VLC network topology design for seamless communication in a urban tunnel

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***Abstract*—Visible Light Communications networks are usually based on isolated access points which deals individually with the handover strategy. Basically when a node is detected by an access point the network's protocol upper layers redirect the traffic to the new access point. This strategy cannot be suitable for vehicle communications and different alternatives of handover should be developed. In this paper, a new network architecture is presented including a novel handover scheme based on distributed receivers. This system has been tested for vehicle to infrastructure applications in a tunnel scenario and results show that, in comparison with classical scheme, it demonstrates an upgrade in general performance.**

***Index Terms*—MAC layer, handover, VLC, network topology, vehicular communication**

I. Introduction

Autonomous vehicles are getting closer to becoming a reality. In previous years, the discussion about the reliability of these systems in real urban scenarios has been on the spot [1]. One of the most important elements of this technology is the need of information gathering from external agents. This is a challenge to fulfill and Dedicated Short Range Communication (DSRC) has been adopted as the main option by the most important vehicle manufactures [2]. However, there are some scenarios where its performance can be severely impacted and alternative technologies are required. One viable option is Visible Light Communications (VLC), a technology that uses the spectrum of the visible light band, instead of traditional radio frequency. In a VLC system, data is transmitted by modifying the intensity of LED sources (street lamps, car's headlights), and using quick light changes to avoid undesirable effects for humans. For vehicular applications, VLC can take advantage of hardware built-in the car to decrease the implementation cost, such as the headlights and the rearlight mainly.

VLC presents some supplementary upsides in the vehicular scenario that becomes it a strong candidate. When the vehicle or Road Side Unit (RSU) has a VLC transmitter incorporated in the car lights, it can save energy consumption since the energy is employed at the same time to light up the streets and communicate. The VLC transmission spectrum is far from radio frequencies used by DSRC, so they cannot interfere each other. Both technologies can work together to increase redundancy and capacity. Additionally, the lamps' relative short range permits VLC system to have high reuse of spectrum in crowded spaces such as the main street during a rush hour.

VLC for vehicular applications has been studied for years by the scientific community and industry [3]–[5]. Vehicle-to-Vehicle(V2V) channel was analized by [6], they considered that the channel has unusual characteristics due to its location and particular headlamp's radiation profile. The authors in [7] dealt with the Infrastructure-to-vehicle case (I2V), where the transmitter is incorporated in a traffic light. Other works such as [8] have studied the channel using a time-varying approximation but assuming that it acts as a wide sense stationary (WSS) in these environments. They characterized the channel fading and link duration in urban scenarios using real information of vehicles position in these areas obtained by video recording and image processing. Nevertheless, works in vehicular VLC has not limited to theoretical models and channel analysis, and some research groups have done experimental validations. For example, the authors in [9] performed a practical validation of VLC standard IEEE 802.15.7 with Commercial Off-The-Shelf (COTS) hardware. They integrated a Universal Radio Peripheral (USRP) to the vehicle's fog lights using Software Define Radio (SDR) for the modulation and codification of light signals. Additionally to traditional VLC schemes based on the photodiode, Optical Camera Communications (OCC) has been recently thought of as a viable option [10], [11]. The main reason is that OCC can provide a long-distance link due to the camera's high sensibility.

As it can be seen, the use of VLC in vehicular applications has been widely studied in literature. However, a great part of these works have not considered the problems regarding network protocols' upper layers that the massive use of this technology can cause due to its particular properties

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and performances. One of these challenges is the limited communication range of VLC-RSU that makes necessary to define specific handover strategies to ensure the user hold the communication link. Current literature on handover mainly study indoor scenarios or vertical schemes [12]. A vertical handover case is where a user loses the VLC link, and it has to be assisted by an additional technology. Nevertheless, the vehicular scenario differs from indoor, because the user stays briefly in the AP coverage area. So, the handover's latency has to be marginal. Neither, DSRC's handover strategies can be used without modifications, due to the strong contrast between both channels. Just a few studies have covered this topic, for example [13]. Here, the user manages two or more simultaneous VLC links (one per AP). These are monitored continuously, when one of the links suffers from a failure, the user changes its packet route using the backup link. This solution requires the use of multiple transmitters and receivers working at different optical wavelengths.

In this paper, we present a system network topology which helps to improve the connectivity of a vehicular user increasing the reliability of the communication and improving the user mobility. This topology will be referred as 2.5 layer topology. Additionally, we propose a handover scheme implemented for these kind of scenarios. The proposed scheme is compatible with the MAC standard IEEE 802.15.7. and the topology and handover scheme are validated together by system-level simulation considering the vehicular tunnels as the use case scenario.

The paper organization is the following. First, we present the proposed topology in Section II. Then, Section III introduces the used handover scheme. In Section IV, we explain the used methodology and provide details about the implementation process. Section V shows the obtained result. And finally, we give our conclusion and future work.

II. System Topology

Commonly, a VLC network has a star topology where there are some VLC Access Points (VLC-AP) distributed on the scenario that provides service. They are connected by a wired medium to a network controller called Aggregation Agent (AA) [14]. VLC-AP consists on a receiver(Rx), a transmitter(Tx), and a control unit that carries on random access and backoff mechanism. The AA manages the traffic, and controls the access of the users when they change from one point to another. This common configuration in this work is referred as "traditional topology". Figure 1 shows an overview of this common system. In our study case, the VLC system will be deployed in vehicular tunnels where DSRC decreases its reliability. Thus, VLC-AP is integrated into the tunnel's luminaries including the control unit and the receiver is located separately to take advantage of its position getting a direct contribution from the car's headlights. It is placed 60 cm from the floor near the tunnel walls.

The introduced topology, referred to as the "2.5 layer" topology, proposes a different functionality for receivers. Instead of receivers exclusively associated with an AP, we

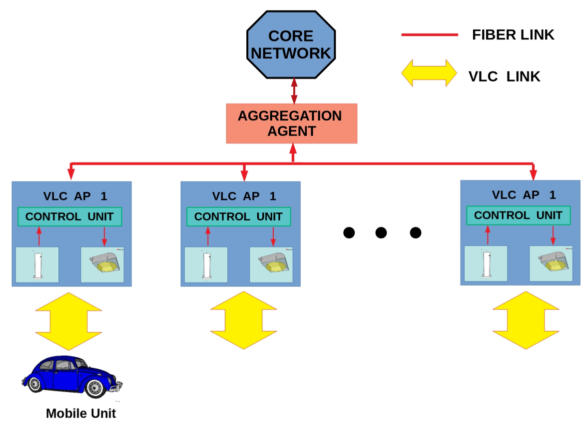

Fig. 1. Traditional VLC network topology.

propose to implement a receiver arrangement included to a sublayer controlled by a switch. Any of these receivers can get the information destined to any of the AP. Furthermore, the receiver at the same time senses the signal power and attaches this information to the frame. The switch collects these frames and removes redundant packets. It uses the logical address (OWPAN ID) to determine who is the addressee AP. At the same time, it compiles Signal-to-Noise Ratio (SNR) information from every Rx. This information is used by Handover Manage Entity (HME), to know when it is necessary to perform a mobility scheme. We can see this arrangement in Fig. 2.

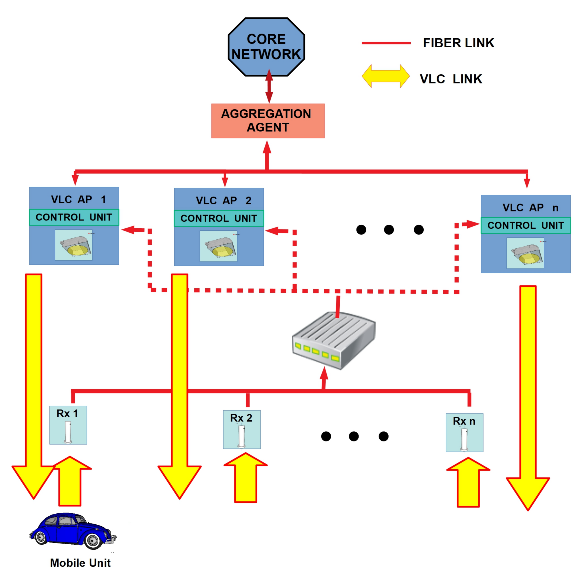

Fig. 2. The proposed topology.

The main difference between both topologies is that in traditional topology, the Rx is connected to one AP, and it can only provide communication to this point. But, Rx location is the same in both. The changes in the topology are intended to increase redundancy in the mobile transmission and avoid abrupt interruptions in the uplink. In the test tunnel scenario configuration, the optical signal from the vehicle increases when the vehicle approach the receiver, but this suddenly goes down. In [15], we studied time-varying optical channel for this system, where this problem is addressed.

III. Handover scheme

Complementary to the topology design, this work presents a handover scheme specifically designed for dealing with the new receivers deployment. The protocol requires low latency because the user should change from an AP to another in less than a second. On the other hand, the tunnel scenario predetermines a linear movement of the user with a steady speed which makes predictable the moment for the cell exchange. In consequence, a simple logic in the decision can determine when the user is coming to the new station, and when to apply the handover function.

The proposed handover protocol uses Hierarchical Mobile IPv6 (HMIPv6) as a reference [16]. In HMIPv6, the networks keep the IP address in Mobility Anchor Point (MAP) and manage the user localization with a short address. All updates are local with a layer 2 handshake, this action reduces the latency considerably. Figure 3 shows the handover process followed described. Before it starts, it is necessary that the mobile node be associated with any VLC-AP AP_n previously. The association process is described in the standard IEEE 802.15.7. When the user transmits a data packet to the receiver cluster, each Rx gets the optical signal and estimates the transmission SNR. HME collects these values to determine if the user achieves the conditions to begin the mobility process. For our work, the handover decision is made by a simple method comparing the value with a fixed limit. Nonetheless, a more resilient criterion needs to be implemented in further steps of our research line. When the SNR over lapses a fixed threshold in a receiver referenced Rx for the AP_{n+1} the procedure starts. HME sends a handover request to the MAP. It verifies that there are enough resources in the next site (AP_{n+1}) to proceed and communicates to it. The mobile node is notify about a handover request by AP_{n+1}. But only when it can respond it, the handover process is completed. Then, AP_{n+1} notifies MAP to divert the data traffic and also advertises the AP_n that the user does not belong more to its network. The protocol design was done to avoid problems from asymmetrical links. A similar protocol was implemented in the traditional topology to make a fair comparison between them. Due to the hardware limitations in the traditional system, AP_{n+1} senses the optical signal and triggers the mobility process.

IV. Methodology

The study was performed using system-level simulations in the OMNET++ platform. These simulations recreate the interaction among network elements without a detailed model of the internal node's processes. Some libraries permit the inclusion of PHY and MAC layer of VLC standard IEEE 802.15.7, for example, [17]. Nevertheless, we have built our own programmed modules to have the flexibility to include the modifications in the system design and the handover scheme.

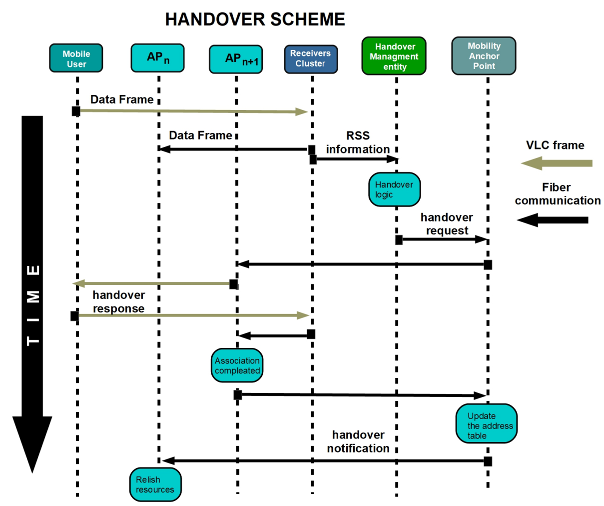

Fig. 3. Handover scheme for vehicular tunnel.

As it was commented before, the solutions were done considering the context of a Vehicular tunnel. To represent this environment, we have made the following setup in the simulations. The scenario is composed of 32 VLC-AP, each one is in the typical placement of tunnel lamps. VLC-AP is at 4.5 m height pointing downwards near the tunnel wall. The receivers are mounted at a height of 0.6 m from the floor with an elevation angle of 90^o in the vehicle direction. The receiver is separated 13 m onwards on the road from its transmitter, this position was set experimentally. The VLC-AP are separated from 8 to 13 m, according to the tunnel specification [18] to avoid the flickering effects on the drivers. Fig. 4 illustrates the distribution of the elements for the tunnel simulation scenario.

The vehicle lamp's and its receiver are situated at 1 m height. As well, the headlamps have an elevation angle of 85^o. The receiver is placed on the vehicle's hood. Usually, the lateral distance between the vehicle right headlamp's and the wall is around 2.4 meters considering an error margin of $\pm$ 0.225 m. In the simulations, the uplink and downlink were evaluated considering the radiation profile of real light sources (vehicle and tunnel lamps). These profiles can be seen in Fig. 5.

During the simulation, the mobile node moves linearly at 80 km/h for 10 seconds. It receives a data rate of 450 kbps from the infrastructure which fulfill the minimum requirements for vehicular safety applications. When the vehicle is leaving the coverage area of AP_n, the handover mechanism acts to ensure a soft transition. When this mechanism fails or does it untimely, the vehicle can eventually lose its connection. Consequently, it has to re-join the network which is a slower process than the handover itself. This means that for a period of at least 200 ms, the vehicle interrupts its service. While,

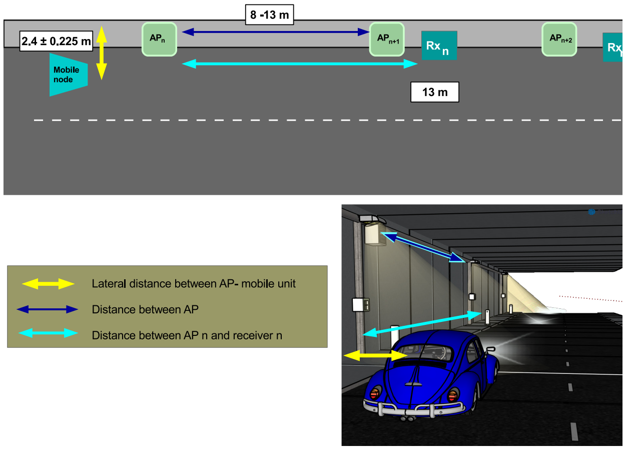

Fig. 4. Diagram of the element distribution for the simulation for both system evaluation.

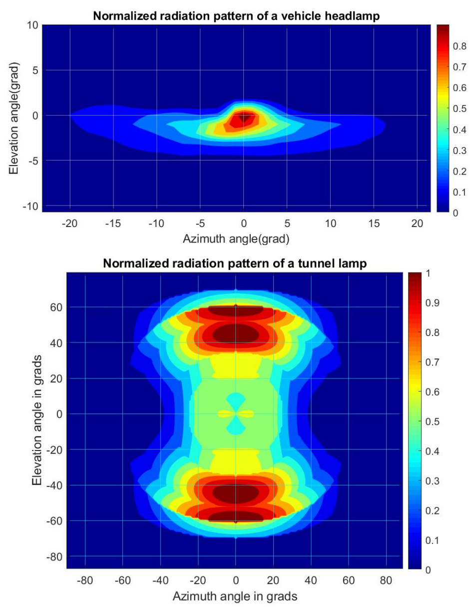

Fig. 5. Optical radiation profile of the transmitter in system evaluation. (a) The radiation profile of a vehicle lamp (b) The radiation profile of a tunnel's lamp.

AP_n detects the link failure, it will lose some frames. The data traffic is re-established when a new connection has been set up.

For the simulations, we have considered the different delays in the core communication during the handover resolution. The network discovery, synchronization, and data transmission fulfill the protocols from standard IEEE 802.15.7.

Each experiment was repeated 100 times. The system was evaluated using the follow metrics, which reflects the status of the connection, how much reliable is the new communication link when a handover happens and how is the service.

- Normalize connected time: This is the ratio of time when the user is able in the network.
- Number of tries: This is the number of additional times that a VLC frame is sent by backoff mechanism for successful packet delivery. When it increases the channel is busy for longer periods.
- Data rate: This is the mean of payload bits delivered correctly to the mobile user per time unit.
- End-to-end Packet Delivery Probability (EPDP): This shows the reliability to deliver correctly a frame in the system. It is calculated as successfully delivered frames divided by the total of frames received in AA from the Core Network. This metric takes into count the lost frame during the handover transition.

TABLE I
SIMULATION PARAMETERS FOR THE PHY AND MAC LAYERS.

Parameter	**Value**	**Parameter**	**Value**
Simulation time	10 s	BO , SO	7, 5
Simulations numbers	100	Data frame payload	1000 bits
VLC-AP Tx power	50 w	Frame header	270 bits
vehicle's Tx power	15 w	Biding update payload	448 bits
vehicle's speed	80 km/h	number Backoff	5
Distance between APs	8-13 m	Number of slots	16
Photodiode area (Rx)	1 cm	Optical clock	60 MHz
Photodiode FOV (Rx)	40º	Backoff unit	200
aBaseSlotDuration	60	maxMaxBE	3
Datarate per user	450 kbps	Handover trigger	SNR= 21 dB
Code	10B8B	Handover L2 resolution	2 ms
Modulation	OOK	Association Resolution time	200 ms

As it was commented before, the evaluation of handover was performed using the protocols of the IEEE 802.17.5 standard. Table I shows the parameters corresponding to the network configuration.

V. RESULTS

Simulation experiments have been conducted to evaluate the proposed VLC network topology which includes a new handover scheme. The results of these simulations are compared to traditional network topology results, see Fig. 1. Some preliminary simulations were necessary for setting up the initial parameters of the networks' configuration. These initial results showed us that the traditional system's performance degrades drastically unless precise values for parameters are used, E.G. the handover threshold. Additionally, the system cannot accomplish an accurate detection when the vehicle is not perfectly aligned to the lane road. On the other hand, the proposed topology is more resilient to these variations in the system configuration and the scenario. In this work, we present the comparison of both system's performance using the described metrics. On each figure, the top part shows the result of the traditional system. While in the bottom part, there are the results of our proposal. The VLC-AP receiver is set at $13m$ from its transmitter in both configurations. Also, the handover initializes when AP_{n+1} collects the optical signal with an SNR over $21dB$. Most of the time, VLC networks have to adapt to the illumination system configuration. Thus, we have estimated the performance considering multiple distances between adjacent VLC-AP, from 8 to 13 m. The distance is presented in the X-axis on the charts, while the Y-axis shows the metric value. The results are presented in boxplot format which shows the statistical information. The rectangular shape illustrates their distribution while the red cross represents their outlier values, and the red line is the mean value.

Figure 6 shows the connection percentage for the mobile user. In traditional topology, the median value of connection cannot be supported without more reliable handover criteria. Because of the narrow radiation profile of the headlamp, the low variations of its lateral placement cause a decrease of the received power and changes the uplink range. As consequence, the handover initialization has a delay, and the communication link breaks. Additionally, we can see that the results have high variability especially when the nodes are separated from 10 to 11.3 meters. On the other hand, 2.5-layer system can support communication until the system fulfills the handover conditions. But, the are some cases when the performance degrades. Moreover, for a longer distance than 12 meters, it is necessary to fix a new handover threshold. The two systems can improve their connection time if the handover logic uses a dynamic threshold and a more sturdy detection method.

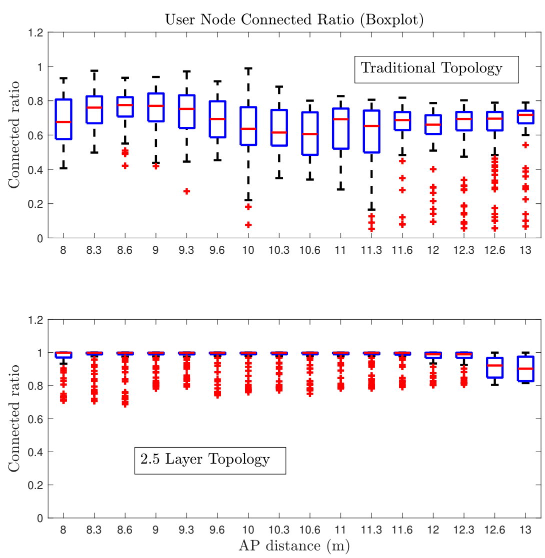

Fig. 6. The percentage connected time by the mobile user using both topologies.

Another helpful metric is the number of re-transmission required by each frame, they are shown in Figure 7. This value reflects the quality of the VLC link. Not always an inopportunely handover causes an interruption of the link, sometimes just flawed temporally the communication. In our proposal, the AP habitually does not need an extra transmission to deliver the frame successfully. Besides, the worst-case barely presents a difference. Furthermore, the traditional topology requires more resources to sustain communication. And, in some isolated cases the link is highly affected, causing that the backoff mechanism works continuously. This is a global picture of the transmission during the entire simulation. This behavior changes during different phases, when the mobile user is at the edges of the coverage area requires more transmissions. Contrarily, when it is closer to the AP center, this number decreases. This metric is related to channel occupancy, so limit the network capacity.

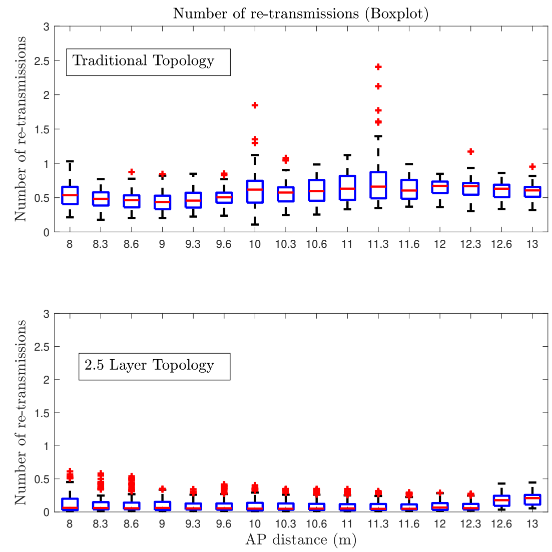

Fig. 7. Number of times that a packet need to be send to arrive successfully.

Figure 8 display the datarate. According to it, our proposal can provide an average datarate close to our expected goal (450 kbps). However, some low-performance cases decrease our mean performance to 90 %. On the other hand, the service on traditional topology suffers from a lot of variation. It keeps a mean service between 250 to 200 kps.

Finally, figure 9 shows the link probability. A frame can be drop at several moments. Mainly, it can be lost during the transmission. But also when a user left the site, the AP scrub its queued message and losing some more during the handover resolution. Our proposal exceeds 98 % of the probability of successful packet delivery. Nevertheless, the traditional system has approximately 92 % probability. In both systems, the number of packets lost can be considered high for safety applications. This reflects that it is essential to implement a packet recovery protocol to avoid packet loss during the handover resolution. Even, when 2.5 layer system can support reliable communication, it needs to improve its vulnerabilities to stay connected almost all the time. Otherwise, a traditional system can have several problems to hold a session.

VI. Conclussion

This paper introduces some modifications in the orthodox conception of network construction. In our scheme, the

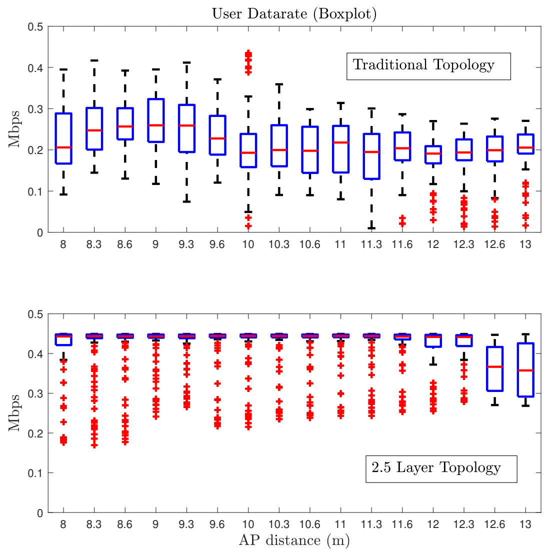

Fig. 8. The average datarate during the simulation for the mobile user.

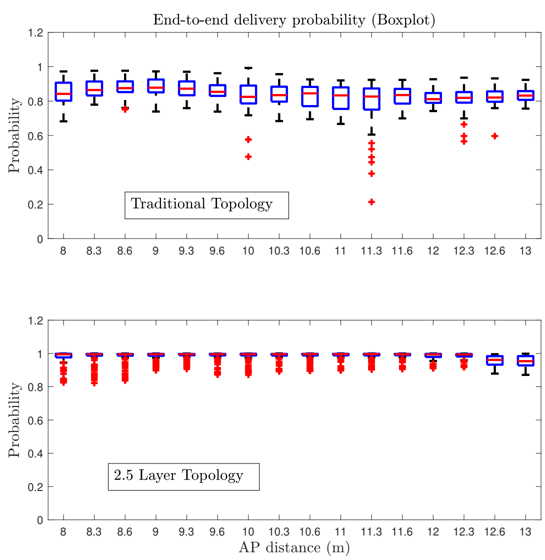

Fig. 9. Probability to deliver successfully a packet in both topologies.

receivers are separated into an intermediate layer. This approach shows good results, increasing the redundancy and general stats in the network. Moreover, the 2.5 layer system demonstrates flexibility to adapt its hardware to the scenario necessities, it can be easily reshaped without a profound evaluation. In the real world, it is rarely possible to take control of network elements and the scenario, so this is a great advantage. The redundancy helps to avoid abrupt interruptions on the communication in most cases. However, the solution has not been finished yet, and some details have to be solved. Among others, it is necessary to implement a better handover strategy to improves its reliability. In future work, we are going to do a deeper analysis of this proposal. Furthermore, a robust handover logic needs to be developed and tested under irregular movement conditions. Finally, the system can take advantage of a packet recovery scheme after the handover has been completed.

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