Hybrid VLC/WiFi Architectures with Priority Feedback Channels

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***Abstract*—In this paper, we consider integrating Visible Light Communication (VLC) and WiFi technologies in an ultra-dense (massive) Internet of Things scenario, where WiFi links are used for complementing VLC links and vice-versa. Indeed, in case of mobility and/or bidirectional communications, limited coverage areas and self-generated interference can be an issue.**

We consider hybrid VLC/WiFi nodes where the VLC link is used for the majority of (data) traffic and the WiFi link is employed as a feedback channel (e.g. transmitting TCP ACKs). In presence of intense WiFi traffic, the WiFi network may be congested and thus, to fully exploit the VLC bandwidth, we discuss possible priority mechanisms to fully exploit the VLC link. Simulations in NS-3 demonstrate the effectiveness of the proposed solutions.

***Index Terms*—Visible Light Communication, VLC, WiFi, Radio Frequency, Hybrid architecture, EDCA.**

I. Introduction

Due to the pervasive diffusion of mobile and smart devices connected to the Internet, the capacity demand for wireless networks has exploded in the last few years. According to Cisco, by 2022 mobile traffic will be 71% of total Internet traffic, with over 80% of data generated in indoor environments [1]. Thus, traditional RF-based systems are becoming overburdened as demand grows, particularly in indoor environments. As a result, sophisticated spectrum coexistence solutions [2]–[6], or new spectrum portions (e.g. mmWave or Visible Light Communications - VLCs) have been presented as feasible solutions. In particular, VLC is a very promising option that is being explicitly considered in the development of 6G systems. The extensive use of Light-Emitting-Diodes (LEDs) for illumination has further aided the development of VLC communications. When compared to typical incandescent bulbs, LED lights consume 75% less energy and have a 2500% longer lifespan [7]. From 2020 to 2027, LED lighting's market share is predicted to increase at a 13.4% annual growth rate. Exploiting the LEDs that are used for lighting to manipulate light signals and send data is a fascinating prospect. However, designing an integrated lighting and data distribution infrastructure necessitates the resolution of specific issues. Indeed, VLC has narrow coverage area, which allows for high-density spatial reuse, but at the same time makes mobility management difficult. Another issue is the support of bi-directional links, because the light emitted for illumination purposes is a source of interference for uplink transmissions. As a result, alternative spectrum parts, such as infrared signals [8] or RF signals [9], [10], can be used to create uplink channels.

Hybrid VLC/RF systems have been developed as state-of-the-art solutions to mitigate the mobility/coverage and uplink transmission issues [11]–[13]. Several prior research, such as [14]–[16], have used hybrid VLC/RF networks to improve the performance of both technologies. For example, an omni-directional RF connection is merged with multiple directional VLC links in [11] to optimize downlink capacity under various network conditions. In [17], the authors examine a comparable system, focusing on per-user performance. Generally, the RF link is employed as a backup link for VLC coverage gaps or as a VLC feedback and control channel [9] (e.g., for sending TCP ACKs or link quality information to the sender).

In this paper, we analyze hybrid VLC/WiFi networks, in which downlink and uplink flows are transferred separately through the VLC and WiFi interfaces of the same node. In particular, since WiFi generally has greater range compared to VLC, we study high-density scenarios where the WiFi network may become crowded (perhaps caused by background WiFi activity), and this in turn might affect the performance of VLC. Indeed, assuming that in the hybrid VLC/WiFi network VLC is used for data transfers and that a TCP-like transport protocol is used, then on the reverse path acknowledgements (ACKs) could flow through the WiFi links, while data is sent via the VLC channel. Thus, when the WiFi network experiences congestion, the performance of the high-density VLC data transfers is degraded, we first discussed in [10]. Compared to the work in [10], in this paper we investigate the influence of such scenarios in further depth, analyzing also data uploads where VLC links are used by mobile devices to transfer data towards the fixed infrastructure and ACKs are flowing back through the WiFi Access Point (AP). As a result, we examine the impact of WiFi performance constraints on the entire integrated system in both download (i.e. downlink VLC) and upload (i.e. uplink VLC) scenarios. Moreover, we analyze possible improvements exploiting the WiFi EDCA parameters to mitigate the congestion on the reverse channel, and we propose the EDCA-ACK priority channel access as a feedback channel for VLC communications. NS-3 simulations

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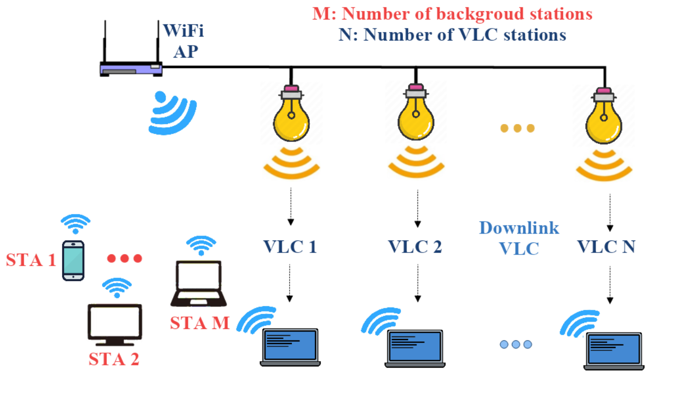

Fig. 1. The reference scenario for the hybrid VLC/WiFi system with downlink VLC data transfers.

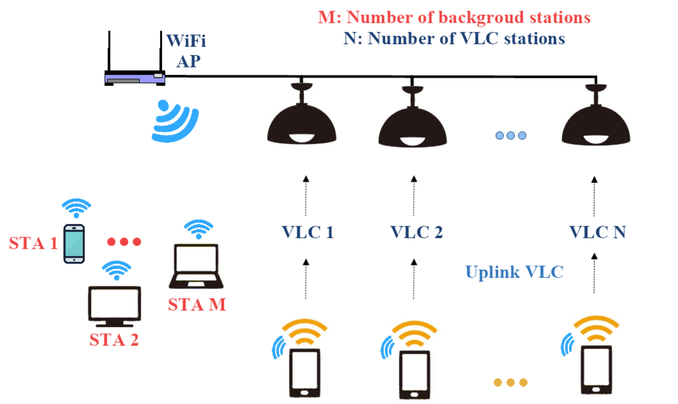

Fig. 2. The reference scenario in hybrid VLC/WiFi network with uplink VLC data transfers.

demonstrate the advantages of the proposed approach.

The remainder of this paper is organized as follows. Sec. II, details the network scenario and motivates our work, while Sec. III, presents the proposed channel priority access and frame aggregation schemes for WiFi feedback channels. In Sec. IV reports on the NS-3 simulations and numerical results obtained. Finally, Sec. V concludes our paper.

II. Scenario and Motivations

In this paper, we consider a local area network with hybrid VLC/WiFi devices deployed in indoors, where VLC/WiFi nodes cohabit with WiFi Access Points and WiFi legacy devices. As a result, the area is covered by several high-density APs supporting both VLC and WiFi technologies. The configuration of each AP, including the setting of internal routes and the physical and access layer parameters, is handled by a central controller. To avoid transmitter/receiver interference, VLC links are not bidirectional and each VLC receiver uses a WiFi transmitter as feedback channel, similar to [11].

The reference scenario of our hybrid VLC/WiFi network is shown in Figure 1 for the VLC downlink case and in Figure 2 for the VLC uplink case. For simplicity, we assume that VLC connections are isolated (i.e., no VLC nodes interfere with each other), unidirectional (i.e., from VLC transmitter to VLC receiver), and VLC receivers relay feedback via the WiFi interface. A single WiFi Access Point can cover the entire surroundings, even if there are other (single-interface) WiFi nodes. Since mobile nodes transfer data using both WiFi and VLC technologies, coupling effects between the two coexisting networks might appear. In general, neighboring mobile WiFi node transmissions may collide, but VLC signals are orthogonal. Because most services have bidirectional flows, even if the majority of the data is transmitted in one direction only (i.e. downlink VLC or uplink VLC), it is vital to determine when the feedback WiFi links become a limitation for the performance of the VLC links.

For example, consider a scenario where mobile devices download data from the Internet with the TCP protocol. Each VLC link generates TCP acknowledgements that compete in the same WiFi network. As a result, the number of VLC connections cannot be exceedingly high, otherwise TCP ACK delays or losses on the feedback WiFi links might cause VLC transmitters to restrict their transmission rate. Furthermore, even in the presence of a single VLC link, rate degradation caused by TCP congestion control could still happen in presence of background WiFi traffic. Similar considerations can be done for uplink VLC data transfers.

III. Enhancing Performance of Feedback Channels

This section discusses several options for preventing the WiFi link to become a bottleneck in hybrid VLC/WiFi networks. The goal is to employ access categories in the well-known EDCA protocol to give VLC uplink or VLC downlink traffic priority. Another idea is to deliver several TCP ACKs in a single channel access using frame aggregation.

A. Channel priority access and frame aggregation

The random access technique used by WiFi nodes is based on the EDCA protocol. To transmit packets, stations must first initiate the carrier sense and determine whether the channel is available or busy. Depending on the access category of the pending frame, stations can transmit if the channel as inactive for a period of time called arbitration inter-frame space (AIFS). Otherwise, a contention window range is used to derive a random backoff counter, whose maximum ($CW_{\max}$) and lowest ($CW_{\min}$) values are also determined by the access category. When the channel is idle, the backoff counter is subtracted, while if it is busy the backoff counter is frozen. The station can only aim for a channel transmission when the counter reaches zero. When a transmission initiative fails, the contention window is doubled (up to $CW_{\max}$), and when a transmission attempt succeeds, it is reset to $CW_{\min}$. As a result, the AIFS interval and the average contention window influences the likelihood of accessing the channel. Both parameters have an impact on the time it takes to reset the backoff counter to zero.

In EDCA, four separate access categories are defined for differentiating traffic flow's priority: voice (AC_VO), video

(AC_VI), best-effort (AC_BE) and background (AC_BK). The settings for high priority classes (AC_VO and AC_VI) is of 2 backoff slots for AIFS, $CW_{\min}$ of 3 and 7, and $CW_{\max}$ of 7 and 15, respectively. For low priority classes, $CW_{\min}$ and $CW_{\max}$ are 15 and 1023 respectively; moreover, AC_BE has an AIFS of 3 backoff slots, whereas AC_BK has an AIFS of 7 slots.

A station can keep the channel for a time period known as a transmission opportunity (TXOP) after winning the contention and receiving channel access. If the transmission opportunity lasts longer than the frame transmission time, multiple frames may be transmitted in the same channel access, and per-frame or cumulative acknowledgements can be used. This technique improves the efficiency of channel utilization and balances the channel holding times of nodes transmitting at various rates or frame sizes. Another strategy for improving channel efficiency in IEEE 802.11ac and 802.11n is frame aggregation, in which multiple service data units sent by upper layers can be packaged together and transmitted as a single frame, up to a maximum size [18]–[20]. As shown in [10], this approach is particularly appropriate for TCP ACK transmission, which are small and lead to huge overheads at MAC layer when sent as separate frames.

B. Giving priority to the VLC feedback channel

We suggest using EDCA prioritizing techniques for improving the performance of TCP ACK flows produced by the VLC data transfers. For two reasons, we suggest allocating these traffic flows to the AC_VI priority class: i) to minimize TCP ACK access delays, and thus reduce TCP round trip times, in order to fully utilize the capacity of the VLC links. ii) to reduce the risk of contentions by VLC nodes, enabling transmissions of multiple ACKs within the same AC_VI TXOP (default value 3.01 ms).

Despite the fact that TCP ACKs only use a little amount of bandwidth compared to the main VLC data transfer, in case of congestion the WiFi link might not guarantee that such bandwidth is available. In fact, transmission of TCP ACKs in the legacy 802.11 access protocol might be wasteful due to the contention process and MAC layer overhead. It has been demonstrated that inter-frame spaces and contention windows have varied effects on channel share differentiation [21]. Indeed, when priority mechanisms are not applied, the throughput ratio of contending flows is proportional to the inverse of the minimum contention windows. Because additional waiting is caused any time the channel is recognized as busy, the impact of different inter-frame spacing is dependent on the network's congestion condition.

To compute the maximum share possible allocated to VLC nodes, we can consider the VLC constantly in saturation in order to examine the maximum bandwidth required by TCP ACKs. If the TCP ACKs' capacity requirement is less than the maximum allowable on the WiFi link, other flows might take full advantage of the excess resources. Assume that each VLC station only has one contending flow and that there are M WiFi background nodes (i.e., greedy nodes requiring the maximum feasible capacity) coexisting with N VLC receivers on the WiFi network, each of which expecting s kbps. Clearly, s is proportionate to the VLC link capacity, because these flows are derived from TCP ACKs on VLC lines. The following factors determine the total available capacity C on the WiFi network: i) the number of WiFi nodes contending, which impacts the resources lost due to collisions or channel idle intervals, and ii) the channel holding times T_{WiFi} and T_{VLC}, caused by background WiFi and VLC nodes, respectively. Then, the maximum channel share x_{VLC} accessible for each VLC node is determined by $T_{\mathrm{VLC}}/(M \cdot T_{\mathrm{WiFi}} + N \cdot T_{\mathrm{VLC}})$. If each TCP ACK is sent in separate frames, x_{VLC} can be really small (i.e. when T_{VLC} is substantially lower than T_{WiFi}). In theory, the WiFi network can accommodate all TCP ACK flows whenever $x_{\mathrm{VLC}} \cdot C > s$. However, because of the delay jitters, the ACK rate can be further decreased due to the TCP congestion algorithm.

We thus propose to employ a priority scheme to boost the performance of VLC nodes. Let k be the ratio between the minimum contention window of background WiFi nodes and the one of VLC nodes. Adopting priority, the weight of WiFi nodes in background is lowered by a factor of k when calculating the VLC maximum share, i.e. $x_{\mathrm{VLC}} = T_{\mathrm{VLC}}/(M/k \cdot T_{\mathrm{WiFi}} + N \cdot T_{\mathrm{VLC}})$. Increasing the AIFS value of the VLC receivers, further decreases the channel share for WiFi background nodes. We propose using the access priority AC_VI class to ensure a greater share of the channel dedicated to TCP ACKs of VLC transfers, while background WiFi nodes use the AC_BE category. Indeed, compared to AC_BE, the AC_VI class uses smaller contention windows and AIFS values, as well as a transmission opportunity of $3.01ms$, allowing several TCP ACKs to be sent in the same TXOP. We name such a priority technique applied to TCP ACK transmission as *EDCA-ACK*.

IV. Numerical Results

In this section, we evaluate the performance of the designed hybrid VLC/WiFi system, analyzing the impact of EDCA-ACK on VLC traffic by varying the number of background nodes and considering both download and upload scenarios. We omit instead the results with frame aggregation due to space reasons and refer the interested reader to [10].

A. Scenario and simulation parameters

We employed the NS-3 simulator to build the hybrid VLC/WiFi network scenarios of Figure 1 for VLC downlink and Figure 2 for VLC uplink. Apart from the WiFi AP, which covers the whole area, we consider two different types of nodes: single WiFi legacy nodes (namely STA 1 to STA M) acting as background traffic, and nodes equipped with both WiFi and VLC interfaces (VLC 1 to VLC N). Similarly to [10], we implement VLC links in NS-3 as orthogonal channels (modifying the existing IEEE 802.11ac module), with Friis propagation model [22].

The legacy WiFi nodes are connected to the same AP, with QoS support, a PHY layer based on 802.11a and fixed data

TABLE I
SIMULATION PARAMETERS

Parameters	Values
Mobility model	Constant position
Simulation duration	10–100 seconds
Maximum transmission unit	1500 bytes
Number of VLC nodes	1–4
VLC node application rate	10 Mbps
VLC nodes transport protocol	TcpNewReno
Number of background nodes	1–8
Background nodes transport protocol	UDP
Default EDCA for AC_VI	AIFS=2, CWmin/max=7/15

rate of 6 Mbps. Moreover, all the STAs have the same distance from the AP. Finally, the VLC/WiFi nodes are close to each other without mobility. We designed the nodes in order to forward all TCP ACKs through the common WiFi network by configuring a static routing table for each device. The EDCA contention parameters set are AC_BE for WiFi background nodes, while VLC/WiFi nodes employ either AC_BE (no priority) or AC_VI (EDCA-ACK priority). The full list of parameters are summarized in Table I.

B. Performance of the hybrid VLC/WiFi architecture

We now present the results obtained both in the VLC download scenario and in the VLC upload scenario, in presence of several WiFi background streams in saturation. Considering a single VLC link and a source data rate of 10Mbps and a packet size of 1500 bytes, the reverse traffic flow caused by TCP ACKs is estimated to be 190 kbps at the maximum VLC download rate.

1) Download Scenario: In this scenario, we considered a network similar to [10]. Figure 3 shows the download throughput (solid lines) of a single VLC node when varying background WiFi nodes from 0 to 8, with or without WiFi contention priority for the uplink TCP ACKs. When the TCP ACKs are transmitted with AC_BE (blue line), few active WiFi background nodes provide significant throughput reduction. The figure also shows the ACK throughput (dashed lines, right y-axis scale), has a sudden reduction already with 2 background stations. This is due to the fact that the WiFi shared channel capacity is not enough for allocating a flow of 190 kbps. Indeed, with several TCP ACK colliding on the WiFi link, the transmission rate on the VLC link is decreased in response to the TCP congestion control.

Since the reference VLC link functions effectively up to M = 8 background nodes, different results are obtained when the AC_VI priority for the TCP ACKs is established (red dashed line). When M is within the range $[3, 8]$, with this access mode we can guarantee a rate of 140 kbps for TCP ACK transmission. It should be noted that TCP ACKs can be supported in a single TXOP with the default AC_VI value of 15. Thus, the improvement in VLC performance is due both to the increased channel utilization and the channel access priority together.

Figure 4 shows the results in a similar scenario with $N = 4$ VLC/WiFi nodes, and a variable number of background STAs.

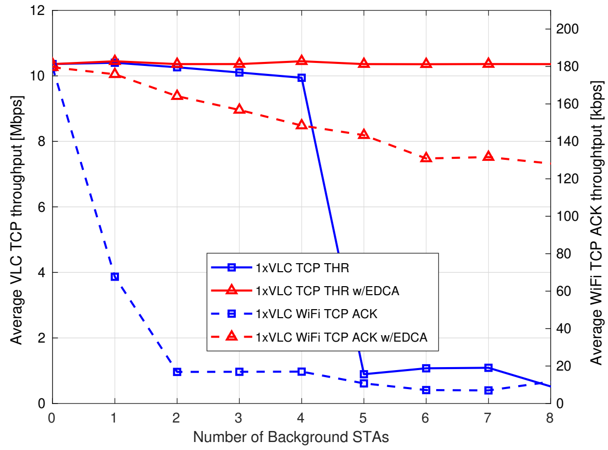

Fig. 3. Comparison of VLC downlink (solid)/WiFi uplink (dashed) throughput, for N=1 Hybrid VLC/WiFi station

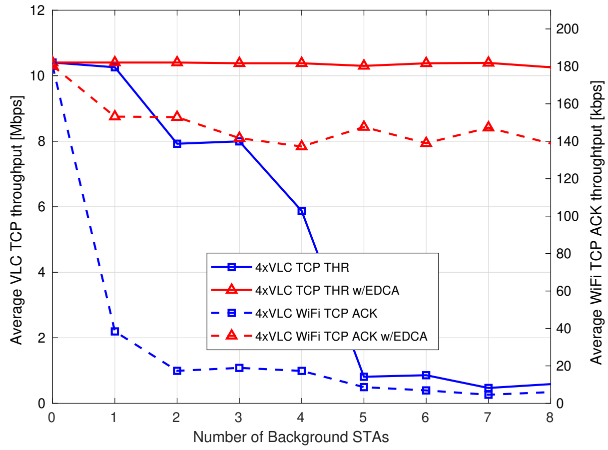

Fig. 4. Comparison of VLC downlink (solid)/WiFi uplink (dashed) throughput, for N=4 Hybrid VLC/WiFi stations

Although multiple TCP ACK flows are contending at the same time in this scenario, the behavior is similar to the previous case. Although the ACK flows use a small contention window (priority AC_VI is especially vulnerable to collisions in the same access category), the WiFi network still supports multiple coexisting VLC feedback flows before becoming saturated. This is due to the fact that the TCP ACK flow rate is low (note that for $M = 0$ the reference VLC link operates at the maximum rate despite the absence of EDCA-ACK priority). While using prioritization throughput reduction is only 20% for the worst congested case $M = 8$, the degradation is more dramatic when TCP ACKs are transmitted without EDCA.

Figure 5 shows average delay measurements for TCP ACK transmissions with and without priority for single VLC (solid lines) and N=4 VLC links (dashed lines). We can observe that the delay is significantly reduced with priority compared to TCP ACKs transmitted with best effort access category. Indeed, prioritization mechanism allows to reduce delays by

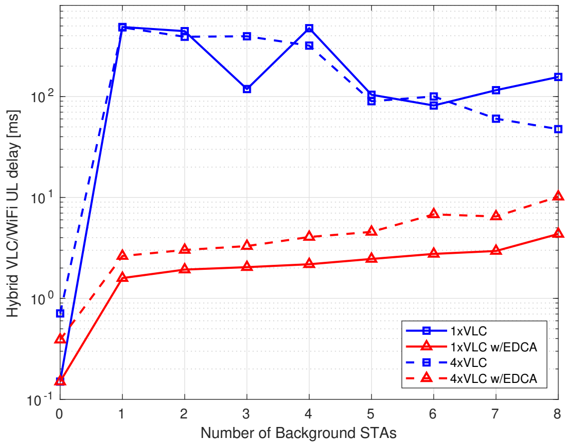

Fig. 5. Uplink end-to-end delay of TCP ACK flows.

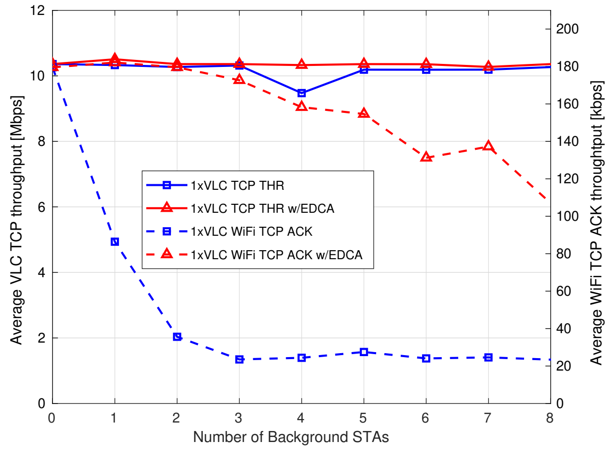

Fig. 7. Comparison of VLC Uplink (solid)/WiFi Downlink (dashed) throughput, for N=1 Hybrid VLC/WiFi stations

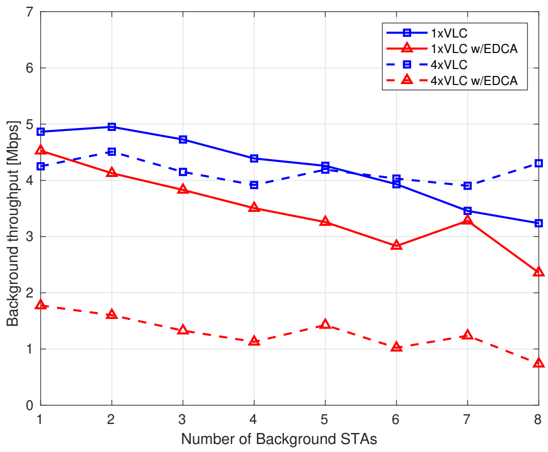

Fig. 6. Background STAs overall throughput in the downlink scenario.

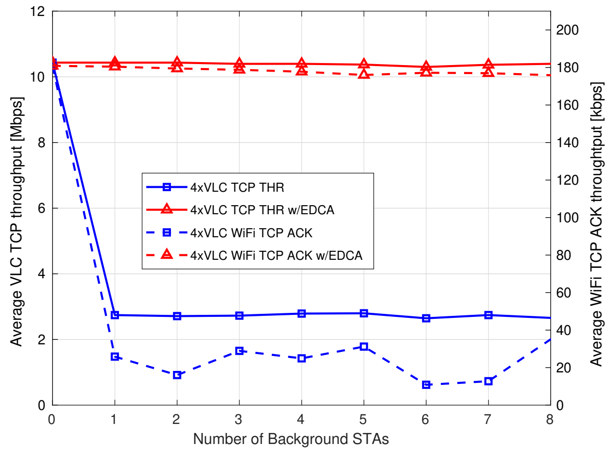

Fig. 8. Comparison of VLC Uplink (solid)/WiFi Downlink (dashed) throughput, for N=4 Hybrid VLC/WiFi stations

one order of magnitude compared to the ones transmitted with AC_BE (red curves vs. blue curves).

Finally, the WiFi background nodes' throughput is displayed in Figure 6, in both the scenarios of a single VLC link (solid line) and four VLC links (dashed lines). As expected, when the VLC links use a prioritization mechanism (red curves), the throughput reduction for WiFi background nodes is more noticeable, especially when multiple priority flows are active (dashed red curve).

2) Upload Scenario: We performed upload simulations by exchanging the direction of the flows, in the scenario depicted in Figure 2. In 7 and 8, we analyze VLC upload traffic (with TCP ACKs traffic flowing on the WiFi downlink) for a number of VLC nodes equal to N=1 and N=4, respectively. In figure 7, solid blue lines shows the uplink VLC data throughput which is comparable and close to the maximum application data rate, even in case of severe background traffic. This means that the number of received TCP ACKs is still enough to avoid timeouts (e.g. thanks to Selective acknowledgements) accommodating for lost ACK segments. Instead, dashed lines show that without TCP ACK priority the throughput of the ACK flows quickly drops under 30Kbps, while priority allows a throughput close to 120 kbps even with 8 background nodes.

Figure 8 shows a different performance behavior in case of N=4 VLC nodes. In this case, uplink traffic on VLC link is stable when priority is enabled, while in case of legacy WiFi for the TCP ACK flows, throughput becomes less than 3 Mbps already with a single background node. Indeed, without priority the ACK throughput on the WiFi link becomes unstable, causing TCP timeouts. Regarding the delay of the ACKs and the performance of the background nodes, similar results have been obtained as in the previous download scenario and are omitted for brevity.

In conclusion, our simulation results demonstrate that EDCA-ACK offers a promising, standards-compliant way to enhance the performance of hybrid VLC/WiFi systems.

V. CONCLUSIONS

In this paper, we studied WiFi priority mechanisms to improve hybrid VLC/WiFi networks. We considered a scenario in which the WiFi network is congested, causing significant delay and jitter to the feedback channel used for TCP ACKs, with a reduction in the overall network performance. We analyzed different options at the WiFi MAC level to improve the VLC/WiFi nodes. While it is not possible to assign fixed portions of WiFi channels for VLC feedback, aggregation of TCP packets in a single WiFi frame (or TXOP) could improve spectrum use significantly. Moreover, MAC priority based on EDCA parameters can be exploited to prioritize the TCP ACKs of the hybrid VLC/WiFi nodes and therefore increase the performance of the VLC links. In this direction, we quantified the gain achieved by the VLC segment with or without ACK priority on the WiFi link, both in download and upload scenarios, using the NS-3 simulator and demonstrating the effectiveness of the proposed solutions.

As future work, we plan to generalize the results of this paper with state-of-art VLC and WiFi data rates, and to study the performance of the presented solutions also in presence of node mobility, with coexisting WiFi networks and when multiple high-priority flows are present.

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