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Design and Analysis of an Energy-Efficient CSMA Protocol for Asynchronous Multiple-Packet Reception

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ABSTRACT This paper proposes a carrier-sensing multiple access protocol for asynchronous multiple-packet reception (MPR), which enables wireless receivers to correctly decode partially time-overlapping packets. Unlike previous studies, which require back-off nodes to constantly monitor the channel, our design requires only that each node sense the number of transmitting nodes after the completion of the back-off period for determining whether to begin transmission in the next time slot. In addition, we develop an analytical model to evaluate relevant parameters and performance metrics of the proposed protocol. Our model relies on the channel-sensing probability of a node in a randomly chosen slot, rather than channel-accessing probability adopted in previous models for asynchronous MPR. The results are validated through numerical study under a variety of network conditions. We also show that the proposed protocol is quite robust to imperfect estimation in channel sensing, and is more energy-efficient than other similar threshold-based protocols.

INDEX TERMS CSMA, asynchronous multiple-packet reception, throughput, energy-efficient.

I. INTRODUCTION

Due to the distributed nature and inherent flexibility, carrier sensing multiple access (CSMA) algorithms have been widely adopted in various random-access protocols for wireless networks, such as the IEEE 802.11 standard and the IEEE 802.15.4 standard. Traditional studies on CSMA assumed a single packet reception (SPR) channel, and hence aimed to discourage concurrent transmissions from multiple contending nodes. However, the SPR model has become somewhat restrictive, due to the advance of multiple-packet reception (MPR) techniques at the physical layer (PHY) with the enhanced capability of decoding time-overlapping packets. One such example is MU-MIMO supported in IEEE 802.11ac. To fully utilize MPR channels, it is expected that the design requirement of CSMA under MPR could be quite different from that under SPR.

A variety of MPR models have been proposed in the literature to characterize different MPR channels for different channel conditions and different MPR techniques. Along the lines of [1]–[10], this paper focuses on the γ-MPR channel, with γ meaning that the receiver is capable of decoding up to γ simultaneous packet transmissions. We refer to γ as the MPR capability.

Recently, there has been much research published on CSMA schemes with γ-MPR [1]. Most of them [2]–[5] are subject to the packet-synchronous requirement, that is, time-overlapping transmissions occur only when they simultaneously begin. However, this restriction may significantly limit the channel utilization gains benefiting from γ-MPR, especially when concurrent packet transmissions occupy different time durations. Motivated by such observation, it is strongly required to develop CSMA protocols for asynchronous

γ-MPR that allow nodes awaiting transmission to access to the channel before the completion of ongoing transmissions.

Under the above mentioned objective, Babich and Cossimo in [6] proposed a CSMA scheme for asynchronous γ-MPR, in which each node decreases its backoff counter only when the number of transmitting nodes is equal to or smaller than a predefined positive threshold value. An adaptive backoff scheme for this threshold based protocol can be found in [7]. Furthermore, [8] extended the work in [6] by incorporating acknowledgments (ACKs). The central ideal therein is to require nodes to freeze their backoff counters when the number of concurrent transmissions either exceeded $\gamma - 1$ or decreased. Similarly, in [9], the nodes are allowed to contend for the channel access if the number of recorded concurrent transmissions is smaller than γ, and otherwise defer their access attempts until the channel becomes idle again. In addition, Jung *et al.* [10] presented an asynchronous protocol which required each node to decide the transmission probability by the vacant space information of γ-MPR obtained through an additional feedback link.

It should be pointed out that, to our best knowledge, all previously known CSMA schemes for asynchronous γ-MPR require each node to constantly monitor the channel status during the backoff stage, which is obviously undesirable in distributed wireless networks imposed with strict energy constraints.

To address the energy overhead issue, this paper proposes a non-persistent CSMA protocol for asynchronous MPR without requiring the backoff nodes to monitor the channel. The advantages of the proposed protocol are as follows. It requires each node to sense the number of transmitting nodes only after the completion of the backoff period for determining whether to begin transmission or not in the next time slot. In this manner, the energy consumption can be dramatically reduced, with respect to those in [6]–[10]. Moreover, such a power saving mode does not incur any performance degradation on other performance metrics, which will be shown in the section for numerical study. To our best knowledge, this paper is the first work to introduce non-persistent CSMA to asynchronous γ-MPR.

In addition, we develop an analytical model to evaluate relevant parameters and performance metrics of our design. The form of analysis is similar in some aspects to that used in [6], as they have a common feature in the usage of backoff and access threshold. However, a new model is needed owing to the differences between these two algorithms. In particular, unlike [6] that utilized the channel accessing probability of a node in a randomly chosen slot, our model utilizes the channel sensing probability.

The remainder of this paper is organized as follows. In Section II, we describe the system model and in Section III, we propose a CSMA protocol for asynchronous MPR. Section IV presents an analytical model and Section V reports the numerical results. Conclusions are summarized in Section VI.

II. SYSTEM MODEL

As commonly assumed in [2]–[10], we consider a fully connected network, where n ($n \geq 2$) contending nodes have infinite backlogged packets ready for transmission to one receiver. The communication channel is divided into time slots of equal duration. Every packet transmission occupies an integer number of slots, and only can begin at the slot boundaries of the channel. We also make the following key assumptions in this paper.

(i) The receiver has the capability of asynchronous γ-MPR to correctly decode multiple packets. The MPR capability γ ($1 \leq \gamma < n$) is defined as one that guarantees any transmitted packet to be correctly received, as long as there are γ or fewer transmissions in the channel at any instant during the packet transmission lifetime and to be unsuccessfully received if otherwise. More discussion on practical implementation can be found in [6], [8], and [10].

(ii) Each node is able to estimate the number of ongoing transmissions over the channel by channel sensing. This assumption is also adopted in [6]–[8] and [10] for protocol design, and a PHY technique for this purpose based on multiple antenna systems can be found in [11]. As such, a node equipped with at least L antennas can estimate if the number of concurrent transmissions is $0, 1, \ldots, L-1$ or larger than L.

(iii) Following [6] and [10], we assume the packet length (in slots) to be geometrically distributed with an average Λ, that is, the probability that a packet has length λ is equal to:

$$p_{\text{length}}(\lambda) = \frac{1}{\Lambda}\left(1 - \frac{1}{\Lambda}\right)^{\lambda-1}$$

for $\lambda = 1, 2, \ldots$.

(iv) For the sake of energy efficiency and channel utilization, ACK and retransmission mechanisms are not employed. If ACKs are incorporated, a node may need to constantly monitor the channel for a long time duration after the completion of its packet transmission, until it receives a corresponding ACK. Moreover, the presence of ACKs defers the next transmissions of those nodes awaiting ACKs, and hence degrade the throughput performance. This is because time-overlapping packet transmissions may end at different time slots, and the receiver only can echo back ACKs when all nodes keep silent. Obviously, this problem will become more serious when transmission durations are dynamically varying. On the other hand, a non-ACK mode has been widely used for scenarios where only a fraction of reports need to be collected [12], [13].

Remark: For improving the channel utilization of asynchronous γ-MPR, other researchers also made some assumptions on ACKs different from the above. For example, [6] assumed that each node becomes aware of their transmission outcome immediately without relying on ACKs, and [10] assumed an additional feedback channel for ACK transmissions.

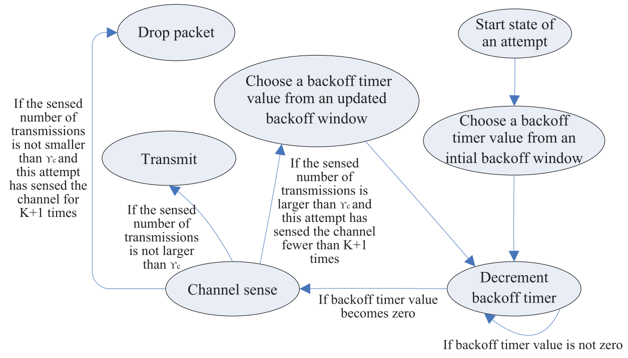

FIGURE 1. Finite state machine for a node.

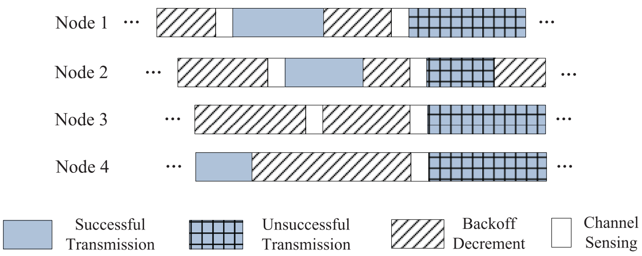

FIGURE 2. Time line of a possible scenario for $\gamma = 3, \gamma_c = 1$.

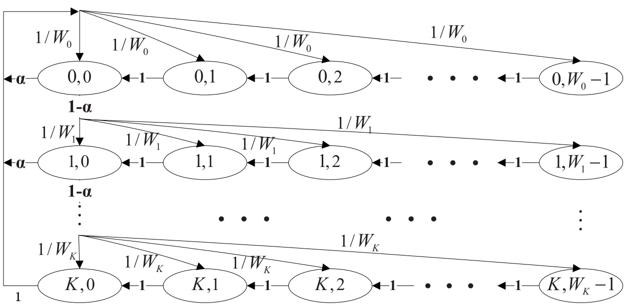

FIGURE 3. Markov chain model.

III. PROTOCOL DESIGN

Under the system model introduced in Section II, we propose a CSMA protocol for asynchronous MPR that does not require backoff nodes to continuously monitor the channel. Our approach can be seen as an extension of the CSMA algorithm adopted in the IEEE 802.15.4 standard. The finite state machine that characterizes the behavior of a node is shown in Fig. 1. The detailed procedure is as follows:

(i) Before a transmission attempt, the CSMA protocol initializes the value of one parameter: $i = 0$, to record the times of channel sensing of this attempt.

(ii) When a node has a packet ready for transmission, it uniformly chooses a backoff timer value from $[0, W_0 - 1]$, in which W_0 is the initial backoff window size.

(iii) The node counts down the backoff timer at every slot boundary until the timer reaches the zero value, regardless of the channel state. When the backoff timer is zero, the node performs channel sensing at the PHY.

(iv) The node starts to transmit its packet if the sensed number of ongoing transmissions is not larger than γ_c; but otherwise increases ts by one, and delays the transmission for a random number of slots uniformly chosen from $[0, W_i - 1]$, where $W_i = 2^i W_0$. Following [6], we set $\gamma_c = \max(\gamma - 2, 0)$ in order to obtain better throughput performance than synchronous MPR, i.e., $\gamma_c = 0$.

(v) If the value of i is greater than K, the node terminates this transmission attempt by discarding the packet.

A time line of a possible scenario for the case $\gamma = 3$, $\gamma_c = 1$ is shown in Fig. 2. This figure shows that, each node defers its transmission when it has sensed two transmissions, and begins its transmission when it has sensed fewer than two transmissions. In particular, when an overlapping occurs among the three nodes, the involved three transmissions are all considered lost.

IV. PERFORMANCE ANALYSIS

In this section, we develop an analytical model for the proposed protocol. We aim to evaluate the throughput, reliability and energy consumption in saturated traffic conditions. As all n nodes are homogeneous, we tag an arbitrary node for performance analysis and call it the tagged node.

A. CHANNEL SENSING PROBABILITY

In our proposed CSMA protocol, the node counts down its backoff timer regardless of the channel state, and senses the channel only when the backoff timer reaches zero. Hence, the probability that the tagged node begins to transmit adopted in [6], [8], and [10] is not suitable for describing the behaviour here. Instead, similar to the methods in [12]–[14], we utilise the probability of the tagged node in the channel sensing state.

Let τ be the probability that the tagged node is in the channel sensing state provided that it is not transmitting. Let α be the probability that the node senses γ_c or fewer than γ_c ongoing transmissions in the channel sensing state. We first provide a relationship between τ and α by using a Markov chain to describe the behavior of the tagged node. As shown in Fig. 3, the state (i, k) represents the i-th backoff and the backoff counter value k if $k \in [1, W_i - 1]$, and represents the i-th channel sensing if $k = 0$. Then, we can obtain the transition probabilities as follows:

$$\begin{aligned}
Pr\{i, k-1|i, k\} &= 1 \quad i \in [0, K],\ k \in [1, W_i - 1];\\
Pr\{i+1, k|i, 0\} &= \frac{1-\alpha}{W_{i+1}} \quad i \in [0, K-1],\\
&\qquad\qquad\qquad k \in [0, W_{i+1} - 1];\\
Pr\{0, k|i, 0\} &= \frac{\alpha}{W_0} \quad i \in [0, K-1],\ k \in [0, W_0 - 1];\\
Pr\{0, k|K, 0\} &= \frac{1}{W_0} \quad k \in [0, W_0 - 1].
\end{aligned} \tag{1}$$

Let $b_{i,k}$ denote the stationary probability of the state (i, k) in the Markov chain for $i \in [0, K],\ k \in [0, W_i - 1]$. By using (1) and manipulating, the channel sensing probability τ can be calculated as:

$$\tau = \sum_{i=0}^{K} b_{i,0} = \frac{2[1-(1-\alpha)^{K+1}]}{\alpha \sum_{i=0}^{K}(W_i+1)(1-\alpha)^i}. \tag{2}$$

Clearly, the evaluation of τ in (2) requires the knowledge of the probability α, of which the approximation needs to take into account that the channel can accommodate time-overlapping asynchronous transmissions. Let $p_{\mathrm{act}}(l)$ be the probability that l nodes are transmitting in the present slot. It is easy to see that α can be quantized by using

$$\alpha = \sum_{l=0}^{\gamma_c} p_{\mathrm{act}}(l). \tag{3}$$

In the following, we investigate how to evaluate $p_{\mathrm{act}}(l)$ with $\beta(l,j,h)$, which is defined to be the probability that j nodes are transmitting in the next slot when l nodes are transmitting in the present slot, and h of these l complete the transmission at the end of the present slot. Let $p_o = \frac{1}{\Lambda}$ be the probability that a node completes a packet transmission at the end of the present slot. On the other hand, if there are γ_c or fewer than γ_c nodes transmitting in the present slot, only those nodes performing channel sensing in the present slot can start their transmissions in the next slot. Note that, as channel sensing must precede a transmission, each node *cannot* immediately commence a new transmission after the completion of last transmission. Then we have

$$\beta(l,j,h) = \begin{cases} \binom{l}{h} p_o^h (1-p_o)^{l-h} & \binom{n-l}{j-l+h} \tau^{j-l+h}(1-\tau)^{n-j-h} \\ & \text{if } h \le l \le \gamma_c,\, l-h \le j \le n-h; \\ \binom{l}{h} p_o^h (1-p_o)^{l-h} & \text{if } \gamma_c < l \le n,\, j = l-h; \\ 0 & \text{otherwise.} \end{cases} \tag{4}$$

Let $T_{\mathrm{act}}(l,j)$ be the probability that j nodes are transmitting in the next slot when l nodes are transmitting in the present slot. After summing over all possible $\beta(l,j,h)$ in (4), one obtains:

$$T_{\mathrm{act}}(l,j) = \sum_{h=0}^{l} \beta(l,j,h). \tag{5}$$

Further, for $j = 0, 1, \ldots, n$, we have

$$[p_{\mathrm{act}}(0), \ldots, p_{\mathrm{act}}(n)][T_{\mathrm{act}}(0,j), \ldots, T_{\mathrm{act}}(n,j)]^T = p_{\mathrm{act}}(j). \tag{6}$$

Therefore, from equations (2)–(6), both τ and α can be evaluated.

B. TRANSMISSION SUCCESS PROBABILITY

Assume the tagged node performs the channel sensing at the 0-th slot and transmit a tagged packet from the first slot to the λ-th slot. We want to derive $p_s(\lambda)$, the probability that this tagged packet is successfully received, i.e., at most γ nodes are transmitting at any time instant during these λ slots.

For $m = 0, 1, \ldots, \lambda$, let $\theta_m(l)$ represent the probability of having l active transmissions (not take into account the tagged node) at the m-th slot, provided that this tagged packet has no collided slots until the $(m-1)$-th slot. Since that at most γ_c packets are being transmitted at the 0-th slot, we have:

$$\theta_0(l) = \begin{cases} p_{\mathrm{act}}(l) / \sum_{u=0}^{\gamma_c} p_{\mathrm{act}}(u) & \text{if } 0 \le l \le \gamma_c; \\ 0 & \text{otherwise.} \end{cases} \tag{7}$$

Without considering the tagged node, let $\beta'_m(l,j,h)$ denote the probability that j nodes are transmitting in the m-th slot when l nodes are transmitting in the $(m-1)$-th slot, and h of these l complete the transmission at the end of the $(m-1)$-th slot. Then for $m = 1, 2, \ldots, \lambda$, we have:

$$\beta'_m(l,j,h) = \begin{cases} \binom{l}{h} p_o^h (1-p_o)^{l-h} & \binom{n-1-l}{j-l+h} \tau^{j-l+h}(1-\tau)^{n-1-j-h} \\ & \text{if } h \le l \le \gamma'_c,\, l \le j+h \le n-1; \\ \binom{l}{h} p_o^h (1-p_o)^{l-h} & \text{if } \gamma'_c < l \le n-1,\, j = l-h; \\ 0 & \text{otherwise.} \end{cases} \tag{8}$$

in which $\gamma'_c = \gamma_c$ if $m = 1$, and otherwise $\gamma'_c = \gamma_c - 1$. The values of γ'_c take into account that the tagged node transmit from the first slot to the λ-th slot.

Then, for $m = 1, 2, \ldots, \lambda$, we can obtain:

$$\theta_m(j) = \sum_{l=0}^{n-1} \theta_{m-1}(l) q(l) \sum_{h=0}^{l} \beta'_m(l,j,h), \tag{9}$$

in which $q(l) = 1$ if $l < \gamma$ and $q(l) = 0$ otherwise.

Therefore, one obtains:

$$p_s(\lambda) = \sum_{l=0}^{\gamma-1} \theta_\lambda(l). \tag{10}$$

C. THROUGHPUT

In this subsection, we evaluate the throughput by analyzing the transmission success probability of each new transmission for all involved slots.

Let $T_{\mathrm{next}}(l,j_2)$ describe the probability that j_2 nodes begin transmissions in the next slot, when l nodes are transmitting in the present slot. As one node begins its transmission in the next slot only if it performs channel sensing in the present slot and $l \le \gamma_c$, we obtain:

$$T_{\mathrm{next}}(l,j_2) = \begin{cases} \binom{n-l}{j_2} \tau^{j_2}(1-\tau)^{n-l-j_2} & \text{if } l \le \gamma_c < n,\, j_2 \le n-l; \\ 1 & \text{if } \gamma_c < l \le n,\, j_2 = 0; \\ 0 & \text{otherwise.} \end{cases} \tag{11}$$

Let $s(j_2)$ describe the probability that j_2 nodes begin their transmissions in a generic slot. It is easy to see that

$$s(j_2) = \sum_{l=0}^{n} p_{act}(l) T_{\mathrm{next}}(l,j_2). \tag{12}$$

Finally, the network throughput can be evaluated as:

$$S = \left[\sum_{\lambda=1}^{\infty} \lambda p_s(\lambda) p_{\text{length}}(\lambda)\right] \sum_{j_2=0}^{n} j_2 s(j_2). \qquad (13)$$

D. RELIABILITY

In our protocol, packets are considered lost due to access failures or collisions. An access failure happens when a packet fails to sense fewer than γ_c concurrent transmissions in the channel sensing state within $K+1$ backoffs. As there is no retransmission, a packet is discarded if a packet suffers from a collision involving more than γ nodes. Therefore, the reliability of the network R, defined as the average ratio between the number of successfully transmitted slots and the total number of transmitted slots, can be obtained as:

$$R = \frac{\sum_{\lambda=1}^{\infty} \lambda p_{\text{length}}(\lambda)[1-(1-\alpha)^{K+1}]p_s(\lambda)}{\Lambda}. \qquad (14)$$

E. ENERGY CONSUMPTION

Energy consumption is another important performance metric considered in our protocol. To investigate the energy overhead issue, we use the normalized energy consumption E which is defined as the average energy consumption to successfully transmit one slot of packet.

We derive the expression of E by considering the energy consumption of the tagged node as the sum of the contribution in backoff, carrier sensing and transmitting states. Note that the node sets its radio to idle mode during the backoff state, and sets its radio to receiving mode during the carrier sensing state. As the tagged node is during the backoff state with the probability $1-\tau$, performs channel sensing with the probability τ, and transmits a packet with the probability $\tau\alpha$, we have

$$E = \frac{(1-\tau)P_{idle} + \tau P_{rx} + \tau\alpha \sum_{\lambda=1}^{\infty} \lambda p_{\text{length}}(\lambda) P_{tx}}{\tau\alpha \sum_{\lambda=1}^{\infty} \lambda p_s(\lambda) p_{\text{length}}(\lambda)}, \qquad (15)$$

where P_{idle}, P_{tx} and P_{rx} respectively denote the energy consumption in one slot for the idle, transmitting and receiving mode.

V. NUMERICAL RESULTS

In this section, we investigate performance metrics of the proposed protocol through Monte Carlo evaluation. We set $K = 4$, $\Lambda = 10$, and assume a slot lasts 320 μs. The Chipcon CC2420 radio transceiver [15] based energy model is used in the experiments. The power consumption for the idle, transmitting and receiving mode are 1.28, 52.2 and 56.4 mW, respectively. It should be noted that we put the nodes to idle when they are in backoff. All nodes are assumed in saturated traffic conditions.

In the first two subsections, we confirm the accuracy of the analytical results ($\gamma_c = \max(\gamma - 2, 0)$) with respect to different γ, n and W_0. The results of synchronous MPR case, i.e., $\gamma_c = 0$ are also presented for comparison purpose. In addition, the third subsection shows the impact of imperfect estimation, and the fourth subsection compares the proposed protocol against the protocol in [6].

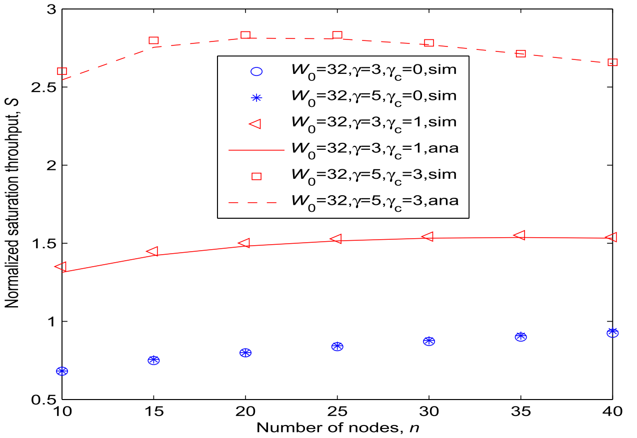

FIGURE 4. **Saturation throughput as a function of number of nodes for different values of γ.**

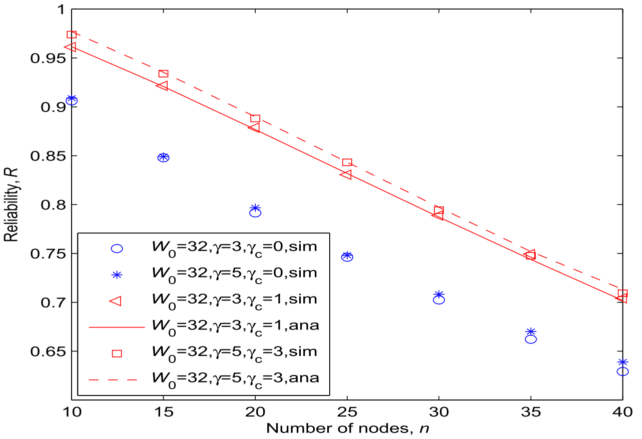

FIGURE 5. **Reliability as a function of number of nodes for different values of γ.**

A. NETWORK SIZE

Figs. 4–6 present the saturation throughput, reliability and energy consumption of the proposed protocol as a function of number of nodes for $\gamma = 3, 5$ and $W_0 = 32$, respectively. We see a good agreement between analytical and numerical results in all the scenarios.

In Fig. 4, as expected, a larger γ allows more concurrent packets to be successfully received, and thus enjoys a better throughput performance. The curves further indicate that the saturation throughput first increases and then decreases as the network size becomes large, due to the varied contention level. On the other hand, Fig. 4 shows that the proposed protocol yields a significant throughput improvement over synchronous MPR, as our protocol allows new transmissions to begin while the channel is occupied by other transmissions. We also find that the throughput values of synchronous MPR for $\gamma = 3, 5$ are very close. This phenomenon can be attributed to the fact the probability that more than three nodes simultaneously begin their transmissions is very small when $W_0 = 32$.

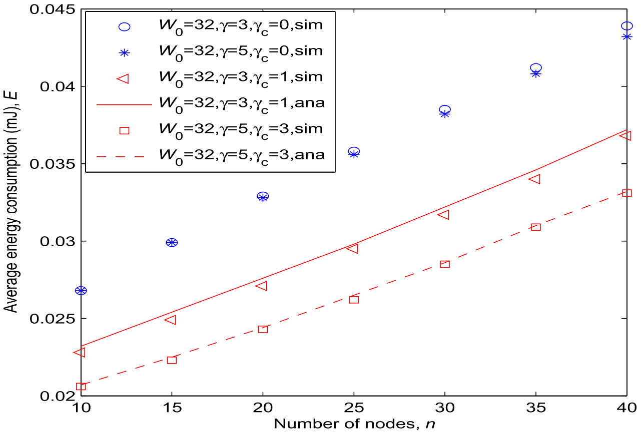

FIGURE 6. **Average energy consumption as a function of number of nodes for different values of γ.**

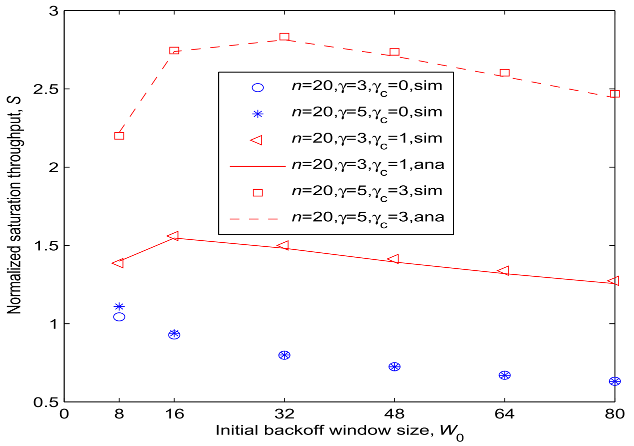

FIGURE 7. **Saturation throughput as a function of initial backoff window size for different values of γ.**

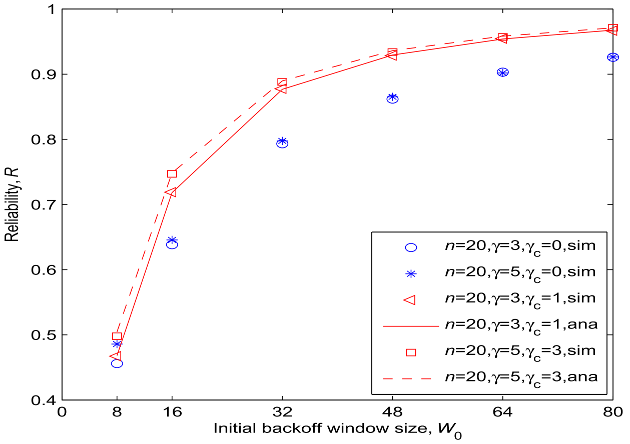

FIGURE 8. **Reliability as a function of initial backoff window size for different values of γ.**

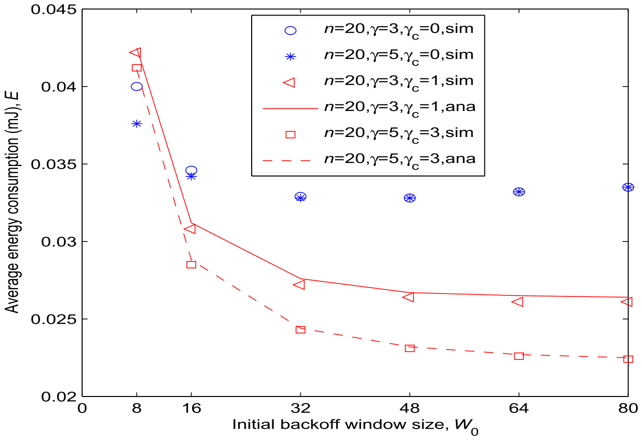

FIGURE 9. **Average energy consumption as a function of initial backoff window size for different values of γ.**

In Fig. 5, as expected, the reliability decreases as the number of nodes grows, and a larger γ produces a higher reliability. We also find that the synchronous MPR case has a worse reliability in all cases, since more packets are discarded due to channel access failures for $\gamma_c = 0$.

From Fig. 6, we observe that a larger γ leads to lower energy cost, as it allows more successes of access attempts and more successes of transmissions. We also see that proposed protocol enjoys lower energy cost than synchronous MPR, as the latter experiences more failures of access attempts and has lower throughput in the examined cases as shown in Fig. 4.

B. INITIAL BACKOFF WINDOW

Figs. 7–9 show the saturation throughput, reliability and energy consumption of the proposed protocol as a function of initial backoff window size for $\gamma = 3, 5$ and $n = 20$, respectively. Once again, the accuracy of our analytical model is validated by simulations.

Fig. 7 indicates that a larger W_0 should be adopted for a larger γ to achieve the maximum throughput. This behavior is because that a larger γ allows nodes to more aggressively access to the channel, and needs a larger W_0 to jointly attain the optimal access probability. From Fig. 8, we see that the reliability increases as W_0 increases, due to the reduced contention level. Fig. 9 demonstrates that the nodes spend less energy consumption to successfully transmit one slot of packet as W_0 increases. This is because that the nodes spend more time in idle mode, and the throughput variation is relatively small as W_0 increases. We notice that when $W_0 = 8$ the proposed protocol is too aggressive to access to the channel which leads to much energy waste in collisions, and thus requires more energy cost than synchronous MPR.

C. IMPERFECT ESTIMATION

To examine the impact of imperfect estimation in channel sensing, following [8], we assume that each node has an estimation error probability p_e to sense that there are j concurrent transmissions while there actually are $j+1$ transmissions, and probability $1 - p_e$ to obtain a perfect estimation.

Figs. 10–12 show the saturation throughput, reliability and energy consumption of the proposed protocol as a function

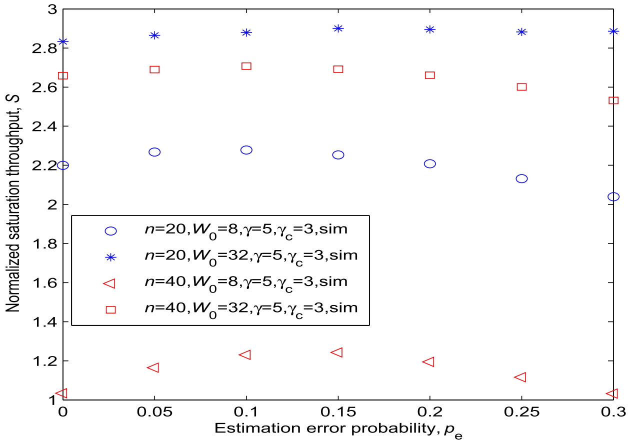

FIGURE 10. **Saturation throughput as a function of estimation error probability for different values of W_0 and *n*.**

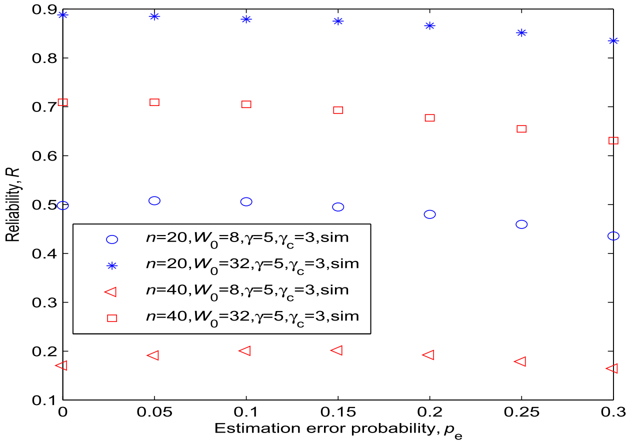

FIGURE 11. **Reliability as a function of estimation error probability for different values of W_0 and *n*.**

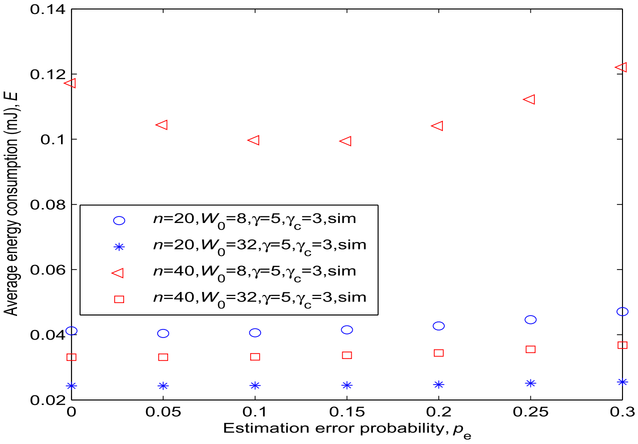

FIGURE 12. **Average energy consumption as a function of estimation error probability for different values of W_0 and *n*.**

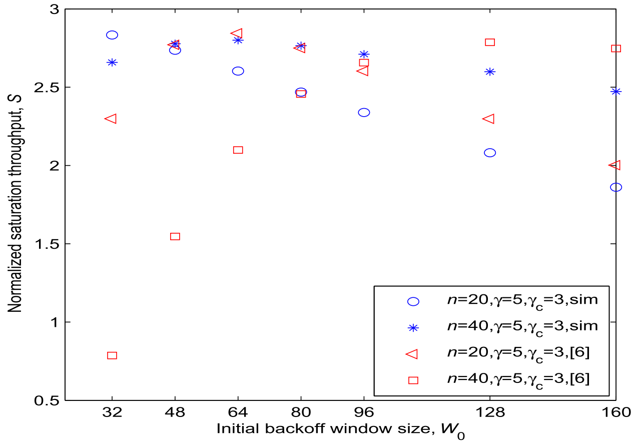

FIGURE 13. **Saturation throughput as a function of initial backoff window size for a comparison with [6].**

of p_e for $\gamma = 5$, $W_0 = 8, 32$ and $n = 20, 40$, respectively. Only numerical results are reported to improve the readability.

From Fig. 10, we observe that the saturation throughput first increases and then decreases when p_e increases from 0 to 0.3, and there is only at most 7.3% throughput loss in all the examined cases even if p_e is as high as 0.3. This phenomenon implies that the existence of estimation error may contribute to the throughput improvement, and can be attributed to the fact that an appropriate p_e allows one or more nodes to accidentally utilize the vacant space of MPR channel when there are more than γ_c but fewer than γ concurrent transmissions. From Figs. 11–12, we also see that estimation error has a similar effect on the reliability and energy consumption.

In sum, we find that the proposed protocol is quite robust to estimation error in channel sensing.

D. A COMPARISON WITH [6]

Finally, we investigate the advantage of the proposed protocol over the protocol in [6] which requires each node to decrease its backoff counter only when it have sensed γ_c or fewer than γ_c concurrent transmissions and attempt the transmission if the backoff counter reaches the zero value.

The curves in Fig. 13 reveal that, for each given γ and n, the maximum throughput is maintained nearly constant for both two protocols, although the W_0s to attain the maximum throughput are different due to the different backoff progresses. Besides, Fig. 14 shows that the proposed protocol always enjoys a higher reliability for a given W_0, since it allows at most $K + 1$ access attempts, whereas the protocol in [6] only allows a unique transmission attempt at the absence of ACKs.

As expected, from Fig. 15, we see that the proposed protocol spends much less energy than the protocol in [6] to successfully transmit one slot of packet in all the scenarios. Obviously, the energy benefit comes from allowing the nodes to keep idle when backoff. Moreover, Figs. 13-15 jointly show that such low energy cost does not incur any performance degradation on throughput and reliability if an appropriate W_0 is adopted.

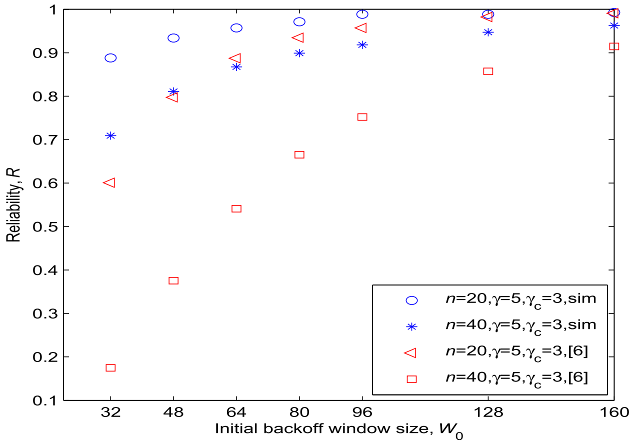

FIGURE 14. **Reliability as a function of initial backoff window size for a comparison with [6].**

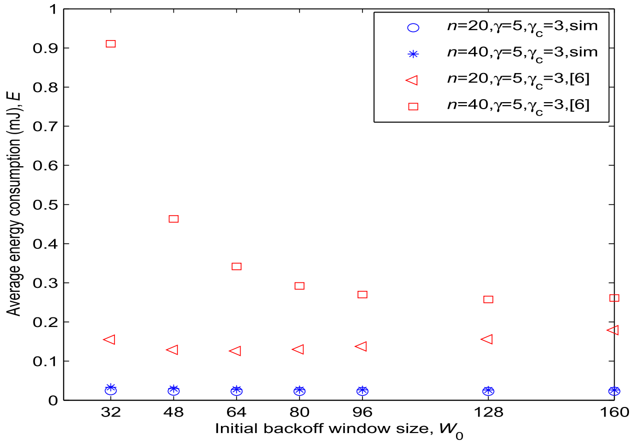

FIGURE 15. **Average energy consumption as a function of initial backoff window size for a comparison with [6].**

VI. CONCLUSIONS

To address the energy overhead issue in previously proposed asynchronous MPR protocols, we in this paper have proposed a CSMA scheme for asynchronous MPR, which does not require backoff nodes to monitor the channel. Through performance analysis and simulations, we investigate our proposed scheme in terms of throughput, reliability and energy consumption. We also show that the proposed protocol is quite robust to estimation error in channel sensing; and moreover, is more energy-efficient than the asynchronous MPR scheme in [6] which requires the backoff nodes to constantly monitor the channel.

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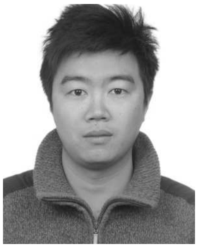

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