Cross-layer Optimization of a CSMA protocol with Adaptive Modulation for Improved Energy Efficiency in Wireless Sensor Networks

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***Abstract*—We investigate the energy efficiency in a wireless sensor networks that implements a non-persistent CSMA MAC protocol with adaptive MQAM modulation at the physical layer. The system throughput is estimated based on the number of received ACK packets. The backoff probability at the MAC layer and the modulation order at the physical layer are jointly adapted according to the traffic dynamics, leading to improved system energy efficiency while satisfying a given constraint on the packet retransmission delay. Through numerical examples and simulations, we verify the significant energy-efficiency improvements achieved by this joint optimization compared to the backoff-probability-only and the modulation-order-only adaptations.**

I. Introduction

Wireless sensor networks (WSNs) have recently been the focus of extensive research [1]. Numerous applications have been envisioned for such networks, including environmental monitoring, data collection, intrusion detection, etc. Due to the limited battery lifetime of sensing devices, the design of highly energy-efficient communication protocols for WSNs has been the focus of many recent studies.

At the MAC layer, commonly used channel-access approaches for wireless networks follow the Carrier Sense Multiple Access (CSMA) paradigm. Essentially, there are two variants of CSMA: $p-$persistent and non-persistent. As shown in [7], the MAC protocol used in the IEEE 802.11 standard can be well modeled by a $p-$persistent CSMA scheme. In contrast, several MAC schemes proposed for WSNs are similar to that of non-persistent CSMA. In this paper, we will focus on non-persistent CSMA.

Both variants of CSMA have been extensively studied over the past three decades. Throughput and delay characteristics were derived for slotted and unslotted channels, under finite- and infinite- population models [2], [4]. However, analytical results related to the energy efficiency were only recently reported for a slotted CSMA system with a finite population [5], [7]. In these works, the system is assumed to contain a small number of stations (usually less than 100), and each station is assumed to operate under heavy traffic, i.e., each station always has packets be transmit. The finite-population and heavy-traffic assumptions best describe the situation in a WLAN, but do not adequately characterize a WSN. In contrast to a WLAN, a WSN typically consists of a large number (thousands) of nodes. Each individual node contributes only a small amount of traffic to the network through infrequent access to the channel (i.e, low duty cycle). Such a setup makes the model with an infinite population and moderate traffic load more appropriate for analyzing random channel access in a WSN.

In this paper, we investigate the energy efficiency of a non-persistent CSMA MAC for a WSN with infinitely many nodes. To better optimize the energy efficiency, defined as the energy consumption for successfully transmitting a bit, we assume that at the physical layer a node is capable of adjusting its modulation order according to the instantaneous traffic load of the system. By using adaptive modulation, the system can control the transmission duration of each packet, leading to a controllable traffic load and packet retransmission probability. Analytically, we demonstrate that the energy efficiency can be minimized by jointly optimizing the modulation order at the physical layer and the backoff probability at the MAC layer. To the best of our knowledge, this is the first work that jointly considers the physical and MAC layers in optimizing CSMA systems.

The rest of this paper is organized as follows. We describe the system model in Section 2. The energy efficiency is optimized in Section 3. Section 4 presents numerical and simulation results, and Section 5 concludes the paper.

II. System Model

We consider the system in Figure 1. It consists of a single AWGN channel, a traffic-load monitor, and a large number of nodes that generate packets independently and share the same channel through random access. The functional abstraction of a node contains three components: a packet generator, an M-ary quadrature amplitude modulation (MQAM)-based physical layer, and a non-persistent CSMA-based MAC layer. Packet generation at each node follows a Poisson process. Packets have the same size, say L bits. A node only contributes an infinitesimal traffic to the channel. Nodes collectively form a Poisson source with aggregate rate λ packets/second. The traffic-load monitor, typically a sink in a WSN, periodically samples the traffic load over the channel (e.g., by counting ACK packets) and decides on an appropriate modulation order, say M, that will be used by the physical layers at all the nodes under the current traffic load. The MQAM modulator at a node maps a packet from L bits to $\frac{L}{\log_2 M}$ symbols. Denote the transmission rate of the channel by R symbols/second. So the transmission time of a packet is $T = \frac{L}{R \log_2 M}$ seconds. As in [2], we consider a slotted system in which the slot duration τ

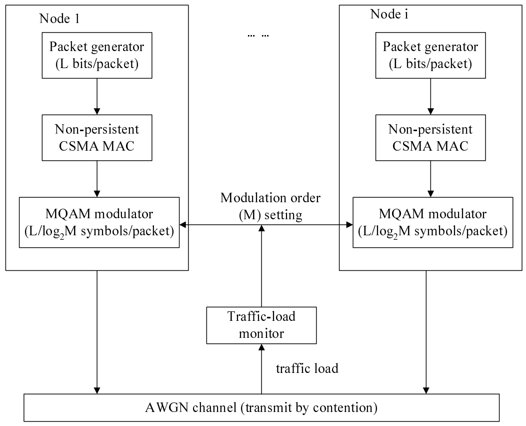

Fig. 1. System model.

corresponds to the maximum propagation time in the network. Let $a \stackrel{\text{def}}{=} \tau/T$.

The processing unit at the MAC layer is a packet with length $l = T/\tau$ slots. Communication is based on a slotted non-persistent CSMA protocol [2]. A tagged node will first sense the channel before it transmits a packet. The activity of sensing the channel is referred to as a *transmission attempt*. Depending on the channel occupancy and noise conditions, there are four possible consequences following a transmission attempt: (i) the channel is busy (occupied by other communications), so the tagged node conducts a *backoff* before it senses the channel again; (ii) the channel is idle and the packet is transmitted, but a collision occurs during the transmission so the node backs off before trying again; (iii) the channel is idle and the packet is transmitted, but the transmission is corrupted by AWGN so the node backs off before another retransmission attempt; and (iv) the channel is idle and the packet is successfully transmitted. We denote the probabilities of the above four possibilities by P_{busy}, $P_{collision}$, $P_{corruption}$, and $P_{success}$, respectively. We assume the node learns the result of its transmission immediately after it completes this transmission. To make our analysis tractable, we further assume that the backoff duration follows a geometric distribution with a success probability p. Later in the simulations, we relax this assumption by considering more practical backoff policies: the uniform backoff and the binary exponential backoff [4]. We show that the distribution of the backoff has only a minor influence on the energy efficiency as long as the average backoff duration remains the same. Because our energy optimization involves physical-layer techniques, our model incorporates the effect of the AWGN on random access through the probability $P_{corruption}$. In addition, we assume no energy is consumed during backoff, i.e., the node sleeps during backoff by turning off most of its circuits.

The bit error rate (BER) for coherent MQAM with two-dimensional Gray coding over an AWGN channel is given by [3]:

$$P_{be}(M,\gamma) = \frac{1}{5} e^{-\frac{1.5\gamma}{M-1}} \tag{1}$$

where $\gamma \stackrel{\text{def}}{=} \frac{E_S}{N_0}$ is the received symbol-energy-to-noise-density ratio under ideal Nyquist pulses for the modulated symbols.

The delay, denoted by D, for successfully transmitting a packet is our quality of service (QoS) metric of interest. Because of the data redundancy in WSNs, here we consider a soft delay requirement in the form $\Pr\{D > T_{\text{limit}}\} < \delta$, where T_{limit} and δ are given parameters.

III. Analysis of Energy Efficiency

A. Energy Consumption for One Transmission

In this section, we derive the minimum per-packet energy consumption that guarantees the delay requirement. Figure 2 shows the access process for a tagged packet that is generated at time t_0 and is to be transmitted at the next slot. Let N be the number of transmission attempts conducted before a successful transmission and let W_i be the delay due to the ith attempt. We let W_0 be the access delay between t_0 and the start of the next slot. The packet transmission delay D is the time between the generation of the packet and the moment it is successfully transmitted. It is given by

$$D = \sum_{i=0}^{N} W_i. \tag{2}$$

In [8], it was shown that under the assumption of Poisson arrivals and for large backoff periods, N can be accurately approximated by a geometric distribution with success probability $P_{success}$, i.e.,

$$\Pr\{N = n\} = (1 - P_{success})^{n-1} P_{success}. \tag{3}$$

For a non-persistent CSMA system with an infinite population and *without* AWGN , $P_{success}$ has been derived in [2]:

$$P_{success} = \frac{ae^{-aG}}{(1 - e^{-aG}) + a} \tag{4}$$

where G is the *offered packet rate*, representing the average number of combined new-and-retransmitted packet arrivals during the transmission time T. Accounting for the effect of the AWGN, the probabilities of success and corruption become:

$$P_{success} = \frac{ae^{-aG}(1 - P_{pe})}{1 - e^{-aG} + a} \tag{5}$$

and

$$P_{corruption} = \frac{ae^{-aG} P_{pe}}{1 - e^{-aG} + a} \tag{6}$$

where P_{pe} is the packet error probability in an AWGN channel, and is given by

$$P_{pe} = 1 - (1 - P_{be})^L. \tag{7}$$

Depending on the outcome of a transmission attempt, the delay (in number of slots) due to the ith attempt can be enumerated as follows

$$W_i = \begin{cases} B_i, & 1 \le i \le N-1 \text{ and outcome is `busy'} \\ B_i + \frac{T}{\tau}, & 1 \le i \le N-1 \text{ and outcome is (`collision'} \\ & \text{or `corruption')} \\ \frac{T}{\tau}, & i = N \text{ and outcome is `success'} \end{cases} \tag{8}$$

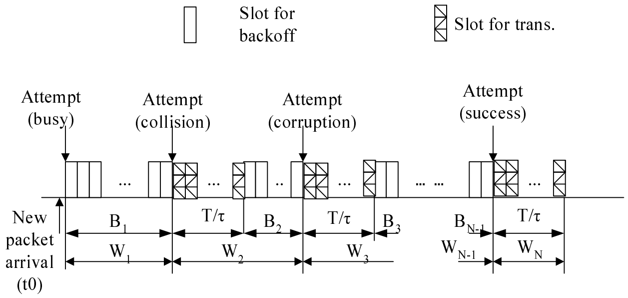

Fig. 2. Illustration of the access process.

where B_i is the number of backoff steps in the ith retransmission attempt; B_i follows a geometric distribution with success probability p. The probabilities associated with each of W_i's possible values are P_{busy}, $P_{collision}+P_{corruption}$, and $P_{success}$, respectively. It has been shown in [4] that

$$P_{busy} = \frac{1-e^{-aG}}{1+a-e^{-aG}} \tag{9}$$

$$P_{collision} = \frac{a(1-e^{-aG})}{1+a-e^{-aG}}. \tag{10}$$

Substituting (8) into (2) and ignoring W_0, we have

$$D = \sum_{i=1}^{N-1} B_i + N_{\text{CCS}}\frac{T}{\tau} \le \sum_{i=1}^{N} B_i + N_{\text{CCS}}\frac{T}{\tau} \tag{11}$$

where N_{CCS} is a random variable denoting the number of transmission attempts whose consequences are collision, corruption, or success. In (11), the inclusion of B_N into the summation is a conservative approach because as long as the RHS of the equation is less than the required delay bound, its LHS equation must also satisfy the delay bound. The distribution of D was derived in [4] by using a recursive numerical algorithm. However, the results in [4] are non-invertible and not in closed-form. By expressing the distribution of D in closed form, we will be able to derive the minimum per-bit energy efficiency. To proceed with our derivation, here we assume that the average backoff periods are sufficiently longer than the transmission duration of a packet, i.e., $N_{\text{CCS}}\frac{T}{\tau} \ll N\text{E}\{B_i\}$, such that $N_{\text{CCS}}\frac{T}{\tau}$ can be ignored. We will verify the validity of this assumption later in the numerical examples. With this assumption, (11) can be further simplified into

$$D \approx \sum_{i=1}^{N} B_i. \tag{12}$$

It is easy to obtain the moment generating function of D:

$$H(s) \overset{\text{def}}{=} \sum_{i=1}^{\infty} \Pr\{D=i\} s^i = \frac{P_{success}ps}{1-(1-P_{success}p)s}. \tag{13}$$

The structure of (13) reveals that this is the moment generating function of a geometric distribution with success probability $P_{success}p$. Let $K = \left\lceil \frac{T_{limit}}{\tau} \right\rceil$ be the normalized delay bound. The packet loss probability due to delay is given by

$$\begin{aligned} P_{loss} &= \Pr\{D > K\} \\ &= \sum_{i=K+1}^{\infty} (1-P_{success}p)^{i-1} P_{success}p \\ &= (1-P_{success}p)^K. \end{aligned} \tag{14}$$

To satisfy an upper bound δ on the packet loss probability, the minimum success probability is given by

$$P_{success} \ge \frac{1-\delta^{\frac{1}{K}}}{p}. \tag{15}$$

A WSN is typically characterized as a low-power, low rate, and short per-hop communication range application. For such an application, the parameter $a = \frac{\tau}{T}$ can usually be ignored. For example, for a distance of 300 meters, packet length of 1000 bits, and transmission rate of 250 kbps (this is the largest data rate supported by IEEE 802.15.4 standard), the value of a is $2.5 \times 10^{-4} \approx 0$. From (5), we derive

$$\lim_{a \to 0} P_{success} = \frac{1-P_{pe}}{1+G}. \tag{16}$$

Noting $P_{success} = \frac{S}{G}$, where $S = \lambda T$, we can rewrite G by reformulating (16)

$$\lim_{a \to 0} G = \frac{S}{1-P_{pe}-S}. \tag{17}$$

Substituting (17) into (16), we get

$$P_{success} = 1 - P_{pe} - S. \tag{18}$$

Substituting (18) into (15), the maximum packet error probability that satisfies the delay requirement is given by

$$P_{pe} \le 1 - S - \frac{1-\delta^{\frac{1}{K}}}{p}. \tag{19}$$

Accordingly, the maximum BER is given by

$$P_{be} \le 1 - \left(S + \frac{1-\delta^{\frac{1}{K}}}{p}\right)^{\frac{1}{L}}. \tag{20}$$

Substituting (20) into (1), we determine the minimum energy-per-bit for a transmission

$$E_b = \frac{2(M-1)N_0}{3\log_2 M} \ln \frac{1}{5\left[1-\left(S+\frac{1-\delta^{\frac{1}{K}}}{p}\right)^{\frac{1}{L}}\right]}. \tag{21}$$

B. Analysis for Average Number of Retransmissions

Consider a tagged packet when the number of total transmission attempts until a successful transmission is N (including the successful transmission), the average number of actual transmissions is given by

$$\begin{aligned} \text{E}\{N_{\text{CCS}}|N\} &= N(P_{success}+P_{corruption}+P_{collision}) \\ &= N(1-P_{busy}). \end{aligned} \tag{22}$$

¿From (9), it is easy to derive that

$$\lim_{a\to 0} P_{busy} = \lim_{a\to 0} \frac{e^{-aG}G}{1+e^{-aG}G} = \frac{G}{1+G}. \quad (23)$$

Therefore, the unconditional average number of retransmissions for a tagged packet is

$$\bar{N}_{\text{CCS}} = \bar{N}(1-P_{busy}) = \frac{1}{1-P_{pe}}. \quad (24)$$

Substituting (19) into (24), we derive the average number of retransmissions for a tagged packet as a function of the traffic load S and the backoff probability p:

$$\bar{N}_{\text{CCS}} = \frac{1}{S+\frac{1-\delta^{\frac{1}{K}}}{p}}. \quad (25)$$

C. Optimization for Energy Efficiency

we define the energy efficiency η as the average energy consumption for successfully transmitting a single bit. Formally,

$$\eta = E_b \bar{N}_{\text{CCS}} = -\frac{2}{3} N_0 \frac{M-1}{\log_2 M} \frac{1}{x} \ln 5 \left(1-x^{\frac{1}{L}}\right) \quad (26)$$

where

$$x \stackrel{\text{def}}{=} 1-P_{pe} = S + \frac{1-\delta^{\frac{1}{K}}}{p}\lambda\frac{L}{R\log_2 M} + \frac{1-\delta^{\frac{1}{K}}}{p}. \quad (27)$$

For (26) to hold, the following constraint must be satisfied:

$$0 \le P_{be} \stackrel{\text{def}}{=} 1-x^{\frac{1}{L}} \le 0.2 \quad (28)$$

or equivalently,

$$\left(\frac{4}{5}\right)^L \le x \le 1. \quad (29)$$

In a CSMA-based network, the receiver confirms a successful reception by sending a positive ACK packet to the transmitter. Due to the sharing nature of the channel, the channel traffic-load monitor, typically a sink in a WSN, can also overhear this packet. Therefore, the monitor can estimate the instantaneous channel throughput λ by sampling the number of overheard ACK packets. Given the availability of traffic load information, our optimization minimizes η by controlling the modulation order M and the backoff probability p. More specifically, the optimization problem is formulated as

$$\begin{cases} \text{minimize}_{\{M,p\}} & \left\{\eta = -\frac{2}{3}N_0\frac{M-1}{\log_2 M}\frac{1}{x(M,p)} \right. \\ & \left. \times \ln 5\left(1-x(M,p)^{\frac{1}{L}}\right)\right\} \\ \text{such that} & \\ \left(\frac{4}{5}\right)^L \le x(M,p) \le 1 & \\ 0 \le p \le 1 & \\ M \in \left\{2^i | i = 1,2,\ldots\right\} & \end{cases} \quad (30)$$

where x is notated as a function of M and p, as defined in (27).

Because variable M is discrete, we can apply a variable-decomposition method to solve the optimization problem (30). For a given M, denote the conditional x by $x_M(p)$. In this case, the optimization problem in (30) is simplified into the following formulation:

$$\begin{cases} \text{maximize}_{\{p\}} \quad \left(5-5x_M(p)^{\frac{1}{L}}\right)^{\frac{1}{x_M(p)}} \\ \text{such that} \\ x_M(p) = \lambda\frac{L}{R\log_2 M} + \frac{1-\delta^{\frac{1}{K}}}{p} \\ \left(\frac{4}{5}\right)^L \le x_M(p) \le 1 \\ 0 \le p \le 1. \end{cases} \quad (31)$$

It is easy to see that $x_M(p)$ is an equivalent expression of p in the sense that there is a one-to-one mapping between them. Therefore, the objective function in (31) is a single-variable function in p. Numerical algorithms can be used to solve this optimization problem. Denote the optimal solution to (31) by p_M^o. Utilizing the discrete nature of the modulation order, the optimal modulation order and backoff probability to problem (30), denoted by (M^o, p^o), are given by

$$(M^o, p^o) = \text{argmin}_{(M,p_M^o)} \eta(M, p_M^o), \quad M = 2^1, 2^2, \ldots. \quad (32)$$

IV. Numerical Examples and Simulation Results

We conduct numerical experiments using MATLAB to evaluate the efficiency of the proposed joint backoff-modulation optimization. We also perform simulations using CSim to validate our assumptions and analysis. In our numerical examples, we set $L = 1000$ bits, $R = 250$ Ksymbols/second, $T_{\text{limit}} = 500$ ms, $\delta = 0.01$, and the largest distance in the network $d_{\max} = 200$ meters, which corresponds to a slot length of $\tau = 0.66\mu s$.

In Figure 3, we compare the energy efficiency for joint modulation-order-and-backoff-probability adaptation, modulation-order-only adaptation, and backoff-probability-only adaptation. In the modulation-order-only adaptation, we arbitrary fix the backoff probability at $p = 4.2539 \times 10^{-6}$ (any other fixed value of p gives a similar behavior). In the backoff-probability-only adaptation, we fix the modulation order at $M = 16$. From Figure 3, we first note that the joint M-and-p adaptation provides the best energy-efficiency among the three schemes. Furthermore, we observe that the backoff probability has a big impact on η. Specifically, under a fixed modulation order ($M = 16$), p can be adapted to the traffic load such that the system energy-efficiency remains constant irrespective of λ. This behavior is valid as long as the traffic load is within the capacity region of the current modulation order. In contrast, if p is fixed, the turning point of the traffic load where the system needs to shift to a higher order modulation to save energy is about 100 packets/second smaller than that when p is adaptive.

A key approximation in our analysis is that $N_{\text{CCS}}\frac{T}{\tau} \ll N\text{E}\{B_i\}$, so that (12) holds. We justify this approximation using Figure 4, where the p^o (the optimal backoff probability) is plotted as a function of λ. For illustration purposes, consider the segment of the graph when $M = 2$. When $\lambda < 200$ $p^o < 10^{-5}$. It is easy to verify that $\text{E}\{B_i\} = \frac{1}{p^o} > 10\frac{T}{\tau}$.

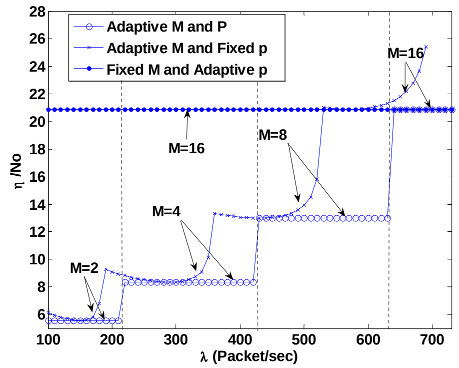

Fig. 3. Normalized energy efficiency vs. traffic load.

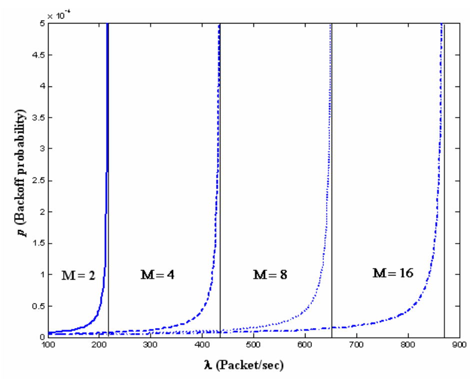

Fig. 4. Optimal backoff probability vs. traffic load.

Noting $N_{\text{CCS}} \leq N$, it can be asserted that $N_{\text{CCS}}\frac{T}{\tau} \ll N\text{E}\{B_i\}$. On the other hand, as λ approaches the capacity region, Figure 4 shows that $\text{E}\{B_i\}$ is comparable to the length of a packet. It can be verified from (23) that P_{busy} approaches 1 in this case. According to (22), it is expected that $N_{\text{CCS}} \ll N$. This makes our approximation still accurate. Similar observations can be made for other modulation order because of the similar behaviors of p^o and P_{busy}.

Finally, to validate our analysis, we compare our energy-efficiency expression (26) with the simulation results in Figure 5. Using CSim, we simulate a non-persistent CSMA system consisting of 500 nodes distributed over a 100×100 square (in meters). We set $\lambda = 400$ packets/second and $M = 8$. Three backoff policies are simulated: a geometric backoff, a uniform backoff, and a binary exponential backoff [4]. The parameters for the latter two policies are set in such a way that their average backoff steps are equal to that of the geometric policy with a given p. From Figure 5, it is noted that the analytical expression well approximates the simulation results. In addition, we can observe that the distribution of the backoff policy has a minor impact on the energy efficiency as long as the average backoff periods are the same. Similar observations were also reported in [4].

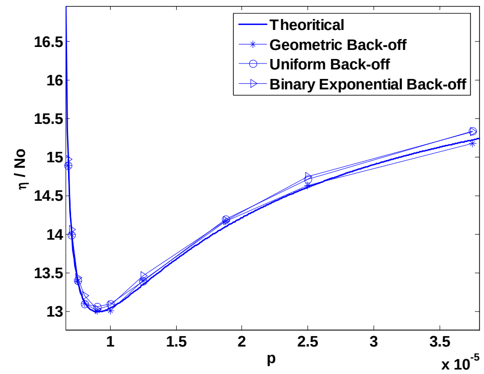

Fig. 5. Energy efficiency vs. backoff probability under different distributions for the backoff duration.

V. CONCLUSIONS

In this work, we developed a cross-layer design for non-persistent CSMA, typically used in wireless sensor networks. Our design combines adaptive modulation at the physical layer and adaptive backoff at the MAC layer for the purpose of maximizing the communication energy efficiency. The modulation order and the backoff probability at each node are periodically adapted according to the traffic load. Numerical results demonstrated the significant energy-efficiency improvement of this joint optimization over the backoff-probability-only and the modulation-order-only adaptations. Although a geometric distribution for the backoff process was used in our analysis, our simulations verified that the performance is not significantly impacted by the distribution of the backoff processes.

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