Energy adaptive MAC protocol for IEEE 802.15.7 with energy harvesting

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The medium access control (MAC) protocol for indoor visible light communication (VLC) with energy harvesting is explored in this paper. The unfairness of throughput exists among devices due to the significant difference of their energy harvesting rates which changes with distance, acceptance angle and the obstruction probability. We propose an energy harvesting model, a new obstruction probability model and an energy adaptive contention algorithm to overcome the unfairness problem. This device can adjust its contention window according to the energy harvesting rate. As a result, the device with lower energy harvesting rate can get shorter contention window to improve its transmission opportunity. Simulation results show that our MAC protocol can achieve a higher degree of fairness.
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In recent years, the visible light communication (VLC) as a favorable complementary technology for radio frequency (RF) communication has caught much attention[1,2], and energy harvesting is an alternative method to solve the energy problem that converts the ambient energy from environment into electricity to power device, which is actively studied in the field of RF[3,4]. There are a variety of energy sources for the energy harvesting, including solar energy, wind energy, thermal energy, RF energy and so on. In this paper, we make use of visible light for energy harvesting.

To the best of our knowledge, almost all existing researches about energy harvesting are in the field of RF. However, the VLC with energy harvesting (EH-VLC) has not been actively studied. Recently, there are only two papers about EH-VLC[5,6]. Haas Harald[5] predicted that the VLC would be a new way of energy harvesting for wireless communications. The visible light was first used for energy harvesting[6], and the hardware design criteria of the wake-up system, such as solar panel and capacitor type choices, is researched. However, there is no research on the medium access control (MAC) protocol for EH-VLC system.

MAC protocols with energy harvesting in RF have been studied[7-10]. Masashi Kunikawa et al[7] proposed a fair MAC protocol based on polling scheme for energy harvesting wireless sensor network (WSN). Lin et al[8] proposed a DeepSleep protocol for IEEE 802.11 supporting energy harvesting devices efficiently and evaluated its performance in terms of energy efficiency and fairness. However, they didn't take into account the difference between the devices and didn't make it up when they evaluated the fairness. Jaeho Kim et al[9,10] presented an adaptive MAC protocol for WSNs based on RF energy transfer to achieve a degree of fairness. In RF systems with energy harvesting, they only need to consider the effect of distance on the energy harvesting rate. However, in the VLC system, the field of view (*FOV*) and the obstruction probability are the impact factors that cannot be ignored due to the directionality characteristic of visible light. In this paper, we propose a MAC protocol with adaptive contention window algorithm for the VLC system according to energy harvesting rate, which takes into account distances, acceptance angles and the obstruction probabilities of different devices.

We consider a star topology EH-VLC system which consists of one access point (AP) and several devices. An AP comprises four coordinators, and the coordinator is mains-powered and merges the functionalities of illumination and data communication. The device is considered as a passive node, which has no original energy and harvests energy from the AP.

In this paper, we assume that the LED layout of white LED arrays for the indoor VLC system is as shown in the inset of Fig.1. All the coordinators are on the ceiling, and the devices are deployed on the wall of the room. Each coordinator consists of 3 600 LEDs, and the transmitted power of each LED is P_t, which is the power level transmitted from the coordinator to devices. $P_{r,i}$ is the power level received by the device i, which is given by

$$P_{r,i} = \eta \cdot H(0) \cdot P_t , \quad (1)$$

where η denotes the optical-to-electrical (O/E) conversion efficiency. $H(0)$ is the channel direct current gain in

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line-of-sight (LOS), and is given as[11]

$$H(0)=\begin{cases}\dfrac{(m+1)A}{2\pi D^2}\cos^2(\phi)T_s(\psi)g(\psi)\cos(\psi), & 0\le\psi\le\psi_c\\ 0 \quad , & \psi>\psi_c\end{cases}, \quad (2)$$

where A is the detector physical area of the photodetector (PD), D is the distance between a transmitter and a receiver, ψ is the angle of incidence, ϕ is the angle of irradiance, $T_s(\psi)$ is the gain of an optical filter, m is the order of Lambertian emission, which is given by the semi-angle at half illumination of an LED $\Phi_{1/2}$ as $m=-(\ln 2)/\ln[\cos(\Phi_{1/2})]$, and the gain of an optical concentrator $g(\psi)$ can be given as

$$g(\psi)=\begin{cases}a^2/\sin^2\psi_c, & 0\le\psi\le\psi_c\\ 0 \quad , & \psi>\psi_c\end{cases}, \quad (3)$$

where a denotes the refractive index.

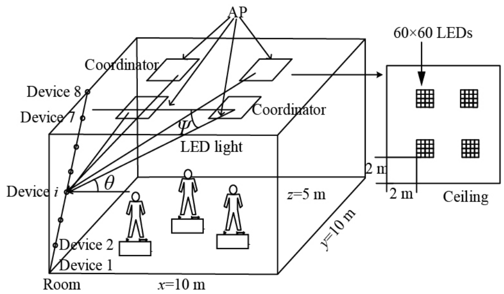

Fig.1 Schematic diagram of indoor EH-VLC system

The distribution of the energy collected by a device is shown in Fig.2, and the parameters used in this simulation are listed in Tab.1. From Fig.2, we can see that the received energy levels of different devices on the wall are different due to different distances and acceptance angles, which can lead to different harvested energy level of devices to send data packets and result in unfairness problem. The closer devices can harvest more energy from the LED light compared with the farther ones, and thus the former ones can transmit more data packets during a period, so the distance can influence the fairness.

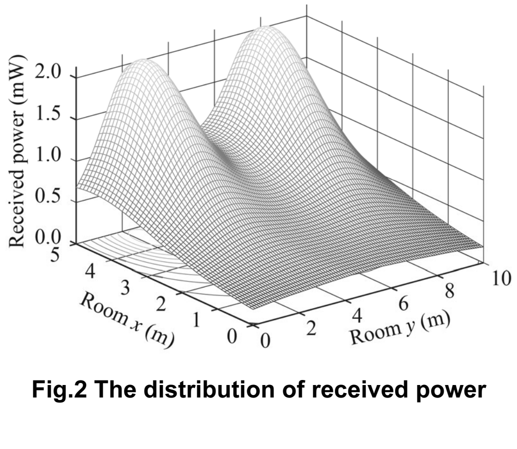

Fig.2 The distribution of received power

When the acceptance angle is larger than the device's *FOV*, the device cannot receive the light, which indicates that the acceptance angle is an important factor as well. Our energy harvesting model takes into account the two important factors, and the deployment of the devices is shown in Fig.1, aiming at the maximum difference of devices to reveal the unfairness problem.

Tab.1 Parameters for EH model of VLC

Parameter	Value
Transmitted optical power P_t (mW)	40
Semi-angle at half power $\Phi_{1/2}$ (°)	70
Center luminous intensity (cd)	0.73
Number of groups	4
Size of LED light (m×m)	0.59×0.59
FOV at a receiver (°)	70
Detector physical area of a PD A (cm^2)	1.0
Gain of an optical filter $T_s(\psi)$	1.0
Refractive index of lens at a PD	1.5
O/E conversion efficiency η (A/W)	0.7
Room size (m×m×m)	10×10×5
Height of LEDs (m)	4.5

The directionality characteristic of visible light introduces the difficulty to accurately predict the harvested energy in mobile scenarios because the mobility will influence the communication link. As humans or other objects move, the device on the wall may be obstructed with a certain probability. We propose a model of obstruction probability for indoor VLC to describe the effect of the object's movement as shown in Fig.3, where P_o is the obstruction probability and $\alpha\ge\beta\ge\gamma$ considering the height of the moving objects. Therefore, the obstruction probability of the device on the lower part of the wall is larger than that near the upper part of the wall, which will further increase the difference among devices. Our algorithm considers the influence of the obstruction probability.

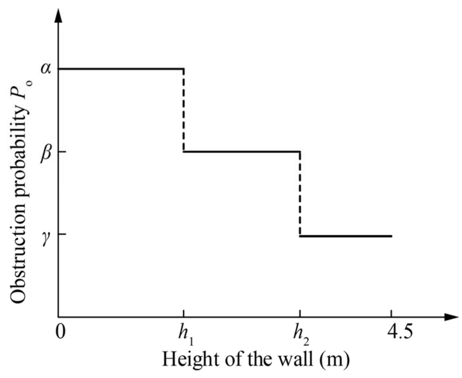

Fig.3 Model of obstruction probability for VLC

We assume that the device has the VLC transceiver and the energy harvester. The VLC transceiver is responsible for data sending and receiving. The VLC energy harvester can harvest light energy from the light and transform it to electric current to charge the energy storage like battery. Devices can carry out energy harvesting and data transmission at the same time as they are separate modules.

In the EH-VLC system, we assume that the four coordinators in an AP send the same information, and all coordinators receive the same data packet sending by the device. The AP receives the data from the devices all the time, and the devices convert to active state and energy harvesting state back and forth. In the active state, a device contends for accessing the channel and transmits data. In the energy harvesting state, a device completely turns off its transceiver to reduce the power consumption and harvests energy from LED light. We assume that a device can transmit at most one packet in an active state, and the packet has a fixed length. Let E_{th} be the minimum amount of energy to make the device to an active state, which is called the energy threshold and expressed as

$$E_{\mathrm{th}} = E_{\mathrm{CCA}} + E_{\mathrm{T}} , \tag{4}$$

where E_{CCA} and E_{T} refer to the amount of energy consumption for clear channel assessment (CCA) and packet transmission, respectively.

We propose an energy adaptive contention algorithm (EA-CSMA/CA) for the EH-VLC based on IEEE 802.15.7[12]. The main distinguishing feature of our EA-CSMA/CA is that the backoff time of each device is adjusted according to its current energy harvesting rate.

Each device i shall maintain three variables of NB_i, BE_i and K_i for each transmission attempt. NB_i is the number of CCA performed in the EA-CSMA/CA algorithm so far. BE_i is the backoff exponent, K_i is the window adjustment factor, and it is used to mitigate the unfairness among devices due to the significant difference between their energy harvesting rates, which can be calculated by Algorithm 1.

In Algorithm 1, each device updates its harvested energy E_i^c of current stage at the end of every energy harvesting period that has M backoffs. Thus, E_i^{c} is given by

$$E_i^{\mathrm{c}} \leftarrow E_i^{\mathrm{c}} + E_i, \tag{5}$$

where E_i denotes the harvested energy for device i in this energy harvesting period.

At the end of each stage that has N superframes, every device updates its EH_i^1 and EH_i^{c} by

$$EH_i^1 = EH_i^{\mathrm{c}} , \tag{6}$$

$$EH_i^{\mathrm{c}} \leftarrow EH_i^{\mathrm{c}} + E_i^{\mathrm{c}} , \tag{7}$$

where EH_i^1 denotes the harvested energy of last stage, and EH_i^{c} denotes the harvested energy of current stage.

Meanwhile, every device obtains its energy harvesting rate λ_i by

$$\lambda_i = \left(EH_i^{\mathrm{c}} - EH_i^1\right) / T , \tag{8}$$

where T is the period of a stage. Then the device sends the energy harvesting rate to the AP.

The AP calculates the average energy harvesting rate $\bar{\lambda}$ and broadcasts it to all the devices. Finally, every device obtains its individual current window adjustment factor K_i using $f(\lambda_i / \bar{\lambda})$, which is given as

$$f(x) = \begin{cases} c, & x \le c \\ x, & c < x \le 1 \\ x^3, & x > 1 \end{cases} . \tag{9}$$

Algorithm 1 K_i updating algorithm

Initialization device i:
$EH_i^{\mathrm{c}} \leftarrow 0$; $EH_i^1 \leftarrow 0$;
$E_i^{\mathrm{c}} \leftarrow 0$; $K_i \leftarrow 1$;
for i =1 **to** *MaxSuperframes*
  for j=1 **to** *MaxBackoffs*
    every M backoffs, $E_i^{\mathrm{c}} \leftarrow E_i^{\mathrm{c}} + E_i$;
  end for
  if i % N==0
    $EH_i^1 \leftarrow EH_i^{\mathrm{c}}$;
    $EH_i^{\mathrm{c}} \leftarrow EH_i^{\mathrm{c}} + E_i^{\mathrm{c}}$;
    $\lambda_i \leftarrow (EH_i^{\mathrm{c}} - EH_i^1)/T$, send λ_i to the AP;
    AP: $\bar{\lambda} \leftarrow \left(\sum_{i=1}^{n} \lambda_i\right) / n$, broadcasts it;
    $K_i \leftarrow f(\lambda_i / \bar{\lambda})$ using Eq.(9). $E_i^{\mathrm{c}} \leftarrow 0$;
  end if
end for

The EA-CSMA/CA algorithm is illustrated in Algorithm 2. Firstly, NB_i and BE_i are initialized to 0 and *minBE*, respectively. If the energy of device i is not enough or it does not have data packets in the data buffer, the device will stay in energy harvesting state to harvest energy. Otherwise, the device gets the window adjustment factor K_i by Algorithm 1 and calculates the maximum contention window CW_i as

$$CW_i = INTU(K_i \cdot 2^{BE_i}) , \tag{10}$$

where *INTU* denotes the nearest integers towards infinity.

Device i selects a random backoff time as

$$T_i = \begin{cases} Uniform[INTU(CW_i / 2, CW_i - 1)], & K_i > 1 \\ Uniform[0, CW_i - 1] \quad , & K_i \le 1 \end{cases} . \tag{11}$$

The devices are divided into two parts with noninterference for each other, which can decrease the collision and increase the network throughput. After the backoff timer expires, the device i performs CCA in order to check whether the channel is busy or not. If the channel is idle, the device can transmit the data packet. If the channel is busy, the device increases both NB_i and BE_i by one, and the BE_i cannot be more than *macMaxBE*. If the value of NB_i is not more than *maxCSMABackoffs*, the device should return to another random backoff procedure, as detailed in Algorithm 2. If the value of NB_i is larger than *macMaxRABackoffs*, the device discards the data packet and terminates the random access algorithm.

Algorithm 2 EA-CSMA/CA for EH-VLC

1. $BE_i \leftarrow macMinBE$;
2. $NB_i \leftarrow 0$;
3. **if** *EnergyEnough*(i)==1 and *HasPacket*(i)==1
4. the device i selects a random backoff time:
5. **if** K_i>1
6. $T_i \leftarrow Uniform[INTU(CW_i/2), CW_i-1]$;
7. **else**
8. $T_i \leftarrow Uniform[0, CW_i-1]$;
9. **end if**
10. the device i performs CCA
11. **if** the channel is idle
12. transmit the data packet;
13. **else**
14. $NB_i \leftarrow NB_i + 1$;
15. $BE_i \leftarrow min(BE_i, maxMaxBE)$;
16. **if** NB_i <= *macMaxRABackoffs*
17. repeat step 3;
18. **else**
19. discard the data packet,
20. go to energy harvesting state;
21. **end if**
22. **end if**
23. **else**
24. stay in energy harvesting state to harvest energy;
25. **end if**

We evaluate the performance of our MAC protocol of EH-VLC in the MATLAB R2015b. Tab.2 summarizes the key parameters that we use for each device.

Tab.2 Parameters for the MAC protocol of EH-VLC

Parameter	Value
macMinBE	3
macMaxBE	5
macCSMARABackoffs	4
Power consumption of CCA E_{CCA} (dBm)	−17
Power consumption of transmitting E_T (dBm)	−15
Data rate (Mbit/s)	1.25
A backoff slot (μs)	32
Energy threshold E_{th} (mW)	0.051 6
Packet length (Bytes)	300
Number of superframes in a stage	5
The obstruction probability α	0.15
The obstruction probability β	0.1
The obstruction probability γ	0.05
The height of h_1 (m)	2
The height of h_2 (m)	4

In the simulation, we deploy one AP consisting of 4 coordinators and 8 devices. The devices are located at the places with almost the maximum difference of the energy harvesting rate as shown in Fig.1. We compare the throughput of devices in the context of varying transmitted power of LED lighting from the four coordinators. We also compare the performances of the MAC protocol of the EH-VLC with and without energy adaptive contention algorithm. We call the former as EH-MAC/EAC and the latter as EH-MAC.

The throughput of EH-MAC is shown in Fig.4(a). We see that the closer the device is to the AP, the higher throughput the device can achieve. As the contention window of each device is constrained by the same MAC parameters, the amount of its harvested energy determines the number of transmitted packets and its throughput.

Fig.4(b) shows the throughput of EH-MAC/EAC. In EH-MAC/EAC, the window adjustment factor is used to mitigate the unfairness. Devices with different energy harvesting rates adjust to various contention window size. From Fig.4(a) and (b), we can observe that with the help of our energy adaptive contention algorithm, the throughput of the devices with lower energy harvesting rate is increased, while the throughput of the devices with higher energy harvesting rate is decreased. The throughput of the device which has the farthest distance to AP and the largest obstruction probability is increased by 50% approximately. And the throughput of the device with the nearest distance to AP and the smallest obstruction probability is decreased by 18% approximately.

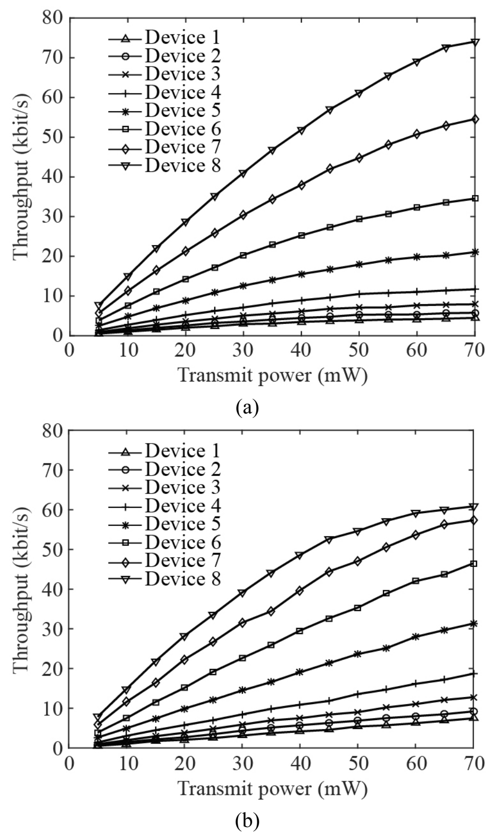

Fig.4 Throughput of devices with (a) EH-MAC and (b) EH-MAC/EAC

In order to better describe the degree of fairness among devices, Jain's fairness index is introduced into this paper which is given by

$$FI = \frac{(\sum_{i=1}^{n} S_i)^2}{n\sum_{i=1}^{n} S_i^2} , \tag{12}$$

where n is the number of devices, and S_i is the throughput of device i. The fairness index FI has a value between 0 and 1, and in general, as the degree of fairness increases, the value of FI also increases. From Fig.5, we can observe that the EH-MAC/EAC achieves a higher degree of fairness than the EH-MAC, which implies that we can achieve a higher degree of fairness among devices with our energy adaptive contention algorithm.

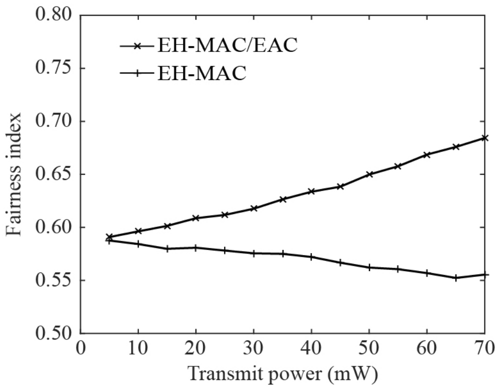

Fig.5 Comparison of fairness indices in EH-MAC and EH-MAC/EAC

In this paper, we propose an MAC protocol with energy adaptive contention algorithm that can be used in VLC networks based on energy harvesting. The device adjusts its contention window size according to its energy harvesting rate for achieving the fairness among devices with the proposed MAC protocol. Simulation results demonstrate that the EH-MAC with the energy adaptive contention algorithm can significantly improve the fairness compared with the EH-MAC without it.

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