applied sciences

MDPI

Article

Adaptive Polling Medium Access Control Protocol for Optic Wireless Networks

Dawson Ladislaus Msongaleli *, Kerem Kucuk and Adnan Kavak

Department of Computer Engineering, Kocaeli University, Kocaeli 41380, Turkey; kkucuk@kocaeli.edu.tr (K.K.); akavak@kocaeli.edu.tr (A.K.)
* Correspondence: 156112001@kocaeli.edu.tr

Received: 17 February 2019; Accepted: 12 March 2019; Published: 14 March 2019

check for updates

Abstract: The emergence of optical wireless networks (OWNs) is a potential solution to the quest for the increasing bandwidth demand. Existing bandwidth assignment strategies are not suitable for OWNs, considering factors such as differences between the physical properties of radio networks and OWNs. In order to eliminate collision, minimize delay and enhance system utilization and fairness, we propose the non-contention bandwidth assignment protocol called adaptive polling medium access control (APMAC) protocol for OWNs. The APMAC protocol involves association, data transmission and dissociation phases. Moreover, the APMAC protocol exploits features of the IEEE 802.15.7 visible light communication (VLC) standard. While assigning bandwidth to the visible light nodes (VLNs), the visible light access point (VLAP) establishes a polling table that contains the identity, buffer size and round-trip time of each VLN that issued bandwidth request. The contents of the polling table enable the computation of the maximum transmission unit and time-slot for each VLN that requests bandwidth assignment. In order to achieve convincing results, we simulate the protocol under varying network sizes ranging from 1 to 10 VLNs per access point, then we compare the results against the medium transparent medium access control (MT–MAC) protocol that is a non-contention MAC protocol. We demonstrate numerical results of our study considering average waiting time, packet collision, system utilization and fairness. Numerical results reveal that the APMAC protocol outperforms the MT–MAC protocol.

Keywords: optical wireless network (OWN); visible light communication (VLC); medium access control (MAC); light emitting diode (LED); IEEE 802.15.7 Standard

---

1. Introduction

The high reliance on the internet is the major cause of sudden increase in new Internet subscribers. In fact, the number of Internet subscribers increases every year at unpredictable rate. For example, Cisco forecasts that the global mobile data traffic will grow from an annual rate of 86.9 Exabytes of the year 2016 to 587.4 Exabytes in 2021 [1]. Statistics show that between 2016 and 2021, mobile traffic is expected to increase two times faster than fixed network traffic [1]. Furthermore, the high reliance on social networks and other web-based applications available on the Internet are the major cause of high traffic from mobile devices such as smartphones, tablets, and other handheld devices [2]. The radio waves of the electromagnetic spectrum have been exploited for wireless networks signal transmission over the past decades. However, excessive Internet subscribers have stretched the radio spectrum to its limit. There is no more spectrum for new subscribers while the number of new users is increasing every year. Several solutions have been proposed to address the problem of new capacity demand such as the use of unlicensed radio spectrum. However, the proposed new solutions cause other problems such as high energy consumption, signal interference, capital and operating expenditure [3,4]. Exploiting the visible light spectrum for signal transmission is the promising solution to the increasing internet capacity demand. There are many reasons that support this argument such as significant bandwidth available in the visible light spectrum i.e., from 430 nm to 790 nm, inherent physical security, no impact on human health, low capital expenditure, and energy efficiency. Different groups such as [5–12] have demonstrated that visible light spectrum can be used for communication purpose. Unlike visible light communication (VLC) that focuses on point to point communication, light fidelity (LiFi) is an extension of VLC that uses light emitting diodes (LEDs) to provide fully networked visible light wireless access network [13,14]. Although at its infancy stage, LiFi has demonstrated potential advantages of using visible light spectrum in communication.

Applications of VLC include vehicular networks, indoor mobile network, indoor localization, visible light sensing, gesture recognition, under water communication systems, security systems and health sector [15]. The existence of LEDs in automobiles promotes the use of VLC in transportation systems [16–19]. In [20], the authors suggest the VLC-based vehicular network for urban mobile crowd sensing that aims at supporting driving automation. The performance of VLC with respect to full duplex communication is investigated in [21] where numerical results show that there is an increase of 10% in data delivery rate. Localization of user equipment is another interesting application of VLC technology, in particular where radio frequency and GPS may not work or give inaccurate information [22]. The VLC-based beaconing infrastructure for indoor localization applications is designed in [23]. This study demonstrates that unknown camera location can be determined accurately by using four fixed beacons. Moreover, VLC can play a significant role in cooperative communication by exploiting light sources available in indoor environments as relay nodes [24]. Furthermore, VLC can be used in real time applications such as command control systems, and air traffic control systems. The authors in [25] suggest a VLC-based real time vital signal transmission system. Results from this study demonstrate that exploiting VLC for real time systems improves communication speed. Unlike other spectrums, visible light spectrum is not harmful to human health; thus, it can be used in medical care for communication purpose. A hybrid VLC-request frame (RF) system for health communication system is presented in [26]. The proposed system can be used to transmit laboratory test to patients.

Nevertheless, the benefits of using the visible light spectrum in communication can only be realized if several challenges such as medium access control for multi-user access, precise channel model, interference mitigation techniques and software-defined networks (SDN) for visible light-based networks are well addressed [13]. In this study, we investigate the problem of multi-user access for optical wireless networks (OWNs). We propose the non-contention protocol namely adaptive polling medium access (APMAC) protocol that minimizes waiting time, and packet collision while maximizing system utilization and fairness. Moreover, the APMAC protocol considers the physical properties of the physical layer of OWNs. The APMAC protocol exploits the dynamic future knowledge (DFK) algorithm for estimating the maximum transmission unit presented in [27] and involves three phases such as association, data transmission, and dissociation phases. The rest of this study is organized as follows. Section 2 presents existing research publications related to this study. Section 3 describes the statement of the problem and assumptions we considered in this study. We narrate the APMAC protocol in Section 4 considering the association, data transmission and dissociation phases. Experimental setup and numerical results are presented in Section 5. Finally, the conclusion of this study is found in Section 6.

2. Related Studies

Existing MAC protocols fall into three major categories: (i) non-contention protocols such as polling and token passing, (ii) contention-based protocols such as Aloha and carrier sense multiple access (CSMA), and (iii) channelization-based protocols like frequency division multiple access (FDMA) and time division multiple access (TDMA) [28]. In non-contention protocols, one device is controlling other devices and each device is assigned a specific time for using shared resource; therefore collision cannot occur. Contention-based protocols do not require control device that controls other devices. Usually contention-based protocols involve asynchronous competition in order to get access to shared resources. However, contention-based protocols suffer from hidden nodes interference, low system utilization, and throughput degradation at high network loads.

The IEEE 802.15.7 standard defines the physical layer and the MAC layer for short range wireless optical communication. The specifications of MAC layer allow four ways of accessing a shared channel such as (i) beacon enabled slotted random access (ii) beacon enabled unslotted random access (iii) non-beacon enabled slotted random access and (iv) non-beacon enabled unslotted random access [12]. Moreover, the IEEE 802.15.7 standard allows three types of network topologies namely peer-to-peer, star, and broadcast network topologies. Note that the beacon enabled modes divide time into superframes that are bounded by beacons transmitted via a coordinator. The authors in [29–31], present MAC protocols for the convergence of fiber and short radio wave based wireless communication. The medium-transparent MAC protocol proposed in [29,31] provides seamless and dynamic bandwidth allocation in radio over fiber networks via the contention-based mechanism. In [32] the authors present the broadcasting based MAC protocol for VLC. This protocol exploits the channelization techniques such as TDMA to enhance the quality of service in VLC. Non-contention MAC protocol for ethernet passive optical network (EPON) is presented in [33]. This protocol eradicates collision and increases system utilization because communication operates in non-contention mode.

Cooperative MAC protocol for VLC is proposed in [34], wherein the authors aim at enhancing reliability and increasing the coverage area. Moreover, this protocol can be exploited for VLC based vehicular communication. The contention-based MAC protocol for VLC that minimizes dual transmission over several access-points is presented in [35]. The novel energy efficient medium access scheme for VLC is studied in [36] to improve the performance of the CSMA/CA considering unsaturated conditions. Wang et al., in [37] investigate the contention-based full-duplex MAC protocol for VLC. Mao et al., in [38], present the novel VLC MAC protocol that combines time division multiple access (TDMA) and code division multiple access (CDMA). The authors in [38] consider delay minimization in vehicle to vehicle communication. Moreover, in [39] the polling-based MAC protocol for wireless networks is presented; wherein the focus is reducing polling overhead, dropping probability, and delay. Furthermore, the resource allocation scheme that exploits channelization technique such as TDMA for indoor VLC is presented in [40]. The energy consumption minimization problem for VLC is studied in [40], wherein, energy minimization subject to throughput maximization is the key points of consideration. Nishio et al., in [41] present the visual recognition based MAC protocol that aims at minimizing collision by using both radio and visible light spectrum. The proposed protocol in [41] increases throughput by 40% comparing to CSMA/CA. In order to mitigate the problem of signal interference caused by intersecting angle of irradiance, the authors in [42] propose the hidden avoidance enabled CSMA/CA protocol for VLC. The dynamic contention window-based MAC protocol that increases channel utilization for VLC is presented in [43]. A critical analysis of the IEEE 802.15.7 standard for VLC is suggested in [44] wherein the authors present a Markov chain model for CSMA/CA node behavior. Moreover, in [45] a multi-channel MAC protocol for the integration of VLC and radio waves networks is presented. Heting et al. in [46] investigate a contention-based protocol for VLC that considers dynamic contention window to improve channel access and throughput. Currently, the problem of shared medium access in VLC is not well investigated. In particular, existing research publications adopt contention-based and channelization strategies that have some limitations such as interference, low system utilization, and increased waiting time. Table 1 summarizes existing research publications on MAC protocol for VLC. Unlike existing research publications, this study presents the novel APMAC protocol for VLC that minimizes delay and packet collision while increasing system utilization, and fairness.

Table 1. Research publications on medium access control (MAC) protocols for optical wireless networks (OWNs).

Study	Type	Transmission Medium	Application	Waiting Time	Utilization	Fairness
Kalfas et al. [29]	Contention	Radio over Fiber (RoF)	Outdoor	Yes	No	No
Maniotis et al. [30]	Contention	Radio over Fiber (RoF)	Outdoor	Yes	No	No
Kalfas et al. [31]	Contention	Radio over Fiber (RoF)	Outdoor	Yes	No	No
Le et al. [32]	Channelization (TDMA)	Visible light spectrum	Indoor	No	No	No
Kramer et al. [33]	Non-contention (Adaptive Polling)	EPON	Outdoor	Yes	Yes	No
Le et al. [34]	Contention	Visible light spectrum	Outdoor	No	Yes	No
Xu et al. [35]	Contention	Visible light spectrum	Indoor	No	No	No
Liu et al. [36]	Contention	Visible light spectrum	Indoor	No	No	No
Wang et al. [37]	Contention	Visible light spectrum	Indoor	No	Yes	No
Mao et al. [38]	Channelization (TDMA and CDMA)	Visible light spectrum	Vehicular Communication	Yes	Yes	No
Kim et al. [39]	Non-contention (Multi-Polling)	Radio spectrum	Indoor	Yes	No	No
Vega et al. [40]	Channelization (TDM)	Visible light spectrum	Indoor	No	Yes	No
Nishio et al. [41]	Contention	Radio and Visible light spectrum	Indoor	No	Yes	No
Wang et al. [42]	Contention	Visible light spectrum	Indoor	No	Yes	No
Liu et al. [43]	Contention	Visible light spectrum	Indoor	Yes	Yes	Yes
Nobar et al. [44]	Contention	Visible light spectrum	Indoor	Yes	Yes	No
Mai et al. [45]	Contention	Radio and Visible light spectrum	Indoor	Yes	Yes	No
Heting et al. [46]	Contention	Radio and Visible light spectrum	Indoor	Yes	Yes	No
This study	Non-contention (Adaptive Polling)	Visible light spectrum	Indoor	Yes	Yes	Yes

3. Problem Description and Assumptions

OWNs originate from the VLC concept wherein visible light is a conduit of signals from the source to the destination [47]. It should be noted that the VLC aims at providing point to point communication via visible light spectrum, whereas OWNs such as the LiFi extends the idea of point to point communication to full networking concepts such as broadcasting, multi-casting and point to point communication [13]. LiFi is the prominent example of OWNs that exploit traditional LEDs available in our surrounding to provide fast data transmission [13]. The IEEE 802.15.7 standard for VLC allows three types of network topologies namely peer-to-peer, broadcast and star topologies [12]. Accessing shared resources in star and broadcasting topologies can be challenging and often causes network performance degradation.

In this study, we investigate the problem of bandwidth assignment for multiple users sharing the same visible light access point (VLAP). The visible light nodes (VLNs) in this context refer to normal devices such as computers and mobile phones that are enabled with optic transmitters such as LEDs and optic receivers such as photo-diodes. Similarly, the VLAP refers to the access point that provides

Internet connectivity via visible light spectrum. The VLAP is also enabled with an LED that transmits signals via light rays to several VLNs that fall within its angle of irradiance and has photo-diodes for visible light signal reception. We consider a simple star topology network that has one VLAP and several VLNs. Currently, it is not realistic to achieve full duplex communication in VLC-based access networks. This is because of challenges such as interference, glare and user equipment power limitation. However, VLC can be complimented by other spectrums in order to achieve full duplex communication. Two ways have been used to complement VLC: (i) using infra-red for uplink channel and VLC for downlink channel and (ii) using radio spectrum (WiFi) for uplink channel and VLC for downlink channel. In this study, we consider infra-red as the means of providing uplink channel and VLC for downlink channel as applied in LiFi. This is due to the fact that the uplink channel consumes less bandwidth than downlink channel. Therefore, the benefit of huge bandwidth available in VLC can be more fruitful if exploited for the downlink channel. Moreover, existing research publications suggest that currently infra-red can support 4Mbps data rate. Moreover, while assigning bandwidth to each VLN, we consider a beacon-enabled channel access methods stated in [12]. A sample star topology network is presented in Figure 1. The problem is assigning a shared VLAP to multiple VLANs, where minimum waiting time, low packet collision, high system utilization and fairness are key performance metrics. To the best of the authors' knowledge, this is the first study to address this problem considering these performance metrics, the non-contention approach and the physical layer properties of the OWNs.

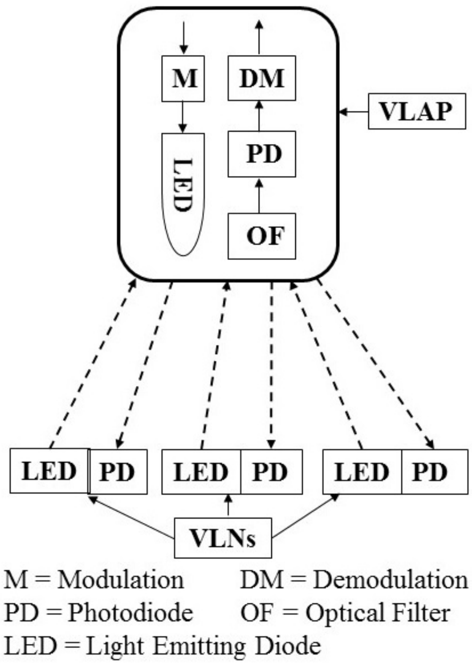


Figure 1. The common indoor optical wireless network (OWN) scenario.

4. The Adaptive Polling Medium Access Control (APMAC) Protocol

We propose the APMAC protocol for OWNs, that considers physical properties of OWNs and key network performance metrics such as waiting time, packet collision, utilization and fairness [43,44,48,49]. The APMAC protocol operates in three phases: (i) association phase wherein VLNs establish connections with the VLAP (ii) data transmission phase in which data transmission between VLNs and VLAP occurs, and (iii) the dissociation phase in which connection between the communicating devices is terminated. For simplicity, we provide common abbreviations used in this study and their complete form in Table 2. Figure 2 presents the APMAC protocol considering association, data transmission and dissociation phases. Furthermore, Figure 3 shows the finite state machine of the VLAP and Figure 4 depicts the finite state machine of the VLNs considering association, data transmission and dissociation phases. The superframe is divided into collision avoidance slot (CAS) and non-contention slots. During CAS, VLNs contend for association. The mechanism of contention in this case is described by the control frame collision avoidance algorithm (CFCA) in Section 4.1. In the non-contention slots, VLNs communicate with the VLAP without contention.

Table 2. Abbreviations and their complete names.

Abbreviation	Complete Form
VLAP	Visible light access point
VLN	Visible light node
ADF	Availability data frame
ARF	Access request frame
AGF	Access grant frame
DAF	Data availability frame
DTF	Data transmission frame
FOV	Field of view
RTT	Round trip time
MTU	Maximum transmission unit
CTR	Connection termination request
CTA	Connection termination acknowledgment
ADFT	Availability data frame transmission state
ADFR	Availability data frame reception state
ARFT	Access request frame transmission state
ARFR	Access request frame reception state
AGFT	Access grant frame transmission state
AGFR	Access grant frame reception state
DAFT	Data availability frame transmission state
DAFR	Data availability frame reception state
DTFT	Data transmission frame transmission state
DTFR	Data transmission frame reception state
CTRT	Connection termination request transmission state
CTRR	Connection termination request reception state
CTAT	Connection termination acknowledgment Transmission state
CTAR	Connection Termination acknowledgment Reception state

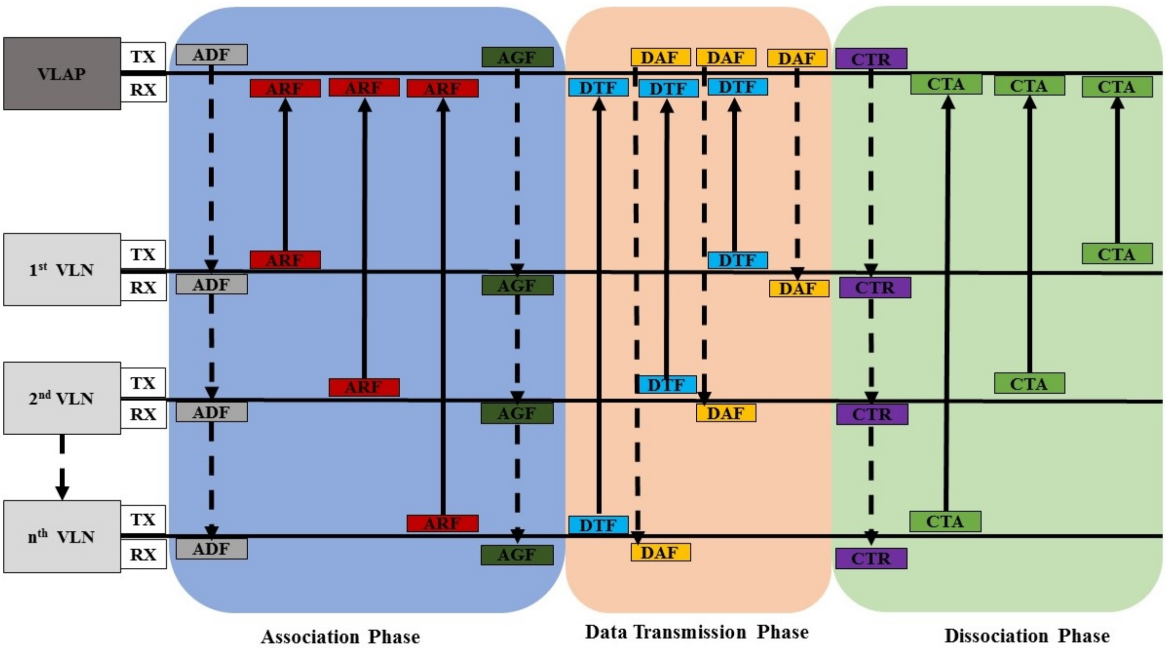


Figure 2. The adaptive polling medium access Ccontrol protocol.

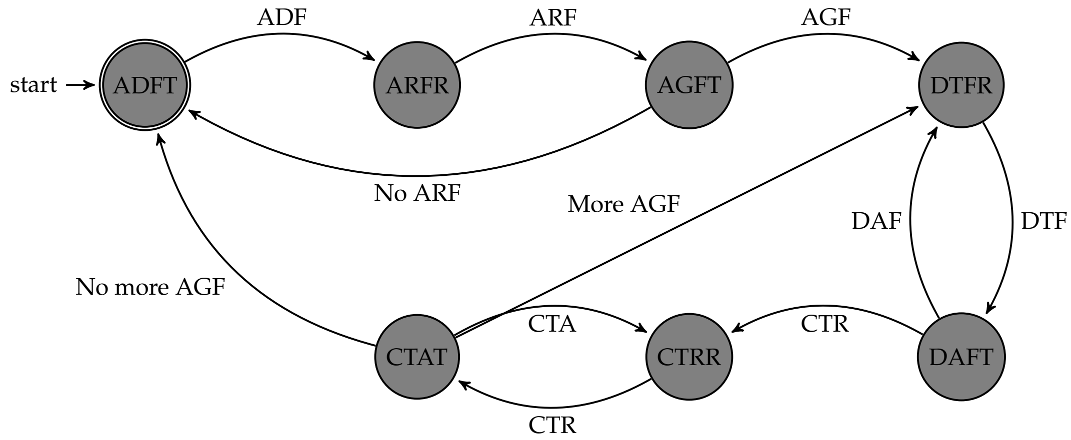


Figure 3. The visible light access point (VLAP) finite state machine in the adaptive polling medium access control (APMAC).

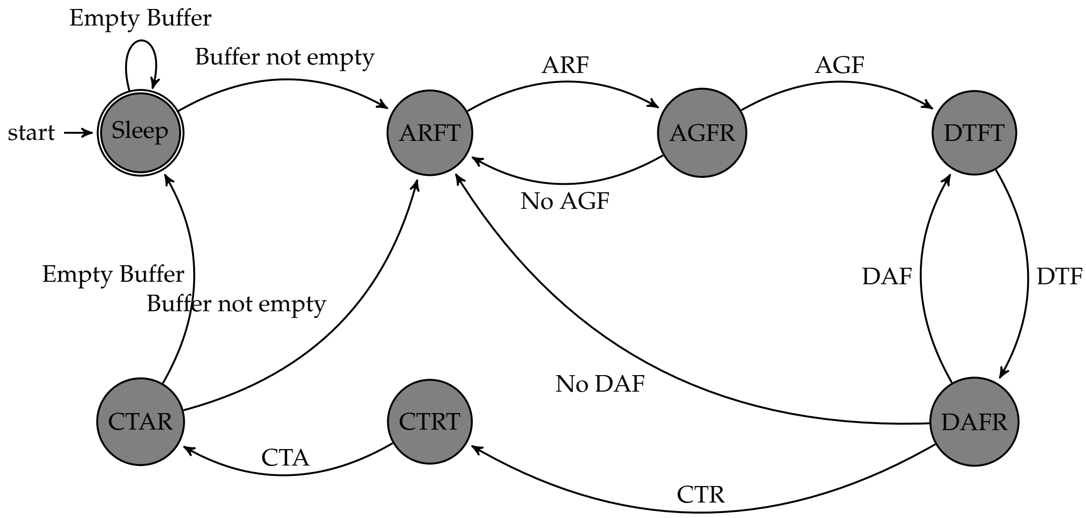


Figure 4. The visible light nodes (VLN) finite state machine in the APMAC.

4.1. Association Phase

In the APMAC protocol, the connection between VLNs and VLAP can be initiated by any of the two devices. When the VLAP initiates communication, it sends the DTF directly to the VLN; this is a point to point communication; therefore there is no collision. However, when the VLNs initiate communication, collision of ARFs from different VLNs at the receiver of the VLAP may occur. Initially, the VLAP broadcasts ADF to all VLNs falling within its angle of irradiance. ADF contains several parameters such as channel frequency, the physical address of the VLAP. The buffer size and destination physical address are optional parameters that are included in the ADF in case the VLAP has some data to transmit to a particular VLN. Otherwise, it is turned off during the ADF broadcasting. After receiving the ADF, VLNs within the angle of irradiance of the VLAP respond by transmitting the ARF to the VLAP wherein it requests access to use the shared channel for data transmission. Within the ARF, several parameters are included such as the physical address of the VLN and buffer size. Note that VLNs issue ARF at random time, therefore collision of ARF may occur. We define the control frame collision avoidance algorithm (CFCA) that mitigates collision of ARF during association phase as follows:

- Let η represent the theoretical maximum number of VLAN per VLAP.
- Let α_t represent the mean maximum round trip time (RTT) between VLAP and VLN.
- Let collision avoidance slot (CAS), that is the maximum contention time be denoted by $CAS = \eta\alpha_t$

- At the beginning of the CAS slot, the VLAP broadcasts the ADF.
- Upon receiving the ADF, VLNs that wish to associate with the VLAP select a random time $z|\alpha_t < z < \eta\alpha_t|$. At time z if a VLN senses an idle channel, it sends ARF to VLAP then it waits for AGF. If no AGF arrives within $z + 2\alpha_t$ time unit, the VLN checks if $z + 2\alpha_t < \eta\alpha_t - \alpha_t$.
- If $z + 2\alpha_t < \eta\alpha_t - \alpha_t$, the VLN selects another random time $z_i|z + 2\alpha_t < z_i < \eta\alpha_t - \alpha_t|$. At time z_i, VLN sends ARF to the VLAP if the channel is idle, otherwise it checks again if the condition $z + 2\alpha_t < \eta\alpha_t - \alpha_t$ is satisfied then it selects another random time z_i, otherwise it waits another ADF from the VLAP.
- At $\frac{\eta\alpha_t}{2}$, the VLAP checks if there is no any ARF that arrived from 0 to $\frac{\eta\alpha_t}{2}$ then it resets its timer and broadcasts another ADF. This is done to improve system utilization by avoiding idle waiting because VLNs may not receive the ADF from the VLAP, hence no ARF will be transmitted thereby causing idle waiting.

After broadcasting ADF, the VLAP creates the polling table that contains the physical addresses, buffer size and RTT of each VLN that issued ARF. The estimation of RTT is done by considering the time taken from broadcasting ADF until when the ARF is received at the VLAP. Following this, the VLAP transmits to each node the AGF. The AGF specifies several parameters such as the transmission slot, maximum transmission unit (MTU), and the direction of data transfer. i.e., transmission or reception. If the direction parameter implies transmission, then the VLN should transmit, otherwise it should receive. The mechanism used to determine the MTU in this study considers the dynamic future knowledge maximum transmission unit (DFK-MTU) algorithm studied in [27]. The DFK-MTU allows the VLAP to dynamically adjust the size of the MTU depending on the current content of the polling table. Moreover, for each particular instance of the polling table, the MTU is the average size; this enhances achieving optimal MTU. It is important to note that the process of MTU for each particular polling table instance serves as the upper bound. For more clarification, the DFK-MTU algorithm is illustrated in Algorithm 1. The transmission time slot available in the AGF for each VLN is obtained by adding RTT and the processing time. After each consecutive data transmission time-slot, a guard time is added in order to avoid signal interference.

Algorithm 1: Dynamic future knowledge maximum transmission unit (DFK-MTU) algorithm adopted from [27].

```
for each schedule duration do
    • Establish a new Polling Table (PT).
    • Calculate MTU = Average of the current PT.

    while PT ≠ Empty do
        for each node k : {k = 1, ..., n} ∈ PT do
            if node k buffer ≥ current PT MTU then
                The current PT MTU is the MTU for node k.
            end
            if node k buffer < current PT MTU then
                Buffer size of k is the MTU k.
            end
            if node k buffer = current PT MTU then
                The current PT MTU is the MTU for node k.
            end
        end
    end
end
```

4.2. Data Transmission Phase

Data transmission phase follows the association phase. In this phase, actual data transmission between VLAP and VLNs occurs. The VLAP starts receiving DTF from each VLN that issued ARF. Each VLN transmits DTF within its specific time interval as stated in the AGF. DTF contains the physical address of the VLAP and VLN, payload, and the remaining buffer size at the VLN. If the remaining buffer size at the VLN is zero, then the VLAP knows that there is no more data to be transmitted. Moreover, if the buffer size in the DTF is greater than zero, it means there is more data to be transferred. In this case, the VLAP calculates the next time slot for this payload based on the next time-slot available. VLAP replies to the VLN with the DAF in which it specifies the next allowed MTU that the VLN can transmit and the slot time in which it can perform next data transfer. VLAP updates its polling table by changing the new RTT and buffer size for each VLN.

4.3. Dissociation Phase

After completing data transmission, the VLAP and VLN should decide either to maintain or to terminate the connection. In this context, the choice depends on the state of the two devices. For instance, if the VLN is sending data to the VLAP and after completing its available buffer size the VLAP may have some bits destined to that VLN. Instead of terminating the connection, the VLAP may continue transmitting its data. Likewise, if the VLN is receiving data from the VLAP, after data transmission from the VLAP, the VLN may have some data in its buffer destined to the VLAP. In this case, terminating the existing connection can cause unnecessary new connection request. The two devices can keep transmitting data using existing connection. However, if there is no more data transmission from either device, then the connection should be terminated. In this case, the transmitting node should send the CTR to its counterpart. The CTR contains the communicating nodes' identities, sending time, and the connection termination time. In order to avoid premature termination, the device that sends CTR should wait for the CTA from its counterpart device. If the RTT duration finishes without receiving the CTA, the device can terminate the connection. Moreover, if the device receives CTA within the RTT, it terminates the connection. After connection termination the VLAP updates its polling table by removing the details of VLNs that have completed data transmission.

5. Experimental Setup and Numerical Results

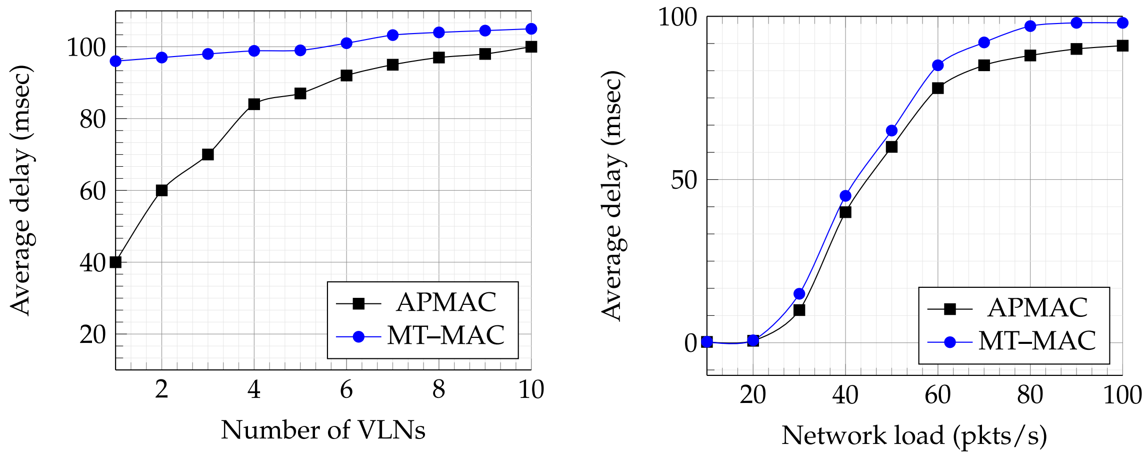
We validated our study by simulating our protocol in the NS3 simulator. We considered four performance metrics in evaluating potential benefits of our study, viz., average waiting time, average packet collision, average system utilization, and average system fairness. The average waiting time in this context refers to the average time interval between the instant at which the VLN sends the ARF and the moment at which it starts sending DTF. In a nutshell, this is the duration the VLN is in association phase. Moreover, the average packet collision is the mean value of occurred collisions. The average system utilization refers to the mean time the system is not idle. System fairness was another performance metric we considered in expressing numerical results. We expressed system fairness by using the fairness index defined in [50] as follows:

$$\text{fairness index} = \frac{\sum(\frac{t_i}{\omega_i})^2}{N(\sum(\frac{t_i}{\omega_i}))^2} \tag{1}$$

where t_i represents throughput of node i, ω_i denotes the weight of the node i, and N represents the number of nodes in the network. In our simulation, we assumed that all VLNs have equal weight and the number of VLNs in each scenario ranges from 1 to 10 per VLAP. The small number of users per cell is attributed by inter-cell interference and contention during resource arbitration with the access point during association phase. The fairness index expressed in Equation (1) ranges from 0 to 1, where the high value of fairness index implies that the system is fairer. In this study, the downlink data rate was 120 Mbps, and the uplink data rate was 4 Mbps. The maximum propagation distance was 10 m, this is due to the fact that within this range VLC signals can be reliably detected. Network traffic was generated randomly at each node following poison process of constant rate λ packets per second. In order to evaluate potential benefits of our study, for each performance metric we compared the APMAC protocol against the medium transparent medium access control (MT–MAC) demonstrated in [29]. Furthermore, for each scenario, we rerun each simulation 50 times and the results presented are averages of the results obtained for each category with 97% confidence interval.

5.1. Average Delay

In Figure 5a,b we present our numerical results considering average delay as a function of network size and network load. Figure 5a shows the delay against network size, where network size ranges from 1 to 10 VLNs. Numerical results suggest that APMAC performs better than MT–MAC in terms of average delay. The DFK-MTU algorithm and non-contention approach we adopted in APMAC protocol are key factors for the low average waiting time recorded in Figure 5a. The average delay increased when network size increased for both APMAC and MT–MAC because when there are many VLNs in a network, resources arbitration between VLNs and VLAP consumes a lot of time. Figure 5b demonstrates average delay as function of network load for both APMAC and MT–MAC protocols. Numerical results in this context suggest that delay increases with respect to network load. This is due to the fact that each VLN holds resources longer when there are many packets to be transmitted. However, APMAC protocol performs better than the MT-MAC protocol in this case.



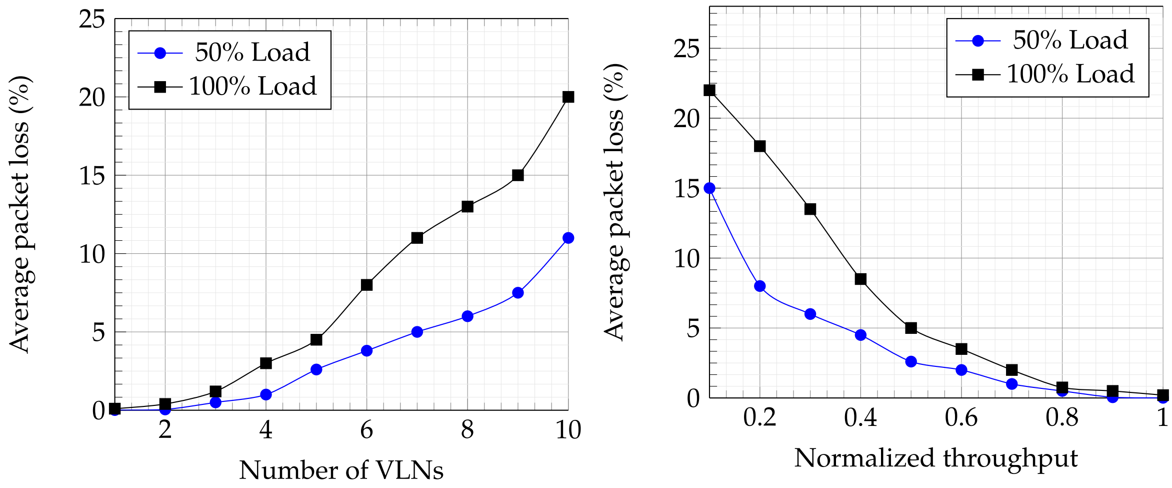
(**a**) Average delay versus network size.

(**b**) Average delay versus network load.

Figure 5. Average delay versus network size and network load.

5.2. Average Packet Collision versus Network Size and Network Load

Figure 6a,b demonstrate the numerical results of our study by taking into account packet collision/loss against network size and normalized throughput. In this case we also considered 50% and 100% of the theoretical maximum network capacity. In Figure 6a packet loss increased when the network size increased. This is due to the fact that when there are many VLNs in the network, the odds are that many packets are generated and transmitted. Therefore more collision can occur at high values of network size. In addition, the network load also contributed to packet loss/collision as it can be seen that there is more packet loss when the network load is 100% compared to 50%. Figure 6b shows that the average packet loss affects the throughput of the system. Thus packet loss decreases the throughput in both the 50% and 100% network load.

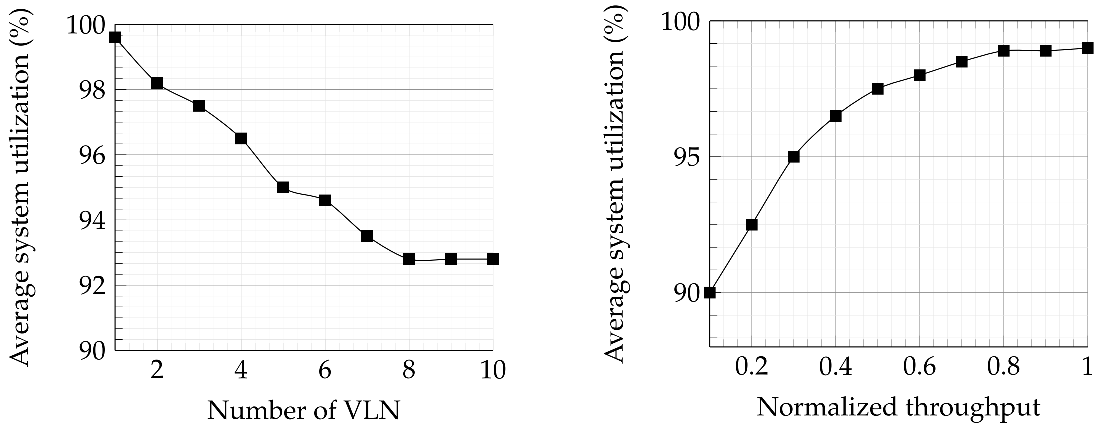


(**a**) Average packet loss vs. network size. (**b**) Average packet loss vs. normalized throughput.

Figure 6. Average packet loss vs. network size and network load.

5.3. Average System Utilization versus Network Size and Normalized Throughput

Furthermore, Figure 7a shows average system utilization against network size where the system utilization decreases with respect to increase in network size. The significant decrease in utilization was caused by time taken by VLNs for resources arbitration. Figure 7b presents numerical results considering average system utilization against normalized throughput. Numerical results in this case show that utilization and throughput are direct proportional. Moreover, our protocol records between 90% and 99% system utilization in both case because of the non-contention approach.

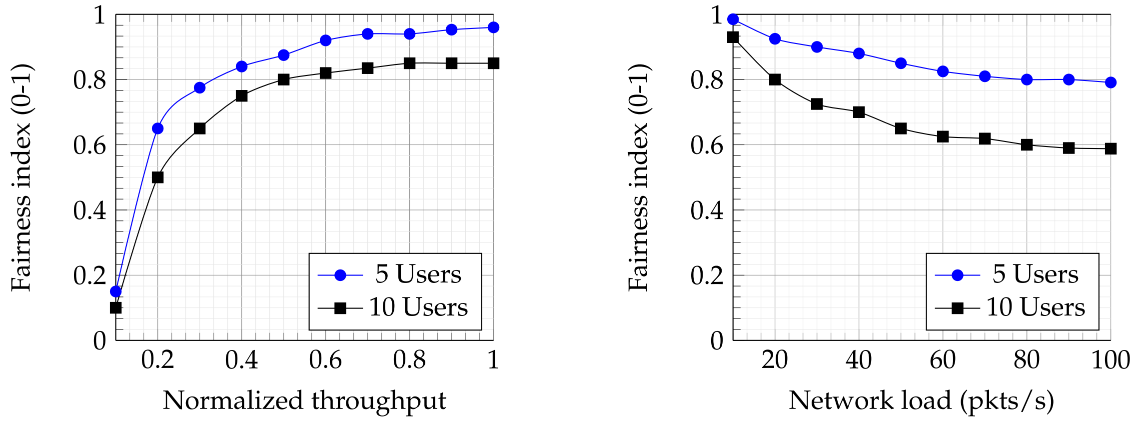


(**a**) Average system utilization vs. network size. (**b**) Average system utilization vs. normalized throughput.

Figure 7. Average system utilization vs. network size and network load.

5.4. Average System Fairness versus Normalized Throughput and Network Load

In Figure 8a,b, we present numerical results considering fairness index as a function of normalized throughput and network load respectively. For simplicity, we elaborate our results by considering two cases; (i) five users and (ii) ten users in the network. Figure 8a shows that the fairness index increases with respect to normalized throughput. This suggests that when the system is fairer, its throughput increases. Moreover, when the network size is large, fairness index decreases as suggested by fairness index when there are 5 VLNs compared to 10 VLNs in Figure 8a,b. Thus, it is difficult to distribute resources fairly when there are more nodes in a network. Moreover, in Figure 8b we consider the fairness index against network load for five and 10 users. In this case, the value of fairness index decreases when network load increases, thus distributing resources fairly to all VLNs at high network load becomes more difficult.



(**a**) Fairness index vs. normalized throughput. (**b**) Fairness index vs. network load.

Figure 8. Fairness index versus normalized throughput and network load.

6. Conclusions

Given the monumental bandwidth available in the visible light spectrum, the VLC has sufficient capacity to address the current Internet capacity demand. In order to realize potential benefits of the VLC, several hurdles must be addressed. These challenges include the design of a novel MAC protocol that considers the physical properties of the OWNs. This study presents the novel non-contention bandwidth assignment protocol named APMAC. The focus of this study is minimization of waiting time and packet collision while increasing system utilization and fairness by exploiting non-contention technique. We consider a simple star topology network with one VLAP and several VLNs. The VLAP is the coordinator while the VLNs act as clients. In order to validate our study, we present numerical results that show the superiority of the protocol we propose against existing protocols such as MT–MAC. Numerical results from simulation show that the APMAC protocol outperforms the MT–MAC in terms of average waiting time. Moreover, APMAC minimizes packet collision, and increases system utilization and fairness significantly.

Author Contributions: D.L.M. conceived, designed and simulated the protocol; K.K. and A.K. contirubted to analysis of the protocol and to discuss the results; D.L.M., and K.K. wrote the paper with the aid of A.K.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Cisco VNI Mobile Forecast Highlights, 2016–2021. Available online: https://www.cisco.com/assets/sol/sp/vni/forecast_highlights_mobile/ (accessed on 15 February 2019).
2. Smart Insights. Available online: https://www.smartinsights.com/internet-marketing-statistics/happens-online-60-seconds/ (accessed on 15 February 2019).
3. Msongaleli, D.L.; Kucuk, K. Reliability and cost-aware network upgrade for the next generation mobile networks. In Proceedings of the 2017 International Conference on Computer Science and Engineering (UBMK), Antalya, Turkey, 5–8 October 2017; pp. 496–501.
4. Musumeci, F.; Bellanzon, C.; Carapellese, N.; Tornatore, M.; Pattavina, A.; Gosselin, S. Optimal BBU Placement for 5G C-RAN Deployment Over WDM Aggregation Networks. *J. Lightw. Technol.* **2016**, *34*, 1963–1970. [CrossRef]
5. Pure LiFi. Available online: https://purelifi.com/(accessed on 15 February 2019).

6. Tanaka, Y.; Haruyama, S.; Nakagawa, M. Wireless optical transmissions with white colored LED for wireless home links. In Proceedings of the 11th IEEE International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC), London, UK, 18–21 September 2000; pp. 1325–1329.
7. Visible Light Communications Consortium (VLCC). Available online: http://www.vlcc.net/(accessed on 15 February 2019).
8. Japan Electronics and Information Technology Industries Association (JEITA). Available online: http://www.jeita.or.jp/ (accessed on 15 February 2019).
9. Infrared Data Association (IrDA). Available online: http://www.irda.org (accessed on 15 February 2019).
10. Home Gigabit Access (OMEGA) Project. Available online: http://www.ict-omega.eu/ (accessed on 15 February 2019).
11. Visible Light Communications Association (VLCA). Available online: http://vlca.net/ (accessed on 15 February 2019).
12. *IEEE Standard for Local and Metropolitan Area Networks—Part 15.7: Short-Range Wireless Optical Communication Using Visible Light*; IEEE: Piscataway, NJ, USA, 2011; pp. 1–309.
13. Haas, H.; Yin, L.; Wang, Y.; Chen, C. What is LiFi? *J. Lightw. Technol.* **2016**, *34*, 1533–1544. [CrossRef]
14. Dimitrov, S.; Haas, H. *Principles of LED Light Communications: Towards Networked Li-Fi*; Cambridge University Press: Cambridge, UK, 2015.
15. Pathak, P.H.; Feng, X.; Hu, P.; Mohapatra, P. Visible Light Communication, Networking, and Sensing: A Survey, Potential and Challenges. *IEEE Commun. Surv. Tutor.* **2015**, *17*, 2047–2077, doi:10.1109/COMST.2015.2476474. [CrossRef]
16. Zhang, Y.; Yu, H.; Zhang, J.; Zhu, Y. Signal-Cooperative Multilayer-Modulated VLC Systems for Automotive Applications. *IEEE Photonics J.* **2016**, *8*, 1–9. [CrossRef]
17. Mohammed D.; Bourzig, D.K.D.; Abdelkim, M.; Mokhtar, K. Digital data transmission via Visible Light Communication (VLC): Application to vehicle to vehicle communication. In Proceedings of the International Conference on Control Engineering and Information Technology (CEIT), Hammamet, Tunisia, 16–18 December 2016; pp. 1–5.
18. Yamazato T.; Kinoshita, M.; Arai, S.; Souke, E.; Yendo, T.; Fujii, T.; Kamakura, K.; Okada, H. Vehicle Motion and Pixel Illumination Modeling for Image Sensor Based Visible Light Communication. *IEEE J. Sel. Areas Commun.* **2015**, *33*, *1793–1805*. [CrossRef]
19. Petrariu, A.I.; Lavric, A.; Coca, E. VLC for vehicular communications: A multiple input multiple output (MIMO) approach. In Proceedings of the International Conference on Development and Application Systems (DAS), Suceava, Romania, 24–26 May 2018; pp. 134–137.
20. Masini, B.M.; Bazzi, A.; Zanella, A. Vehicular Visible Light Networks for Urban Mobile Crowd Sensing. *Sensors* **2018**, *18*, 1177. [CrossRef] [PubMed]
21. Masini, B.M.; Bazzi, A.; Zanella, A. Vehicular visible light networks with full duplex communications. In Proceedings of the IEEE International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS), Naples, Italy, 26–28 June 2017; pp. 98–103.
22. Eroglu, Y.S.; Guvenc, I.; Pala, N.; Yuksel, M. AOA-based localization and tracking in multi-element VLC systems. In Proceedings of the IEEE Annual Wireless and Microwave Technology Conference (WAMICON), Cocoa Beach, FL, USA, 13–15 April 2015.
23. Zachar, G.; Vakulya, G.; Simon, G. Design of a VLC-based beaconing infrastructure for indoor localization applications. In Proceedings of the 2017 IEEE International Instrumentation and Measurement Technology Conference (I2MTC), Turin, Italy, 22–25 May 2017; pp. 1–6.
24. Narmanlioglu, O.; Kizilirmak, R.C.; Miramirkhani, F.; Uysal, M. Cooperative Visible Light Communications with Full-Duplex Relaying. *IEEE Photonics J.* **2017**, *9*, 1–11. [CrossRef]
25. Namonta, P.; Cherntanomwong, P. Real time vital sign transmission using IEEE 802.15.7 VLC PHY-I transceiver. In Proceedings of the International Electrical Engineering Congress (iEECON), Pattaya, Thailand, 8–10 March 2017; pp. 1–4.
26. Vats, A.; Aggarwal, M.; Ahuja, S. Outage analysis of AF relayed hybrid VLC-RF communication system for E-health applications. In Proceedings of the International Conference on Computing, Communication and Automation (ICCCA), Greater Noida, India, 5–6 May 2017; pp. 1401–1405.

27. Msongaleli, D.L.; Kucuk, K. Dynamic Future Knowledge Maximum Transmission Unit (DFK-MTU) for Optic Wireless Networks. In Proceedings of the 2018 26th Signal Processing and Communications Applications Conference (SIU), Izmir, Turkey, 2–5 May 2018.
28. Rao, S.P.V.S.; Chalam, S.V.; Rao, D.S. A Survey on MAC Protocols for Wireless Multimedia Networks. *Int. J. Comput. Sci. Eng. Surv.* **2011**, *2*, 57–74. [CrossRef]
29. Kalfas, G.; Pleros, N. An Agile and Medium-Transparent MAC Protocol for 60 GHz Radio-Over-Fiber Local Access Networks. *J. Lightw. Technol.* **2010**, *28*, 2315–2326. [CrossRef]
30. Maniotis, P.; Kalfas, G.; Alonso, L.; Verikoukis, C.; Pleros, N. Throughput and delay fairness through an agile medium-transparent MAC protocol for 60GHz fiber-wireless LAN networks. In Proceedings of the 2012 IEEE Wireless Communications and Networking Conference (WCNC), Shanghai, China, 1–4 April 2012; pp. 3769–3773.
31. Kalfas, G.; Vardakas, J.; Alonso, L.; Verikoukis, C.; Pleros, N. Non-Saturation Delay Analysis of Medium Transparent MAC Protocol for 60 GHz Fiber-Wireless Towards 5G mmWave Networks. *J. Lightw. Technol.* **2017**, *35*, 3945–3955. [CrossRef]
32. Le, N.; Jang, Y.M. Broadcasting MAC protocol for IEEE 802.15.7 visible light communication. In Proceedings of the 2013 Fifth International Conference on Ubiquitous and Future Networks (ICUFN), Da Nang, Vietnam, 2–5 July 2013; pp. 667–671.
33. Kramer, G.; Mukherjee, B.; Pesavento, G. IPACT a dynamic protocol for an Ethernet PON (EPON). *IEEE Commun. Mag.* **2002**, *40*, 74–80. [CrossRef]
34. Le, N.T.; Choi, S.; Jang, Y.M. Cooperative MAC protocol for LED-ID systems. In Proceedings of the (ICTC), Seoul, Korea, 28–30 September 2011; pp. 144–150.
35. Xu, B.; Zhang M.; Sha, Y. Design of Media Access Control in visible light communication system and a simple way to avoid dual transmit over dual Access Point. In Proceedings of the 2016 15th International Conference on Optical Communications and Networks (ICOCN), Hangzhou, China, 24–27 September 2016; pp. 1–3.
36. Liu, H.; Zhang, L.; Jiang, M. Energy efficient medium access scheme for visible light communication system based on IEEE 802.15.7 with unsaturated traffic. *IET Commun.* **2016**, *10*, 2534–2542. [CrossRef]
37. Wang, Z.; Liu, Y.; Lin, Y.; Huang, S. Full-duplex MAC protocol based on adaptive contention window for visible light communication, *IEEE/OSA J. Opt. Commun. Netw.* **2015**, *7*, 164–171. [CrossRef]
38. Mao, Q.; Yue, P.; Xu, M.; Ji, Y.; Cui, Z. OCTMAC: A VLC based MAC protocol combining optical CDMA with TDMA for VANETs. In Proceedings of the 2017 International Conference on Computer, Information and Telecommunication Systems (CITS), Dalian, China, 21–23 July 2017; pp. 234–238.
39. Kim, B.; Kim, S.W.; Fang, Y.; Wong, T.F. Link-adaptable polling-based MAC protocol for wireless LANs. In Proceedings of the IEEE Global Telecommunications Conference GLOBECOM, Dallas, TX, USA, 29 November–3 December 2004; pp. 2997–3001.
40. Vega, M.T.; Famaey, J.; Koonen, A.M.J.; Liotta, A. Resource allocation in optical beam-steered indoor networks. In Proceedings of the IEEE/IFIP Network Operations and Management Symposium, Istanbul, Turkey, 25–29 April 2016; pp. 418–426.
41. Nishio, T.; Nishioka, R.; Morikura, M.; Yamamoto, K. VRMAC: A novel WLAN medium access control mechanism using LEDs and a camera. In Proceedings of the IEEE Globecom Workshops, Atlanta, GA, USA, 9–13 December 2013; pp. 1121–1126.
42. Wang, Q.; Giustiniano, D. Intra-Frame Bidirectional Transmission in Networks of Visible LEDs. *IEEE/ACM Trans. Netw.* **2016**, *24*, 3607–3619. [CrossRef]
43. Liu, H.; Zhang, L. A Medium Access Scheme with Dynamic Contention Window-based Successive Transmission for Visible Light Communications System. In Proceedings of the 2016 International Conference on Information and Communication Technology Convergence (ICTC), Jeju, Korea, 19–21 October 2016; pp. 499–504.
44. Nobar, S.K.; Mehr, K.A.; Niya, J.M. Comprehensive performance analysis of IEEE 802.15.7 CSMA/CA mechanism for saturated traffic. *IEEE/OSA J. Opt. Commun. Netw.* **2015**, *7*, 62–73. [CrossRef]
45. Mai, V.V.; Thang, T.C.; Pham, A.T. CSMA/CA-based uplink MAC protocol design and analysis for hybrid VLC/Wifi networks. In Proceedings of the IEEE ICC Workshops, Paris, France, 21–25 May 2017; pp. 457–462.
46. Liu, H.; Zhang, L.; Wu, Z. A successive transmission medium access scheme with dynamic contention window for VLC system with saturated traffic. *Photonic Netw. Commun.* **2017**, *34*, 63–74. [CrossRef]

47. Ayyash, M.; Elgala, H.; Khreishah, A.; Jungnickel, V.; Little, T.; Shao, S.; Rahaim, M.; Schulz, D.; Hilt, J.; Freund, R. Coexistence of WiFi and LiFi Toward 5G: Concepts, Opportunities, and Challenges. *IEEE Commun. Mag.* **2016**, 54, 64–71. [CrossRef]
48. Hongxu, L.; Shengda, T.; Liansheng, T.; Wei, Z. Blocking and delay analysis of single-wavelength optical buffer with delay constrained packets. *Photonic Netw. Commun.* **2018**, *35*, 11–19. [CrossRef]
49. Zabini, F.; Bazzi, A.; Masini, B.M.; Verdone, R. Optimal Performance Versus Fairness Tradeoff for Resource Allocation in Wireless Systems. *IEEE Trans. Wirel. Commun.* **2017**, *16*, 2587–2600. [CrossRef]
50. Jain, R.; Durresi, A.; Babic, G. Throughput Fairness Index: An Explanation. *ATM Forum*, February 1999.