A Parallel Transmission MAC Protocol in Hybrid VLC-RF Network

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***Abstract*—**This paper proposed a parallel transmission MAC protocol for an indoor hybrid wireless network consists of visible light communication (VLC) and radio frequency (RF). Combining the CSMA/CA algorithm and the concept of parallel transmission, the protocol can solve the multiple access problems for nodes in the hybrid network. This paper uses a two-dimensional Markov chain model to construct the channel reservation model and also gives the throughput theory analyzing algorithm of parallel channel. According the numerical results, the proposed mechanism improves the throughput and efficiency of the hybrid network.

***Index Terms*—**Parallel transmission MAC, hybrid wireless network, visible light communication, markov chain

I. Introduction

Wireless network data consumption is experiencing drastic increase due to growing demand of mobile services and applications. Forecast shows the traffic of wireless and mobile devices will exceed traffic of wired devices by 2016[1]. However, most of the spectrum is already allocated under license [2]. Wireless networks using radio frequency (RF) are characterized by a shared medium, limited available spectrum and limited ability to scale with increasing demand of high-speed communication.

Visible Light Communication (VLC) emerges as a potential means to overcome the crowded radio spectrum for high-speed communication [3], [4]. Its available spectrum width ranges from 400THz to 750 THz [5], [6]. Due to its broader spectrum width in the optical domain, VLC could be used for high rate transmission that can be higher than 1Gbps [7], and support illumination in indoor environments. The combination of communication and illumination leads to lower cost, because of that the communication devices could be built on the base of illumination devices. In addition, the straight light makes nodes not easy to disturb other ones, so VLC can be applied in the areas where need a better electromagnetic environment, such as in operating room and airplane compartment.

Although compared with RF, VLC has many superiorities, but it has some challenging tasks to solve. Firstly, the medium access control (MAC) in VLC network is immature. To simplify the network, a single frequency visible light is commonly used in VLC networks. In one VLC access point (AP), if many nodes send packets at the same time, their signals may collide and lead to a failing communication. We need a MAC protocol to coordinate nodes' channel allocation. Besides, light is easy to be disturbed by moving objects, and communication also may be influenced when nodes go far away from the LED.

In order to overcome these disadvantages of VLC technology, scholars proposed the concept of hybrid network with VLC and RF and devote their energy to study the MAC protocol of the hybrid network. Olivier [8], [9] described the next generation home network with using radio frequency and visible light technologies. In [10], Rahaimc *et al.* proposed an indoor hybrid system that contains WiFi and VLC in which VLC is only used for broadcasting. The downlink can be divided into three cases：1) Packets are sent only on WiFi channel; 2) All traffic packets are sent on VLC channel; 3) Transfer to VLC channel when WiFi channel has reached its capacity. A simplified handover mechanism was proposed, but the access mechanism has not considered the user mobility. Xu Bao *et al.* Reference [11] proposed a hybrid network model of VLC and orthogonal frequency-division multiplexing access (OFDMA) in which the VLC channel is only used for downlink transmission, and a novel protocol was presented. But OFDMA scheme increases the system complexity, and the communication can only use one channel which is a waste of channel resource.

In this work, in order to support fair chance for nodes in the hybrid network using VLC and WLAN, we proposed a PT-MAC protocol containing CSMA/CA algorithm and the concept of parallel transmission. Our mechanism uses the RF channel as control channel to transmit control packets, while both the RF and VLC channel can be data channel.

The rest of this paper is organized as follows: The proposed PT-MAC protocol based on CSMA/CA algorithm and parallel transmission concept is described in Section 2. Analytical model and performance analysis is addressed in Section 3; Numerical results are given in Section 4; Finally, this paper is summarized in Section 5.

II. System Background

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Indoor rooms are the most important application scenarios of VLC. In these scenario, the users' principal traffic are asymmetric including WEB browsing, file downloading and High-definition video, which have large differences between the uplink and downlink traffic. For example, in 3W browsing, the proportion is generally from 1: 5 to 1:10. And in the FTP files downloading, it can be up to 1:20 to 1: 100. Considering the natural combination between VLC and lighting, visible light is an ideal downlink to construct the indoor network. In the downstream link, using visible light can effectively solve the problem of spectrum scarcity. While the uplink can be used in the following manner:

(1) Using light (Visible Light, Infrared Ray (RF)) as the uplink, in this way you can achieve two-way communication without the help of other transmission medium, with no need to apply additional spectrum resources. Also, the visible and RF will not produce electromagnetic interference. This method can be used in hospitals, aircraft, gas stations and other electromagnetic radiation-sensitive scenarios.

(2) Using radio frequency (RF) as the uplink. In this way you can apply for a new spectrum resource as the uplink channel of VLC network. It also can make use of the existing WLAN as its uplink to achieve collaborative networking with different transmission media. This method is applicable to a widely-area access to the family room, large public spaces and other places needing wireless access. Considering the indoor environment, a hybrid network of RF was constructed using RF and visible light. The basic network architecture is as shown in Fig. 1.

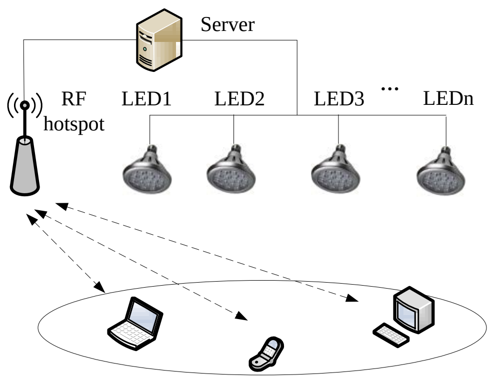


Fig. 1. The Structure of hybrid VLC-RF network

Generally, the coverage area the indoor signal of a single wireless station is very broad, ranging from tens to hundreds of meters depending on the specific environment. The radiation range of a LED array is about from 2 to 5 meters. So in a hybrid VLC-RF network, to make the range basically same, a wireless hotspot configuration is set with n LED arrays. The RF hotspot supports the Wi-Fi protocol, which is a two-way transmission way, so the wireless radio can be used as a parallel transmission solution with the visible downlink communication in downlink.

III. PT-MAC PROTOCOL

A. Design Considerations

The network topology of a feasible asymmetric network of VLC and RF is shown in Fig. 2. Nodes use RF channel to transmit uplink traffic, and use both RF and VLC channel to transmit downlink traffic, thus we construct an indoor high speed network.

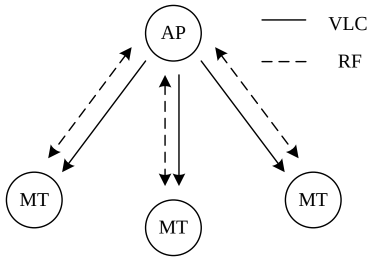


Fig. 2. Hybrid network topology

In traditional MAC protocols, such as the IEEE 802.11DCF protocol [12], [13], if nodes have packets to send, they must contend the sending chance of radio channel via CSMA/CA firstly. Nodes keep a backoff state when there are packets on the channel. These mechanisms make nodes using the channel in order, while the efficiency is low. Because of the lack of radio frequency width, indoor high speed traffic cannot be ensured with the rapid development of mobile communication.

Nowadays, research on MAC protocol of indoor VLC network is little, and multiple access protocol of hybrid network has hardly been proposed. We note that, in hybrid network of RF and VLC, there is an idea allowing nodes to access the network at a high speed: when a node has a requirement of downlink data, it can send its control packets and uplink data on RF channel via CSMA/CA algorithm; AP allocates the VLC channel and the extra RF channel for the requested nodes, and also transmits downlink data to these nodes in order.

B. Protocol Procedure

The idea of parallel transmission MAC protocol is based on CSMA/CA algorithm and the concept of parallel transmission. RF channel acts as the control channel, both RF channel and VLC channel are the data channel.

The process of the protocol contains network access period (NAP), channel contention period (CCP) and data transmission period (DTP).

(1) NAP: Nodes in rooms are firstly added into the WLAN network; If MTs enter into the coverage of VLC hotspots, they can contend the VLC channel only until receiving the ID segment which is sent periodically by AP.

(2) CCP: Nodes send the RTS packet via the RF channel by CSMA/CA algorithm. Then they upload the uplink data after receive the CTS packet.

(3) DTP: AP receives the uplink data and answers them with the downlink data. AP divides all data into two

parts, which are sent by the VLC channel and the RF channel. Nodes receive and answer with BA to ensure the data is received correctly through the RF channel.

In the PT-MAC protocol, the concept of parallel transmission can be reflected in the following two aspects:

(1) The data for a node can be sent by both VLC and RF channel by AP.

(2) When the VLC channel is transmitting data packets, the RF channel can transmit control packets at the same time.

C. *Terminals*

Terminals perform as shown in Fig. 3. Terminals send RTS join into the hybrid network and monitor the statement of the RF channel first. When a terminal has traffic to transmit in the network, it send RTS packet after waiting until the RF channel is idle. If an RTS is sent successfully, the terminal that sent the RTS waits for a CTS packet. If no CTS is received, the terminal transitions to back off time. If multiple terminals send an RTS packet at the same time and a collision occurs, it is not fatal. When RTS collisions occur, the terminals go into back off time.

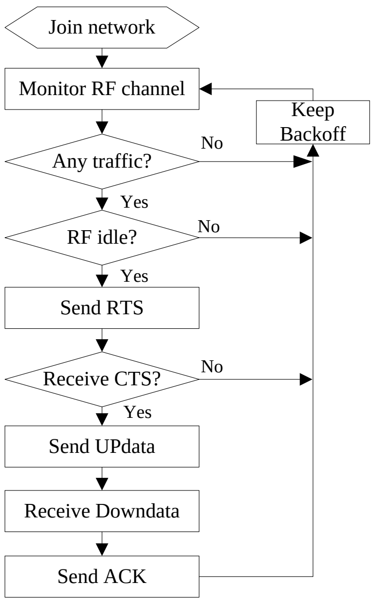


Fig. 3. Terminal diagram

D. *Access Point*

The access point operates as shown in Fig. 4. In the process, the main function of AP is to receive the UPdata and to calculate data allocation ratio on the both channels. according to the request information from the uplink data.

IV. Analytical Model

A. *Assumptions*

In order to analysis the system model, firstly make the following assumptions:

(1) All nodes in the network have the same priority. They can access the network independently with the same distribution probability at any time.

(2) After access the network successfully, the sender and the receiver can communicate with free error.

(3) All nodes work in a saturated state. That is, they always have packets to send.

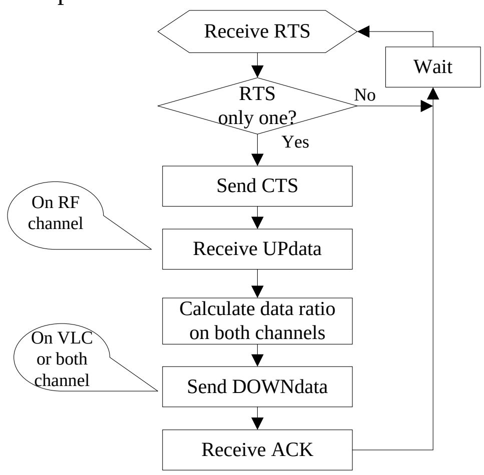


Fig. 4. Access point diagram

B. *Markov Model*

According to the PT-MAC protocol and the assumptions, only the RTS packets sent by different nodes on the RF channel may collide. RTS packets are sent by CSMA/CA algorithm. The process of nodes' backoff can be described by the two-dimensional Markov model. Define some parameters such as: $W_0 = CW_{min}$, $W_i=2^iW_0$. Where $i \in (0,m)$ is called "backoff stage." k is the current value in the backoff counter. p is referred to as conditional collision probability, meaning that this is the probability of a collision seen by a packet being transmitted on the channel. In this Markov chain, the one-step transition probabilities are:

$$\begin{cases} P\{i,k \mid i,k+1\} = 1 & k \in (0,W_i-2] \quad i \in [0,m] \\ P\{i,k \mid i-1,0\} = p/W_i & k \in (0,W_i-1] \quad i \in [1,m] \\ P\{0,k \mid i,0\} = (1-p)/W_0 & k \in (0,W_0-1] \quad i \in [0,m] \\ P\{0,k \mid m,0\} = p/W_0 & k \in (0,W_0-1]. \end{cases} \tag{1}$$

Thus, we can express the probability τ that a station transmits RTS packet in a randomly chosen slot time:

$$\tau = \sum_{i=0}^{m} b_{0,0} = \frac{b_{0,0}}{1-p} = \frac{2(1-2p)}{(1-2p)(W+1)+pW(1-(2p)^m)} \tag{2}$$

C. *Channel Allocation and Performance Analysis*

Let S be the system throughput, defined as the fraction of time the channel is used to successfully transmit payload bits. To compute S, let us analyze what can happen in a randomly chosen slot time. Let P_{tr} be the probability that there is at least one transmission in the considered slot time. If n stations contend the channel, each transmits with probability τ , so we have:

$$P_{tr} = 1-(1-\tau)^{n} \tag{3}$$

The collision probability of p is:

$$p = 1-(1-\tau)^{n-1} \tag{4}$$

Combining Equation (3) and Equation (4), we can solve the probability P_s that a RTS transmission occurring on the RF channel is successful:

$$P_s = \frac{n\tau(1-\tau)^{n-1}}{P_{tr}} \tag{5}$$

In the hybrid network, a node sends RTS packet on the RF channel, if it is successful to access the network, it sends its uplink data immediately. Let *UP* be the length of the uplink data, the time that RTS packet and uplink data is sent successfully and leads a collision are:

$$\begin{cases} T_s^{rts} = DIFS + RTS + \delta + SIFS + CTS + \delta + SIFS \\ \qquad + UP + \delta + SIFS + BA + \delta + SIFS \\ T_c = RTS + \delta + DIFS \end{cases} \tag{6}$$

The average delay of the node to access the network successfully is:

$$\bar{T} = \bar{T}_{backoff} + (1/P_s - 1)T_c + T_s^{rts} \tag{7}$$

where, the average backoff time of the node, $\bar{T}_{backoff}$ is usually 8.5 slots [14]. $1/P_s - 1$ is the average times that a node sends the RTS until the successful time.

In the IEEE802.11n protocol, there are two aggregation frame structures. In A-MSDU frame, if any error occurs as sending the aggregation frame, the entire frame must be retransmitted. But in A-MPDU frame, the node can only retransmit the wrong sub-frames. This paper considers the A-MPDU frame structure in the protocol design and analyzes the network's throughput. The AP once sends N sub-frames for the same length l. According the protocol, all sub-frames are divided into two parts and sent on both VLC and RF channel. The number on the VLC channel is α, while the number on the RF channel is $N-\alpha$. The transmission rate are R_v and R_r, respectively. Therefore, on the two channels, the successful transmission time is:

$$\begin{cases} T_s^{Rdata} = T_{PHY} + (N-\alpha)(l + L_{DI} + L_{MAC})/R_r \\ \qquad + DIFS + \delta + BA \\ T_s^{Vdata} = T_{PHY} + \alpha(l + L_{DI} + L_{MAC})/R_v \\ \qquad + DIFS + SIFS + 2\delta \end{cases} \tag{8}$$

where the number α and $N-\alpha$ are computed by the AP according the traffic parameters, and the result is sent to the node through the CTS packet, as shown in Fig. 5:

(1) If the downlink data transmit totally on the VLC channel, and the total time is less than $\bar{T}$, which is shown in the Fig. 5(a), the AP can send all the downlink data on the VLC channel. We have:

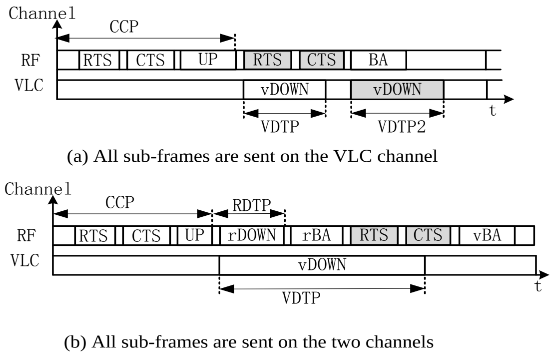
$$0 < \frac{Nl}{R_v} - \bar{T} < \frac{l}{R_r} \tag{9}$$

Hence, meeting the condition $N < \frac{R_v}{R_r} + \frac{R_v}{l}\bar{T}$, we can get $\alpha = N$. The throughput of the hybrid network is the throughout on the VLC channel. We can calculate it through:

$$S_v = \frac{P_{tr}P_s Nl}{(1-P_{tr})\sigma + P_{tr}P_s(T_s^{rts} + T_s^{Vdata}) + P_{tr}(1-P_s)T_c} \tag{10}$$

(2) If the downlink data transmit totally on the VLC channel, but the total time is more than $\bar{T}$, which is shown in the Fig. 5(b), the AP can divide all the downlink data into two parts and send them by both the channels. In this allocation scheme:

$$\frac{Nl}{R_v} - \bar{T} > \frac{l}{R_r} \tag{11}$$



(a) All sub-frames are sent on the VLC channel

(b) All sub-frames are sent on the two channels

Fig. 5. The Parallel Transmission Protocol Situations

In order not to waste time, the total time occupied on the RF channel is less than that on the VLC channel:

$$\bar{T} + \frac{(N-\alpha)l}{R_r} < \frac{\alpha l}{R_v} \tag{12}$$

Hence, if N meets $N < \frac{R_v}{R_r} + \frac{R_v}{l}\bar{T}$, α should be:

$$\frac{R_v}{R_v + R_r}N + \frac{R_v R_r}{R_v + R_r}\frac{\bar{T}}{l} < \alpha < N \tag{13}$$

Because α is the number of packets transmitted on the VLC channel, α can be described by:

$$\alpha = [\frac{R_v}{R_v + R_r}N + \frac{R_v R_r}{R_v + R_r}\frac{\bar{T}}{l}] \tag{14}$$

Definition: $y = [x]$, y is the smallest integer greater than *x*. So the throughput of the two channels and the total network are:

$$\begin{cases} S_r = \dfrac{P_{tr}P_s(N-\alpha)l}{(1-P_{tr})\sigma + P_{tr}P_s(T_s^{rts} + T_s^{Rdata}) + P_{tr}(1-P_s)T_c} \\ S_v = \dfrac{P_{tr}P_s\alpha l}{P_{tr}P_s T_s^{Vdata}} \end{cases} \tag{15}$$

The transmission efficiency η is the channel utilization ratio of the network, which can be represented as:

$$\begin{cases} \eta_v = \dfrac{S_v}{R_v} \\ \eta_r = \dfrac{S_r}{R_r} \\ \eta_{total} = \dfrac{S_v + S_r}{R_v + R_r} \end{cases} \tag{16}$$

V. Numerical Analysis

In this section, the PT-MAC protocol will be validated through two performance metrics: throughput and transmission efficiency. The numerical result also bases on the parameters given in the Table I in specifications of the IEEE 802.11n. Assumed that the channels are ideal, we set the basic rate of the RF channel is 2*Mbits* and the data rates are $R_v = 500Mbits$ and $R_r = 100Mbits$, respectively.

TABLE I. The Parameters Used to Obtain Numerical Results

Parameters	Value
CW	32
RTS	$160bits+PHY_{hdr}$
CTS	$112bits+PHY_{hdr}$
UP	400 *bits*
BA	256 *bits*
PHY_{hdr}	128 *bits*
l_{DI}	32 *bits*
l_{MAC}	288 *bits*
$DIFS$	34 μs
$SIFS$	16 μs
δ	1 μs
σ	15 μs

From the equation (7), (9) and (14), the packet allocation scheme is associated with the variables: the number of the nodes is *n*, the number of the sub-frame is *N*, and the length of the sub-frame is *l*. Setting $n = 5$ and $N = 50$, we reported the throughput of the hybrid network supporting the PT-MAC protocol that depends on the length of the sub-frame, which is shown in Fig. 6. The figure shows that, when the sub-frame length is shorter, according to the PT-MAC protocol, all sub-frames for one node are allocated to transmit on the VLC channel, thus the throughput of the RF channel is null. When *l* increases to a certain value, all the sub-frames are divided into two parts on the two channels. The throughput of the total network has a sudden increase.

At present, the research on the MAC protocol in hybrid VLC-RF network is hardly studied. To prove the good performance of our proposed PT-MAC protocol, we compared the throughput of PT-MAC protocol with a Hybrid MAC protocol and the IEEE 802.11n protocol. The hybrid VLC-RF network is: using the RF channel as the control channel and the VLC channel as the data channel. It can be called "Hybrid MAC protocol". The IEEE802.11n protocol in radio network with $R_r = 100Mbits$, and the hybrid MAC protocol in which the parameters are shown in the Table I by the Hybrid protocol and the PT-MAC protocol. Setting $n = 5$ and $l = 4000bits$, we analysis the throughput of the three protocols and find the PT-MAC protocol is the best in throughput performance, as shown in Fig. 7. Then, setting $n = 5$ and $N = 50$, we reported the throughput of the three protocol that depends on the length of the sub-frame, which is shown in Fig. 8. Observation shows that the PT-MAC protocol has potential to perform better than either protocol, especially when the traffic data is longer.

Then the network transmission efficiency is analyzed. As *l* increasing, the result is shown in Fig. 9. The PT-MAC protocol has a high efficiency, especially when the length of sub-frame is long. But it is a bit lower than the IEEE 802.11n protocol. That is because in the hybrid network, most of the packets are transmitted on the VLC channel and the RF channel has some free band width.

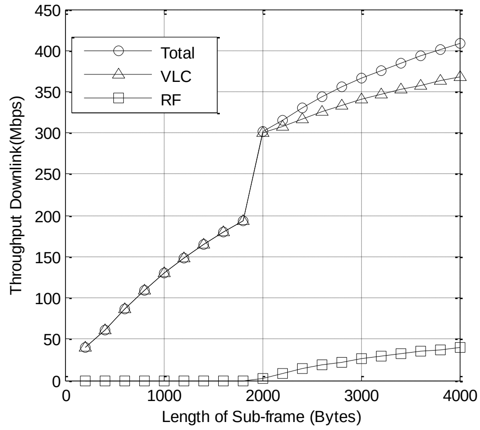


Fig. 6. The channel throughput of the hybrid network

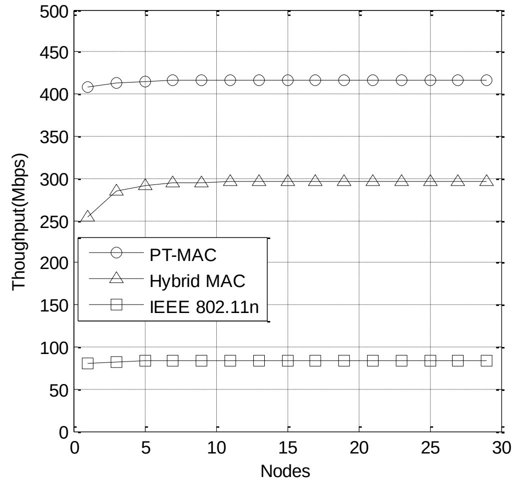


Fig. 7. Throughput comparisons when the number of nodes rises

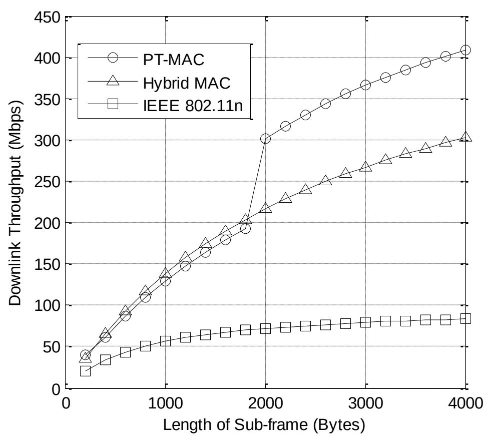


Fig. 8. Throughput comparisons when the length of the Sub-frame Rises

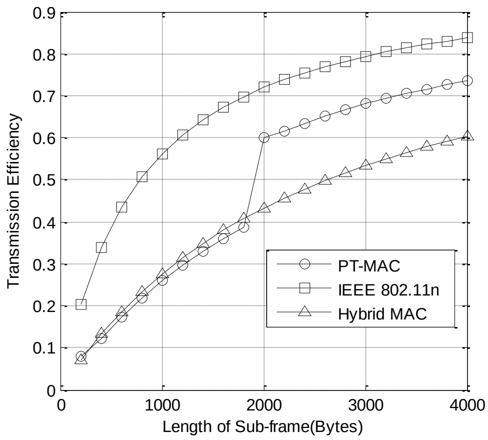


Fig. 9. Transmission Efficiency Comparisons

VI. CONCLUSIONS

In this paper, we have proposed and analyzed a parallel transmission protocol in a hybrid network of VLC and WLAN. Through analytical and numerical analysis, we have shown that our protocol provides higher throughput compared with the traditional IEEE802.11n protocol in radio network and a simple hybrid protocol based on the IEEE802.11n. The dynamic allocation scheme of sub-frames that are sent to a node by the AP makes the hybrid network gains a perfect transmission efficiency.

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