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Investigation on random access in a VLC system with multipacket reception in the presence of hidden devices and obstructions

CAI Wen-jing (蔡文静), CHI Xue-fen (迟学芬)*, and ZHAO Lin-lin (赵琳琳)
College of Communication Engineering, Jilin University, Changchun 130012, China

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Due to the directionality of light, the hidden device problem and the obstruction cannot be ignored for carrier sense multiple access with collision avoidance (CSMA/CA)-based uplink visible light communication (VLC). In this paper, we introduce multipacket reception (MPR) to handle the hidden device problem in VLC system. We model the traffic of the device with on/off Markov source. With the unsaturated traffic, we formulate a two dimensional (2D) Markov chain to model the CSMA/CA-based slotted random access procedure to evaluate the effects of hidden devices and obstructions on the performance of MPR-aided VLC system, which are mapped into the transition probabilities of the Markov chain. Then, we analyze the throughput and the reception power efficiency (*RE*) of MPR-aided VLC system with the obstructed optical channel. Numerical results show that the effect is negative when hidden devices or obstructions appear solely. But when they appear simultaneously, they will interact with each other to mitigate the negative effects.

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IEEE 802.15.7 standard suggests four types of random access mechanisms for visible light communication (VLC), where the slotted carrier sense multiple access with collision avoidance (CSMA/CA) is the most popular one. Nobar et al have investigated the performance of the slotted CSMA/CA in IEEE 802.15.7 in the saturated[1] and unsaturated systems[2], respectively. In Ref.[3], Nan et al have conceived the model of CSMA based on hard-core point process (HCPP) in indoor VLC system and optimized the carrier sensing threshold. There are some authors introducing multipacket reception (MPR) to improve the performance of VLC system. Yu et al[4] have proposed a Markov-based physical layer and medium access control layer (PHY-MAC) integrated model to investigate the throughput of the CSMA/CA of the MPR-aided VLC system. Zhao et al[5] have proposed a novel quality of service (QoS) driven non-carrier sensing random access (NCSRA) mechanism for the MPR-aided VLC system.

However, the above works do not consider the effects of obstructions and the hidden devices on the performance of VLC system. The obstructions and hidden devices are serious and non-ignorable in VLC system, due to the directionality of light, which weaken the functionality of carrier sensing largely. The hidden device problem has been evaluated in wireless local area networks (WLANs) adequately[6-10]. However, there is only one work published by C Ley-Bosch et al[11] which investigated the effects of hidden devices on the performance of VLC system with CSMA/CA via simulating on OMNET++. In their system, the coordinator sent a signaling pattern to all devices when it is receiving a data frame so as to solve the hidden device problem.

In this paper, we utilize a Markov-based analytical model to expound the hidden device problem and introduce MPR capability to cope with hidden devices in the unsaturated MPR-aided VLC system with the obstructed optical channel. Based on the Markov chain model, we also analyze the effect of obstructions on the system performance. The transition probabilities of the Markov chain model depend on the arrival of the traffic, the parameters of CSMA/CA-based random access procedure, the obstruction probabilities of optical links, as well as the number of hidden devices and covered devices. Then, we derive the throughout and reception power efficiency (*RE*) which is defined as the ratio of the bits received successfully in a unit slot to the total power used for receiving bits in this paper to investigate the integrated effects of hidden devices, obstructions and MPR capability.

We consider a star topology unsaturated MPR-aided VLC system with the obstructed optical channel. The system consists of a coordinator with M receivers and n devices, as shown in Fig.1.

* E-mail: chixf@jlu.edu.cn

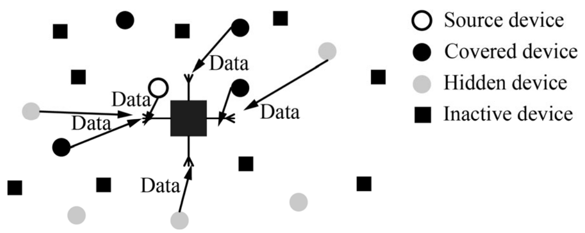

Fig.1 System model

We only consider the line-of-sight (LOS). The random variable B denotes the obstructed event of the LOS in this system. The model of the obstructions is[12]:

$$f(B)=\begin{cases}1-P_{\mathrm{b}}, & B=0\\ P_{\mathrm{b}}, & B=1\end{cases}. \tag{1}$$

The time is divided into basic slots whose length is σ, namely, a backoff period. At the beginning of basic slots, Markov sources randomly generate packets which are pushed into the queue of the MAC layer of devices and wait to be transmitted. The on/off Markov source model which describes the traffic of device is shown in Fig.2, where μ and ε are the transition probabilities. The source is paused when the queue is not empty, until no backlogged packets in the queue. We assume the packet is constant-length which occupies L basic slots.

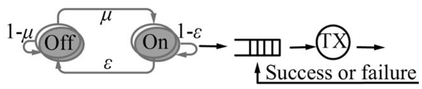

Fig.2 Traffic model of the unsaturated device

According to Fig.2 and balance equations, we obtain

$$\begin{cases}P_0=\dfrac{\mu}{\mu+\varepsilon}\\ P_1=\dfrac{\varepsilon}{\varepsilon+\mu}\end{cases}, \tag{2}$$

where P_0 and P_1 are the steady-state probabilities of state 'on' and state 'off', respectively.

Based on the slotted CSMA/CA of IEEE 802.15.7, our CSMA/CA-based random access procedure is as follows: if a device has packets to transmit, it initializes *NB* as 0 and *BE* as *macMinBE*, where *NB* denotes the backoff stage and *BE* denotes the backoff exponent. Then the device selects a random number in the range of (0, $2^{BE}-1$) as the value of backoff counter and delays. When the backoff counter is reduced to zero, clear channel assessment (CCA) is performed to check the channel, whether it is busy or idle. If the channel is idle, the device transmits the packet which waits in the queue and backlogs the packet into the queue to retransmit it in the context of obstructions or collisions, unless it receives acknowledgement (ACK). If no obstructions and the number of unobstructed packets transmitted simultaneously is not bigger than M, the coordinator responds to ACKs. Otherwise, the transmissions fail and the packets are retransmitted. The device attempts to retransmit packets and increases *NB* and *BE* by one, then it repeats the procedure of backoff, performing CCA and transmitting packets. If the channel is busy, the device also increases *NB* and *BE* by one. Then the device checks whether *NB* is bigger than *macMaxCSMABackoffs*. If so, it discards the packet and proceeds to the next one; else, checks whether *BE* is bigger than *macMaxBE*. If so, *BE* keeps the maximum to discard the packet; else, *BE* is increased next time.

If a device is transmitting, we regard it as the source device whose transmission is affected by its covered devices which select the same values of backoff counters and its hidden devices. We define the possible affected period as the interactive period. For covered devices, the interactive period is one basic slot. For hidden devices, the interactive period is L basic slots.

In general, we assume N devices contend for accessing to the coordinator, $N\le n$. For a source device, there are N_{h} hidden devices and N_{c} covered devices, $N_{\mathrm{h}}+N_{\mathrm{c}}+1=N$. In order to evaluate the effects of hidden devices and obstructions, we model the CSMA/CA-based slotted random access procedure of a single device as a 2D Markov chain ($S(t)$, $C(t)$), which is shown in Fig.3.

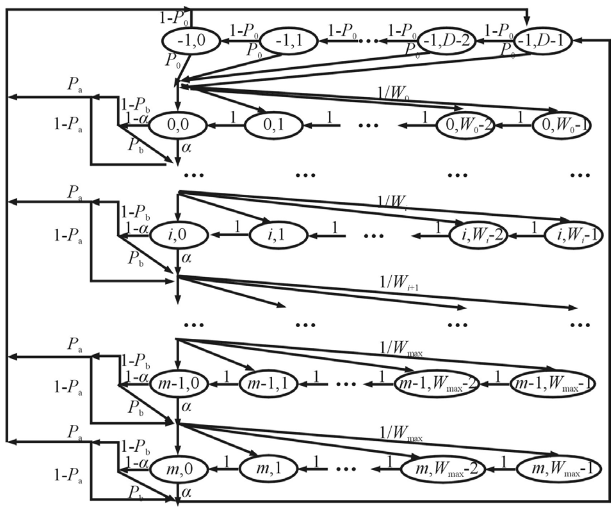

Fig.3 2D Markov chain model of random access procedure

Define $S(t)$ and $C(t)$ as the stochastic processes standing in the backoff stage and the backoff counters experienced by a device at time t. Suppose m denotes the maximum of backoff stage, and W_i denotes the size of backoff windows, then we can have

$$W_i=\begin{cases}2^iW_0, & i\le z\\ 2^zW_0=W_{\max}, & i>z\end{cases}, \tag{3}$$

where $W_0=2^{macMinBE}$, and $z=macMaxBE-macMinBE$. According to the CSMA/CA-based slotted random access procedure, we can obtain transition probabilities of Markov chain as below:

$$\begin{cases} P(-1,d-1\mid -1,d)=1-P_0, & d\in[0,D-1] \\ P(0,j\mid -1,d)=P_0/W_0, & d\in[0,D-1], j\in[0,W_0-1] \\ P(i+1,j\mid i,0)=(\alpha+(1-\alpha)(P_b+(1-P_b)(1-P_a)))/W_{i+1}, & i\in[0,m-1], j\in[0,W_{i+1}-1] \\ P(i,j-1\mid i,j)=1, & i\in[0,m], j\in[0,W_i-1] \\ P(-1,D-1\mid i,0)=(1-\alpha)(1-P_b)P_a, & i\in[0,m-1] \\ P(-1,D-1\mid m,0)=1, & \end{cases} . \tag{4}$$

Define $b_{i,j}=\lim_{t\to\infty}\{S(t)=i,C(t)=j\}$ as the probability distribution of steady state of Markov chain, for $i\in(-1,m)$ and $j\in(0,W_i-1)\cup(0,D-1)$. According to Markov chain regularities and Eq.(4), we obtain

$$\begin{cases} b_{i,j}=(W_i-j/W_i)b_{i,0} \\ b_{i,0}=\{\alpha+(1-\alpha)[P_b+(1-P_b)(1-P_a)]\}^i\, b_{0,0} \end{cases}, \tag{5}$$

$$b_{\text{idle}}=\sum_{d=0}^{D-1}b_{-1,d}+(1-\alpha)(1-P_b)P_a\sum_{i=0}^{m-1}b_{i,0}+b_{m,0}, \tag{6}$$

where b_{idle} is the idle probability, α is the probability that channel is busy at CCA, and P_a is the probability that a transmitting device can transmit its packets successfully. P_a states that if a device expects to transmit successfully, no obstructions and at most $M-1$ unobstructed devices which consist of its covered devices with the same values of backoff counters and its hidden devices are transmitting together with it. According to the normalization condition, we obtain

$$1=b_{\text{idle}}+\sum_{i=0}^{m}\sum_{j=0}^{W_i-1}b_{i,j}. \tag{7}$$

According to Eqs.(5), (6) and (7), $b_{0,0}$ can be obtained as

$$b_{0,0}=\begin{cases} \dfrac{2(1-y)(1-2y)P_0}{(1-2y)(1-y^{m+1})P_0+(1-y)(1-2y^{m+1})W_0P_0+\beta+2P_0y^m(1-y)(1-2y)+2(1-y)(1-2y)}, & m\le z \\ \dfrac{2(1-y)(1-2y)(2-y)P_0W_0}{VP_0+2(1-y)(1-2y)(2-y)W_0+(2-y)\beta W_0+2(1-2y)(2-y)(1-y)P_0y^mW_0}, & m>z \end{cases}, \tag{8}$$

where $y=\alpha+(1-\alpha)(P_b+(1-P_b)(1-P_a))$, $\beta=2(1-2y)\times(1-y^m)(1-\alpha)(1-P_b)P_aP_0$ and $V=(1-y^{z+1})(1-2y)\times(2-y)\times W_0+(1-y)(1-(2y)^{z+1})W_0^{\,2}(2-y)+2(1-2y)W_{\max}(y^{z+1}-y^{m+1})\times W_0(2-y)-2(1-2y)(1-y)W_{\max}(W_{\max}-1)((y/2)^{z+1}-(y/2)^{m+1})$.

Based on our 2D Markov chain model, we obtain the parameters α and P_a as:

$$\alpha=(1-(1-\tau_1(1-P_b))^{N_c-1})\times((L+2)P_a+(1-P_a)L), \tag{9}$$

$$P_a=\sum_{l=0}^{M-1}\sum_{k=0}^{M-1}I_{\{k+l\le M-1\}}C_{N_c}^{k}(\tau_1(1-P_b))^k(1-\tau_1(1-P_b))^{N_c-k}C_{N_h}^{l}(\tau_2(1-P_b))^l(1-\tau_2(1-P_b))^{N_h-l}, \tag{10}$$

where

$$\tau_1=(1-\alpha)\sum_{i=0}^{m}b_{i,0}=(1-\alpha)(1-y^{m+1}/1-y)b_{0,0}, \tag{11}$$

$$\tau_2=(1-\alpha)\sum_{i=0}^{m}\sum_{j=0}^{L}b_{i,j}=$$

$$\begin{cases} (1-\alpha)[(L+1)\dfrac{1-y^{m+1}}{1-y}-\dfrac{L(L+1)}{2W_0}\dfrac{1-(y/2)^{m+1}}{1-(y/2)}]b_{0,0}, & L<W_0 \\ 1, & L>W_{\max} \\ (1-\alpha)[\dfrac{1-y^X}{2(1-y)}+\dfrac{(1-2y^X)W_0}{2(1-2y)}+\dfrac{(L+1)(y^X-y^{m+1})}{1-y}-\dfrac{L(L+1)((y/2)^X-(y/2)^{m+1})}{2W_0(1-(y/2))}]b_{0,0}, & W_{X-1}\le L\le W_X \end{cases}, \tag{12}$$

$$S=\frac{(\sum_{l=0}^{M}\sum_{k=0}^{M}I_{\{k+l+1\le M\}}(k+l+1)P_s)\mathrm{E}(O)}{(P_iT_i+P_sT_s+P_cT_c)}=\frac{(\sum_{l=0}^{M}\sum_{k=0}^{M}I_{\{k+l+1\le M\}}(k+l+1)C_N^1(\tau_1(1-P_b))C_{N_c}^k(\tau_1(1-P_b))^k(1-\tau_1(1-P_b))^{N_c-k}}{(P_iT_i+P_sT_s+P_cT_c)}\times$$

$$\frac{C_{N_h}^{l}(\tau_2(1-P_b))^l(1-\tau_2(1-P_b))^{N_h-l})\mathrm{E}[O]}{(P_iT_i+P_sT_s+P_cT_c)}. \tag{13}$$

Then, the probability that a covered device transmits in a randomly chosen slot is given as Eq.(11).

The probability that a hidden device transmits during the interactive period is given as Eq.(12), where X is the minimum backoff stage at which the size of backoff widows is greater than L. Thus the system throughout is obtained as Eq.(13), where E[O] is the average payload length in bits. $T_{\rm i}$ is the duration of an idle slot spent when the channel is idle, $T_{\rm s}$ is the duration of successful transmission, and $T_{\rm c}$ is the duration of collisions. Their expressions are given as:

$$\begin{cases} T_{\rm i} = \sigma \\ T_{\rm s} = (N_{\rm c}/N)T_{\rm s1} + (N_{\rm h}/N)T_{\rm s2} \\ T_{\rm c} = (N_{\rm c}/N)T_{\rm c1} + (N_{\rm h}/N)T_{\rm c2} \end{cases}, \tag{14}$$

where $T_{\rm s1}=t_{\rm cca}+t_L+t_{\rm ack}$ is the time of successful transmission when no hidden devices transmit. If there is a hidden device transmitting during the interactive period, we assume that the hidden device begins to transmit at the beginning of each basic slot of the interactive period with the probability of $1/L$. Thus we can obtain the average time spent on the transmission of the hidden device after the source device finishes its transmission as below:

$$T_{\rm ex} = 1/L + 2/L + ... + (L-1)/L , \tag{15}$$

so the time of successful transmission when hidden devices are transmitting is $T_{\rm s2}=t_{\rm cca}+t_L+t_{\rm ack}+T_{\rm ex}$. The time of failing transmission if no hidden devices transmit is $T_{\rm c1}=t_{\rm cca}+t_L+t_{\rm ex}$. $T_{\rm c2}=t_{\rm cca}+t_L+t_{\rm ex}+T_{\rm ex}$ is the time of failing transmission if there are hidden devices transmitting. $t_{\rm cca}$ is the duration of CCA procedure, t_L is the time spent on transmitting packets, the time for waiting and transmitting ACK is $t_{\rm ack}$, and $t_{\rm ex}$ is the extra time after failing transmission. We assume that if there are hidden devices transmitting successfully, they can transmit the whole packet in $T_{\rm s2}$.

$P_{\rm i}$ is the probability that the channel is in the duration of an idle slot, i.e., there are no devices occupying the channel. $P_{\rm s}$ is the probability that the channel is in the duration of a successful transmission, i.e., the unobstructed packets transmitted simultaneously are no more than M. $P_{\rm c}$ is the probability that the channel is in the duration of a failing transmission. They are given as below:

$$P_{\rm s} = \sum_{l=0}^{M}\sum_{k=0}^{M} I_{\{k+l+1\le M\}} C_N^1(\tau_1(1-P_{\rm b}))C_{N_{\rm c}}^k(\tau_1(1-P_{\rm b}))^k \times$$

$$(1-\tau_1(1-P_{\rm b}))^{N_{\rm c}-k} C_{N_{\rm h}}^l(\tau_2(1-P_{\rm b}))^l(1-\tau_2(1-P_{\rm b}))^{N_{\rm c}-l} , \tag{16}$$

$$P_{\rm i} = (1-\tau_1(1-P_{\rm b}))^N , \tag{17}$$

$$P_{\rm c} = 1 - P_{\rm i} - P_{\rm s} . \tag{18}$$

Then we obtain the RE which measures the power efficiency of the coordinator with MPR capability as:

$$RE = \frac{S}{M \times P_{\rm r}} , \tag{19}$$

where $P_{\rm r}$ is the power used by a receiver to receive packets.

We present some numerical results to validate our analysis. We depict the throughput when the number of devices changes and the RE when the MPR capability changes. For convenience, we assume the average probability that hidden devices exist is $P_{\rm h}=N_{\rm h}/N$ and the probability is the same for each device. The parameters of the unsaturated MPR-aided VLC system are shown in Tab.1.

Tab.1 The Parameters of unsaturated MPR-aided VLC system

Parameter	Value
MaxCSMA Backoffs	4
MinBE	3
MaxBE	5
optical clock	200 kHz
backoff slot	50 [optical clock]
BeaconOrder	5
SuperframeOrder	5

In Fig.4, we compare the exact value and the analysis result of throughput with P_0=0.5, $P_{\rm h}$=0.6 and $P_{\rm b}$=0.1. The four curves indicate that MPR capability changes from 1 to 4. It is obvious that there is a gap between the exact value and the analysis result, because the superframe is limited for the exact value and the duration of transmission for the analysis result is the average value.

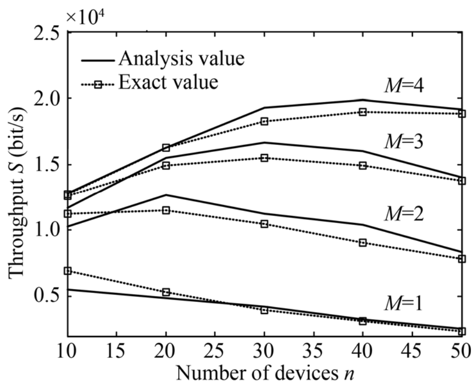

Fig.4 Throughput versus the number of devices with P_0=0.5, $P_{\rm h}$=0.6 and $P_{\rm b}$=0.1

In Fig.4, we can see that the throughput increases firstly and then decreases as n increases when $M \ge 1$, because the used MPR capability is not large enough to cope with the collisions when the number of devices is large. In Fig.5, we show the RE with P_0=0.5, $P_{\rm h}$=0.6 and $P_{\rm b}$=0.1 when the number of devices ranges from 20 to 50. We can see that RE is larger with small MPR capability when n is smaller.

Fig.6 and Fig.7 depict the throughput and RE with P_0=0.5, $P_{\rm h}$=0.6 when the obstruction probability ranges from 0.1 to 0.9. In Fig.6, we can see that when n is small, the throughput is bigger with smaller P_b. But it is reverse for large n. It shows that the obstructions can mitigate some collisions caused by hidden devices. But if P_b is too big, it will decrease the number of packets transmitted to the coordinator. Thus the throughput also decreases. In Fig.7, we can see that *RE* is bigger with large P_b when the MPR capability is small. But it is reverse for large MPR capability. Because the received packets do not fully utilize the power.

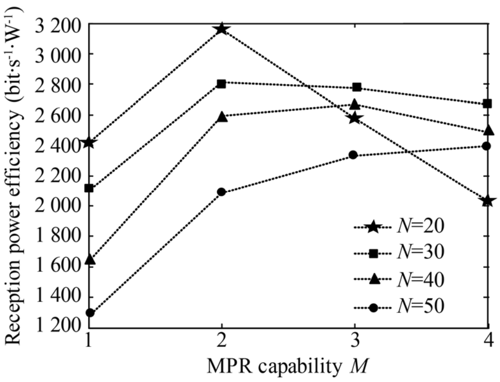

Fig.5 *RE* versus the MPR capability with P_0=0.5, P_h=0.6 and P_b=0.1

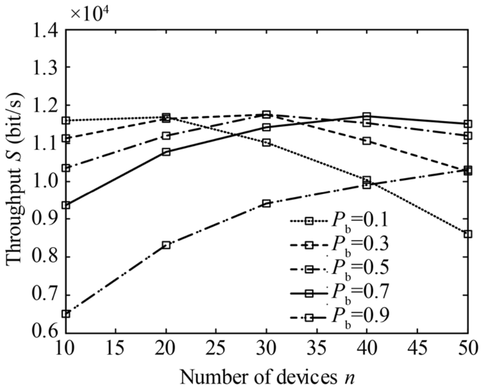

Fig.6 Throughput versus the number of devices with P_0=0.5 and P_h=0.6 for different obstruction probabilities

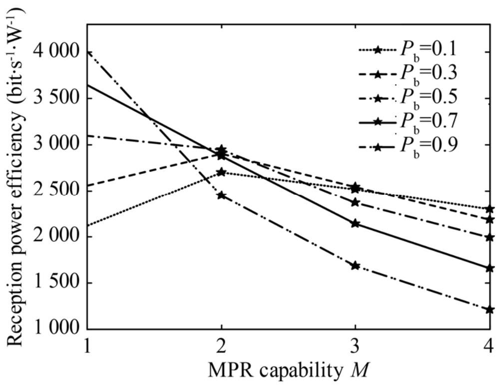

Fig.7 *RE* versus the MPR capability with P_0=0.5 and P_h=0.6 for different obstruction probabilities

Fig.8 and Fig.9 depict the throughput and *RE* with the probability that hidden devices exist ranging from 0 to 0.8. In Fig.8, we can see that when n is small, the throughput with P_h=0.4 is bigger than that with P_h=0.2 and P_h=0. It shows that the hidden devices can mitigate the effect of obstructions. But if P_h is too big, the negative effect of hidden devices is larger than its positive effect. In Fig.9, we can see that *RE* with P_h=0.4 is bigger than that with P_h=0.2 and P_h=0 when the MPR capability is larger. Because the effect of hidden devices can be mitigated by obstructions and the MPR capability. Thus the power used for receiving packets is fully utilized. But when P_h=0.8, the collisions caused by hidden devices are too many, so the coordinator which receives less packets wastes the power.

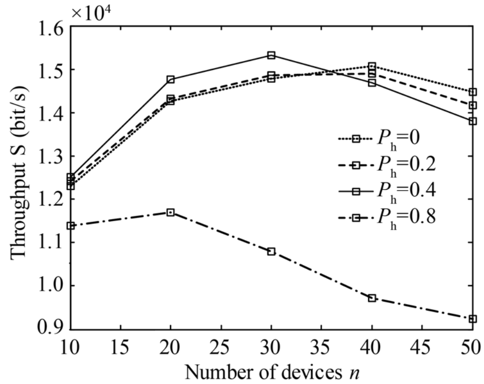

Fig.8 Throughput versus the number of devices for different probabilities that hidden devices exist

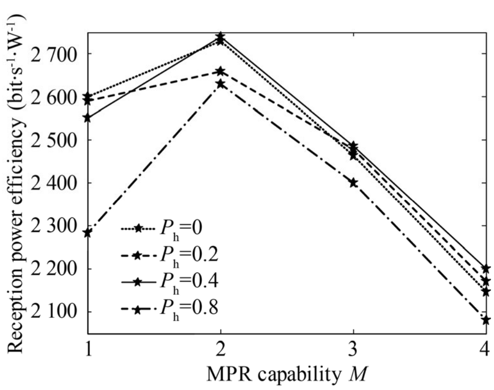

Fig.9 *RE* versus the MPR capability for different probabilities that hidden devices exist

In this paper, we investigate the CSMA/CA-based slotted random access to evaluate effects of hidden devices and obstructions on the performance of MPR-aided VLC system. A 2D Markov chain is used to model the random access procedure which is based on the CSMA/CA of IEEE 802.15.7 to analyze the throughput and *RE*. Numerical results indicate that the coordinator with MPR capability can cope with the hidden device problem and improve the throughput effectively. When we consider the integrated effects of hidden devices and obstructions, they will interact with each other to mitigate the negative effects of them. Future work can focus on the optimization of MPR-aided VLC system through adjusting the MPR capability.

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