Energy-aware Adaptive MAC Protocol for Real-time Sensor Networks

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***Abstract*—One of the important objectives in Wireless Sensor Networks (WSNs) is to minimize energy consumption while satisfying delay constraints. Although, several energy-aware MAC layer protocols exist, the absence of channel adaptation and load adaptation results in energy wastage due to retransmissions and low success rate. In this paper, we propose an Adaptive-CSMA/CA protocol which accounts for varying channel and load conditions at a node by influencing the selection of either low energy or low delay transmission option. We devise an energy-delay metric that helps a node select the best message and modulation to obtain joint reduction in energy and delay at the time of transmission. Our simulation results show that the proposed Adaptive-CSMA/CA scheme results in upto 87% improvement in energy consumption under varying channel conditions and upto 150% higher success ratio under varying load as compared to the CSMA/CA specified in IEEE 802.15.4.**

I. INTRODUCTION

IEEE 802.15.4 has been widely adopted as a standard for the Wireless Medium Access Control (MAC) and Physical Layer (PHY) specifications for Low-Rate Wireless Personal Area Networks (WPANs) including WSNs. Carrier sense multiple access with collision avoidance (CSMA/CA) mechanisms have been used for contention based medium access for WSNs because of their energy saving features. However, the absence of adaptation to varying channel conditions leads to energy wastage due to retransmissions by nodes experiencing deep fading. The readings of a sensor node that is deployed for the purpose of data monitoring and control must reach the receiver by the intended deadline for real-time decision making. Each sensor message is either transmitted to its destination before its deadline or is discarded. Higher transmission rates lead to low transmission delays but also incur higher energy. Thus energy consumption and delay have an inherent tradeoff.

Dynamic Modulation Scaling (DMS) has been studied as an effective rate adaptation scheme for real-time networks [3], [4]. It trades off transmission energy with transmission latency in networks employing wireless communications. We propose an adaptation of the slotted CSMA/CA described in IEEE 802.15.4 combined with the Dynamic Modulation Scaling scheme for a soft real-time WSN. Depending on channel state and the load index at a node, the best modulation level can be selected such that the energy consumption can be reduced and the goodput of the system can be increased. Our adaptive CSMA/CA is implemented in an entirely distributed manner. The runtime variations occur as a result of integrating the channel and load state information at each node.

We focus on the combined reduction in energy consumption and transmission delay while considering the time varying channel and the real-time nature of the messages. However considering that the two metrics have an inherent tradeoff, we propose an energy-delay metric which is a weighted linear combination of the transmission energy and transmission delay. At times when the node is heavily loaded, the metric selects the low delay option for faster data transmission. Alternatively, when the node is lightly loaded, the metric selects low energy option to reduce energy consumption.

The paper is organized as follows: we explain the system model in section II. The protocol details are in section III. In section IV we present the simulation results, cite related research in section V and conclude the paper in section VI.

II. SYSTEM MODEL

A. PHY Layer

We use the frequency flat Rayleigh fading channel to model the time varying fading wireless channel between two devices. Each link is assumed to be constant during a packet transmission and vary independently according to a Rayleigh distribution. In order to make the communication system energy aware, we use DMS [3] which uses Quadrature Amplitude Modulation (QAM) as the transmission scheme. Let k denote the number of bits per modulation constellation symbol. The basic idea of DMS is to vary the number of bits per symbol while keeping the symbol rate constant. For a packet of fixed size, this results in an energy-delay pair for each modulation level. At higher modulation level, a packet can be transmitted at higher energy than a message at lower modulation level. However, the transmission delay of the message at higher modulation level is less than that of a lower modulated message. The best modulation level can be chosen depending on whether the packet needs to be transmitted in an energy-efficient manner or a delay-efficient manner. As we explain later, this tradeoff can be leveraged by noticing that at times operating at higher modulation level is beneficial and at other times the reverse could be more efficient. Table I specifies relevant symbols used in the paper.

In order to reliably transmit a packet from source to destination, the transmitted signal power must be enough to combat the erroneous channel. We fix the bit error probability, P_b, for reliable transmission as 10^{-6}. Given the instantaneous channel

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TABLE I
RELEVANT SYMBOLS

k	Modulation Level
d	Transmitter-Receiver distance
G_R	Antenna gain
λ	Wavelength of the transmitted signal
A_R	Effective area of the antenna
SNR	Signal to noise ratio
R_s	Symbol rate
h	Channel gain
W	Channel bandwidth(Hz)
P_b	Bit error probability
E_{CCA}	Energy consumption per channel sample
E_{ACK}	Energy consumption per acknowledgement

gain, h and the Signal to Noise ratio (SNR), the required bit error probability in case of QAM can be calculated as [8],

$$P_b \geq \frac{4}{k} \cdot Q\left(\frac{3 \cdot h^2 \cdot SNR}{(2^k - 1) \cdot R_s}\right)^{\frac{1}{2}} \tag{1}$$

where Q function is defined as, $Q(z) = \int_z^\infty \frac{1}{\sqrt{2\pi}} e^{-y^2}\, dy$ and k can take values from the set $K = \{2, 4, 6, 8, 10\}$.

Alternatively, by fixing P_b, we can find the minimum received SNR required for the signal to be correctly demodulated at the receiver for each value of k as,

$$SNR_{min} = Q^{-1}\left(\frac{k \cdot P_b}{4}\right) \cdot \frac{2^k - 1 \cdot R_s}{3 \cdot h^2} \tag{2}$$

From the received SNR, the transmitted power, P_{tx}, can be found as

$$P_{tx} \geq \frac{SNR_{min} \cdot A_d \cdot N_0}{A_R} \tag{3}$$

$$A_R = \frac{G_R \cdot \lambda^2}{4 \cdot \pi} \tag{4}$$

where the effective area in which power radiates is given by

$$A_d = c \cdot d^{\alpha} \tag{5}$$

where c is a constant and α takes values between 2 to 5. The transmitted power values P_{tx} will be calculated for each k. Given that each transmitter has a limit on the maximum output power value, P_{max}, the values of k for which $P_{tx} \geq P_{max}$ will be discarded. The corresponding channel transmission rate in bits per second can be calculated as Wk. The time, t, taken for transmitting an L-bit message in the wireless medium is calculated as $\frac{L}{Wk}$. The energy per transmitted signal can be calculated as $P_{tx}.t$.

Thus the information about the current state of the channel decides the appropriate power level for the transmitted signal and the possible modulation levels.

B. MAC Layer

The IEEE 802.15.4 MAC standard specifies a beacon enabled mode for the purpose of channel state estimation. We consider the active part of the superframe to be made up of beacon slot and Contention Access Period (CAP) slots only. For superframe structure, we set beacon order, BO = 5 and superframe order, SO = 0, which gives a duty cycle of 3.25% and the duration of the active part of the superframe as 15.36 ms. All other CSMA/CA parameters are assumed to be the default values as defined in IEEE 802.15.4 standard.

IEEE 802.15.4 does not have any option for finding out the channel state, except from the beacon transmission at the start of every superframe. The nodes in the cluster receiving the beacon can calculate the Link Quality Indicator which can be used to find the channel quality [2], [10]. The channel under consideration is a time variant channel. Considering that the frequency of beacon transmission depends on the values of BO and SO which are defined by the application, the beacon might not provide up to date information about the channel quality. For such cases, we propose the inclusion of multiple beacon transmissions per superframe depending on the coherence time of the channel.

Coherence time is a statistical measure of the time duration over which the channel impulse response is essentially invariant [8]. The coherence time is inversely proportional to the maximum doppler shift. To illustrate the wide variation in coherence time, consider two sample application scenarios: a sensor network deployed for the data monitoring of an electrical transmission line [9] and one that is deployed for wildlife monitoring. In the transmission line application, there could be vehicles moving at high speed (≈45km/hr) in the vicinity of the transmission towers and hence the maximum doppler shift will be greater (typically of the order of 100 Hz). In the case of wildlife monitoring, if we assume that the entities are moving at a velocity of (≈4.5 km/hr), then the maximum doppler shift will be of the order of 10 Hz. The coherence time can be calculated as 4.23 ms in the former case and 42.3 ms in the latter case. Given the different time scales with which the channel might vary, a single beacon transmission per superframe may lead to obsolete channel state information in the former case. Therefore, in our scheme, we include multiple beacons in the active period of the superframe depending on the application and the coherence time of the channel. The inclusion of extra beacon frames leads to the added overhead in terms of extra energy consumption for the transmission and reception and also adds to the delay. However, as shown by our simulations, this overhead is shadowed by the energy saved due to channel aware transmissions.

III. CHANNEL AND LOAD STATE AWARE CSMA/CA

With the advent of new sensor technologies, it is possible to integrate a large number of sensors in one sensor node. We assume here that each node is equipped with a suite of sensors, maximum being m. Given the application requirement, the sampling frequencies could be predecided and may be different from one another. For example, while monitoring the electrical overhead transmission lines, temperature variations on the transmission line happen at a much smaller time scale than the variation in tilt of the transmission tower. Also sensors sample the environmental parameters which tend to change gradually. For slow varying phenomenon, the successive sensor readings might not differ from each other. In such scenarios, the repeating sensor measurements can be discarded to avoid expenditure of communication energy. Thus after each sampling

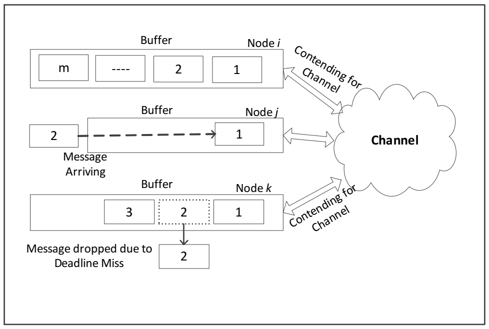

Fig. 1. Channel Contention amongst nodes

the reading is compared with the previous reading. A close match results in discarding the redundant message.

Each sensor message, i in the suite is characterized by the tuple $\{G_i, D_i, P_i\}$, where G_i is the generation time of the sensor message, D_i is the deadline of the message and P_i is the period of the message. All the sensors in the suite sample periodically. At each period, the sensor reading constitutes a message. If relevant, this message needs to be transmitted before the deadline.

In contention based access protocols, the nodes start contending for a channel in the active period of the superframe, if they have at least one backlogged message. During the contention period, the message stays in the node buffer till either the node wins contention and transmits the message. Else if the message is not transmitted by its deadline, the message is dropped. Thus at any time in the sensor buffer there can be at most one message from each sensor stream and in total there can be a maximum of m messages. The different scenarios are represented in Fig. 1. During the contention period, the node might get more messages from other sensors in its suite. Also varying deadlines means different sensors contribute differently to the load with the contribution being inversely proportional to the period. Load index of a node is calculated as,

$$LI = \sum_{i=1}^{m} \frac{WCTx_i}{P_i} \tag{6}$$

where $WCTx_i$ is the worst-case transmission time of a message. The load index of a node is the sum of the utilization demands of the messages in its buffer. After each message transmission, the load index is reduced. In order to maximize this reduction, the message with the smallest P_i must be picked for transmission.

Consider a network of nodes contending for exclusive access to the channel. The method of contention is the same as the slotted CSMA/CA described in IEEE 802.15.4 specifications [7]. Fig. 2 shows the sequence of steps followed by each node for the joint selection of message and modulation. Each node follows these steps after winning contention and acquiring the channel. Once a node wins contention, there are two choices to be made:

- which message should be picked for transmission, and
- what modulation level should be used to transmit this selected message.

With respect to the message selection, the node makes a greedy decision of selecting the message with the least P_i, so that its load index can be reduced by the maximum amount (step 2). The channel state influences the required transmission power and hence the transmission energy to meet bit error restriction (step 3). Given the power restrictions, it means selecting which modulation levels are possible (step 4). Amongst the possible modulation levels, the load index influences the selection of the best (step 8).

In order to select the best modulation level for transmission, we propose a novel metric called the *energy-delay metric*, M_i as,

$$M_i = \beta \cdot E_i + \gamma \cdot D_i \tag{7}$$

where E_i is the normalized transmission energy consumption and D_i is the normalized transmission delay, at modulation level i.

$$\gamma = 1/LI, LI \leq 1 \tag{8}$$

$$\beta = 1 - \gamma \tag{9}$$

The modulation level i for which the metric M_i has the minimum value is the best modulation level under the current channel and load conditions. Since the objective is the combined reduction of energy and delay, the minimum value of the metric selects the best option. If the node is heavily loaded, the modulation with the least transmission time (D_i) is selected by the metric. Alternatively, if node is lightly loaded, the modulation with the least transmission energy (E_i) is selected. Thus, channel and load variations influence the selection of either low energy or low delay transmission.

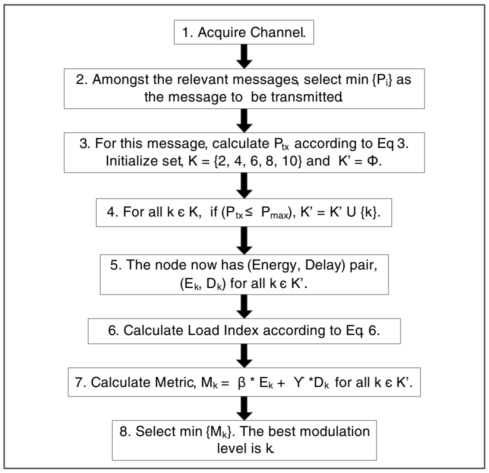
1. Acquire Channel.
2. Amongst the relevant messages, select min $\{P_i\}$ as the message to be transmitted
3. For this message, calculate P_{tx} according to Eq 3. Initialize set, K = {2, 4, 6, 8, 10} and K' = Φ.
4. For all k є K, if ($P_{tx} \leq P_{max}$), K' = K' U {k}.
5. The node now has (Energy, Delay) pair, (E_k, D_k) for all k є K'.
6. Calculate Load Index according to Eq 6.
7. Calculate Metric, $M_k = \beta * E_k + Y * D_k$ for all k є K'.
8. Select min $\{M_k\}$. The best modulation level is k.

Fig. 2. Joint selection of message and modulation at a node

IV. PERFORMANCE EVALUATION

Due to the unavailability of devices that implement DMS, we build a custom Java simulator for performance evaluations. We perform extensive simulations to quantitatively assess the performance of our scheme, Adaptive-CSMA/CA and the one used in IEEE 802.15.4, referred to as CSMA/CA. For fair comparison, the transmission energy and transmission time of each message in CSMA/CA is calculated with respect to the QAM scheme with k = 2. The performance metrics of interest are normalized total energy consumption and success ratio. Total energy consumption, E_t is computed as,

$$E_t = (P_{tx}+n\cdot P_{rx})t_{Beacon}\cdot i+2\cdot E_{CCA}+(P_{tx}+P_{rx})t_{Data}+E_{ACK}+C \tag{10}$$

where n is the number of nodes in the system and i (=3) is the number of beacon transmissions per superframe for up-to-date channel state information, t_{Beacon} and t_{data} are the beacon and data transmission times respectively, P_{tx} and P_{rx} are the transmission and reception power per message respectively and C is the energy overhead for transmission and reception circuitry.

Success ratio is the ratio of successful transmissions to the total number of messages generated. Generally, unsuccessful transmissions could be either due to the transmission of message while the channel is in a deep fade, collision with another packet or a deadline miss while waiting in the node buffer. Considering that the wireless link is assumed to be constant during a packet transmission and the packet transmission power is adapted to be enough to combat the channel according to Eq. 3; and collisions are avoided by the CSMA/CA protocol, the loss of a packet is only due to violation of its deadline due to the delay in its transmission. Lower the transmission delay of a message, the faster the node will relinquish the channel and the earlier it is available for another contending node. Thus, success ratio affects the transmission delay.

A. *Simulation Parameters*

We consider a star topology with a Personal Area Network (PAN) coordinator and 10 nodes. This is because the other topology proposed by the standard, peer-to-peer topology, suffers from beacon frame collisions when the beacon enabled mode is used [11]. The nodes are at a distance of 50m from the PAN coordinator. The nodes being equidistant, removes the effect of path loss so that the effect of fading can be studied. The values of other parameters are as follows: R_s= 3Mbps, N_0 = 4.11* 10^{-16}, G_R = 3.3dB, λ = .125m, P_b = 10^{-6}, data packet size, L = 1024B, beacon packet size, B = 200B, E_{CCA} = 17.3μJ [12], t_{Beacon} = 266μ sec, P_{tx} and P_{rx} for beacon = 80.5mW, WCTx = 1365 μsec. P_{tx} and P_{rx} for data packets are calculated depending on the channel gain. Each point on every plot is an average of 20 simulation runs. For a plot, the energy values are normalized with respect to the highest energy consumed amongst the two schemes in that plot. We simulate diverse scenarios and our results archive better energy savings and success ratios than the existing CSMA/CA scheme.

B. *Effect of Channel*

Fig. 3 compares the performance of Adaptive-CSMA/CA over CSMA/CA with respect to energy consumption and success ratio. We use the threshold model used in [2] to gauge the channel quality. Channel health rate is defined as the ratio of the number of times channel was in good condition to the total number of times the channel was sampled for transmission. For each node load is kept constant at 0.25 and percentage of redundant nodes is constant at 0%. Since CSMA/CA never adapts to the varying channel, huge amount of energy is wasted during retransmissions. Because of the added delay due to retransmissions, the messages waiting in the buffer miss their deadlines, thus reducing the success ratio.

C. *Effect of Number of Contenders*

The number of contenders effect the contention delay experienced by nodes. With increasing contention delay, the number of messages missing their deadlines increase which leads to lower success ratios. Also, as contention delays increase, more messages are waiting in the buffer, which increases the load indices of nodes. Greater load indices lead to nodes selecting higher modulation levels, hence increasing the energy consumption. In both cases, as shown in Fig. 4, Adaptive-CSMA/CA performs better than CSMA/CA.

D. *Effect of Load*

Fig. 5 shows the effect of load variation, where the performance is characterized with delay-only and energy-only schemes too. For these two cases, the modulation level chosen is always the one with the least transmission delay and the least transmission energy respectively. The performance of these two schemes shows the influence of ignoring the effect of load index, while the performance of CSMA/CA is due to the use of a single fixed modulation scheme. The results reinforce the finding that metric based Adaptive-CSMA/CA strikes a balance between low energy and low delay schemes. However, in cases of high load, Adaptive-CSMA/CA trades off energy consumption for improvement in success ratio. At high load conditions, the metric decides for higher modulation levels, thus improving the success ratio but expending more energy,

E. *Effect of Redundancy*

Fig. 6 shows the effect of varying number of redundant nodes. As expected, energy consumption reduces linearly as the number of relevant messages decrease. The success rate shows similar increasing trend. In both cases, Adaptive-CSMA/CA performs better than CSMA/CA.

V. RELATED WORK

The effect of fading in wireless channels is known to reduce goodput and increase the amount of power wasted in retransmissions [2]. Channel-aware variable rate systems [6] have been proposed to enhance throughput in wireless environments. But the focus has been on reduced latency and increased throughput rather than energy consumption.

In [1], a channel varying scheme is devised for a TDMA system, where messages are postponed till the channel transitions into a good state. However, a waiting mechanism like this is not suitable for real-time messages.

In order to improve the energy and delay efficiency of a network using contention based schemes, several protocols use the contention window adaptation method. In [5], authors present separate optimal contention window sizes for energy optimized and delay optimized scenarios. In [13], authors use the combination of queue and channel state information. But in both the cases, the contention window optimization needs to be done by a centralized coordinator incurring overheads.

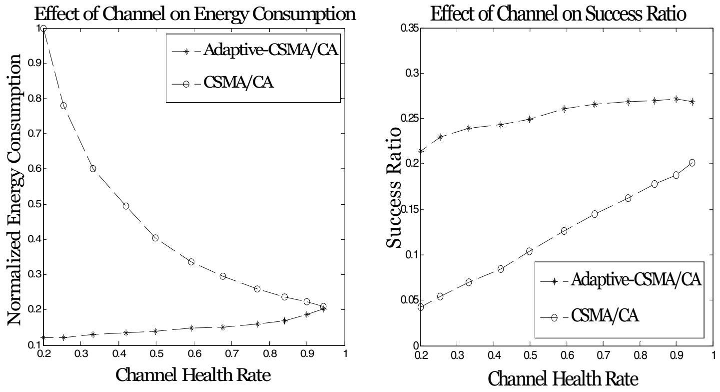

Fig. 3. Effect of channel variation

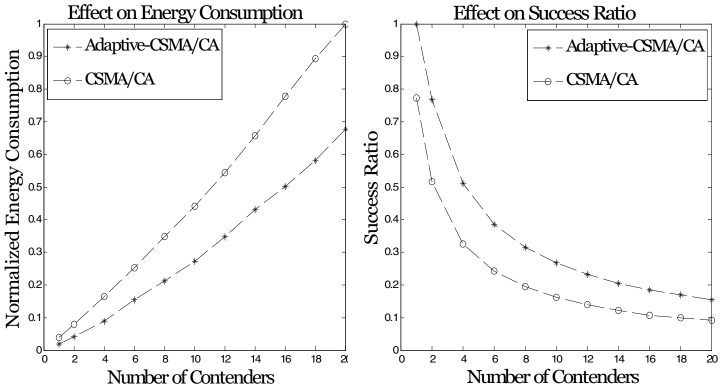

Fig. 4. Effect of variation in number of contenders

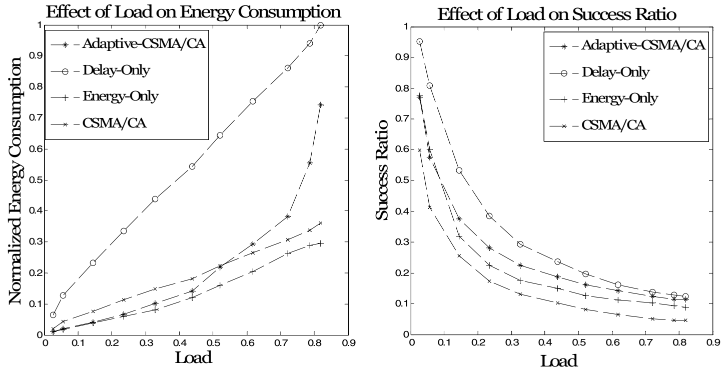

Fig. 5. Effect of variation in load

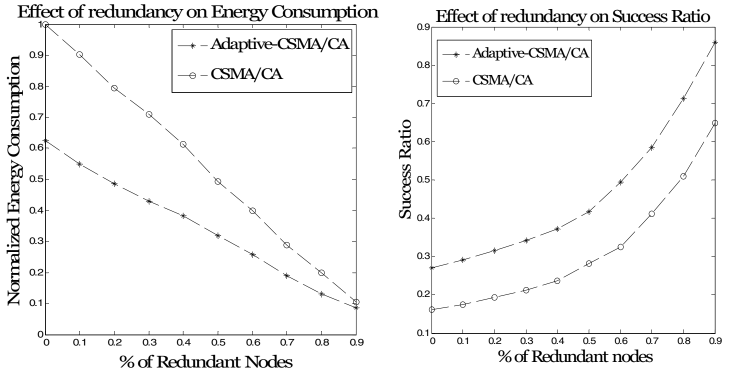

Fig. 6. Effect of variation in sensing redundancy

DMS has been used for the energy efficient real-time scheduling of messages in [4] and [14] etc. We propose the use of DMS for energy and delay efficient operation in the existing IEEE 802.15.4 protocol. Thus, our work differs from the existing research as we consider the combined effects of channel variation with the instantaneous load for the joint reduction of energy consumption and delay of a soft real-time WSN in a distributed manner.

VI. CONCLUSION

IEEE 802.15.4 defines a fixed set of transmission rates and does not provide methods for adapting to the time varying channel which leads to low success ratio and wasted energy due to retransmission attempts. In this paper, we show that adapting the transmission strategy with respect to the instantaneous load and channel by dynamically changing the transmission energy and rate through the use of dynamic modulation scaling can lead to lower energy consumption and higher success ratios. Our proposed scheme jointly improves the energy consumption and success ratio as compared to the IEEE 802.15.4 CSMA/CA under varying scenarios.

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