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► **To cite this version:**

Meysam Mayahi, Valeria Loscri, Antonio Costanzo. Link Adaptive Protocol for V2LC. IoL 2021 - Internet of Lights, Jun 2021, New York, Virtual, United States. pp.13-17, 10.1145/3469264.3469807. hal-03519701

**HAL Id: hal-03519701**

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Submitted on 10 Jan 2022

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# Link Adaptive Protocol for V2LC

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*Abstract—*

**As the Visible Light Communications (VLC) is growing up, it is not restricted anymore to the traditional indoor applications such as LiFi or positioning, but it finds new customers at outdoor vendors like underwater and vehicle applications. In this paper we looked at VLC challenges in Vehicular Communications from Medium Access Control point of view. We proposed Link Adaptive Protocol where a single handshake association and fast handover algorithms prolong VLC connectivity. Moreover, adaptive modulation has been suggested in order to increase the throughput. Simulation results show the link adaptive protocol outperforms slotted-aloah in outage probability and goodput, properly achieving a trade-off between pilot rate and protocol efficiency.**

*Keywords—* Vehicular VLC, MAC, Visible Light Communications, Adaptive Modulation.

## I. INTRODUCTION

VLC is a subset of optical wireless communications (OWC), allowing the use of commercial Light Emitting Diodes (LED) for both illumination and data transfer operations. This paradigm exploits huge free-licensed optical spectrum and it represents an extensive-capacity technology complementary to radio frequency (RF) communications[1]. The use of VLC as a transmission medium, opened new horizons in communication systems and potentially promised to solve many issues associated to the wide range of applications, such as last mile connectivity, positioning and underwater communications. Since the time it came into beings, VLC physical metrics such as data rate and communication range, grabbed the majority of the academic attention, while the Medium Access Control (MAC) issues, including network formation and handover, have been partially ignored, because the target application sector was mainly indoor.

**Vehicular Visible Light Communication - V2LC** Outdoor applications including Vehicular Communication (VC), have a great capacity to host VLC technology based on the already-existed infrastructures such as vehicles and road side units equipped with Light Emitting Diodes (LED) and cam-

eras. The main dilemma of Vehicular VLC (V2LC) is to maintain the connectivity at modest bitrate under the Line of Sight (LoS) constraints of VLC and rapid flexibility of VC, which in this paper has been committed from MAC layer perspective [2].

**Previous Contributions** The early efforts on VLC MAC layer backs to 2003 in Japan where VLC Consortium sets basic protocols for VLC positioning and later on has been revised by IEEE 802.15.7 VLC Task Group to include Channel Sensing Multiple Access (CSMA) MAC protocol [3]. It is the same standard used by LiFi technology which supports indoor wireless networking system including bi-directional multiuser communication [4]. Bi-directional VLC link was also adopted in [5] in order to implement the adaptive modulation control but in unfair uplink-downlink bandwidth. Essential differences between indoor and outdoor applications triggered prospective developments of distinct model in VLC ad-hoc networks where infrastructure-less mobile nodes qualified to tackle network failures. However, the techniques used in this area were randomly drawn from RF networks [6][7]. Opportunistic MAC protocol designed for VLC and based on three-way handshake [8] are not able to follow the high dynamicity of a vehicular context. The performance of V2LC has been enhanced in atmospheric turbulence condition by Aperture Averaging (AA) technique. AA uses a lens in front of PD to increase the collection area of the receiver so that the Signal to Noise Ratio (SNR) increases [9]. Platooning is another popular application in vehicular communication with autonomous vehicles grouped inside close proximity and interested in accessing each other's information [10]. Post-Crash Notification as an example of safety messages has been disseminated through IEEE 802.11p assisted by VLC within the area of accident to prevent possible accumulation in platoon [11]. In the context of Infrastructure to Vehicle (I2V) communication, the street lights have been served as access points and handover among them has been performed based on coordinated multipoint (CoMP) algorithm which modifies the handover margin and time-to-trigger value regardless of the vehicle velocity [12].

In this paper, a channel model with two signal attenuation factors has been adopted: Sunlight shot noise via Lamber-

tian radiation pattern and climate fluctuation model with atmosphere distortion index. Under such pragmatic channel model, Link Adaptive Protocol (LAP) aims to prolong the VLC connectivity as well as boosting the transmission rate collaborative to the quality of the received signal represented in signal to noise ratio (SNR). The later, represented as a safe metric to allocate different modulation schemes once it surpasses the threshold. Detecting large enough SNR triggers the association in single handshake mechanism to proceed in adaptive modulation transmission. By simulation, LAP performance has been verified in terms of coverage and goodput in addition to further analysis in protocol efficiency. Consequently, the main contributions of this paper could be summarized in: realistic outdoor channel model, link adaptive protocol optimised for V2LC and relevant protocol evaluation metrics.

The reminder of this article includes:

- System model, including both channel characterization and proposed Link Adaptive Protocol, has been provided in Section 2.
- Validation of the system model, through an extensive simulation campaign, has been discussed in Section 3.
- Conclusion sums up the outcomes in Section 4.

## II. SYSTEM MODEL

The key elements of every VLC system are shown in Figure 1. A Light emitting diode (LED) represents the transmitter, which transfers the optical power in the free space, while the photo detector (PD) as a receiver generates electrical current proportional to the optical received power. This communication scheme employs intensity modulation and direct detection (IM/DD). Elimination of local oscillators and broad employment of LEDs, nowadays, provide a cost-effective infrastructure for communication services[13]. Intensity modulation assures non-negative instant emitted optical signal  $X(t)$  between minimum and maximum signal power as  $u \leq X(t) \leq U$  with average transmit power  $P_t$  equivalent to expected value of the emitted optical power  $E(X)$ [14].

$$E(X) = P_t \quad (1)$$

### A. Channel Model

Instant received optical signal can be modeled as (2) while the average received power represented by (3):

$$Y(t) = rX(t) \otimes h(t) + N(t) \quad (2)$$

$$P_r = h \cdot E(X) \quad (3)$$

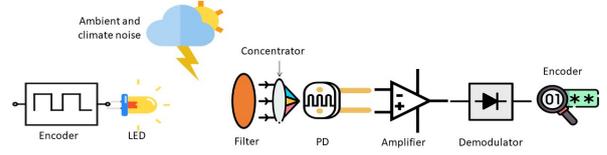


Fig. 1: VLC front-end blocks

Here  $r$  represents photodetector responsivity,  $h(t)$  describes outdoor optical channel impulse response taking into account Lambertian path loss  $h_{Lam}$  and statistical climate impairments  $h_{clm}$  model [15].

$$h = h_{Lam}h_{clm} \quad (4)$$

$N(t)$  stands for AWGN and  $\otimes$  is convolution operator. According to LoS constraint, channel model restricted to Lambertian emission of order  $m$  formulated as:

$$h_{Lam} = \frac{(m+1)A}{2\pi d^2} \cos^m(\phi) T_s(\psi) g(\psi) \cos(\psi) \quad (5)$$

$$m = -\ln(2) / \ln(\cos(\phi_{1/2})) \quad (6)$$

$\phi_{1/2}$  stands for half power semi-angle at the transmitter, photodetector area is  $A$ ,  $d$  indicates the distance between the transmitter and the receiver, angle of radiance and acceptance identified by  $\phi$  and  $\psi$  respectively and  $T_s(\psi)$  is optical filter gain. Photodetector concentrator gain  $g(\psi)$  ruled by (7) with  $n$  refractive index and  $\psi_c$  receiver field of view (FOV)[16].

$$g(\psi) = \begin{cases} \frac{n^2}{\sin^2 \psi_c} & , 0 \leq \psi \leq \psi_c \\ 0 & , 0 \geq \psi_c \end{cases} \quad (7)$$

Outdoor channel however, suffers from additional climate distortion statistically modeled as (8) with log-normal probability density function of climate distortion  $f_{h_{clm}}$  and log-amplitude variance  $\sigma_L^2$  determined through ray tracing analysis [17].

$$f_{h_{clm}}(h_{clm}) = \frac{\exp\left(\frac{(\ln(h_{clm}) + 2\sigma_L^2)^2}{8\sigma_L^2}\right)}{2h_{clm}\sqrt{2\pi\sigma_L^2}} \quad (8)$$

Table 1: Outdoor illuminance range

Illuminance [Lux]	Example
0.002	Moonless night sky
0.27 – 1	Full moon on a clear night
3.4	Twilight
100	Dark overcast day
300 – 500	Sunrise/sunset on a clear day
1,000	Bright overcast day
10,000 – 25,000	Full daylight (not direct sun)
32,000 – 130,000	Direct sunlight

### B. Noise model

The dominant part of the noise in outdoor applications is the daylight shot noise rather than other ambient interference sources like incandescent or fluorescent lamps.

Encountering thermal noise as the other major noise source, the total noise variance ( $\sigma_n^2$ ) will be like:

$$\sigma_n^2 = \sigma_{shot}^2 + \sigma_{thermal}^2 \quad (9)$$

Shot noise variance and thermal noise variance derived from (10) and (11).

$$\sigma_{shot}^2 = 2qrB(P_r + I_2P_{bg}) \quad (10)$$

$$\sigma_{thermal}^2 = 8\pi kT_k \eta AB^2 \left( \frac{I_2 g_m + 2\pi \Gamma \eta A I_3 BG}{g_m G} \right) \quad (11)$$

Background noise power  $P_{bg}$  is estimated as:

$$P_{bg} = 0.0079 E_{det} T_0 A n^2 \quad (12)$$

Table 1 is associated with illuminance range  $E_{det}$  of ambient light [18]. Finally we can define Signal to Noise Ratio as the Quality of Service metric in sort of (13).

$$SNR = \frac{(rP_t h)^2}{\sigma_n^2} \quad (13)$$

### C. Link Adaptive Protocol

Link adaptive model makes a quick connection when a VLC link is available, adjust the data rate based on the quality of the link and moves to other links when the quality of the current link degrades. As shown in Figure 2, the model includes 3 steps: Scanning, Association and Transmission.

In the beginning, the transmitter investigates the VLC environment by sending a tiny control message called pilot every  $T_p$  seconds. The receiver at the same time, estimates the

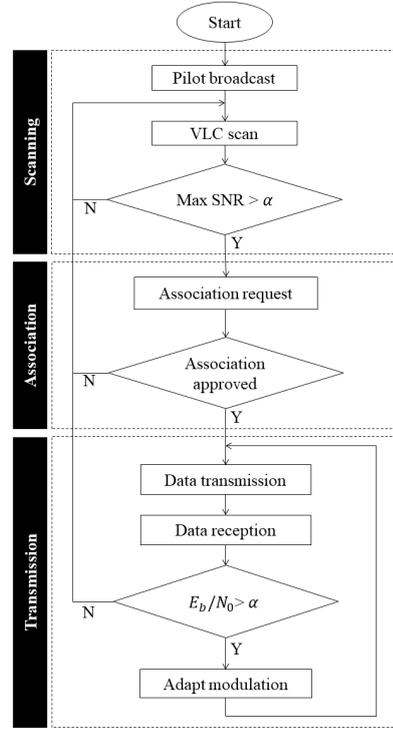


Fig. 2: Link adaptive protocol flowchart

Table 2: Main parameters

Parameter	Term	Value[unit]
Boltzmann constant	k	$1.3086e - 23[J/K]$
Noise bandwidth factors	$I_2, I_3$	0.562, 0.868
Background power	$P_{bg}$	0.533[mW]
Open-loop voltage gain	G	10
FET transconductance	$g_m$	30[mS]
Fixed capacitance of PD	$\eta$	112[pF/cm <sup>2</sup> ]
Responsivity	r	0.2[A/W]
Electric charge	q	$1.60217e - 19[C]$
Equivalent noise b.w	B	3[MHz]
Absolute temperature	$T_k$	298[K]
FET channel noise factor	$\Gamma$	1.5
Filter Transmission coef.	$T_0$	1
Refractive index	n	1.5
Number of LEDs		10
Input voltage		4.5[V]
Data packet size		536[Bytes]
Pilot size		10[Bytes]

SNR, by the received signal power during  $T_p$ . After each  $T_p$  the maximum value of the SNR is derived and once the Max SNR  $\geq \alpha$ , the source of that signal will be nominated for association otherwise, the scanning phase relaunches.  $\alpha$  initially set as the minimum SNR required to achieve a given quality of service(QoS).

In the association phase the source sends an association request to the destination and waits for association respond on the same link. If the association has been accepted before the timeout, it passes to the transmission phase. If not, the scanning phase starts again. Finally the transmission initiates and maintained among different modulation schemes based on modulation table, unless the link quality factor  $E_b/N_0$  drops below the threshold. Since then, the scanning step restarts.

### III. VALIDATION

A generic scenario, shown in Figure 3, has been arranged in a way to include association, adaptive modulation and hand-over algorithms using NS3-based VLC module. [14].

Mobile node1 rides for 20 meters, passing by node2 and node3, each of which equipped with VLC front-end of Figure 1. Simulation parameters are provided in Table 2.

Fixing the maximum error probability for safety applications equal to  $10^{-5}$  we derive  $\alpha = 11.5[dB]$  from Figure 4 and accordingly construct the modulation table 3 [19]. As a result, node1 associates to node2 as soon as  $SNR_{max}$  exceeds 11.5dB and goes to transmission phase. Node1 starts trans-

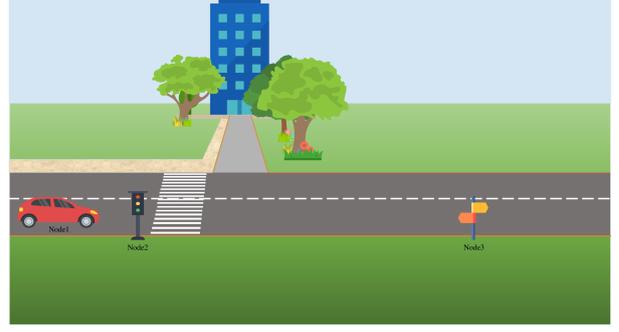


Fig. 3: Generic V2LC scenario

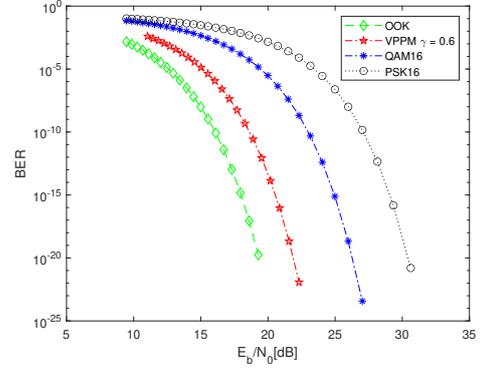


Fig. 4: Bit error probability for different modulations

mission with minimum modulation level (OOK) and as it is approaching to node2 the modulation level upgrades based on modulation table. When node1 traverses node2, the received power from node2 starts to decrease and consequently the modulation level degrades relatively until the SNR drops below the threshold. Here node1 goes to scanning phase where it finds node3's signal quality is rising up to  $\alpha$ . Instantly, node1 associates to node3 and repeats the previous process.

In order to evaluate the performance of the LA protocol an analytical comparison with slotted-aloha has been performed based on outage probability and data rate. Additionally, the protocol efficiency has been examined as a function of pilot frequency.

Outage probability is the Gaussian Q-function of SNR when

Table 3: Modulation table

$E_b/N_0$ range	Modulation scheme	Relative bitrate
11.5 – 15.0[dB]	OOK	150[Kbit/s]
15.0 – 19.0[dB]	VPPM	300[Kbit/s]
19.0 – 23.0[dB]	16QAM	500[Kbit/s]
23.0[dB] $\leq$	16PSK	700[Kbit/s]

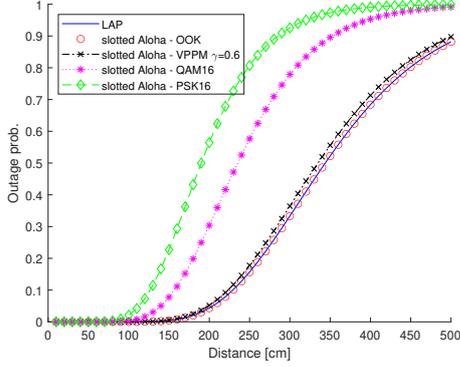


Fig. 5: LAP outage probability comparing to slotted-alooha

it drops below the threshold [15] and can be modeled in following way:

$$P_{out} = Prob(SNR \leq \alpha) = \int_0^{h_{min}} f(h)dh \quad (14)$$

Where  $f(h)$  is the joint probability density function of the climate and path loss distortion, it is formed thereby:

$$f(h) = \frac{1}{h_{Lam}} f_{h_{clm}} \left( \frac{h}{h_{Lam}} \right) \quad (15)$$

According to (5),  $h_{max}$  is the channel gain at maximum transmission range  $d_{max}$  where  $\alpha$  fulfills.

$$h_{min} = \frac{(m+1)A}{2\pi d_{max}^2} \cos^m(\phi) T_s(\psi) g(\psi) \cos(\psi) \quad (16)$$

Properly using (4) to (8),  $P_{out}$  is simplified as:

$$P_{out} = Q \left[ -\frac{\ln \left( \frac{h_{min}}{h_{Lam}} \right) + 2\sigma_L^2}{2\sigma_L} \right] = Q \left[ -\frac{\ln \left( \frac{d^2}{d_{max}^2} \right) + \sigma_L^2}{\sigma_L} \right] \quad (17)$$

Based on figure 5, LAP outage probability is enhanced comparing to VPPM, 16QAM and 16PSK slotted-alooha while it coincides the performance of slotted-alooha with OOK modulation.

To assess the adaptive modulation algorithm we define the goodput as the rate of data delivered to the application layer discarding all the overheads. As it is visible in Figure 6 (a) LAP goodput is improved proportional to the signal quality while the slotted-alooha goodput remains unchanged regardless of increasing the SNR.

The throughput of the adaptive protocol depends on the system awareness of the received signal evolution. The ear-

lier the signal alteration detected, the faster the modulation adapted. A common technique to raise the system awareness is exploring the VLC environment more often. The ideal case happened when the system is able to adapt the transmission criteria to the link condition continuously.

Figure 6 (b) and (c) represent the effects of increasing the pilot frequency on the goodput, comparing to the ideal case. In the same manner, Figure 7 shows the augmentation of the delivered data in respect to the pilot frequency in different speed. On the other side, increasing the pilot rate imposes more overhead to the network, according to Figure 8 which, in consequence reduces the protocol efficiency due to (18) and Figure 9.

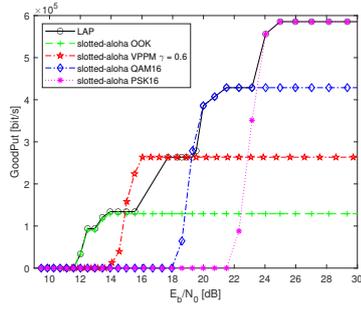
$$\eta_p = \frac{\text{delivered traffic}}{\text{delivered traffic} + \text{overhead}} \quad (18)$$

## IV. CONCLUSION

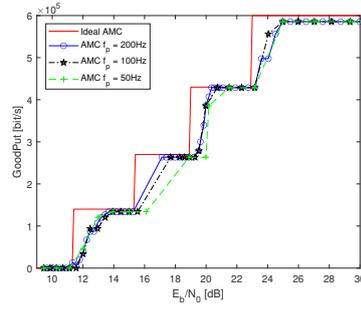
Representing VLC as a confidential complement to RF technology, challenges have been raised in outdoor applications from physical layer to upper layers. Current work tries to address the concerns of V2LC in terms of connectivity and throughput by means of Link Adaptive Protocol. Frequent scanning, tactile association and flexible transmission assure low outage probability and relatively high goodput in comparison to slotted-alooha. Last but not least, a trade-off between protocol efficiency and pilot frequency has been investigated.

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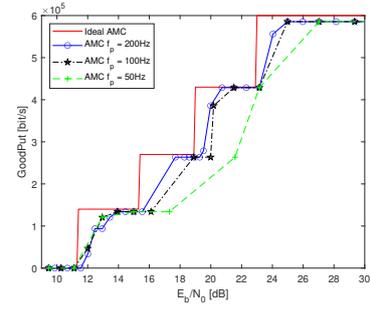
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(a) Achieved goodput of LAP and slotted-alooha



(b) Goodput increases by increasing Pilot frequency at 10m/s



(c) Goodput increases by increasing Pilot frequency at 20m/s

Fig. 6: Goodput as a function of SNR

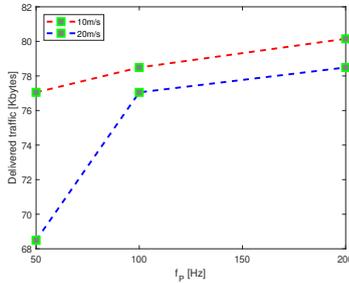


Fig. 7: Delivered traffic versus pilot frequency

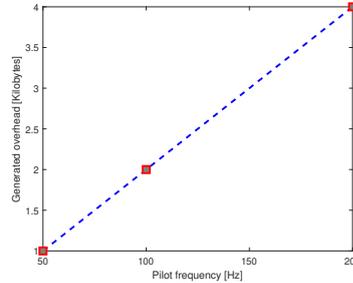


Fig. 8: Control traffic increase with pilot frequency

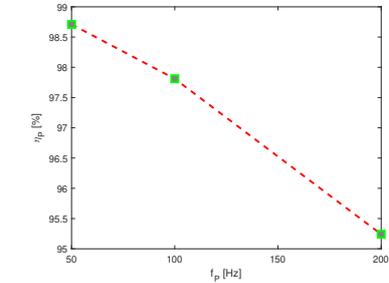


Fig. 9: Protocol efficiency degrades as the pilot rate increases

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