Adaptive Cross-Layer MAC Design for Improved Energy-Efficiency in Multi-Channel Wireless Sensor Networks

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Abstract

We present a novel cross-layer design for improving energy efficiency in a wireless sensor network that utilizes a multi-channel non-persistent CSMA MAC protocol with adaptive MQAM modulation at the physical layer. Cross-layer interactions are achieved through joint, traffic-dependent adaptation of the backoff probability at the MAC layer and the modulation order at the physical layer. The joint optimization of the backoff probability and the modulation order is conducted subject to a constraint on the packet retransmission delay. Such an optimization is shown to produce a significant improvement in the per-bit energy requirement for successful packet delivery. Our analytical findings are verified through numerical results and computer simulations.

I. INTRODUCTION

Wireless sensor networks (WSNs) have recently been used for numerous applications, including environmental monitoring, smart space, data collection, robotic exploration, etc, [1], [2]. The sensing devices in these applications are characterized by a limited battery lifetime, making energy efficiency a critical factor in the design of communication protocols [3] for WSNs. Current channel access protocols for wireless sensor networks can be divided into contention-based and scheduling protocols. Scheduling protocols, which include TDMA-, FDMA-, and CDMA-based schemes, are collision free. Among these protocols, TDMA-based designs are considered the most appropriate for WSNs [4]. However, many factors limit the use of TDMA protocols in WSNs, including scalability and adaptivity to network dynamics [5], [6]. For contention-based (random access) protocols, the most mature channel-access approach is the one that follows the carrier sense multiple Access (CSMA) paradigm. CSMA is characterized by simplicity, flexibility, robustness, and adaptivity to changes in the number of active nodes. No clock synchronization or global topology information are needed. 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, many other MAC schemes proposed for WSNs are similar to that of non-persistent CSMA. In non-persistent CSMA, a node senses the carrier only when it is about to transmit. This limits the time spent on monitoring the medium, and hence conserves energy [1], [8]. Both variants of CSMA have been extensively studied over the past three decades. Stationary throughput and delay characteristics were derived for slotted and unslotted channels, under finite-and infinite-population models [8], [9]. Analytical results related to the energy efficiency were reported for a slotted CSMA system with a finite population size [10], [11], [7]. In these works, the system consists of 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 data packets to transmit. The finite-population and heavy-traffic assumptions best describe the situation in a WLAN, but do not adequately characterize that of a WSN. In contrast to a WLAN, a WSN may consist of a large number (thousands) of nodes. Each individual node only contributes a small amount of traffic to the network through sparse access to the channel (i.e., low duty cycle). Such a setup makes a 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 multi-channel non-persistent CSMA MAC protocol for a WSN with an infinitely large node population. To improve the energy efficiency, which is defined as the energy consumption for successfully transmitting a bit, we consider the joint optimization of the modulation scheme (physical layer) and packet retransmission probability (MAC layer). 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. The key advantage of using a multi-channel scheme is that the traffic load in the network can be distributed over different channels, which leads to fewer collisions and improved capacity. As we show later, this allows for more energy saving and higher network utilization. It should be noted that multi-channel CSMA protocols for wireless networks have previously been considered [12], [13], [14], [15], [16]. It was shown that such protocols are more efficient than their single-channel counterparts. However, these previous works have not considered the joint optimization of the physical layer and the MAC layer, and thus leave the room for further energy efficiency improvement, which is the major goal of this work.

The remainder of this paper is organized as follows. In section II, the system model is presented. An analytical expression for the transmission delay is derived in section III. In section IV, the energy efficiency is optimized. Section V describes the proposed protocol. In section VI, numerical and simulation results are presented. Conclusions are presented in section VII.

II. SYSTEM MODEL

We consider the system in Figure 1. The available bandwidth R is divided into $J+1$ non-overlapping additive white gaussian noise (AWGN) channels. One channel is used for control, while the remaining J channels are used for data. Each data channel has a transmission rate R_i symbols/second. The functional abstraction of a node contains three components: a packet generator, an M-ary quadrature amplitude modulation (MQAM)-based physical layer, and a multi-channel non-persistent CSMA-based MAC layer (described in section VI). Packets have the same size, say L bits. A node only contributes an infinitesimal amount of traffic to the channel. Nodes collectively form a Poisson source with an aggregate rate λ packets/second. The traffic monitor, typically a sink in a WSN, periodically samples the traffic load over the various channels 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 takes an L-bit packet and generates $\frac{L}{\log_2 M}$ symbols. So the transmission time of a packet is $T_i = \frac{L}{R_i \log_2 M}$ seconds. As in [8], we consider a slotted system in which the slot duration τ corresponds to the maximum propagation time in the network. We let $a \overset{\text{def}}{=} \tau/T_i$.

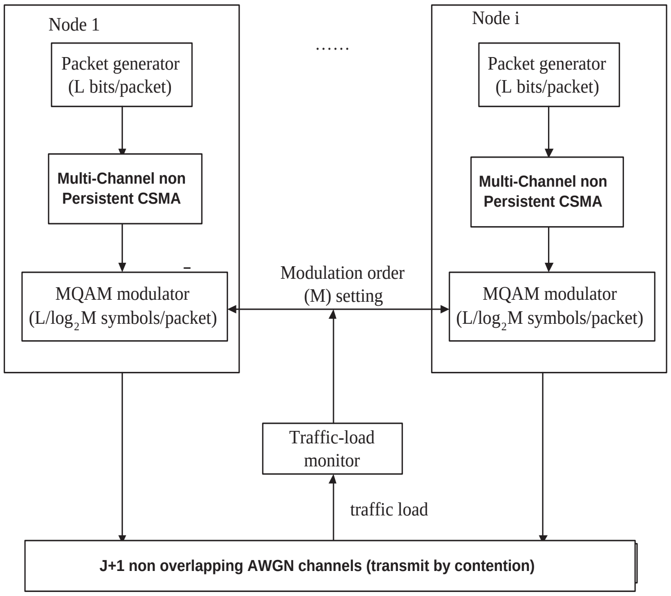

Fig. 1. System model of a node in a WSN.

The processing unit at the MAC layer is a packet of length $l = T_i/\tau$ slots. Communications is based on a slotted multi-channel version of a non-persistent CSMA protocol [8]. A tagged node will first sense the channels sequentially before it transmits a packet (the access mechanism is described later). The activity of sensing the channel is referred to as a *transmission attempt*.

Depending on the occupancy of each channel and the noise conditions, there are four possible outcomes following a transmission attempt at a given channel:

(i) The channel is busy, so the tagged node conducts a *backoff* before considering that channel again.

(ii) The channel is idle and the packet is transmitted, but a collision at that channel occurs during the transmission so the node backs off before considering that channel again.

(iii) The channel is idle and the packet is transmitted, but the transmission is corrupted by AWGN so the node backs off before attempting to transmit on that channel.

(iv) The channel is idle and the packet is successfully transmitted.

We denote the probabilities of the above four events 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 successive backoff durations at each channel constitute a sequence of independent and identically distributed ($i.i.d.$) geometric random variables, each with a success probability p. Later in the simulations, we relax this assumption and consider more realistic backoff policies: the uniform backoff and the binary exponential backoff [9]. We show that the distribution of the backoff has only a minor influence on the energy efficiency, provided that 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 $P_{corruption}$. 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 [17]:

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

where $\gamma \overset{\text{def}}{=} \frac{E_S}{N_0}$ 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 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. DELAY ANALYSIS

Before deriving the minimum per-bit energy efficiency, we first express the distribution of the packet transmission delay D in closed form.

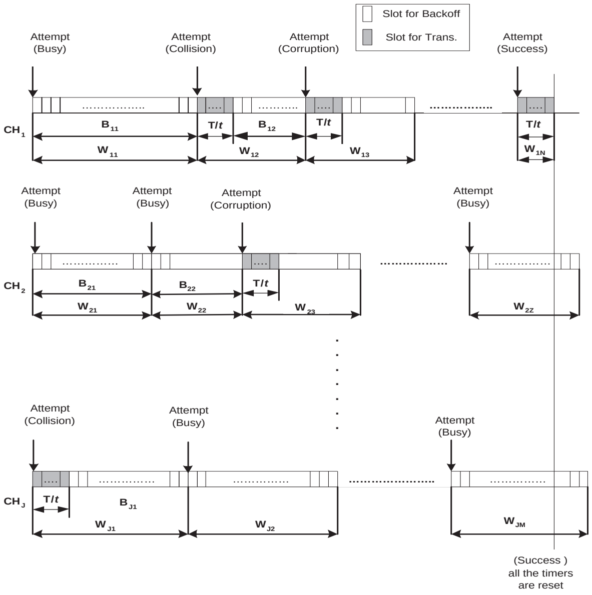

Fig. 2. Illustration of the channel access mechanism.

A. Single-Channel Non-Persistent CSMA

First, we consider the single data channel scenario (i.e., $J = 1$). Figure 2 shows the access process for a tagged packet that is generated at time t_0 and that 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. Let W_0 be the access delay between t_0 and the start of the next slot. Thus, D is given by:

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

In [18], 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., $\Pr\{N = n\} = (1-P_{success})^{n-1} P_{success}, \;\; n = 1, 2, \ldots$. For a non-persistent CSMA system with an infinite population and *without* AWGN, $P_{success}$ has been derived in [8]:

$$P_{success} = \frac{ae^{-aG}}{(1 - e^{-aG}) + a} \tag{3}$$

where G is the *offered load,* which represents the average number of combined new-and-retransmitted packet arrivals during the transmission time T. The relationship between G and the external traffic load $S \overset{\text{def}}{=} \frac{\lambda T_i}{J}$ has been derived in [8]:

$$S = \frac{Ge^{-aG}}{G(1 + 2a) + e^{-aG}}. \tag{4}$$

Accounting for the effect of the AWGN, the probabilities of success and corruption become:

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

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

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 jth attempt can be enumerated as follows:

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

where B_i is the number of backoff slots 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 [9] 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 [9] by using a recursive numerical algorithm. However, the results 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, 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. This assumption is reasonable, since the energy saving due to sleeping is often larger that the energy required to wake up the node. 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 $P_{success}p$.

B. Multi-Channel Non-Persistent CSMA

Figure 2 shows the multi-channel mechanism process for a tagged packet that is generated at time t_0 and is to be transmitted at the next slot over one of the available channels. At a given time, the node can transmit or receive only over one particular channel. For the multi-channel case, the packet transmission delay D that an arbitrary packet undergoes is given by:

$$D = \min\{D^{(1)}, D^{(2)}, \ldots.., D^{(J)}\} \tag{14}$$

where $D^{(i)}$ is the delay associated with channel i. Equation (14) reveals that the packet will be transmitted over the channel that has the minimum delay. From (13), $D^{(i)}$ was found to have a geometric distribution with parameter $P_{success}p$. Thus, its CDF is given by

$$F_{D^{(i)}}(k) = 1 - (1 - P_{success}p)^k. \tag{15}$$

Since D is the minimum of i.i.d. geometric random variables, it is CDF is given by:

$$F_D(k) = 1 - \prod_{i=1}^{J} [1 - F_{D^{(i)}}(k)]. \tag{16}$$

Substituting (15) into (16), we get:

$$F_D(k) = 1 - \prod_{i=1}^{J} (1 - P_{success} p)^k = 1 - (1 - P_{success} p)^{kJ}. \tag{17}$$

IV. ANALYSIS OF ENERGY EFFICIENCY

A. Minimum Energy-Per-Bit for A Successful Transmission

To evaluate the effectiveness of the proposed adaptive cross-layer design, we derive the minimum per-packet energy consumption that guarantees the delay requirement. 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

$$P_{loss} = \Pr\{D > K\} = F_D(K) = (1 - P_{success} p)^{KJ}. \tag{18}$$

To satisfy an upper bound δ on the packet loss probability, the minimum success probability must satisfy

$$P_{success} \geq \frac{1 - \delta^{\frac{1}{KJ}}}{p}. \tag{19}$$

Typical WSNs applications are characterized by low-power, low-rate, and short-distance communications. Under these conditions, the parameter $a = \frac{\tau}{T_i}$ is usually very small. 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), a is 2.5×10^{-4}. Thus, the first-order Taylor series expansion can be used to approximate e^{-aG} by $1 - aG$. By substituting this approximation in (4) and after some algebraic manipulations, we arrive at the following expression for the offered load G in terms of S:

$$G(S) = \frac{-[(a+1)S - 1] - \sqrt{[(a+1)S - 1]^2 - 4aS}}{2a}. \tag{20}$$

This expression is used in the following derivations to decide the energy-per-bit in terms of S.

From (5), we have

$$P_{success} = \frac{(1 - aG(S))(1 - P_{pe})}{G(S) + 1}. \tag{21}$$

Substituting (19) into (21), the maximum packet error probability that satisfies the delay requirement is given by

$$P_{pe} \leq 1 - \left(\frac{(G(S) + 1)}{(1 - aG(S))} \frac{(1 - \delta^{\frac{1}{KJ}})}{p} \right). \tag{22}$$

Accordingly, the maximum BER is given by

$$P_{be} \leq \left[1-\left(\frac{(G(S)+1)}{(1-aG(S))}\frac{(1-\delta^{\frac{1}{KJ}})}{p}\right)^{\frac{1}{L}}\right]. \tag{23}$$

Substituting (23) into (1), we arrive at a closed-form expression for the minimum energy-per-bit for a transmission:

$$\frac{E_b}{N_o} = -\frac{2}{3}\frac{(M-1)}{\log_2 M}\ln\left[5\left(1-\left(\frac{(G(S)+1)}{(1-aG(S))}\frac{(1-\delta^{\frac{1}{KJ}})}{p}\right)^{\frac{1}{L}}\right)\right]. \tag{24}$$

B. Analysis of the Average Number of Retransmissions

Since each node is equipped with one transceiver, a node can only transmit or receive over one channel at a time. Noting that each channel has the same probability of being occupied, it is obvious that the probability of success for the multi-channel case, $P_{success}^{(M)}$, is the same as $P_{success}$ for any channel. This result can be easily explained via a straightforward application of Bayes's rule:

$$\begin{aligned} P_{success}^{(M)} &= \sum_{i=1}^{J}\left[\Pr(success/Tx\ on\ channel\ i)\Pr(Tx\ on\ channel\ i)\right] \\ &= \sum_{i=1}^{J} P_{success}\left(\frac{1}{J}\right)P_{success}. \end{aligned} \tag{25}$$

At first, one may find this result surprising. It can be justified based on the fact that all the channels have the same probability of success and the same probability of being occupied. A similar argument can be used to show that the overall system's probability of collision and corruption (i.e., $P_{collision}^{(M)}$ and $P_{corruption}^{(M)}$) are given by $P_{collision}$ and $P_{corruption}$, respectively. For an arbitrary packet, let N be the total number of transmission attempts over all the channels until and including a successful transmission. The average number of actual transmissions can be expressed as

$$\begin{aligned} \mathrm{E}\left\{N_{\text{ccs}}|N\right\} &= N(P_{success}+P_{corruption}+P_{collision}) \\ &= N(1-P_{busy}). \end{aligned} \tag{26}$$

From (9), it can be shown that

$$P_{busy} = \frac{G}{1+G}. \tag{27}$$

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

$$\bar{N}_{\text{CCS}} = \bar{N}(1 - P_{busy}) = \frac{1}{1 - P_{pe}}. \tag{28}$$

Substituting (22) into (28), we end up with the average number of retransmissions for a tagged packet as a function of the traffic load S, a, and the backoff probability p:

$$\bar{N}_{\text{CCS}} = \frac{(1 - aG(S))}{(G(S) + 1)\frac{1-\delta^{\frac{1}{KJ}}}{p}}. \tag{29}$$

C. Optimization of Energy Efficiency

The previous analysis gives the energy consumption per bit. However, we are more concerned with the energy efficiency η, which is defined as the average energy consumption for successfully transmitting a single bit. Formally,

$$\eta \overset{\text{def}}{=} E_b\bar{N}_{\text{CCS}} = -\frac{2}{3}N_0\frac{M-1}{\log_2 M}\frac{1}{x}\ln 5\left(1 - x^{\frac{1}{L}}\right) \tag{30}$$

where

$$x \overset{\text{def}}{=} \frac{(G(S) + 1)}{(1 - aG(S))}\frac{(1 - \delta^{\frac{1}{KJ}})}{p}. \tag{31}$$

For (30) to hold, the following constraint must be satisfied:

$$0 \leq P_{be} \overset{\text{def}}{=} 1 - x^{\frac{1}{L}} \leq 0.2 \tag{32}$$

or equivalently,

$$\left(\frac{4}{5}\right)^L \leq x \leq 1. \tag{33}$$

In typical WSNs applications, all packets are eventually destined to the data collecting node (sink). Therefore, the sink can play the rule of the traffic-load monitor. We will show later one possible implementation of how the monitor can estimate the instantaneous channel throughput λ. Given the availability of traffic load information, our optimization problem minimizes η by controlling the modulation order M and the backoff probability p according to the instantaneous traffic load. Formally, the optimization problem is formulated as

$$\begin{cases} \text{minimize}_{\{M,p\}} \quad \left\{\eta = -\frac{2}{3}N_0\frac{M-1}{\log_2 M}\frac{1}{x(M,p)}\ln 5\left(1 - x(M,p)^{\frac{1}{L}}\right)\right\} \\ \text{such that} \\ \left(\frac{4}{5}\right)^L \leq x(M,p) \leq 1 \\ 0 \leq p \leq 1 \\ M \in \left\{2^i | i = 1, 2, \ldots\right\}. \end{cases} \tag{34}$$

Noticing that $G(S)$ is a function of M, it is obvious from (31) that x is a function of M and p.

As a result of the discrete nature of M, a variable-decomposition method to solve the optimization problem (34) can be used. For a fixed M, denote the conditional x by $x_M(p)$. The optimization problem in (34) can be reduced into the following single-variable optimization problem:

$$\begin{cases} \text{maximize}_{\{p\}} \quad \left(5 - 5x_M(p)^{\frac{1}{L}}\right)^{\frac{1}{x_M(p)}} \\ \text{such that} \\ x_M(p) = \lambda\frac{L}{R\log_2 M} + \frac{1-\delta^{\frac{1}{K}}}{p} \\ \left(\frac{4}{5}\right)^L \leq x_M(p) \leq 1 \\ 0 \leq p \leq 1. \end{cases} \tag{35}$$

It is easy to see that there is a one-to-one mapping between $x_M(p)$ and p. Therefore, the objective function in (35) is a single-variable function in p. Numerical algorithms can be used to solve this optimization problem. Denote the optimal solution to (35) by p_M^o. Utilizing the discrete nature of the modulation order, the optimal modulation order and backoff probability to problem (34), denoted by (M^o, p^o), are given by

$$(M^o, p^o) = \text{argmin}_{(M,p_M^o)}\eta(M, p_M^o), \quad M = 2^1, 2^2, \ldots. \tag{36}$$

V. PROTOCOL DESIGN

In this section, we describe the proposed multi-channel non-persistent MAC protocol. This protocol is based on RTS-CTS-data-ACK handshaking. We first summarize our main assumptions:

- The control channel has a bandwidth W_c, which is determined off-line and is fixed. The remaining bandwidth (the major part) is evenly divided among the J non-overlapping data channels.
- All the data channels have the same backoff distribution; the traffic is equally distributed over these channels (i.e., λ/J).

- Since there is no interference between data packets and control packets, a node that hears the CTS defers its transmission only until the end of the CTS packet. This allows for more parallel transmissions to take place.
- All the nodes can hear the control messages. The control packets are transmitted at the maximum power.
- Each data packet has a hop-count field, and each node increments this field by one before it transmits the packet. By noticing the hop count at the sink, the traffic load is estimated.

Whenever a node has a packet to send, it first senses the channels sequentially, starting from channel 1 and up to the first idle channel (if any). It then reacts as follows:

i. If there is no idle channel, the node initiates a backoff delay at all the channels, each according to a geometric random variable with parameter p (i.e., it delays its transmission at each channel to a later slot with probability p). When the first backoff timer expires, the node senses the corresponding channel. If it is busy, the node initiates a new backoff at that channel. Otherwise, it reacts as described in steps (iii), (iv), and (v).

ii. If there is an idle channel $j\ (j \leq J)$, then for each busy channel $i = 1, 2, \ldots j-1$, the node initiates a backoff delay according to a geometric random variable with parameter p and reacts as described in step (iii).

iii. At the first idle channel with expired backoff timer, the node transmits an RTS packet to the receiving node over the control channel, informing the receiver of its desire to transmit over the idle data channel. The receiver confirms the sender's channel selection via the CTS packet. Then, both the transmitter and the receiver tune to the agreed channel to start transmission.

iv. If a collision or corruption is detected (by the absence of an ACK message), the node backs off at that channel. At the next time slot, the node checks if any backoff timer expired during the packet transmission. It then sequentially senses the channels with expired backoff as well as the channels that had not initiated backoff timers. For the first idle channel that the node finds, step (iii) is repeated.

v. If the packet is successfully received, the receiver sends an ACK packet over the same data channel that was used for data transmission. Upon receiving the ACK packet, the node resets all of its backoff timers.

VI. NUMERICAL EXAMPLES AND SIMULATION RESULTS

In this section, we present numerical examples and simulation results for our proposed scheme. We conduct numerical experiments using MATLAB to evaluate the efficiency of the proposed joint backoff-modulation optimization. We also perform simulations using CSIM (CSIM is a C-based process-oriented discrete-event simulation package) [19] to validate our assumptions. In our numerical examples, we set $L = 1000$ bits, $R = 250 \times 10^3$ symbols/second, $T_{\text{limit}} = 500$ ms, $\delta = 0.01$, and the largest distance in the network $d_{\max} = 300$ meters, which corresponds to a slot length of $\tau = 1$ μs. Following [12], [13], we fix the bandwidth of the control channel to 10% of the total bandwidth R.

We compare our cross-layer adaptive optimization scheme with two adaptive schemes: modulation-order-only adaptation and backoff-probability-only adaptation. In Figure 3, we compare the energy efficiency for the three schemes. We let $J = 4$. In the modulation-order-only adaptation, we arbitrarily fix the backoff probability at $p = 2.0324 \times 10^{-5}$ (any other value of p gives a similar behavior). In the backoff-probability-only adaptation, we fix the modulation order at $M = 16$. This modulation order is selected because it can support the whole traffic load range plotted in Figure 3. The results indicate 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 certain modulation order, p can be adapted to the traffic load such that the system's energy efficiency remains constant irrespective of λ. This behavior is observed as long as the traffic load is within the capacity region of the current modulation order. In contrast, if p is fixed, much higher energy is consumed than when p is adaptive. Moreover, the turning point of the traffic load where the system needs to shift to a higher order modulation to save energy is smaller than that when p is adaptive.

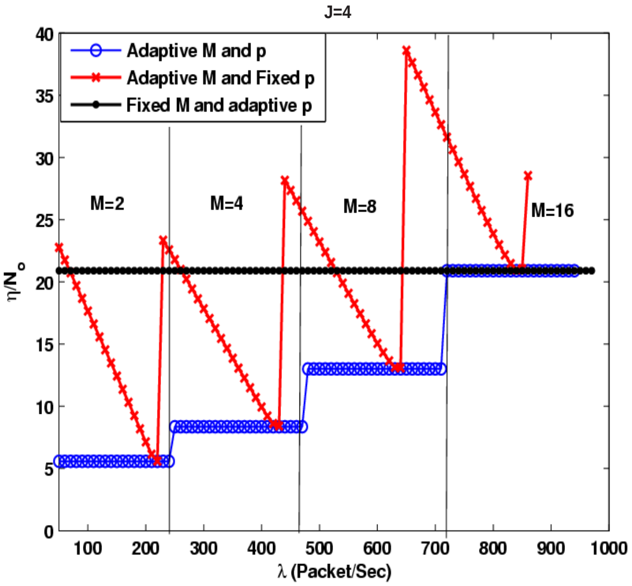

Fig. 3. Normalized energy efficiency vs. traffic load.

The effect of dividing the available bandwidth into multiple channels on the energy efficiency of our proposed joint modulation-order-and-backoff-probability adaptation can be seen in Figure 4. As J increases, the capacity region for each modulation order broadens significantly. This broadening is more profound for larger M (i.e., higher traffic load), allowing for a more significant energy saving. Since higher traffic load can be supported by a lower modulation order. Figure 4 shows that the best performance with the multi-channel protocol is achieved with 4 to 8 channels. As J increases beyond this range, no significant improvement is observed in the energy efficiency.

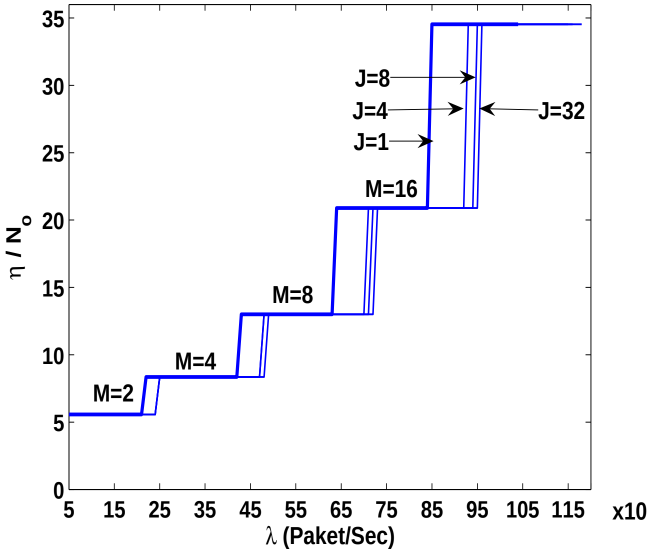

Fig. 4. Effect of J on the normalized energy efficiency for the joint adaptive scheme.

The effect of the proposed scheme on the channel utilization is shown in Figure 5. For illustration purposes, Figure 5 corresponds to the segment in Figure 4 where $M = 2$ (with $J = 1, 4, 16$). It is obvious that as J increases the channel utilization is slightly improved and at the same time the system can support a larger offered load G using a lower modulation order, extending the capacity regions associated with each modulation order. A similar observation can be made for other modulation orders.

A key approximation in our analysis is that $N_{\text{CCS}}\frac{T_i}{\tau} \ll N\text{E}\{B_{ij}\}$, so that (12) holds. We validate the appropriateness of this approximation in Figure 6, where p^o (the optimal backoff probability) is plotted as a function of λ for $J = 4$. For illustration purposes, we consider the segment of the graph when $M = 2$. When $\lambda < 250$, $p^o < 10^{-6}$. It is easy to verify that $\text{E}\{B_{ij}\} = \frac{1}{p^o} \gg \frac{T_i}{\tau}$. Noting that $N_{\text{CCS}} \leq N$, it can be asserted that $N_{\text{CCS}}\frac{T_i}{\tau} \ll N\text{E}\{B_{ij}\}$. As λ approaches the capacity region, Figure 6 shows that $\text{E}\{B_{ij}\}$ decreases. It can be verified from (27) that P_{busy} approaches 1 in this case. According to (26), it is expected that $N_{\text{CCS}} \ll N$. This makes our approximation quite accurate. Similar observations can be made for other modulation orders, because of the similar behaviors of p^o and

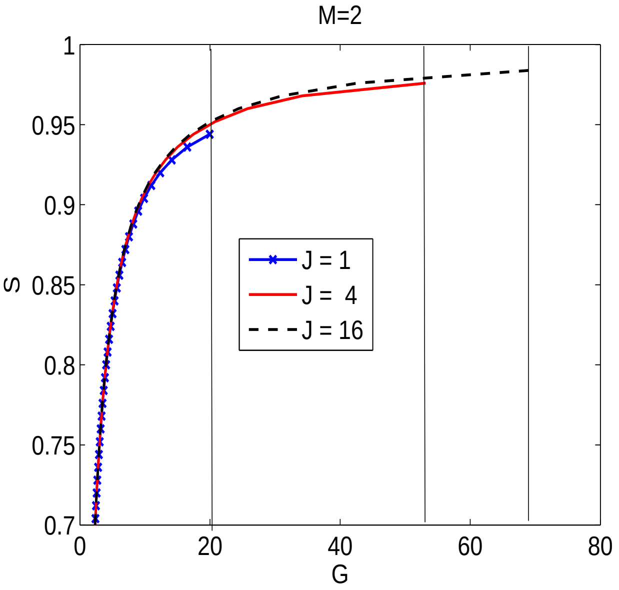

Fig. 5. Channel utilization vs. the offered Load.

P_{busy}.

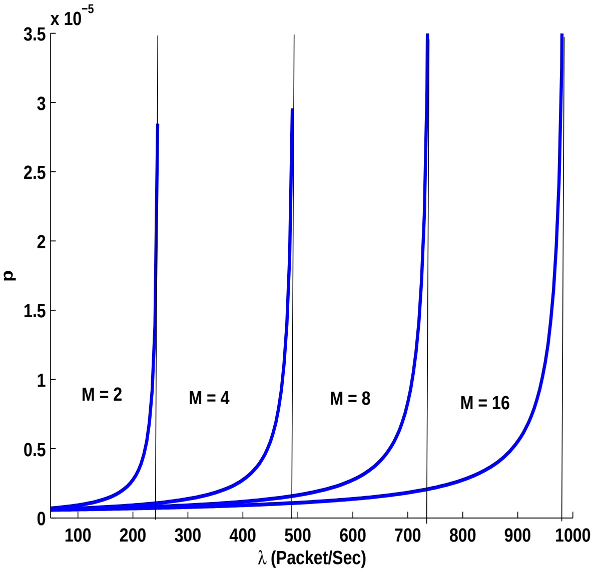

Fig. 6. Back-off probability vs. traffic load.

Finally, to validate our analysis, we compare our energy-efficiency expression (30) with the simulation results in Figure 7. Using CSIM, we consider a multi-channel non-persistent CSMA-based network of 500 nodes, randomly deployed over 100×100 (meter) square area. We set $\lambda = 550$ packets/second, $M = 8$, and $J = 4$. We study the impact of different backoff policies on our proposed scheme. Three backoff policies are simulated: a geometric backoff, a uniform backoff, and a binary exponential backoff [9]. The parameters for the latter two policies are set in such a way that their average backoff durations are equal to that of the geometric policy with a given p. From Figure 7, it is noted that the analytical expression follows the simulation results very closely. 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 [9].

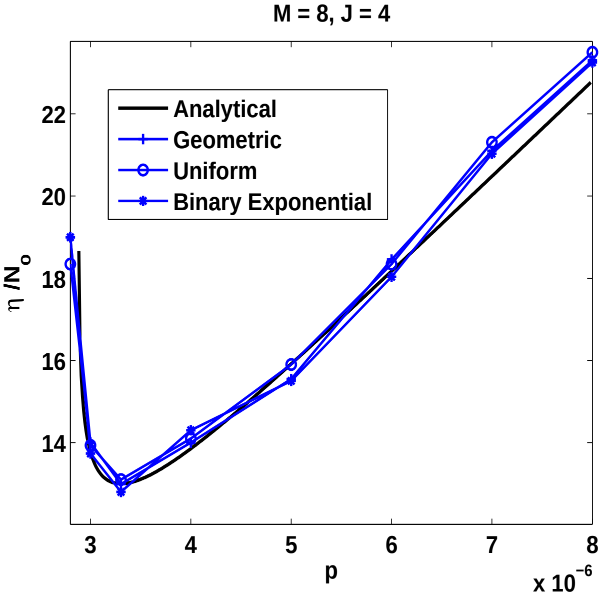

Fig. 7. Energy efficiency vs. backoff probability under different distributions for the backoff duration.

VII. CONCLUSIONS

In this work, we proposed a novel cross-layer design for multi-channel non-persistent CSMA, typically used in wireless sensor networks. Our design combines bandwidth partitioning and adaptive modulation at the physical layer with adaptive backoff at the MAC layer for the purpose of maximizing the energy efficiency. The modulation order and the backoff probability at each node are periodically adapted according to the traffic load. Numerical results demonstrate the significant improvement in the energy efficiency of this joint optimization over the backoff-probability-only and the modulation-order-only adaptations. We showed that the key advantage of using multiple channels is extending the capacity region for each modulation order. Therefore, a significant improvement in the performance, both in terms of energy efficiency and channel utilization, is achieved. 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 process.

REFERENCES

[1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, “A survey on sensor networks,” *IEEE Communications Magazine*, pp. 102–114, Aug. 2002.

[2] W. Ye, J.Heidemann, and D. Estrin, “Medium access control with coordinated adaptive sleeping for wireless sensor networks,” *IEEE/ACM Transactions on Networking*, pp. 493–506, June 2004.

[3] D. Estrin, R. Govindan, J. Heidemann, and S. Kumar, “Next century challenges: scalable coordination in sensor networks,” in *Proceedings of the IEEE/ACM MOBICOM ’99 Conference*, 1999, pp. 263–270.

[4] K. Sohrabi, J. Gao, V. Ailawadhi, and G.J. Pottie, “Protocols for self-organization of a wireless sensor network,” *Wireless Personal Communications*, pp. 16–27, Oct. 2000.

[5] A. Woo and D. Culler, “A transmission control scheme for media access in sensor networks,” in *Proceedings of the IEEE/ACM MOBICOM ’01 Conference*, July, p. 221235.

[6] W. Ye, J. Heidemann, and D. Estrin, “An energy-efficient mac protocol for wireless sensor networks,” in *Proceedings of the IEEE INFOCOM 2002 Conference*, 2002, pp. 1567–1576.

[7] R. Bruno, M. Conti, and E. Gregori, “Optimization of efficiency and energy consumption in p-persistent csma-based wireless lans,” *IEEE Transactions on Mobile Computing*, vol. 1, no. 1, pp. 10–31, Jan.-Mar. 2002.

[8] L. Kleinrock and F. A. Tobagi, “Packet switching in radio channel: Part 1 carrier sense multiple-access modes and their throughput-delay characteristics,” *IEEE Transactions on Communications*, vol. 23, no. 12, pp. 1400–1416, Dec. 1975.

[9] Y. Yang and T. S. Yum, “Delay distribution of slotted aloha and csma,” *IEEE Transactions on Communications*, vol. 51, no. 11, pp. 1846–1857, Nov. 2003.

[10] D. Bertsekas and R. Gallager, *Data Networks*, New York: Prentice-Hall, 1987, second edition.

[11] D. S. Chan, T. Berger, and R. Bridgelall, “Energy efficiency of csma protocols for wireless packet switched networks,” in *Proc. of IEEE WCNC’04 conference*, 2004, pp. 447–452.

[12] A. Nasipuri and S. Das, “Multichannel csma with signal power-based channel selection for multihop wireless networks,” in *Proc. of IEEE Fall Vehicular Technology Conference (VTC 2000)*, Sep. 2000.

[13] N. Jain, S. R. Das, and A. Nasipuri, “A multichannel csma mac protocol with receiver-based channel selection for multihop wireless networks,” in *Proc. of IEEE IC3N 2001*, 2001.

[14] A. Muir and J.J. Garcia-Luna-Aceves, “A channel access protocol for multihop wireless networks with multiple channels,” in *Proc. of IEEE ICC’98, Alanta, Georgia*, June 2001, pp. 1617–1621.

[15] A. Muir and J.J. Garcia-Luna-Aceves, “Hop-reservation multiple access (hrma) for multi packet radio networks,” in *Proc. of IC3N’98*, Oct. 1998.

[16] Yu-Chee Tseng, Shih-Lin Wu, Chih-Yu Lin, and Jang-Ping Sheu, “A multi-channel mac protocol with power control for multi-hop mobile ad hoc networks,” in *Proceedings of 21st International Conference on Distributed Computing Systems Workshops*, Apr. 2001, pp. 419–424.

[17] A. J. Goldsmith and S. G. Chua, “Variable-rate variable-power mqam for fading channels,” *IEEE Transactions on Communications*, vol. 45, no. 10, pp. 1218–1230, Oct. 1997.

[18] L. Kleinrock, *Queueing Systems Volume II: Computer Applications*, New York: Wiley, 1976.

[19] *Mesquite Software Incorporation*, http://www.mesquite.com.