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Distributed Interference-aware Medium Access Control for IEEE 802.15.7 Visible Light Communications

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In this paper, we present a distributed interference-aware medium access control (DI-MAC) for IEEE 802.15.7 visible light communications (VLCs), which improves the spatial efficiency of VLC devices deployed in specific service areas. The DI-MAC adaptively adjusts the backoff exponent (BE) of each VLC device by considering the number of adjacent VLC devices causing the interference, which are called VLC interferers. Therefore, it reduces interference between the VLC devices and unnecessary waiting time for channel access. To this end, the DI-MAC conducts VLC interferer discovery by using the IDs of VLC interferers obtained via hello messages from adjacent VLC devices and then performing a BE adaptation to determine the BE of each VLC device based on the number of VLC interferers. An experimental simulation was conducted to evaluate the performance of the DI-MAC, and the results show that the DI-MAC obtains a higher aggregate throughput performance than the existing IEEE 802.15.7 VLC.

1. Introduction

Recently, visible light communication (VLC), a component of optical wireless communication (OWC) technologies, has emerged as a promising wireless personal area network (WPAN) technology.(1) Since VLC uses unlicensed frequencies ranging from 400 to 800 THz, it is considered to be a complementary technology for radio frequency (RF)-based communications. In VLC, the transmitter [e.g., light-emitting diodes (LEDs)] emits optical signals to transmit the data, and the receiver [e.g., photodiodes (PDs)] detects and converts the optical signal to receive and decode the data.(2) The communication coverage of VLC devices is determined by a narrow fan-shaped field of view (FOV) that points in a particular direction.(3) This directivity of the VLC can provide high spatial efficiency by enabling more VLC devices to transmit data simultaneously in the specific service area as compared with omnidirectional

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communications.

The physical (PHY) and medium access control (MAC) layers of IEEE 802.15.7 VLC are specified as a global standard by the IEEE 802.15 Task Group (TG 7). In particular, this standard provides a superframe structure that can have active and inactive portions to support the data transmission and sleep mode, respectively.[4] The active portion consists of a beacon, contention access period (CAP), and contention free period (CFP). The beacon defines the length of the superframe and is used to transmit the beacon frame without random access. The CAP follows the beacon and is used to transmit data using the carrier sense multiple access with collision avoidance (CSMA/CA).[5–7] The CFP is an optional period that extends the active portion of the superframe and is used to transmit data through guaranteed time slots (GTSs).

According to the standard, VLC uses a random-access algorithm that allows VLC devices to have a different waiting time for channel access (i.e., a backoff period). Specifically, the VLC device randomly selects the number of backoff slots ranging from $[0,2^{BE}-1]$, and increases the backoff exponent (BE) by one when the number of transmission attempts increases. The BE is an important parameter for deciding the length of the backoff period (i.e., the number of backoff slots). However, the initial BE of a VLC device is fixed as the value macMinBE. Thus, frequent collisions may occur with an increase in the number of adjacent VLC devices that cause interference, known as VLC interferers. On the other hand, if the number of VLC interferers is small, the VLC device performance may be degraded owing to the unnecessary waiting time for channel access. This problem may degrade the spatial efficiency of VLC devices deployed in specific service areas owing to the long channel access delay. To improve the spatial efficiency, the centralized approaches for adaptive MAC can be adopted for VLC.[8,9] In these approaches, the single central controller collects information on devices in the vicinity to determine and assign the contention window (CW). However, the centralized approach has many disadvantages, such as cost-inefficient maintenance and low robustness in the case of network failure. In particular, the central controller should be able to handle the heavy traffic load resulting from transmission from a number of VLC devices.

In this paper, we propose a distributed interference-aware MAC (DI-MAC) for IEEE 802.15.7 VLC. The DI-MAC aims to improve the spatial efficiency of VLC devices deployed in specified service areas. In DI-MAC, each VLC device adaptively adjusts its BE by taking into account the number of VLC interferers. This significantly reduces the channel access delay of the VLC devices in both high- and low-device-density cases. In other words, the DI-MAC reduces the number of collisions between VLC devices when a number of VLC interferers are deployed in a specific service area and decreases the unnecessary waiting time for channel access when a small number of VLC interferers are deployed in a specific service area. To do this, the DI-MAC conducts VLC interferer discovery and BE adaptation. For VLC interferer discovery, each VLC device collects the IDs of VLC interferers by receiving hello messages from adjacent VLC devices and maintains these IDs as a VLC interferer list (VIL). In the BE adaptation, each VLC device determines its own BE in accordance with the number of VLC interferers listed in the VIL. To evaluate the performance of the DI-MAC, an experimental simulation is conducted using Visual Studio 2017. The results show that the DI-MAC achieves better performance than the existing IEEE 802.15.7 VLC in terms of aggregate throughput.

The rest of this paper is organized as follows. In Sect. 2, the design of the DI-MAC is described in detail. In Sect. 3, we present the simulation results to verify the effectiveness of the DI-MAC. Finally, this paper is concluded in Sect. 4.

2. Design of DI-MAC

The purpose of the DI-MAC is to improve the spatial efficiency of VLC devices deployed in specific service areas. To achieve this, the operation of the DI-MAC consists of VLC interferer discovery and BE adaptation. VLC interferer discovery starts at the beginning of the beacon interval by collecting the IDs of VLC interferers. After that, BE adaptation is carried out to determine the BE by considering the amount of VLC interferers. The design of DI-MAC is described in detail as follows.

Algorithm 1. VLC interferer discovery

```
initialize IDL(i) ={ID(i)}, i ∈  {0,n} SC = 0 // Initialization for i-th VLC device
start discovery timer
WHILE discovery timer expires DO
    start hello timer
    broadcast hello message with VIL(i)
    WHILE hello timer expires DO
        wait hello message from other devices
        IF receive hello message with IDL(k), k ∈  {0,n}
            VIL(i) ← VIL(i) ⋃ VIL(k) // Update VIL(i)
        ENDIF
    ENDWHILE
    check n(VIL(i)) // Check the change in the number of VLC interferers in VIL(i)
    IF n(VIL(i)) changes
        SC ← 0 // Initialize SC
        go back to start hello timer
    ELSE
        SC ← SC + 1 // Increase SC by one
        IF SC > ST // Compare the SC with SC threshold
            break // Terminate VLC interferer discovery
        ELSE
            go back to start hello timer
        ENDIF
    ENDIF
ENDWHILE
start BE adaptation
```

Algorithm 1 shows the VLC interferer discovery process in which the VLC device searches for all of the VLC interferers and maintains their IDs in the VIL. During VLC interferer discovery, the VLC device first initializes the VIL and the stable count (SC), which is essential for the discovery of VLC interferers. The VIL is a set of the VLC interferers and maintains their IDs as the elements of the set. The VIL is initialized to the IDs of VLC devices performing VLC interferer discovery. The SC indicates the number of times the hello timer has expired consecutively without changing the number of VLC interferers contained in the VIL. The SC is initialized to zero. In the algorithm, i and k are the indices of the i-th and k-th VLC devices, and $\text{VIL}_{(i)}$ and $\text{ID}_{(i)}$ are the VIL and ID of i-th VLC device, respectively. The VLC device repeatedly broadcasts a hello message with the VIL and updates its VIL whenever it receives a hello message from another device. For this, the DI-MAC uses two timers called the discovery timer and hello timer. The discovery timer defines the maximum duration of VLC interferer discovery, and each VLC device can update the VIL until the discovery timer expires. The hello timer defines the time interval for hello message transmission, and each VLC device broadcasts a new hello message when the hello timer expires. There are two conditions for terminating VLC interferer discovery. The first is when the discovery timer expires, and the second is when the SC exceeds the predefined SC threshold (ST), which exists to check whether the VIL is stable. In other words, the VLC device concludes that there are no more VLC interferers (i.e., the VIL is stable) when the SC exceeds the ST. If the second condition is met, the VLC interferer discovery is terminated even before the expiration of the discovery timer. To this end, the VLC checks the change in the number of VLC interferers included in the VIL just after the expiration of the hello timer. If it changes, the SC is set to zero. Otherwise, the SC is increased by one and compared with the ST. After terminating the VLC interferer discovery, the VLC device starts the BE adaptation.

Algorithm 2. BE adaptation

initialize $\text{BE}_{(i)} = 0$
check $n(\text{VIL}_{(i)})$ // Check the number of VLC interferers in $\text{VIL}_{(i)}$
IF $n(\text{VIL}_{(i)}) < 2^{\text{macMaxBE}}$
    $\text{BE}_{(i)} \leftarrow \log_2 n(\text{VIL}_{(i)})$
ELSE
    $\text{BE}_{(i)} \leftarrow \text{macMaxBE}$
ENDIF
select the number of backoff slots ranging from $[0, 2^{\text{BE}(i)} - 1]$
start data transmissions

Algorithm 2 shows the operation of the BE adaptation that adaptively determines the BE by considering the number of VLC interferers included in the VIL. To obtain the proper BE, we take the following considerations into account. First, the maximum number of backoff slots should be set to be greater than the number of VLC interferers in order to reduce the number of collisions between VLC devices. Second, it should be set as small as possible since the increased number of backoff slots leads to a long channel access delay. Consequently, the BE and the maximum number of backoff slots for the i-th VLC device can be determined through Eqs. (1) and (2).

$$\text{BE}_{(i)} = \log_2 n\left(\text{VIL}_{(i)}\right) \tag{1}$$

$$\text{Maximum number of backoff slots} = 2^{\text{BE}_{(i)}} - 1 \tag{2}$$

In the BE adaptation, we assume that the maximum BE is fixed as the value macMaxBE. Therefore, $\text{BE}_{(i)}$ is set to macMaxBE when the number of VLC interferers is greater than or equal to 2^{macMaxBE}.

3. Performance Evaluation

To evaluate the performance of the DI-MAC, the experimental simulation is conducted in an IEEE 802.15.7 VLC MAC/PHY environment. In this paper, spatial efficiency refers to the aggregate throughput for VLC devices deployed in specific service areas. Therefore, we measure the aggregate throughput of DI-MAC and compare it with that of the existing IEEE 802.15.7 VLC. Figure 1 shows an example of a network topology. As shown, all VLC devices are randomly deployed in the 30 × 30 m^2 service area, and their FOV direction is randomly set. The degree of FOV is 60° and the transmission range is 5 m. Each VLC device transmits packets of 1024 bytes in this direction. The discovery timer is set to 360 optical clocks, and the hello timer is set to 30 optical clocks. Note that the time of the single optical clock is 0.008 μs, because it is assumed to use the on-off keying (OOK) modulation scheme of PHY II mode in the simulation. Therefore, the hello message may be transmitted 12 times during the VLC interferer discovery. The ST is set to three, meaning that the VLC interferer discovery is terminated when the hello timer expires three times without changing the number of VLC interferers included in the VIL. The detailed simulation parameters are listed in Table 1.

Figure 2 shows the aggregate throughput for varying numbers of VLC devices. Overall, the aggregate throughput of DI-MAC outperforms the existing IEEE 802.15.7 VLC. This is because

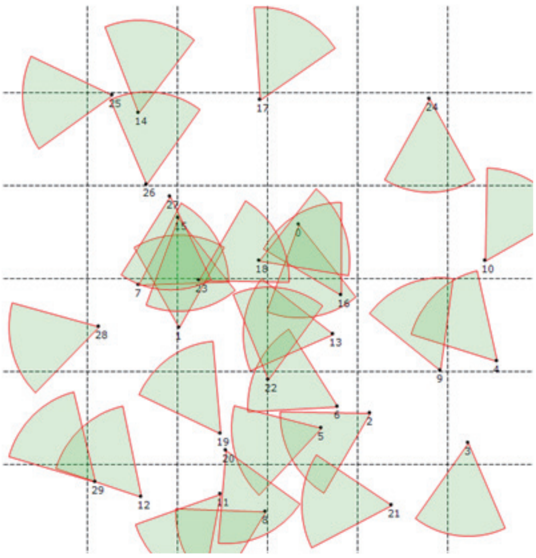

Fig. 1. (Color online) Example of network topology.

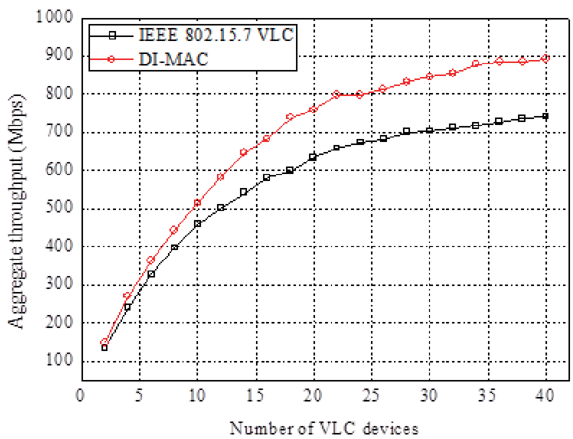

Fig. 2. (Color online) Aggregate throughput.

Table 1
Simulation parameters.

Parameter	Value	Parameter	Value
MAC/PHY model	IEEE 802.15.7	PHY header	200 bits
Data rate	76.8 Mbps	MAC header	72 bits
Size of service area	30 × 30 m^2	Packet size	1024 bytes
Number of devices	2–40	Discovery timer	360 optical clocks
Transmission range	5 m	Hello timer	30 optical clocks
Degree of FOV	60°	ST	3

the DI-MAC reduces the channel access delay by adjusting the BE by considering the number of VLC interferers on each VLC device. Specifically, compared with the existing scheme, the DI-MAC has a shorter waiting time for channel access than the existing scheme when the number of VLC devices is small, and it has fewer collisions when there are many VLC devices. On average, the DI-MAC obtains a 13.5% higher aggregate throughput than the IEEE 802.15.7 VLC.

4. Conclusions

In this paper, we presented a DI-MAC that is proposed to improve the spatial efficiency of the IEEE 802.15.7 VLC. The operation of the DI-MAC consists of VLC interferer discovery and BE adaptation. Through these operations, the DI-MAC adaptively determines the BE of the VLC devices by considering the number of VLC interferers. To verify the effectiveness of the DI-MAC, experimental simulation is conducted in an IEEE 802.15.7 MAC/PHY environment. The results show that the DI-MAC obtains a 13.5% higher aggregate throughput than the existing IEEE 802.15.7 VLC.

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References

1 IEEE 802.15.7 Standard for Local and Metropolitan Area Networks. (2011) Part 15.7: Short-range Wireless Optical Communication Using Visible Light.
2 H. Elgala, R. Mesleh, and H. Haas: IEEE Commun. Mag. **49** (2011) 56.
3 S. Wu, H. Wang, and C. H. Youn: IEEE Network **28** (2014) 41.
4 C. Ley-Bosch, I. Alonso-González, D. Sánchez-Rodríguez, and C. Ramírez-Casañas: Sensors **16** (2016) 216.
5 J. Hwang, T. H. Do, and M. Yoo: Wireless Pers. Commun. **78** (2014) 2025.
6 K. A. Mehr, S. K. Nobar, and J. M. Niya: IEEE/OSA J. Opt. Commun. Networking **7** (2015) 875.
7 P. Shams, M. Erol-Kantarci, and M. Uysal: Trans. Emerg. Telecommun. Technol. **27** (2016) 662.
8 H. Park, T. Shon, S. Park, and E.-J. Kim: Int. J. Adv. Rob. Syst. **9** (2012) 17.
9 E.-J. Kim and J.-J. Jung: Adaptive CAP Assignment Approach for IEEE 802.15.3c: in Computer Science and its Applications, Eds. J. Park, I. Stojmenovic, H. Jeong, and G. Yi (Springer, Heidelberg, 2015) p. 149.