An Energy efficient scheduling scheme for wireless sensor networks

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***Abstract*—We consider Energy efficient multiple access control protocol in wireless sensor networks. With the perspective of a synchronous and schedule access protocol, an optimization problem is formulated to schedule operation modes (transmit, receive and sleep) throughout the network. Using dual decomposition, a protocol is designed collaboratively by sensor nodes over time, each node determines its own schedule. This protocol attains statistical convergence with respect to time-varying channel state information in the time of its scope. Numerical results demonstrate the effectiveness of this protocol in terms of consumed energy in comparison with classical protocols as a result of eliminating *idle listening* in the network.**

***Index Terms*—Multiple access, optimization, scheduling, statistical convergence, wireless sensor networks.**

I. INTRODUCTION

Wireless sensor networks (WSNs) are becoming a promising technology in environmental monitoring and distributed data processing [1]. A WSN consists of a number of small and low-cost nodes deployed in an environment. These nodes sense and forward target data to a central sink in a collaborative and distributed manner. WSNs are typically characterized by energy-constrained sensor nodes. In particular, these nodes are battery-powered and cannot generally be recharged after being deployed. A significant amount of energy in a node is wasted by the radio component when it is in *idle listening* with no activity [2]. Alternatively, one possible solution is to maximize the network life-time through energy-efficient protocols.

One key protocol in wireless networks is medium access control (MAC) protocol. This protocol schedules the nodes access to the broadcast channel in order to avoid interference using a centralized or a distributed manner. Following a MAC protocol, a sensor node switches its own radio *on* to be in active mode. In this mode, a node can either transmit, or receive or be in idle listening. After a period of time with no activity, the node switches its radio *off* and enters the sleep mode to save energy. Ideally, a sensor node should be active only during transmit and receive operations. Therefore, an energy-aware MAC protocol is required to adaptively schedule the operation mode of individual radios within a WSN [3].

The importance of energy efficiency in WSNs motivates the design of MAC protocols in the literature. Survey in [4] investigates the similarities and differences of existing MAC protocols, and that in [5] classifies them based on their problem of investigation. From these studies, MAC protocols in WSNs can be classified in several perspectives: *synchronous or asynchronous, random access or schedule access*. In synchronous protocols, neighboring nodes wake up periodically at the same time, whereas each node chooses its schedule autonomously in asynchronous protocols. In random access, nodes with a packet to send contend for channel access in the expense of collision, whereas network resources such as time are scheduled between transmit nodes in schedule access to eliminate collision. The advantages and disadvantages of such classifications are elaborated in the recent comprehensive review in [6].

The deign of an energy-aware synchronous MAC protocol in single-hop WSNs is the focus of this paper. A special case of this network is wireless area body network, where sensor nodes implemented on the body to monitor biomedical signals [7]. The protocol is to schedule the transmit, receive, and sleep operation modes at individual sensor nodes. This is accomplished through an optimization problem with the objective of minimizing the average cost of energy to perform a certain task during a time interval. The problem is decomposed into a set of subproblems corresponding to individual senor nodes to be run over time progressively. Under the assumption of fading channels between the sink and sensor nodes, we then propose an adaptive algorithm that makes scheduling decisions iteratively to come up with statistical convergence.

The paper is organized as follows. The system model and problem formulation are given in Section II. The solution of the problem and proposed scheduling algorithm is presented in Section III. Numerical results are given in Section IV and the paper is concluded in Section V.

II. SYSTEM MODEL AND PROBLEM FORMULATION

We consider energy efficient scheduling in a network with a sink node and a set $\mathcal{N} \triangleq \{n : n = 1, \dots, N\}$ of sensor nodes. Sensors sample a target environment with data generation rates $\{\lambda_n^t\}_{n=1}^N$ during a time interval consisting of frames, index by $t \in \mathcal{T}$. The structure of frame t is shown in Fig. 1. The frame of length d will be *adaptively* scheduled into transmit mode of power p_n^T, receive (generating data from the sensed environment) mode of power p_n^R, and sleep mode of power p_n^S, at each node n. A typical schedule is also shown in Fig. 1 where durations $\tau_n^T(t)$, $\tau_n^R(t)$ and $\tau_n^S(t)$ indicate transmit, receive and sleep modes, respectively.

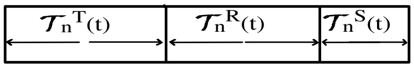

Fig. 1. Frame t of node n

The focus of this paper is on scheduling three operation modes to perform energy optimization in the mentioned setting. Energy per node per frame can be derived in terms of given powers and the fraction of time at each operation mode as

$$W_n(t) = p_n^R \tau_n^R(t) + p_n^T \tau_n^T(t) + p_n^S \tau_n^S(t). \tag{1}$$

The channel between the sink node and node n is assumed to be a flat fading channel with average gain γ_n, which is unvaried during a frame but absolutely can vary over successive frames. Under the assumption of known γ_n^t during frame t and by the means of adaptive modulation [8], channel capacity c_n between the sink and node n is a function of the transmit power p_n^T as

$$c_n(\gamma_n^t) = B \log_2(1 + \gamma_n^t p_n^T / \sigma^2) \quad \text{bps} \tag{2}$$

where B is the channel bandwidth in Hz and σ^2 is AWGN noise power.

As a measure of energy efficiency, the cost of energy is considered in this paper. It is assumed that the cost value is a convex and differentiable function of energy. Even though the following proposed framework is valid for any function with these conditions, we proceed with quadratic cost function and present the average cost minimization problem as

$$\min_{\tau = \{\tau_n^T(t), \tau_n^R(t), \tau_n^S(t)\}_{n\in\mathcal{N}}^{t\in\mathcal{T}}} \frac{1}{L} \sum_{t=1}^{L} \sum_{n=1}^{N} W_n^2(t) \tag{3}$$

$$\text{s.t.} \quad \frac{1}{L} \sum_{t=1}^{L} \sum_{n=1}^{N} c_n(\gamma_n^t) \tau_n^T(t) \geq M \tag{4a}$$

$$\sum_{n=1}^{N} \tau_n^T(t) \leq d \qquad \forall t \in \mathcal{T} \tag{4b}$$

$$\frac{1}{L} \sum_{t=1}^{L} \left(c_n(\gamma_n^t) \tau_n^T(t) - \lambda_n \tau_n^R(t) \right) = 0 \quad \forall n \in \mathcal{N} \tag{4c}$$

$$\tau_n^T(t) + \tau_n^R(t) + \tau_n^S(t) = d \qquad \forall n \in \mathcal{N}, \forall t \in \mathcal{T} \tag{4d}$$

where L is the length of time interval $\mathcal{T}$ in frames. Parameter M in constraint (4a) is the average number of bits required by the sink node per frame to perform a certain task. Constraints (4b) state that the total transmit time to the sink node within a frame should not exceed the frame length d. Constraints (4c) force a balance between inflow and outflow rates at each sensor node in average. This is reasonably needed to have stable queues in sensor nodes [9]. Finally, constraint (4d) is due to the constant frame length d.

With three scheduling decisions at each node per frame, finding the optimal solution in (3)–(4) requires an exhaustive search with worst-case exponential complexity $O(3^{NL})$. This complexity is absolutely prohibitive in WSNs with limited memory and processing resources. In addition, a centralized solution requires the channel state information $\{\gamma_n^t\}_{n\in\mathcal{N}}^{t\in\mathcal{T}}$ to be fully available a priori. This is reasonably not possible in practice due to the time-varying fading channels in the network.

III. DISTRIBUTED SCHEDULING SCHEME

Problem (3)–(4) is a joint optimization of scheduling decisions at all nodes. Due to the concern of complexity and scalability, we are interested in distributed solutions in which all nodes collaborate together to find the solution. Towards this end, we form the Lagrangian as

$$\begin{aligned} L(X, \alpha, \beta, \zeta) = \frac{1}{L} \sum_{t=1}^{L} \sum_{n=1}^{N} W_n^2(t) \\ - \alpha \left(\frac{1}{L} \sum_{t=1}^{L} \sum_{n=1}^{N} c_n(\gamma_n^t) \tau_n^T(t) - M \right) \\ + \beta \left(\sum_{n=1}^{N} \tau_n^T(t) - d \right) \\ + \sum_{n=1}^{N} \zeta_n \left(\frac{1}{L} \sum_{t=1}^{L} \left(c_n(\gamma_n^t) \tau_n^T(t) - \lambda_n \tau_n^R(t) \right) \right) \end{aligned} \tag{5}$$

and the dual function as

$$D(\alpha, \beta, \zeta) = \inf_{\mathbf{X}} \{ L(X, \alpha, \beta, \zeta) : \text{(4d)} \} \tag{6}$$

where $\alpha \geq 0, \beta \geq 0$ and $\zeta = \{\zeta_n\}_{n\in\mathcal{N}}$ are Lagrange multipliers associated with (4a), (4b), and (4c), respectively. Without getting involved into the details, applying dual decomposition, we come up with a problem in primal domain and a series of iterations in the dual domain. Given $\alpha(t), \beta(t), \zeta_n(t)$ and also a certain γ_n^t at frame t, node n evaluates its own dual function using

$$\begin{aligned} \min_{\mathbf{X}_n} \; & W_n^2(t) - \alpha(t) c_n(\gamma_n^t) \tau_n^T(t) \\ & + \beta(t) \tau_n^T(t) \\ & + \zeta_n(t) \left(c_n(\gamma_n^t) \tau_n^T(t) - \lambda_n^t \tau_n^R(t) \right) \end{aligned} \tag{7}$$

$$\text{s.t.} \quad \text{(4d).} \tag{8a}$$

Energy $W_n(t)$ is substituted by its equivalent in (1) and $c_n(\gamma_n^t)$ can ba calculated from (2) with given γ_n^t. Therefore, we come up with a quadratic convex problem that can solved efficiently using existing solvers. Especially, we use gradient-based search iterations such as interior point method (IPM) [10] to find the optimal solution $\mathbf{X}_n$ at each node n per frame t.

Having evaluated $\{\tau_n^T(t), \tau_n^R(t), \tau_n^S(t)\}_{n\in\mathcal{N}}$ at each frame t, it is turn to update these parameters. Beginning with an initial $\{\alpha(0), \beta(0), \zeta_n(0)\}$, given $\{\alpha(t), \beta(t), \zeta_n(t)\}$ at frame t, we obtain $\{\tau_n^T(t), \tau_n^R(t), \tau_n^S(t)\}_{n\in\mathcal{N}}$ from (7)–(8). Lagrange multipliers are then updated as

$$\alpha(t+1) = \alpha(t) + \delta \left(M - \sum_{n=1}^{N} \mathbb{E}_{\gamma_n}[c_n(\gamma_n)\tau_n^T] \right)^+ \quad \text{(9a)}$$

$$\beta(t+1) = \beta(t) + \delta \left(\sum_{n=1}^{N} \tau_n^T - d \right)^+ \quad \text{(9b)}$$

$$\zeta_n(t+1) = \zeta_n(t) + \delta \left(\mathbb{E}_{\gamma_n}[c_n(\gamma_n)\tau_n^T - \lambda_n \tau_n^R] \right) \quad \text{(9c)}$$

where δ is a step size.

Based on the aforementioned solution, we here propose a statistical energy-aware MAC (SEA-MAC) protocol in Algorithm 1. In accordance with the iterative solution, as shown in this algorithm, SEA-MAC is initialized with a set of Lagrange multipliers. At each frame till the end of interval $\mathcal{T}$, each sensor derives its own scheduling decisions and then updates the corresponding $\zeta_n(t)$. This node also let the sink node to know about $\tau_n^T(t)$. With this knowledge, the sink node updates $\alpha(t)$ and $\beta(t)$ as the system-wide Lagrange multipliers and then forwards this renew information to the sensor nodes.

Algorithm 1 SEA-MAC protocol

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Initialization: $t = 0$, $\alpha(0) = \alpha_{\text{init}}$, $\beta(0) = \beta_{\text{init}}$, $\zeta_n(0) = \zeta_{\text{init}} \quad \forall n \in \mathcal{N}$.
while $t \in \mathcal{T}$ do
    for $n \in \mathcal{N}$ do
        Obtain $\{\tau_n^T(t), \tau_n^R(t), \tau_n^S(t)\}$ from (7)–(8).
        Update $\zeta_n(t)$ using (9c).
    end for
    Sink node updates $\alpha(t)$ and $\beta(t)$ using (9a) and (9b), and then broadcasts to the sensor nodes.
    $t = t + 1$.
end while
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Finally, it is imperative to evaluate the complexity and signalling overhead of SEA-MAC. By the means of decomposition, the exponential complexity in (3)–(4) is decreased to $O(LN)$ in Algorithm 1 that is linear in the number of sensor nodes and the length of interval $\mathcal{T}$. Even with this significant achievement, signalling overhead of SEA-MAC is relatively low. Each node n sends transmit time $\tau_n^T(t)$ to the sink at each frame. The sink node in return broadcasts $\alpha(t)$ and $\beta(t)$ in the network. This is the only information required to be exchanged on the air per frame, which worth the complexity reduction.

IV. PERFORMANCE EVALUATION

Numerical results of SEA-MAC are provided in this section. We consider a single-hop network with $N = 10$ nodes located at the same distance from the sink node. The channel between each node and the sink node is assumed to be a Rayleigh fading channel with average gain 0 dB. Arrival rate or generated traffic at all nodes follows a Poisson process with mean 50 bits per frame. The other simulation parameters are shown in Table I.

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TABLE I
SIMULATION PARAMETERS

Parameter	notation	value
Transmit power	p_n^T	75 mW
Receive power	p_n^R	50 mW
Sleep power	p_n^S	25 mW
Noise power	σ^2	-60 dBm
Frame length	d	10 ms
Channel bandwidth	B	1 kHz
Minimum data per frame	M	50 bits
Step size	δ	0.0001

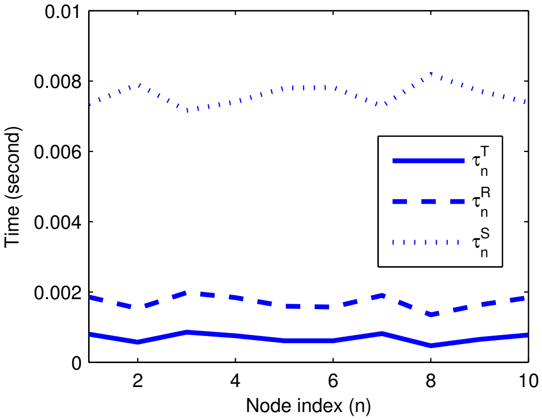

Fig. 2. Average scheduling times

SEA-MAC is run for 500 realizations of the fading channel. The average transmit, receive, and sleep times per node are shown in Fig. 2. Because of the same average channel gains, all nodes mostly demonstrate the same behavior, i.e., the length of each operation mode $(\tau_n^T, \tau_n^R, \tau_n^S)$ is approximately the same for all nodes. Especially, the frame of length 10 ms is uniformly distributed among the nodes for transmission to the sink node.

One fundamental MAC protocol designed for WSNs is S-MAC [11]. This scheme treats all the nodes similarly and divides each frame into two subframes. One node can either be in transmit mode or in receive mode in the first subframe and it switches into sleep mode in the second subframe. The performance of S-MAC is compared with SEA-MAC in the following. We adopt a customized version of S-MAC for this comparison. During a frame, one half of nodes transmit and one half receive. Each node alternates between transmit and receive modes. Transmit nodes use the frame length equally for transmitting to the sink node, i.e., $\tau_n^T(t) = \frac{d}{N/2}$ $\forall t$. For more reasonable comparison, the receive time of every receiving node n at frame t is obtained by

$$\tau_n^R(t) = \frac{c_n(t)}{\lambda_n^t} \tau_n^T(t) \quad \text{(10)}$$

to satisfy constraint (4c). The rest of the frame at each transmit or receive node is considered as sleep time. In the aforementioned network with 10 nodes, the consumed energy per node is shown in Fig. 3 for both SEA-MAC and S-MAC. As shown, SEA-MAC results in lower energy for all

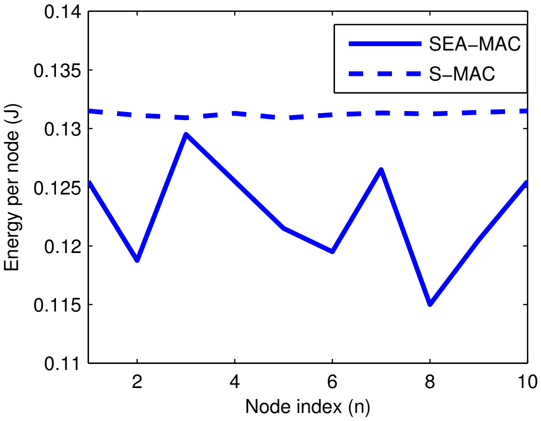

Fig. 3. Energy per node

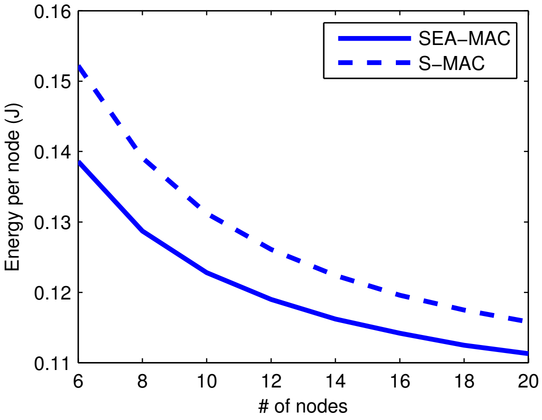

Fig. 4. Average energy per node

nodes. Furthermore, the average energy per node is shown in Fig. 4 when the number of sensor nodes varies between 6 and 20. Again SEA-MAC outperforms S-MAC for all instances. Moreover, energy per node decreases as the number of nodes increases. In other words, the network *life time* increases when the number of sensor nodes increases.

V. CONCLUSION

An energy-aware MAC protocol was proposed for WSNs. With the objective of increasing the network life-time, the protocol schedules transmit, receive, and sleep operation modes through an iterative approach in a linear complexity and low signalling overhead. Numerical results demonstrates that this protocol outperforms classical synchronized protocols as a result of eliminating idle listening.

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