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Flight: A Flexible Light Communications network architecture for indoor environments

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***Abstract*—Recent experimental works have demonstrated the feasibility of the visible light based vehicular communications (VVLC) in intelligent transportation systems (ITS). However, in many respects, this technology is in its infancy and requires further research efforts in several areas. This work presents a flexible network architecture named flexible light (Flight), which is designed for VLC to tackle existing mobility challenges in the network environment. Flight proposes a low-latency handover system that decreases the handover delays to a few tens and hundreds of milliseconds. By means of experiments, we emulate and evaluate indoor mobile network scenarios using only VLC technology.**

***Index Terms*—Visibli Light Communication, network handover, link aggregation, Ethernet bonding, Handover Latency**

I. INTRODUCTION

Wireless communications, in their many flavors, constitute a popular alternative to wired networks, especially in mobile and dynamic scenarios. Several radio-based communication technologies such as Bluetooth, BLE and ZigBee as well as WiFi are characterized by their limited coverage areas. In these cases, in the presence of node mobility there exists a need to manage frequent handovers, which take place each time a mobile terminal associates to or de-associates from an access point. Moreover, network load balancing can also be achieved performing handovers. Improving network management in terms of coverage and robustness is one of the main challenges in vehicular and mobile networks as well as ITS. Light-based communications -also referred to as visible light communications (VLC) is well suited for high data rates links and as a secure interface between a base station and a mobile unit. VLC has the high potential to be considered as a complementary technology to radio-frequency (RF) communications. With VLC, the light emitted by standard light emitting diodes (LEDs) normally employed for lighting is intensity modulated by the desired information. The most widely used modulation schemes are on-off keying (OOK), pulse position modulation (PPM), multicarrier modulations of orthogonal frequency-division multiplexing (OFDM), carrier amplitude and phase offering a range of data rates well beyond the light flickering frequency [1], [2], [3]. VLC has specific advantages described below [4], [5]:

- Introduced no interference to RF cellular networks, and not being effect by the RF induced electromagnetic interference.
- High energy efficiency, i.e., a green technology.
- High security, since light is confined within a room.
- High deployment density.
- Increased network capacity thanks to its very large spectrum.
- Large bandwidth, which implies good spatial resolution.
- Cost efficiency.

Additionally, link blockage due to shadowing, spatial diversity in virtual small cell size and inter-cell co-ordinations are existing challenges in VLC. However, VLC is still considered as a technology for use in indoor ITS networks as well as outdoor environments.

A. *VLC for Automated Guided Vehicles*

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). The AGVs can communicate using wired and wireless technologies 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. VLC is one possible wireless technologies, which can be effectively utilized for establishing robust communications for AGV-to-AGV communications within industrial enthronements at a low cost and high-flexibility.

B. *Problem statement*

Due to the high mobility of AGVs 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. Therefore, there is a need for networks with high levels reliability and low latency in order to provide a robust network with high rates (i.e.,throughput) to address the mentioned problems. In [6], [7], in order to achieve 100mm path accuracy, it is demanded for an overall latency of 50 ms, including the processing latency. Considering that VLC access points (LAPs) have a limited transmission range and there is a high demand for VLC transceivers to stay aligned in order 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 tens of milliseconds, thus leading to improved quality of services.

The remainder of this paper is organized as follows: Section II briefly overviews related approaches using light and RF techniques. Section III presents the proposed network architecture in VLC systems. Section IV presents the practical experimental results and finally, Section V concludes the paper.

II. Related Work

A number of research works focused on the handover in VLC mobile networks have been reported. In [8] 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 [9] 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 [10] power and frequency-based soft 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 [11] 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 [12] 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.

This paper makes use of VLC transceivers,which benefits 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, we have implemented the proposed scheme using VLC for both uplink and downlink.

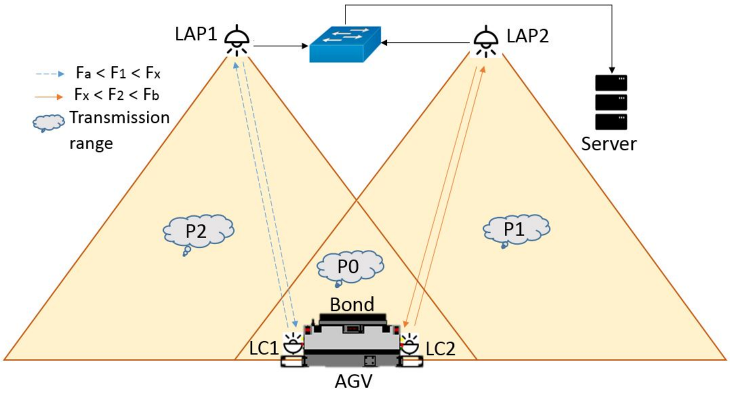


Fig. 1: Flight network architecture.

III. Proposed Network architecture

Flight network architecture is shown in Fig. 1 , which provides VVLC 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 VLC clients (LCs). LCs connect to the ceiling-mounted LAPs, which in turn connect to a server (with a linux operation system) via a configurable switch and a wired backbone network. P1 and P2 are the transmission ranges for LAP1 and LAP2, respectively. And P0 is the mutual transmission range between the two LAPs. As it is shown, there are two full-duplex links between the AGV's LCs and LAPs which are configured on two different frequency ranges as F_1 and F_2. The AGV can move linearly entering in P1, passing through P0 and exiting from P2 area. Finally, the logical bond interface is configured on top of the two Ethernet interfaces of LCs, 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, we propose a simple and flexible practical solution which facilitates the use of commercial off-the-shelf (COTS) VLC devices and a software solution configured based hardware. To this end, we have adopted frequency division multiple access (FDMA) and Linux network bonding feature, which are described in the following subsections.

A. 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. As Table I represents, LAP2 and LC2 are configured to perform between 4 to 52 MHz, which are F_a and F_x, respectively. And LAP1 and LC1 perform between 52 to 96 MHz, which 96 is F_b in this scenario.

Therefore, once the AGV enters the P1 area, LC2 connects to LAP2 on F_2 frequency band and once the AGV arrives at P0 , there will be two parallel VLC active links between the LCs and corresponding LAPs as shown in Fig. 1. Finally, when the AGV continues towards to P2 area, the link between LC2 and LAP2 breaks and only the link between LC1 and LAP1 on F_1 frequency band remains active.

B. 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 in 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 [13]:

- 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 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.
- 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 similar to 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, we 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.

C. COTS VLC links

The used COTS 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 multiplex (OFDM) and G.hn standard [14]. The analog board has been customized in order 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 (PD, Hamamatsu S6968).

TABLE I: IP/VLC network configuration

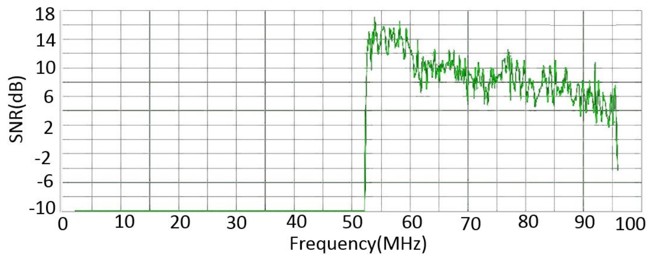
Prototype Units	IP address	Frequency(MHz)
LAP1	192.168.10.10	52 - 96
LAP2	192.168.10.202	4 - 52
LC1	192.168.10.11	52 - 96
LC2	192.168.10.201	4 - 52
Bond	192.168.10.40	-
Switch	192.168.10.12	-
Server	192.168.10.2	-

IV. EXPERIMENTAL RESULTS

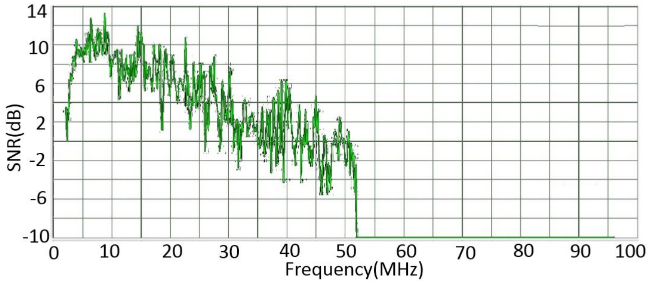
The proposed system architecture is experimentally implemented by developing a prototype in order to validate its performance. A linear scenario using a bi-directional full duplex link has been emulated where the handover time and the system throughput are evaluated once an AGV passes through two LAP transmission ranges. As it is presented in Table I 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 LAPs. Link aggregation has been configured on a mini-PC installed on the AGV. Within this setup, we configured a bond logical interface on top of two physical Ethernet interfaces of the PC, which are connected to LCs using Ethernet cables. An active-backup mode was chosen in the bonding configuration during experimental investigation. The link between LC1 and LAP1 was chosen to be in the active mode and the link between LC2 and LAP2 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.

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 millieconds 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 makes a decision as 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 as long as the active link transmits the acknowledgment from ARP. When the active link does not provide acknowledgment from ARP, the bond interface sends/receives traffic at the backup link provided the backup link provides acknowledgement from the ARP.

Fig. 2a and Fig. 2b show the signal-to-noise ratio (SNR) performance for connection links between LC1 and LAP1 and LC2 and LAP2, respectively. In this setup LAPs and LCs



(a) link connection between LC1 and LAP1



(b) link connection between LC2 and LAP2

Fig. 2: SNR for the link connection between LCs and corresponding LAPs

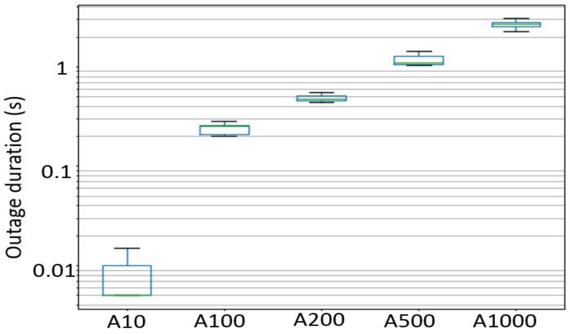


Fig. 3: UDP Outage duration due to handover. A10, A100, A200, A500 and A1000 show the used ARP intervals as 10, 100, 200, 500 and 1000, respectively.

were located in a distance of half a meter away from each other. 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 LAPs.

Three network traffic types; UDP, TCP and ICMP are chosen to evaluate the performance of the proposed network architecture for both uplink and downlink in an indoor environment. Fig. 3, presents the measure outage duration for each set of ARP intervals for UDP packets, which obtained using the 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:

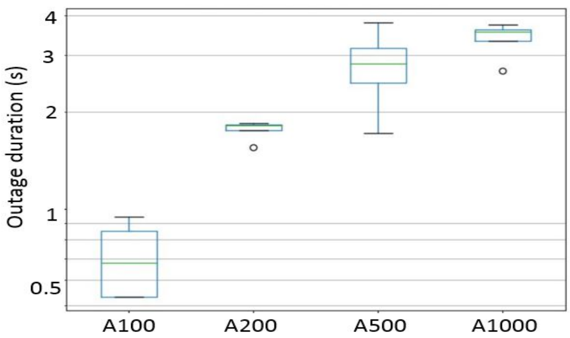


Fig. 4: ICMP Outage duration due to handover. A10, A100, A200, A500 and A1000 show the used ARP intervals as 10, 100, 200, 500 and 1000, respectively.

```
$ 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.

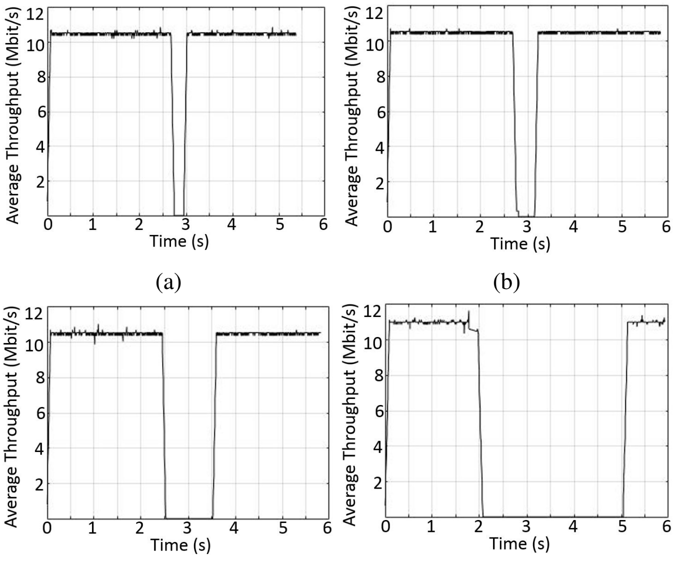
As a result, the outage duration achieved using ARP interval equal to 10 ms decreases the handover latency considerably to less than a hundred of milliseconds. Obviously, increasing the ARP interval values causes the higher outage duration in the network.

Fig. 4 depicts the measured outage duration for the ICMP traffic. 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 pings in milliseconds, -*n* means the number of pings to send to each host, -*T* shows the timestamp whith each reply and -*s* specifies the amount of data in byte. As it is shown in Fig. 4, using ARP interval of 100 ms decreases the outage duration for pings to less than 1 second and by increasing the ARP intervals, the outage duration of the network grows considerably. The experiment has been repeated for five times and as Fig. 4 and Fig. 3 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.

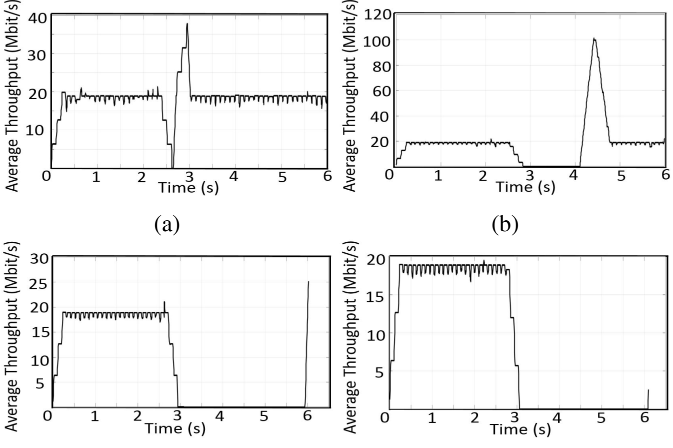
Fig. 5 presents the average throughput for four UDP traffics while using different ARP intervals. The same command setup is configured as utilized in Fig. 3. As it is shown, the network throughput in Fig. 5a, Fig. 5b, Fig. 5c and Fig. 5d are almost the same before and after the handover takes place. However, the handover latencies which are shown as gaps in the graphs are increasing due to ARP interval increments.



(a) (b)

(c) (d)

Fig. 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.



(a) (b)

(c) (d)

Fig. 6: TCP 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= 2.31, 2.53, 2,62 and 2,73 second respectively.

Fig. 6 shows the TCP average throughput for the same ARP intervals as in Fig. 5 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. 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 Fig. 6a and Fig. 6b, there is a peak right after the handover is performed and it is due to a fast retransmit and recovery which is a congestion control algorithm used in TCP/IP in order to quickly recover the lost data packets during the handover. It is mentionable that the same behavior is expected for Fig. 6c and Fig. 6d. The reason behind of not seeing it, is the experimental time. As it can be seen, in all the four figures the experimental time is limited between 0 to 6 seconds. Accordingly, the expected peak values in Fig. 6c and Fig. 6d are not observed.

As the results presented illustrate that the proposed network architecture improves the network robustness and decreases the outage duration during the handover. Thus, leading to improved network stability for uplink and downlink. However, in order to achieve the reasonably low outage duration based on the the project's demand, it is needed to use a rather lower ARP intervals.

V. CONCLUSION

This paper 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. We presented a real-world experiments using COTS 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.

Future work will include two directional scenarios using multi-hop mobile networks and performance evaluation of the provided solutions on similar networks considering other parameters which might have an impact on the outage duration and throughput.

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