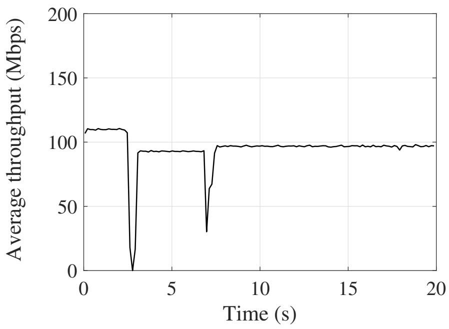
Experiment 2 - The Redundant scheduler: Here the redundant mode is used with



(a) Shadow use case using "Default" scheduler.



(b) Shadow use case using "Redundant" scheduler.



(c) Shadow use case using Backup mode tool.

FIGURE 4.6 – MPTCP performance in VLC with link blockage due to shadow/obstacle in "Default","Redundant" and Backup modes [47].

no latency during the handover and packet transmission continues seamlessly with a low throughput of 85 Mbps, see Figure 4.5b [47].
Experiment 3 – The Backup-mode: As shown in Figure 4.5c [47] maximum latency is achieved during the handover while the traffic transmission changes the paths between the primary and backup links. However, the throughput achieved can be higher than the Redundant mode depending on the link being blocked. In this specific experiment, the link with the highest average throughput is blocked, therefore, the traffic is transmitted over the second link with lower average throughput.

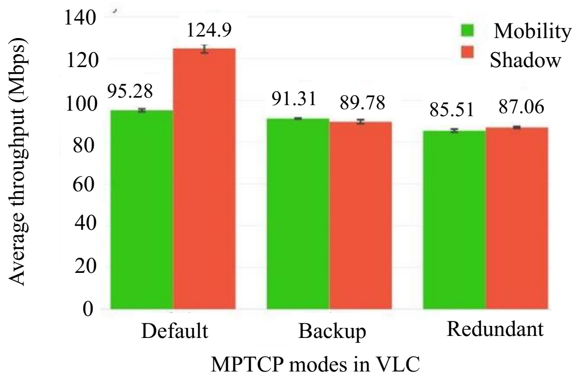


FIGURE 4.7 – Overall average throughput of MPTCP on mobility and shadow use cases [47].

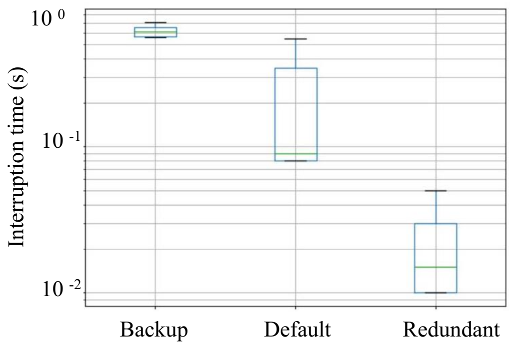


FIGURE 4.8 – Interruption time for mobility use case scenario in a V-VLC network [47].

The following set of experiments are based on the link failure due to shadow/obstacle. Experiment 4 – The Default scheduler: Using the Iperf tools I could achieve results shown in Figure 4.6 [47]. Figure 4.6a shows the data throughput for the link with shadowing, where the throughput dropped from as 173 Mbps to around 80 Mbps due to handover. The link is back to its maximum through level following the availability of the link with no shadowing/blocking.
Experiment 5 – The Redundant mode”: The achieved throughput, see Figure 4.6b [47], is like the experiment 2, where the same number of packets are being transmitted over both links simultaneously. Note, link failure (permanent or temporary) does not impact the latency during handover, but the average throughput is lower com-

pared with other use cases.
Experiment 6 – The Backup-mode: Figure 4.6c [47] shows the throughput with handover for a single VLC link experiencing temporary blocking. Note, the link with the lowest average throughput fails temporarily (i.e., a few seconds), see the notches in Figure 4.6c [47]. Using this mode, I achieve the highest outage duration rate during the handover.
In overall, Figure 4.7 [47] demonstrates the achieved TCP throughput in VLC in both mobility and shadow/obstacle use case scenarios. As a result the "Default" mode provides a VLC network with the highest throughput value both for shadow and mobility use cases as 124.9 and 95.28 Mbps, respectively. In the second place the Backup-mode provides the higher average throughput in comparison with the "Redundant" scheduler mode which provides the TCP average throughput for less than 90 Mbps for both mobility and shadow use case network scenarios.
Decreasing the outage duration during handover in a V-VLC network is considered as one the significant challenges for this type of network. Here I investigate the outage duration of TCP transmission over VLC links for Default and Redundant schedulers and backup-mode tool with handover. Figure 4.8 [47] presents the interruption time for the three cases, with Redundant and Back-up offering the lowest and highest values of 20.4 and 620 ms, respectively.

Finally, I have compared the achieved T_{hod} using Frequency Diversity and Link Aggregation (FDLA) [55] method in data link layer introduced in previous chapter and MPTCP solution in transport layer. As it is presented in Table 4.2, the achieved T_{hod} using Redundant scheduler in MPTCP is 0.02 s, due to broadcasting the traffic over all available sub-flows regardless of path's characteristics. However, there is a trade-off between bandwidth utilization and latency [47] [55]. Although using link aggregation in data link layer leads to a higher value for T_{hod}, it improves the network throughput at the same time [47] [55].

Table 4.2 – comparison of T_{hod} using MPTCP and link aggregation methods [55].

	MPTCP			**Link Aggregation**		
Schedulers/ ARP int (ms)	***Redundant***	***Default***	***Backup***	***50***	***100***	***200***
T_{hod} **(s)**	0.02	0.3	0.6	0.3	0.7	1.5

4.4 Conclusion

This chapter proposed a novel architecture to tackle the handover issues in the upper layer (i.e., the transport layer) in a VLC network to decrease the outage duration and increase the throughput during handover caused by mobility and shadow/obstacle both in uplink and downlink. The architecture includes the use of frequency division on VLC devices and MPTCP on both client and server. We presented a real-world experiment using VLC devices to demonstrate the network performance and showed that the improvement in the network throughput and outage duration depends on the user case scenarios, where there is a high chance of frequent handover caused by mobility and shadowing.

Chapter 5

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

In this chapter I develop an upper layer handover technique for vehicular communication networks using Visible Light Communications (VLC) and Wireless Fidelity (WiFi) technologies called Li-Wi [44]. I assess the effect of link aggregation method in data link layer and Multipath-Transmission Control Protocol (MPTCP) in transport layer separately and together as a combined solution on a hybrid vehicular network where VLC and WiFi act as a primary and backup link, respectively. This chapter also shows how Li-Wi decreases horizontal and vertical handover latencies in a vehicular hybrid network and improves network coverage, reliability and robustness using different wireless technologies.

The chapter also summarizes the existing related approaches and details the potential problems within a vehicular network, and the motivation behind Li-Wi. Moreover, it presents an overall comparison result among Li-Wi and previous V-VLC handover technique solutions. It also presents the Li-Wi network architecture in detail. Later, it describes four different hybrid handover setup experiments. I also describe how efficiently plan the VLC cell sizes in this hybrid network in details and demonstrate the implementation of several handover techniques in hybrid real-world case studies including Li-Wi.

5.1 Related work

The feasibility of a hybrid VLC and Radio Frequency (RF) system has been experimentally validated in [81], [82] and several solutions have been proposed in [45], [46], [48]–[53], [56] to handle handover challenges in an indoor environment. In [48] a VLC+Wifi testbed was designed based on software defined radio and measurements on blockage effect by users considering a practical scenario was set up and used to design multiple decision algorithms for a flawless handover timing. Also, handover mechanisms that improve management and acknowledgement frames on the Medium Access Control (MAC) layer were designed.

In [49] a prediction-based vertical handover mechanism (PVHO) was proposed and evaluated. The proposed PVHO algorithm aimed at providing a seamless handover between VLC and the standardized IEEE802.11p scheme for convoy-based applications. The proposed scheme was validated using NS3 Network simulator and the system performance was evaluated by means of packet delivery ratio (PDR) and the dynamic prediction redundancy period metrics. The results obtained showed a PDR improvement of up to 20% in dense traffic scenario and PVHO reached a 100% prediction success rate thus permitting sufficient redundancy time for seamless handovers to take place for certain scenarios considered.

In [45] to have an efficient inter-system handover scheme for VLC+WiFi integrated systems a channel adaptive dwell vertical handover (CAD-VHO) scheme is presented as an improvement over static D-VHO scheme. The proposed scheme is adaptive to the rate and extent of blockage of the line-of-sight VLC link resulting from the mobility of the user and surrounding objects. Results obtained from the simulation performance evaluation showed that the proposed CAD-VHO scheme can decrease the number of vertical handovers by up to 80%.

While in [50], a hybrid VLC+WiFi system was designed and implemented to show the feasibility of the integration of both systems for communications, results obtained showed a reduction in the packet loss rate as the bias voltage increased. Obviously, with increase in the bias voltage, the intensity of the light source increases and thus the field of view coverage of the light source is enhanced. Also, the total handover latency from WiFi to VLC and VLC to WiFi was 2.75 s.

In [51] a vertical handover (VHO) algorithm for a hybrid VLC-Femto system in a family apartment is proposed. Their approach utilizes analytic hierarchy process (AHP) and cooperative game (CG) to cope with multi-attribute decision making process, which suits different traffic types. Multiple attributes considered in their approach includes dynamic network parameters, and actual traffic preferences. Results obtained from comparison of the average VHO for different schemes evaluated showed that the proposed AHP-CG performs better than just AHP scheme providing a reduction in the average VHO by to 18%.

vertical network handovers between Light Fidelity (LiFi) and RF are simulated in [52] caused by different scenarios such as blockages and random orientation of LiFi receivers. Additionally, a load balancing scheme for a hybrid LiFi/RF network is proposed which is based on evolutionary game theory. After analyzing the performance of the scheme, the results show that it greatly improves the user satisfaction level as reduced computational complexity in comparison with state-of-the-art load balancing techniques. In addition, it shows that an optimal orientation of LiFi receivers and blockage density in hybrid networks would maximize the quality of service for end users.

In [53] a novel method of handover skipping is studied which enables handovers between two non-adjacent APs, in LiFi networks. The proposed method is based on reference signal received power (RSRP), which combines it with its rate of change to determine the handover target. In comparison between the proposed scheme and the standard handover scheme and the conventional handover skipping method, the proposed method can reduce handover rate by up to 29% and 17%, and improve throughput by up to 66% and 26%, respectively.

In this work, I experimentally implement Li-Wi architecture which address the handover issue in a hybrid network in upper layers. The aim of this work is decreasing handover latency and increasing network robustness by using an additional backup technology as WiFi, once vehicular VLC (V-VLC) network faces VLC link failure. As a result, Li-Wi proves decrement of T_{hod} with the high data rates and robustness in an indoor hybrid network environment.

5.2 Problem statement

One of the main challenges in a V-VLC network is providing a robust network with high data rate and less handover delay. Since, there is a high degree of mobility in similar networks, the chance of frequent handover due to mobility, shadowing and obstacle is raising and providing an efficient handover technique is certainly required. Considering a V-VLC network, where there is no handover technique applied, T_{hod} is measured as 15 s. This long delay is not acceptable in industrial networks as it can immediately cause a network disruption. In prior work [1], [58] and [39] I proposed an architecture called Flight which addressed handover challenge in data link layer in a V-VLC network with linear movements. There, I considered each Automated Guided Vehicles (AGV) equipped with two Light Clients (LC) and on the ceiling, there are LAPs configured on two different frequency ranges as their corresponding LCs. We analyzed Flight performance in different connection lost situations caused by shadowing and mobility using different channel selection methods [39], and the least T_{hod} achieved was 0.3 s.

In addition [47], I presented a flexible transport layer protocol architecture for handover in a V-VLC network. There, I used MPTCP to optimize the network throughput and latency. We studied and evaluated in detail how selecting different MPTCP schedulers and modules can pave the way to achieve a higher throughput and least T_{hod}.

There are pros and cons tackling mobility and handover in data link and transport layers. The main advantages of using link aggregation in [1] and [39] are that it is easy to set up and there is no need to use additional devices and finally T_{hod} can optimized up to 0.3 s which still much better than tens of seconds using no handover technique. However, using this technique only addresses handover for AGVs with linear movements and not in any given direction. In addition, in [47], the handover issue is addressed on transport layer and this facilitates achieving a more optimized T_{hod} in comparison with previous method. Moreover, this method is less complicated as there is no modification on packet routing and transmission on data link and Network layers. However, there is a tradeoff to use different types of MPTCP schedulers. For instance, using Redundant scheduler leads to achieve lower network throughput sacrificing the bandwidth but decreasing T_{hod}, considerably. Therefore, depending on specific use case scenario whether throughput or T_{hod} has higher weight, a specific MPTCP scheduler should be selected.

Besides the mentioned handover solutions, still one main concern remains as what happens in case a VLC network gets inaccessible or there is a network hole where there is no coverage by LAPs in the warehouse network area? A possible answer might be, to address network handover not only the handover techniques over data link and transport layers are required, but also using the second wireless technology [83] as a backup connection is certainly needed. In this way, network remains connected even if it experiences VLC or WiFi disconnection due to lack of network coverage.

Therefore, this is the main motivation behind this work to provide a robust vehicular network using a backup technology and build a hybrid system using both VLC and WiFi called Li-Wi. Therefore, Li-Wi aims to provide a seamless handover tackling mobility challenge in both data link and transport layers.

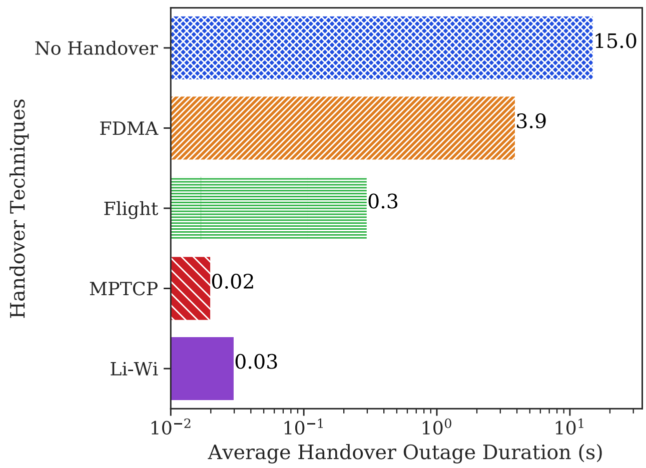


FIGURE 5.1 – Comparison of horizontal handover outage duration for different handover methods [44].

In this chapter, I present Li-Wi which is built upon our previous works and proposed as a hybrid solution using multiple VLC channels and a single WiFi channel to enhance hybrid network reliability and robustness. Figure 5.1 [44] presents an overall comparison of achieved T_{hod} during a horizontal handover using ***(i)*** no handover technique; ***(ii)*** Frequency Division Multiple Access (FDMA); ***(iii)*** Flight [1]; ***(iv)*** MPTCP [47]; and ***(v)*** Li-Wi.

As it is presented in Figure 5.1 [44], Li-Wi provides T_{hod} as 0.03 in case of horizontal handover using MPTCP redundant scheduler. As it is shown, Li-Wi performs quite similar as MPTCP described in [47]. However, the main advantage of Li-Wi is that first of all, it provides a better network coverage utilizing the second wireless technology for backup in case of connection lost, secondly, it brings connectivity over four wireless links as three VLC and a WiFi, which provides an AGV to experience a smooth handover at any given time and direction in a two dimensional (2D) environment.

5.3 Li-Wi Network architecture

In this section, I introduce the designed hybrid system and its network architecture in Physical, data link and transport layers as shown in Figure 5.2 [44]. Li-Wi system is a method designed for a variable outage duration handover in a vehicular network, comprising cells of three LAPs and LCs and using WiFi technology. Li-Wi uses three essential methods as FDMA, link aggregation (Ethernet bonding) and MPTCP.

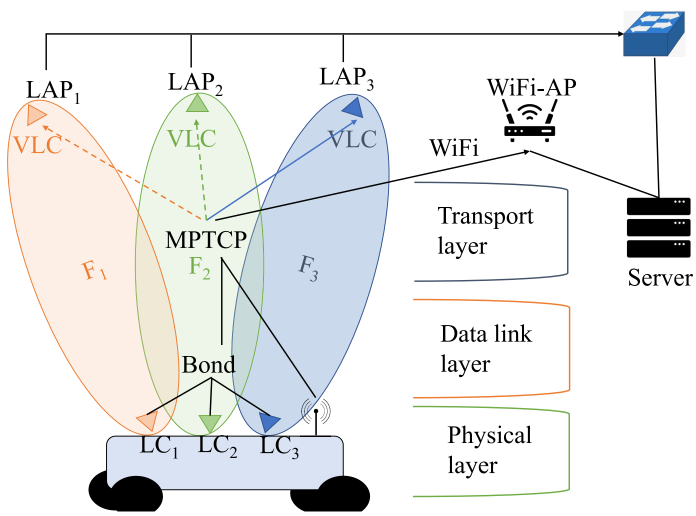


FIGURE 5.2 – Li-Wi architectural design [44].

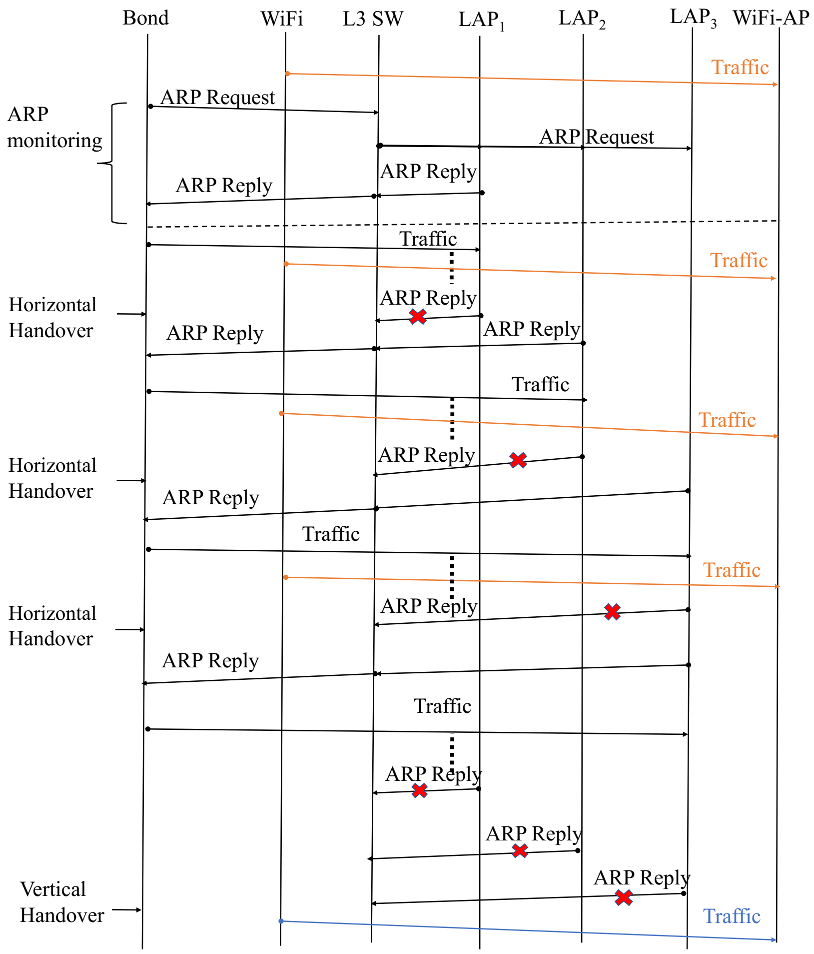


FIGURE 5.3 – Packet flow diagram of Li-Wi [44].

As Figure 5.3 [44] presents the packet flow diagram of Li-Wi. As it is shown, first there is a channel access procedure based on ARP monitoring packet exchanges where, the Bond interface chooses the right available link to establish a VLC connection via the responsive Light Access points (LAP). Note, the WiFi interface in MPTCP Redundant scheduler establishes WiFi link in parallel with VLC link (shown in orange color) and in Default scheduler establishes WiFi link only if there is no available VLC link and vertical handover occurs (shown in blue color).

5.3.1 Physical layer description

As Figure 5.2 [44] presents, the LAPs are placed in a way to achieve seamless coverage of the VLC network with overlapping areas with the other LAPs. They establish FDMA for the V-VLC network with three non-overlapping frequency ranges F_1, F_2

Table 5.1 – Experimental parameters [44]

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 (FoV)	60 degrees
VLC channel Bandwidth	100 MHz
Transmission power of LED	630 mW
Effective active area of photodiode	150 mm^2
Number of LEDs in a VLC COTS	5
Number of photodiodes in a VLC COTS	4

and, F_3 shown in different colors. The LAPs are configured to establish a link within either of the three non-overlapping frequency ranges with three LCs installed on an AGV where each one is capable of MAC layer conversion between Ethernet and light-based communication. Finally, all LAPs are connected to a server using Linux Operating system via a layer three switch (SW).

Both LCs and LAPs used are VLC devices provided by OSRAM, which use Orthogonal Frequency Division Multiplexing (OFDM) as a modulation method and follow G.hn standard in order to provide an average real-time bidirectional communication at 90 Mbps over a transmission distance of 10 m. LCs are consist of five off-the shelf high-power LEDs (OSRAM SFH 4715 AS) with 60 degree half angles and four large-area silicon Photo-Detector (PD) (Hamamatsu S6968). The transmit power of LEDs and their effective areas are 630 mW and 150 mm2, respectively. In addition, there is a WiFi antenna placed on AGV which establishes a wireless link via WiFi-AP to the server. Table 5.1 [44] shows the key experimental parameters adopted in this work.

5.3.2 Data link layer description

The three LC interfaces are configured towards a logical Ethernet Bonding interface called Bond using link aggregation method in data link layer as shown in Figure 5.2 [44]. Each LC is belonged to each of the three predefined frequency ranges. Creating a bond interface, one of the LC interfaces is configured as an active interface of the Ethernet Bonding while the other interfaces are configured in backup mode. To monitor link failure during handover, ARP monitoring tool is used. Periodically, the LC sends an ARP request to the ARP target (in this architecture is defined as SW), in parallel, and in predetermined intervals, to establish the suitability of the VLC link to transmit the packets.

The active LC continues packet transmission if a compatible LAP sends an ARP reply via the switch in between. While the LC is using the active link, and when no ARP reply is received by the LC during a handover time, it changes the packet transmission from the active to the backup link if the ARP replies are received by the backup interface. Similarly, while the AGV is using the backup interface for packet transmission, and when no ARP reply is received at the LC via the backup link from an LAP, it switches from the backup interface to the second backup or the active interface as long as the ARP replies are received via the other backup or the active interface.

5.3.3 Transport layer description

In transport layer of Li-Wi architecture, MPTCP is applied on top of logical Bond and WiFi interfaces of an AGV. MPTCP is a Linux kernel, and in this work, it is installed on Ubuntu 18.04 both on server and client systems. Here, MPTCP version 0.95 with full mesh path manager is adopted, and there is a full mesh of sub-flows between Bond and WiFi interfaces. A Transmission Control Protocol (TCP) connection is established over mentioned two sub-flows as shown in Figure 5.2 [44]. We applied two MPTCP schedulers as Default and Redundant. Using Redundant scheduler, I transmit the traffic over both available sub-flows in a redundant way. This leads us to achieve the lowest possible latency by sacrificing the bandwidth. On the other hand, Default scheduler sends the data on the sub-flow which has the lowest Round Trip Time (RTT) until its congestion-window is full. After, it starts traffic transmission on the other sub-flow with the next higher RTT value.

5.4 Definition of different practical experiments

In this section, I consider four handover options supported by Li-Wi, where handover issue is addressed rather using only link aggregation, MPTCP or, our proposed Li-Wi method experiencing horizontal and vertical handovers in a hybrid network.

5.4.1 Link aggregations

In this architecture, I consider a link aggregation working on two wireless technologies as VLC and WiFi. Therefore, I assume each AGV is equipped with both LC and a WiFi interface and there are LAPs and a WiFi-AP. The goal it to make the AGV connects to the server using rather VLC, WiFi or both communication links. Since in this hybrid system, I consider V-VLC as our main communication network, I configure the VLC link as a primary and WiFi as a backup link applying active-backup mode.

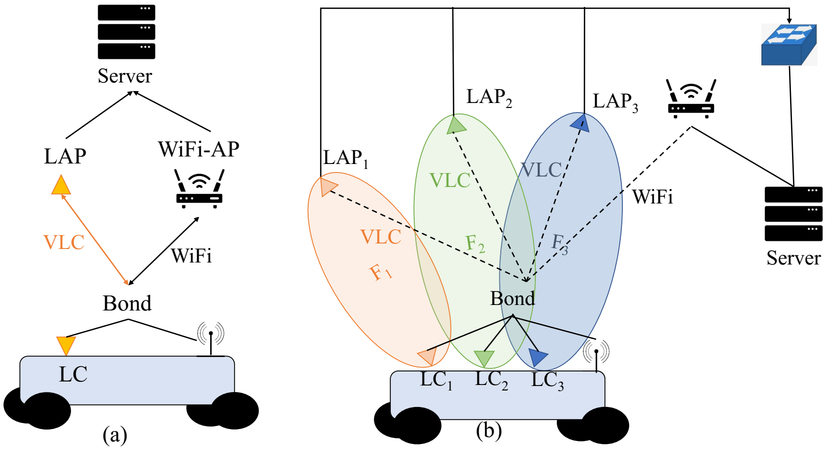


FIGURE 5.4 – Link aggregation between VLC and WiFi use case scenarios [44].

To simplify this architecture, initially I equip each AGV with an LC and a WiFi interface and configure a logical Bond interface on top of them, see architecture (a) in Figure 5.4 [44]. To establish a link between server and AGV, Bond interface will monitor both VLC and RF link using ARP monitoring tool and decide through which link packet transmission is possible.

As it is shown in the architecture (b) in Figure 5.4 [44], an extended and more complex model is proposed to deal with handover in 2D movements of AGV using three LCs and a WiFi interface. The main goal for this technique is decreasing T_{hod} in case of VLC links blockage and using WiFi as a backup connection to maintain network connectivity.

5.4.2 MPTCP

In this architecture, I address a hybrid handover challenge only in transport layer using MPTCP. Two different scheduler methods as Redundant and Default are selected to schedule packet transmission through three VLC and a WiFi sub-flow. As it is presented in Figure 5.5 [44], a MPTCP is configured on top of VLC and WiFi interfaces as four TCP connection links and they start packet transmission based on chosen MPTCP schedulers.

5.4.3 Li-Wi addressing Vertical handover

In this architecture, I apply Li-Wi as shown in Figure 5.2 [44]. Initially, I evaluate the performance of Li-Wi measuring T_{hod} during vertical handover. In this chapter I refer to vertical handover once a link between AGV and server changes the type of connectivity due to handover, and it usually takes place due to mobility. As it

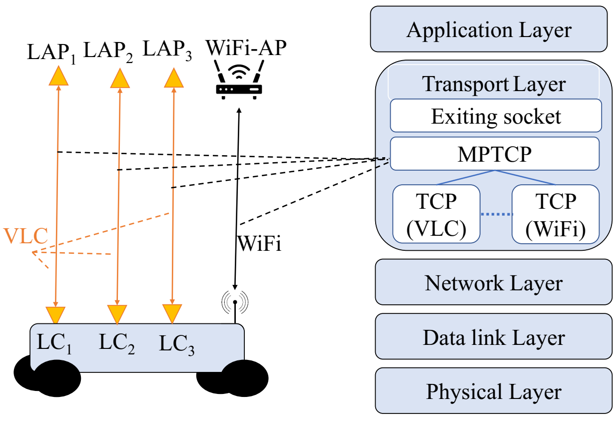


FIGURE 5.5 – MPTCP between VLC and WiFi use case scenarios [44].

is shown in Figure 5.6 [44], AGV experiences vertical handover once the already established link between Bond interface and LAP_2 disconnects, and a new WiFi connection links establish between Bond interface and WiFi-AP.

5.4.4 Li-Wi experiencing both horizontal and vertical handovers

In this architecture, I add more complexity where AGV experience both horizontal and vertical handovers. We evaluate the effect of using Li-Wi to the system architecture shown as Figure 5.2 [44]. In this work I consider horizontal handover once AGV loses connectivity within VLC network and traffic transmission switches

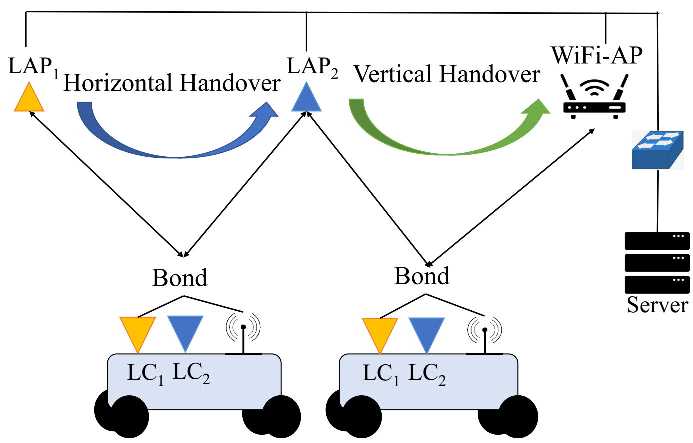


FIGURE 5.6 – Horizontal and vertical handovers presentations [44].

to the other available VLC link within the same network. As it is presented in Figure 5.6 [44], horizontal handover occurs once the VLC link between Bond interface and LAP_1 disconnects, and a new VLC link establishes between the Bond interface and LAP_2.

5.5 Cell planning

One of the main challenges in V-VLC is the high mobility of the network, which can be considered as the significant cause for frequent handovers occurring in the network. Consequently, to decrease handovers and generally network latency, adequate light coverage within the indoor V-VLC network, i.e., cell planning is of paramount importance. Therefore, to achieve an optimized coverage within an indoor V-VLC network, I provide key insights into cell planning and derive a mathematical model to calculate the optimum distances between LAPs based on LAP and channel parameters.

5.5.1 Analysis of light coverage profile

The radiation characteristics of a light source defines the spatial intensity distribution of the emitted light and its coverage field of view [84]. The radiation pattern of each light source, the distances between the light sources and the vertical link span will determine if the emitted beams of light from a cluster of light sources will overlap. Figure 5.7 [44] and Figure 5.8 [44] illustrate overlapping and non-overlapping LAPs beam coverage profiles.

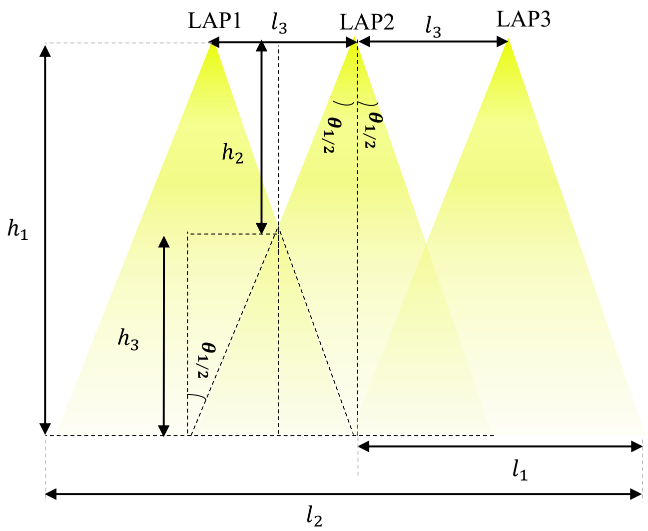


FIGURE 5.7 – Overlapping beam coverage profile [44].

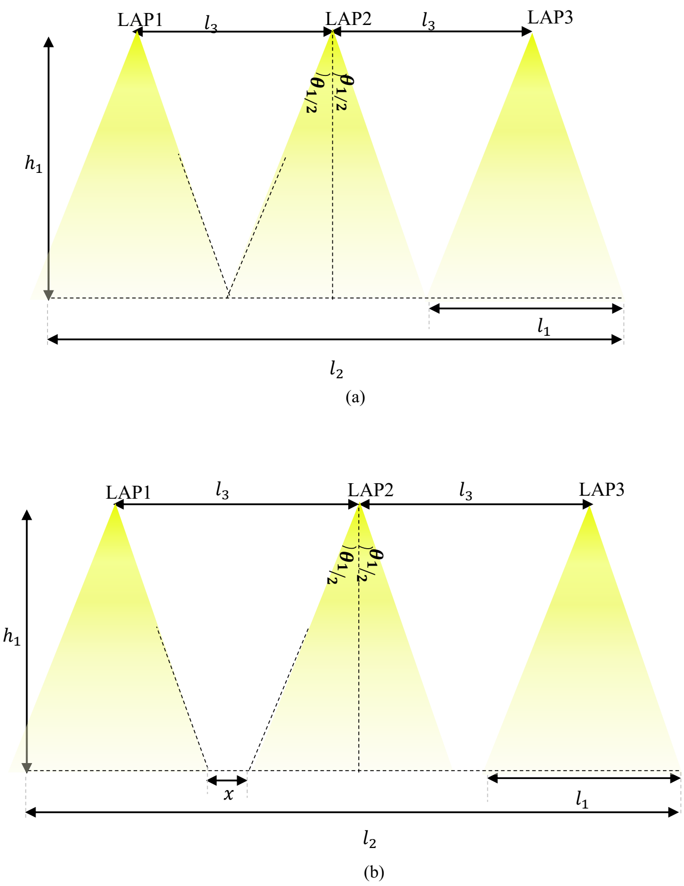


FIGURE 5.8 – Non-overlapping beam coverage profile with (a) no gaps (b) gaps [44].

For Figure 5.7 [44], h_2 depicts the height from the LAPs to the point where the overlapping light area between the LAPs begins, which can be expressed as:

$$h_2 = \frac{l_3}{2\tan(\theta_{1/2})} \tag{5.1}$$

where l_3 is the distance between the LAPs and θ_1 is the half power angle of the LAPs. The beam length of a single LAP is denoted as l_1 and can be expressed as:

$$l_1 = 2h_1 \tan(\theta_{1/2}) \tag{5.2}$$

where h_1 is the vertical link span.

For overlapping LAP beams as shown in Figure 5.7 [44] the coverage length can be expressed as:

$$l_2 = l_3(n-1) + 2h_1 \tan(\theta_{1/2}) = l_3(n-1) + l_1 \tag{5.3}$$

where n represents the number of LAPs.

Figure 5.8 [44] (a) and (b) depicts a non-overlapping beam coverage profile. The entire coverage length for 'n number of LAPs will simply be nl_1 for Figure 5.8(a) [44], while for Figure 5.8(b) [44], within the coverage length there are some gaps (dead zones) which will result in more frequent and unnecessary handovers, which with appropriate cell planning can be avoided.

Note that, for a given $\theta_{(1/2)}$, the h_1 and l_3 values determine if the beam will overlap or not and required values can be determined using (1)-(4). For example, for a given value of h_1, the value of l_3 can be determined for the LAP beams not to overlap or vice versa, see Figure 5.7 [44]. Additionally, beam forming optics can be used to adjust the $\theta_{(1/2)}$ and shape the emitted beam to fit the coverage requirements of the network.

Also, I have:

$$h_3 = h_1 - h_2 = h_1 - \frac{l_3}{2\tan(\theta_{1/2})} \tag{5.4}$$

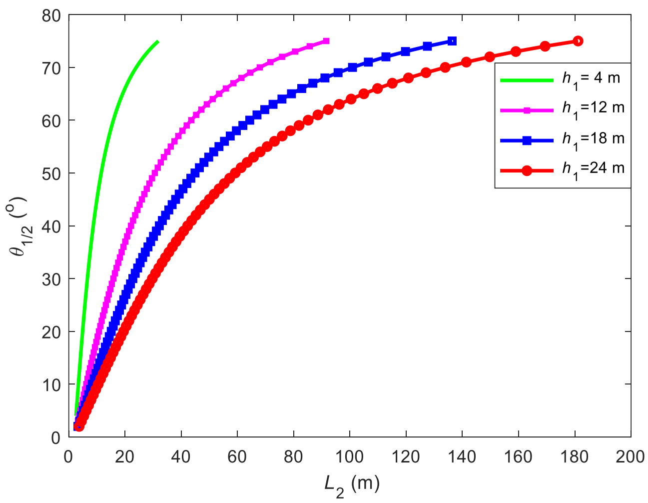


FIGURE 5.9 – LAP's FOV as a function of half power angle for a range of vertical link spans [44].

Figure 5.8(a) or Figure 5.8(b) depict LAPS with no overlapping illumination areas. For Figure 5.8(b), with n number of LAPs the total path length is:

$$l_n = nl_1 + x \tag{5.5}$$

where x 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 $l_3 = 1\text{m}$, and $n = 3$ is presented in Figure 5.9, which show logarithmic profiles. As shown in Figure 5.9, 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:

$$\begin{aligned} A_{ovl} =& 2\Bigg(\Big(h_1 \tan(\theta_{1/2})\Big)^2 \cos^{-1}\Big(\frac{l_0}{h_1 \tan(\theta_{1/2})}\Big) - \\ & l_0 \sqrt{\Big(h_1 \tan(\theta_{1/2})\Big)^2 - {l_0}^2}\Bigg) \end{aligned} \tag{5.6}$$

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:

$$\begin{aligned} A_{n-ovl} &= n\pi\Big(h_1 \tan(\theta_{1/2})\Big)^2, \\ A_{w-ovl} &= n\pi\Big(h_1 \tan(\theta_{1/2})\Big)^2 - (n-1)A_{ovl} \end{aligned} \tag{5.7}$$

5.5.2 Cell Size and Light Density per Cell (VLC units per cell)

The number of VLC units per cell will depend on the desired cell size, the radiation pattern of the transmitter and the receiver sensitivity and of course the eye safety limit. The receiver sensitivity is the minimum optical signal power level required to achieve a particular Bit Error Ratio (BER) performance [85] at a certain bit rate. For example, the receiver sensitivity based on experimental measurement for a target BER of 10^{-6} and 10^{-12} for a specific receiver at 10Gb/s is ∼38 dBm and ∼33 dBm. The sensitivity of the receiver required for a given transmit power P_T for a VLC unit can be calculated from:

$$R_a(dBm) = P_T(dBm) + H_{LOS-db}(dB) - L_{sm}(dB) \tag{5.8}$$

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

where L_{sm} is the link safety margin, and a H_{LOS-dB} is the channel DC gain for the Line-of-Sight (LOS) in dB, which is given by [86]

$$H_{LOS} = \begin{cases} \frac{(m+1)A_{PD}}{2\pi h_4^2} \cos^m(\theta) T_s(\varphi) g(\varphi) \cos(\varphi), & 0 \leq \varphi \leq \xi \\ 0, & \varphi > \xi \end{cases} \tag{5.9}$$

Note that, H_{LOS} is not in dB ($H_{LOS-dB} = 10\log_{10} H_{LOS}$). A_{PD} represents 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 the Lambertian order of emission of the LAP, which is given by [86]:

$$m = -\frac{ln2}{ln(\cos(\theta_{1/2}))} \tag{5.10}$$

Lambertian radiant intensity is expressed as [86]:

$$R(\phi) = \frac{(m+1)}{2\pi} \cos^m(\theta) \tag{5.11}$$

5.5.3 Timing for Handover

With adequate light coverage within a room and no obstructions to the LOS path, the overall system's latency will depend on the handover mechanism for the LAPs as the AGV moves from one cell to the other for the FDMA scheme. Figure 5.10 [44] depicts the configuration of an indoor V-VLC system. To determine the perfect timing for handover within the light overlap area, the speed of the AGV S_{AGV}, the overlap distance l_4, the AFOV of the receiver, needs to be considered aside the latency of the handover mechanism t_{han}. Thus, the suitable timing for handover in the overlap light area should be such that

$$t_{han} + t_{sm} \leq \frac{h_1 \tan(\varphi)}{S_{AGV}}, \varphi \leq \xi \tag{5.12}$$

where $h_1 \tan(\varphi) = l_4$ (for $\varphi = \theta$) and t_{sm} is the time safety margin. With obstructions to the LOS and insufficient non-LOS received power, the handover latency between one LAP to the other will depend on the distance between the LC and the object of obstruction, the height of the object and the FOV of the receiver, which could change randomly and is specific to that environment.

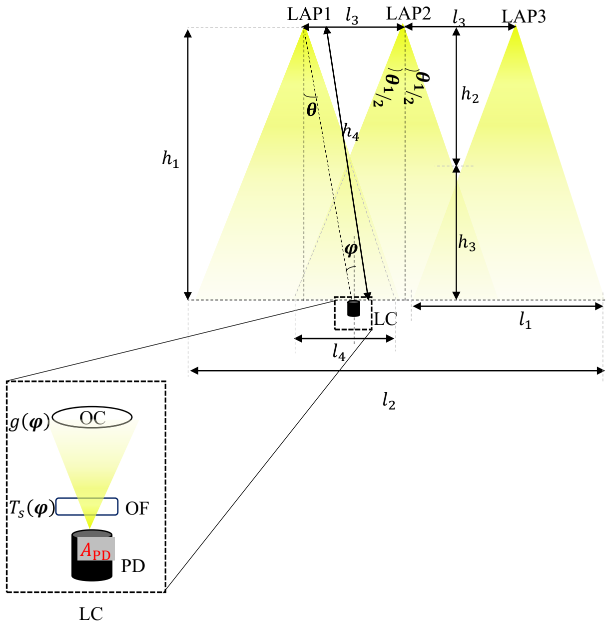


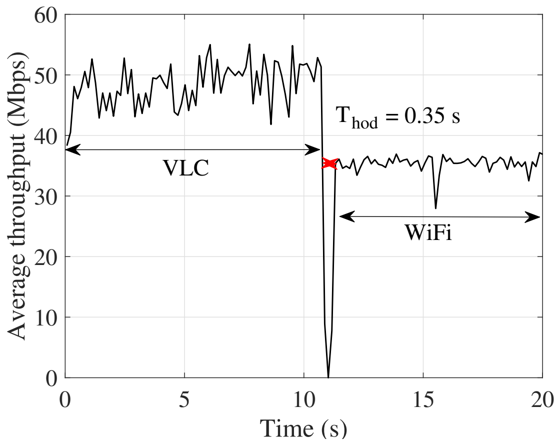
Figure 5.10 – Configuration of an indoor V-VLC system [44].

Table 5.2 – T_{hod} vs. ARP interval values Link aggregations between VLC and WiFi architecture using TCP and UDP [44].

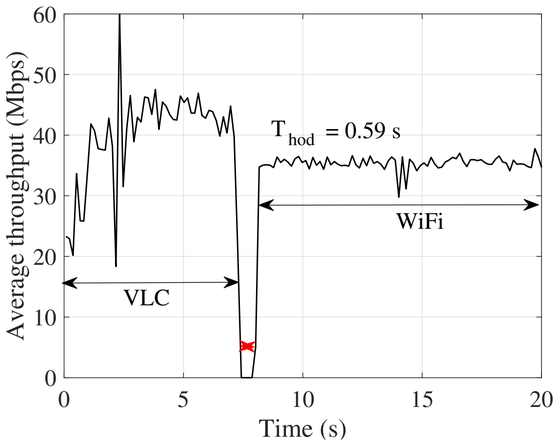
ARP interval (ms) $T_{hod}(s)$	*50*	*100*	*200*
UDP	0.15	0.25	0.7
TCP	0.3	0.7	0.91

5.6 Experimental results

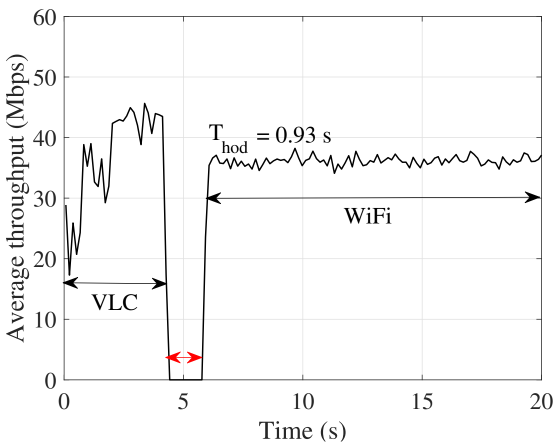
The proposed Li-Wi system is experimentally implemented as a small-scale prototype and its performance validated. We have used 3 pairs of LAPs and LCs with a distance of 1 m between each LC and LAP. In addition, I used a WiFi USB antenna and a WiFi-AP to provide a WiFi connection link. A mini-Pc with Linux-Ubuntu operation system is used a client equipped with three LCs and one WiFi antenna. There are also three LAPs and a WiFi-AP which are connected to a server via a configurable layer three SW. As it shown in Figure 5.2 [44], a logical Bond interface is configured on top of three LCs in data link layer. After, in transport layer the



(a)



(b)



(c)

FIGURE 5.11 – Link aggregation between three VLC and a wifi interface using ARP interval as (a) 50, (b) 100 and, (c) 200 ms [44].

Bond interface and WiFi link work as sub-flows in MPTCP and finally connect to the server.

We have also separately, implemented the handover options supported by Li-Wi to evaluate the results and compare Li-Wi performance with each of them. Note, each test is repeated 10 times per scenario in following subsections.

5.6.1 Link aggregations between VLC and WiFi

As was described in subsection 5.4.1, this is the case in a hybrid network where there is a link aggregation between VLC and WiFi interfaces. Table 5.2 [44] presents the values achieved for T_{hod} using the simple scenario where the Bond interface is configured on only one LC and a WiFi interface installed on AGV. Table 5.2 [44] presents the experimental results for different traffic types as TCP and User Datagram Protocol (UDP) which are implemented for real-case scenarios using Iperf tools. The lowest achieved T_{hod} is 0.15 s in case of UDP packet transmission with ARP interval as 50 ms.

Next, I added more complexity to the system, adding two more LCs and configuring Link aggregation on top of three LCs and a WiFi interface. Figure 5.11 [44] shows the experimental results of T_{hod} for TCP traffic implemented using ARP intervals of 50, 100 and, 200 ms. As it is presented in all three cases, the average throughput values decrease from an average values of 52 to 35 Mbps which reveals a vertical handover occurs between VLC and WiFi. Note, that the opposite switches between WiFi and VLC during the vertical handover, result at similar values of T_{hod}. In addition, the results present that achieved T_{hod} for TCP has not a big difference in comparison with the previous case where I configured Bond interface on top of only 2 interfaces. Therefore, Increasing the number of interfaces does not increase T_{hod} considerably, but it addresses handover challenge in 2D movements of AGV, which is a great benefit and decrease the T_{hod} considerably in comparison where no handover technique is applied.

Table 5.3 – T_{hod} values using MPTCP between VLC and WiFi interfaces [44].

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

5.6.2 MPTCP between VLC and WiFi

Here, I emulate the architecture showed in Figure 5.5 [44] which is well described in subsection 5.4.2. We evaluate T_{hod} in case AGV experiences link failure due to mobility. We apply two different MPTCP schedulers in this case; Redundant and Default, addressing the mobility issue in a hybrid network. As it is presented in the results, applying MPTCP Redundant scheduler provides us a much lower T_{hod} in comparison with the case using Default scheduler. However, it is considerable that the network throughput using Redundant scheduler is 25 mbps which is much lower than Default case which is 55 Mbps. The reason behind is that Redundant scheduler sacrifices bandwidth to provide a better latency. Therefore, there is a tradeoff using these two schedulers, depends on our network demand. Table 5.3 [44] presents the achieved values for T_{hod} during horizontal and vertical handovers. It presents addressing mobility issue in transport layer leads decreasing T_{hod} to 0.2 and 0.85 s in case of horizontal and vertical handovers, respectively using MPTCP Redundant scheduler.

5.6.3 Li-Wi performance during Vertical handover

Here, I finally emulate and evaluate our main proposed Li-Wi architecture which is configured on both data link and transport layers. The architecture is fully described earlier in subsection 5.4.3. In this experimental set-up, I analyze T_{hod} values for the case where AGV only experiences a vertical handover. We use a fixed ARP interval as 100 ms for the Bond interface on top of the LCs to detect the link failure using ARP monitoring.

As shown in Figure 5.12 [44], using both Link aggregation and MPTCP during a vertical handover, leads us reducing T_{hod} to 0.06 and 0.3 s in case of using Redundant and Default schedulers, respectively. Note, in Figure 5.12b [44] the average network throughput decreases by 28 Mbps, however it does not provide any network dis-connectivity and the vertical handover smoothly happens without a major decrement of T_{hod}. Figure 5.12a [44] demonstrates the results with the same architecture but using Default scheduler. In this case, I achieve a higher average network throughput as 55 Mbps before handover occurs but after, due to switching from VLC to WiFi, I achieve the average throughput value as same as the case using Redundant scheduler. Therefore, the same trade off between average throughput and T_{hod} values remains and based on network's demand priority I choose between two MPTCP schedulers.

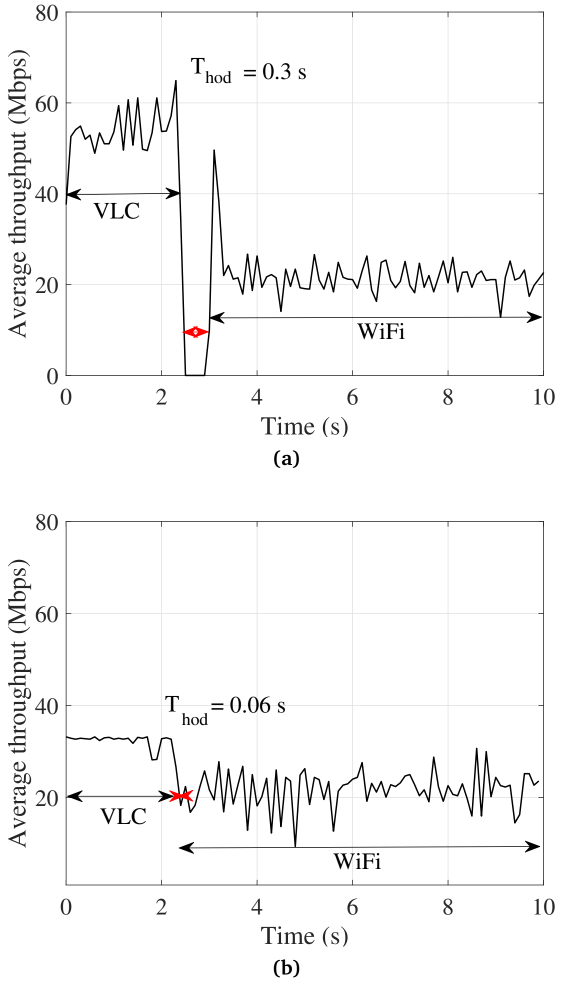


FIGURE 5.12 – Li-Wi performance applied on a hybrid architecture experiencing only vertical handover using (a) Default (b) Redundant schedulers [44].

Table 5.4 – T_{hod} values using Li-Wi during horizontal and vertical handovers [44].

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

5.6.4 Li-Wi performance during horizontal and vertical handovers

Here, I emulate and analyze the performance of Li-Wi in a case described in subsection 5.4.4 where AGV experiences both horizontal and vertical handovers while moving within the hybrid network environment. We use ARP interval as 100 ms for monitoring the link via Bond interface and apply both Redundant and Default schedulers for MPTCP between the Bond and WiFi connection links. As Table 5.4 [44] reveals, using Li-Wi leads decreasing T_{hod} in horizontal handover to 0.1 and 0.03 using Default and Redundant schedulers, respectively.

5.6.5 Comparison between different handover techniques in different network layers

Here, I finally compare the performance of Li-Wi in terms of T_{hod} in case of horizontal and vertical handovers with the other handover techniques proposed in data link and transport layers, individually. As Figure 5.13 [44] presents, Li-Wi not only improves network reliability and robustness using an additional wireless technology as a backup, but also decreases the handover latency to 0.03 and 0.06 s using Redundant scheduler for horizontal and vertical handovers, respectively. In terms of network throughput, Li-Wi performs good achieving up to 55 mbps using Default scheduler with handover delays of 0.1 and 0.3 s for horizontal and vertical handovers, respectively.

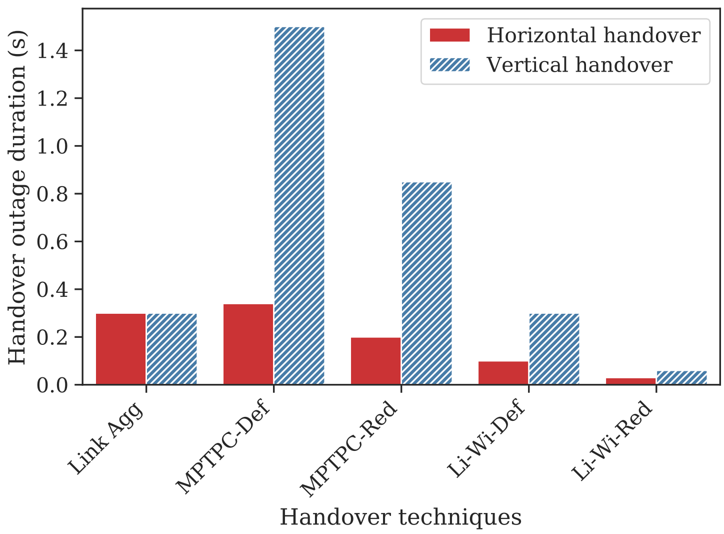


FIGURE 5.13 – Performance comparison between proposed handover techniques [44].

5.7 Conclusion

This chapter presented a hybrid handover solution known as Li-Wi in data link and transport layers based on frequency diversity, link aggregation and MPTCP tool for the hybrid networks. Li-Wi utilized link aggregation method within VLC network over VLC links to provide an efficient channel selection method using three different frequency ranges, therefore it provided a smooth horizontal and vertical handover with minimum T_{hod}. Additionally, MPTCP was used over the Bond and WiFi interface in transport layer, ensuring network connectivity in case of VLC link failure. Therefore, it provided a hybrid network to experience robustness with minimum handover delay within the network.

We also experimentally, implemented and evaluated two other handover options in a hybrid network to be performed separately in each of data link and transport layer. Finally, I compared the experimental results and presented how Li-Wi reduces the handover delay in both cases of horizontal and vertical handovers and provides robustness to the network, thanks to using WiFi link as a backup for the network.

Chapter 6

Conclusion

In the context of this PhD thesis, I focused on vehicular VLC (V-VLC) handover challenges in an indoor network environment. This work specifically aimed at decreasing handover outage duration time in indoor vehicular network environments using Visible Light Communications (VLC) technology as a primary communication links and Wireless Fidelity (WiFi) as a backup connection. I first investigated the link aggregation method in data link layer and using the benefit of Frequency Division Multiple Access (FDMA) approach in a network solution named Flexible Light Communications (Flight) [1]. I designed the flexible and efficient network architecture using only VLC network. This work performed to minimize the outage duration during T_{hod} the possible handovers due to mobility and obstacle/shadowing both in VLC uplink and downlink. I presented real-world experiments using VLC devices to prove the network performance while applying the proposed network architecture. Flight proposed a low-latency handover system that decreases the handover delays to a few tens and hundreds of milliseconds.
Further focusing on optimizing achieved reduced handover outage duration for shadow use cases, I applied "failure" interface selection method instead of the default mode which led to decrease the VLC T_{hod} by 62% and 44% in bonding schemes for Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) network traffic, respectively [39].
From these findings from the Flight architectural design, I built up a new architecture called Frequency Diversity and Link Aggregation (FDLA) [55], in order to enable V-VLC to reduce T_{hod} not only in linear but also in two dimensional (2D) indoor V-VLC environments. I configured each pair of Visible Light Sensors (VLS) to establish links using different predefined frequency ranges and aggregate VLC links on the client side. Therefore, in a V-VLC network and at any given time and direction, Automated Guided Vehicles (AGV) chose the best link established between the client and the server in both up- and down-link with the minimum T_{hod}. The

results showed that the proposed FDLA system implemented in three different use case scenarios and using different traffic types gains a better understanding of the mobility and handover in V-VLC networks and it minimized the T_{hod} up to 0.2 s.
As a follow up on decreasing V-VLC handover outage duration, this thesis also explored the handover techniques in upper layers. In particular in transport layer [47] I proposed an architecture to use in VLC with Multipath-Transmission Control Protocol (MPTCP). I implemented a prototype using the same VLC devices utilizing the frequency division on VLC and MPTCP on both client and server. The achieved results presented that using Redundant and Back-up offer the lowest and highest values of T_{hod} as 2.4 and 620 ms, respectively. In addition, the Default mode provided a VLC network with the highest throughput value both for shadow and mobility use cases as 124.9 and 95.28 Mbps, respectively.
Finally, given the high probability and very often link blockage in VLC, I followed up on the WiFi technology and proposed an upper layer hybrid VLC-WiFi network handover solution named as Li-Wi [44] to address the frequent handover issues in V-VLC due to the mobility, shadowing, and obstacles. Li-Wi utilized the benefits of high data rates and link availability of VLC and WiFi, respectively. It offered robust connectivity with lower T_{hod} and a high network throughput. Based on experimental evaluation results using a small-scale prototype, I demonstrated the advantage of the proposed approach. The experiments revealed 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.
While the proposed handover solutions in the network upper layers have already proven to decrease handover outage duration of V-VLC significantly, there are still some open ideas that might help in future to further improve the results in terms of handover delay. One of the interesting approaches can be introduced in physical layer. Based on what I analyzed in cell planning section of this work, Field of View (FoV) of light transceivers plays a significant role to provide an efficient VLC network coverage and the idea of making the FoV adjustable based on different parameters such as cell size, location of Light Access points (LAP) and their distance to their corresponding Light Clients (LC) in specific use case scenarios can effectively decrease the T_{hod} even further. Another interesting idea can be introduced in Network layer. I believe that configuring a multi-hop V-VLC network can be considered as a complex but rather effective solution which can have a great impact on V-VLC handover outage duration and throughput increment. In this approach, the LC installed on AGV not only can establish a link to their corresponding LAP but also, they can communicate with their immediate neighbor LC of other AGV which are aligned in their Line-of-Sight (LOS). This solution will provide network redundancy and decrease the number of packet lost during VLC link blockage. Finally, the last approach is making use of multiple-input and multiple-output (MIMO) in physical

and upper layers to provide load balancing and network redundancy and improve T_{hod} even further.
Putting everything together, the future of V-VLC cannot to be limited to use only VLC technology, especially when there is a high chance of VLC link blockage and very frequent handovers. The work presented in this PhD thesis highlights the solutions that can be considered for low-latency and high-throughput V-VLC networks. I believe that our work showed the high potential of link aggregation and MPTCP approaches in upper layers together with using the benefit of link availability of WiFi to provide a reliable and robust connectivity for vehicular network with seamless handovers and achieving a minimized T_{hod} in an indoor V-VLC network considering VLC as the primary link connection technology.
As future work, I believe there are still several techniques that need to be assessed to address V-VLC handover issue not only in data link and transport layer but also in physical and network layer. Therefore, as suggested earlier making the radiation pattern adjustable may further improve the V-VLC network reliability as well as providing a low latency network. Moreover, making use of MIMO and multi-hop communications can be also considered as V-VLC network layer solutions which may be further studied to provide load balancing and redundancy, therefore decreasing the number of packet lost and providing a more robust network.

Acronyms

2D two dimensional

3GPP 3rd Generation Partnership Project

AGV Automated Guided Vehicles

AP Access Points

ARP Address Resolution Protocol

BER Bit Error Ratio

DETCP Decoupled TCP

FDLA Frequency Diversity and Link Aggregation

FDMA Frequency Division Multiple Access

Flight Flexible Light Communications

FoV Field of View

Fping Fast Ping

ICMP Internet Control Message Protocol

IP Internet Protocol

Iperf Internet Performance Working Group

ITS Intelligent Transportation System

LAP Light Access points

LC Light Clients

LED Light Emitting Diode

LOS Line-of-Sight

MAC Medium Access Control

MIMO multiple-input and multiple-output

mmW millimetre Wave

MP-DETCP MultiPath DETCP

MPTCP Multipath-Transmission Control Protocol

OFDM Orthogonal Frequency Division Multiplexing

OOK On-Off Keying

PD Photo-Detector

PHY Physical Layer

Ping Packet Internet Groper

RF Radio Frequency

RTT Round Trip Time

TCP Transmission Control Protocol

UDP User Datagram Protocol

V-VLC vehicular VLC

V2I Vehicle-to-Infrastructure

V2V Vehicle-to-Vehicle

VLC Visible Light Communications

VLS Visible Light Sensors

WiFi Wireless Fidelity

WLAN Wireless Local Area Network

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