Channel-Aware Energy Efficient Transmission Strategies For Large Wireless Sensor Networks

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Abstract—Energy saving is the one of the most critical issues in wireless sensor networks (WSNs) due to limited battery power of sensor nodes. In this paper, we propose a channel-aware type-based multiple access (TBMA) scheme for longer lifetime of WSNs. In an effort to minimize data transmission which is the most energy consuming operation in a sensor device, the proposed scheme allows a subset of sensors to be opportunistically activated in TBMA when their channel gains are higher than a threshold broadcasted by the fusion center to satisfy a given detection error performance (DEP). With the assumption of the channel reciprocity in a narrowband time-division duplexing system, the activated sensors by the threshold exploit channel state information and control their transmit power in a way to maximize an error exponent of the DEP. Here, the broadcasted threshold plays a role in minimizing the number of activated sensors, and thereby it is expected to prolong the lifetime of WSNs. We analyze the DEPs of the proposed and a random selection schemes, and our results show that the proposed scheme provides significant energy saving as compared to the random selection scheme especially in the low signal-to-noise ratio regime.

Index Terms—Distributed detection, energy consumption, multiuser diversity, multiple-access channels, types, large wireless sensor networks.

I. INTRODUCTION

An efficient way to use energy stored in sensor nodes is one of the most important issues in wireless sensor networks (WSNs) since it is crucial to determine the lifetime of WSNs. In particular, the energy consumption for data transmission in the waking hour is approximately the same as the one for executing thousand operations [1]. Thus, most researches for energy saving are related to a duty cycle control (sleep/wake scheduling) of sensor nodes [2]. For example, when sensors report their sensing results to a fusion center (FC), it is required an efficient scheduling scheme to minimize the usage of wireless bandwidth and the number of transmissions of sensor nodes, and thereby we can prolong network lifetime of WSNs. In the distributed detection, opportunistic access schemes over parallel access channels have been intensively studied as the control mechanism (see [3], [4], [5] and references therein).

In this paper, we consider a control scheme over a multiple-access channel (MAC) for the type-based multiple access (TBMA) strategy in [6], [7], [8]. TBMA has inherent advantages of energy and bandwidth efficiency due to the fact that transmitted signals from sensor nodes are naturally fused over the MAC. With the TBMA, random access and sequential approaches have combined in a way to reduce the number of times of data transmission in [9] and [10], respectively.

In our case, we propose a channel-aware opportunistic TBMA over a fading channel exploiting the multiuser diversity [11] for large WSNs where all sensors do not need to be activated. By virtue of the multiuser diversity that the more sensors have high channel gains with growing number of sensors in WSNs [11], we allow the sensors experiencing high channel gains to participate in TBMA. The key idea behind our scheme is that such a set of sensor nodes requires small amount of total energy consumed for reliably reporting their observations to the FC, and thus the lifetime of WSNs can be prolonged.

The proposed scheme assumes a channel reciprocity between the sensors and the FC. That is, the FC first broadcasts pilot symbols with a threshold, then only the sensors who have higher channel gains than the threshold transmit waveforms at their controlled transmit power levels or a fixed level in a time-division duplexing (TDD) manner.* We formulate an optimization problem addressing our proposed opportunistic strategy in terms of the threshold and power control policy. Specifically, we consider minimizing the total amount of transmit power of the activated sensors while satisfying a given detection error performance (DEP). In our approach, instead of solving this joint optimization problem, we first determine the optimal power control rule in a way to maximize an error exponent of the DEP, and find an optimal threshold to minimize the total amount of transmit power of the activated sensors. We analyze the DEP of our proposed scheme and find the threshold to satisfy a given DEP. Evaluations of our analysis show that the proposed scheme requires a smaller number of sensors and smaller total energy for the same detection performance in the low signal-to-noise ratio (SNR) regime comparing with the random selection scheme in [9], which is also shown true both with and without the transmit power control.

*Thus, we consider coherent communications in this paper. Note that since the bandwidth of wireless links between sensors and the FC is usually narrow, the circuit for channel estimation and coherent communications may not be complicated and could be implemented in a compact size.
The rest of this paper is organized as follows. In Section II, we will describe the system model and briefly review the TBMA system. Our proposed scheme will be presented in Section III where we will also explain how to determine the threshold and power control rule. In Section IV, we will discuss our numerical and Monte Carlo simulation results. Finally, we will make our conclusion in Section V.

II. System Model and Review of TBMA

Suppose that $\theta \in \{\theta_0, \theta_1\}$ is an unknown target to be detected and $N$ sensors have statistically and temporally independent and identically distributed (i.i.d.) observations on the target, which is depicted in Fig. 1. According to our sensor selection scheme to be described in the next section, we assume that $L$ ($\leq N$) sensors are involved in TBMA. We denote the local observation corresponding to the $\ell$-th sensor ($1 \leq \ell \leq L$) as $X_\ell$ which is quantized to $M$ levels\(^1\) with a probability mass function (pmf) \[ p_{\theta_i} = (p_{\theta_0}(0), \ldots, p_{\theta_0}(M-1)), \forall i \in \{0, 1\}. \]

We further assume that the communication links between sensors and the FC are i.i.d. block fading channels which remain constant during a transmission time of a waveform, say one block, and change independently across blocks and sensors. In the TBMA scheme, there is a set of predetermined $M$ orthonormal waveforms, denoted by $\{\psi_0, \ldots, \psi_{M-1}\}$, corresponding to quantization levels. Therefore, the $\ell$-th sensor transmits the orthonormal waveform $\psi_{X_\ell}$. The transmitted signal from the $\ell$-th sensor, denoted by $u_\ell$, is given by

\[ u_\ell = \sqrt{E} P(a_\ell) e^{-j\phi_\ell} \psi_{X_\ell}, \quad \ell = 1, \ldots, L, \]  

where $P(a_\ell)$ is the power-control rule for a given channel coefficient of the $\ell$-th sensor, denoted by $h_\ell = a_\ell e^{j\phi_\ell} \in \mathbb{C}$, satisfying the long-term power constraint, \[ E_{a_\ell} [P(a_\ell)] \leq 1 \] and $E$ is energy for the transmission. Then, the received signal at the FC over the MAC is modeled as the superposition of the transmitted signals as follows:

\[ z = \sum_{\ell=1}^{L} h_\ell u_\ell + w, \]  

where $w$ is a zero-mean complex Gaussian random variable with variance $\sigma^2$ per dimension.

From the received signal, the FC measures a histogram (or an empirical distribution) of the data $X = [X_1, X_2, \ldots, X_L]^T$ using a matched filter. We define the matched filter output corresponding to the waveform $\psi_m / \sqrt{E}$ as $T_m$, which can be expressed by

\[ T_m = \sum_{\ell=1}^{L} a_\ell \sqrt{P(a_\ell)} 1_{(X_\ell=m)} + w_m, \quad m = 0, \ldots, M-1, \]

where $1_{(X_\ell=m)}$ is the indicator function which is one if $X_\ell = m$ and zero otherwise and $w_m$ is a zero-mean complex Gaussian random variable with variance $\sigma^2 / E$ per dimension.

We here define that $\text{SNR} \triangleq E / \sigma^2$. Then, the histogram from the TBMA scheme can be expressed by a vector form, \[ T = [T_0, T_1, \ldots, T_{M-1}]^T. \] The merit behind TBMA is that in some cases the distribution $T$ provides a sufficient statistic for the detection. That is, when the communication links are perfect, i.e., $w_m = 0$ and $h_\ell = 1$, $T_m$ becomes $N_m = \sum_{\ell=1}^{L} 1_{X_\ell=m}$ with which the log-likelihood ratio (LLR) can be written by [8]

\[ \Lambda = \log \frac{p_{\theta_1}(X)}{p_{\theta_0}(X)} = \sum_{m=0}^{M-1} N_m \log \frac{p_{\theta_1}(m)}{p_{\theta_0}(m)}. \]  

However, in practice the detection performance highly depends on the channel condition. For example, the performance of TBMA remarkably gets worse for a zero-mean fading channel [7], [12].

III. Distributed Detection Using Opportunistic Transmission

In this section, we describe our proposed opportunistic transmission scheme for the TBMA system which selects a subset of sensors called activated sensors. In the proposed strategy, we assume that sensors and the FC share the same channel state information (CSI) via the channel reciprocity which is valid in narrowband TDD systems. Specifically, the FC broadcasts pilot symbols with a threshold $\tau$. Estimating CSI from the pilot symbols, if the channel gain of the $\ell$-th sensor, $a_\ell$ is higher than the threshold, the sensor is waken and transmits a waveform corresponding to its local decision. Otherwise, the sensor remains dormant. In addition, since CSI is available at the sensor side, a power control strategy can also be employed at the sensor level if they are smart enough to control their transmit power.

With this strategy, our goal in this paper is to minimize energy consumption of deployed sensors for a longer lifetime of WSNs while satisfying the given DEP constraint which is given by

\[ p_e = \delta (1 - \bar{p}_d) + (1 - \delta) \bar{p}_f, \]
where $\tilde{p}_d$ and $\tilde{p}_f$ are the average detection and false alarm probabilities, respectively and $\delta$ is a weighting factor having $0 \leq \delta \leq 1$. It is obvious that by selecting sensors with high channel gains, we can minimize the number of activated sensors to achieve the given DEP constraint. The multiuser diversity promises with a high probability that there are more sensors with high channel gains as the number of sensors grows, which leads us to a channel-aware transmission strategy.

To address this problem, it is required to formulate an optimization problem in terms of the lifetime model of sensors. It is noted that the model is an application-specific and flexible. In this paper, we only consider the energy consumption for transmission of sensor nodes which is the most energy consuming operation in a sensor device [2]. Taking our considerations into account, the optimization problem can be formulated by

$$
\min_{\tau, P(a_k)} \sum_{L=0}^{N} \binom{N}{L} (p_T(\tau))^L (1 - p_T(\tau))^{N-L} \mathbb{E}_{a_k}[\sum_{L=1}^{L} P(a_k)]
$$

subject to $p_e(\tau, P(a_k)) = c$ (constant),

$$
\mathbb{E}_{a_k}[P(a_k)] \leq 1,
$$

$\tau \geq 0$.

where $p_T(\tau) = \Pr\{a > \tau\}$ is the activation probability of the sensor nodes. We remark that (6) is to minimize the total amount of transmit power of the activated sensors (i.e., network lifetime) in the average sense.

However, if we consider that both $\tau$ and $P(a_k)$ are variables to be optimized for minimizing energy consumption of deployed sensors, it is hard to find an optimal solution satisfying the given DEP constraint, and needs a heuristic searching algorithm for solving the problem. Instead of such an approach, in this paper, we first determine the power control scheme which maximizes an error exponent of DEP, and then optimize $\tau$ in a way to minimize energy consumption of sensors. We adopt the following channel inversion rule as our power control policy:

$$
P(a_k) = \left\{ \left( \frac{\alpha}{\sqrt{\tau}} \right)^2, \quad \tau < a_k \leq \infty, \quad \ell = 1, \ldots, L, \right\}
$$

where $\alpha$ is a scaling factor satisfying the equality of the individual power constraint, $\mathbb{E}_{a_k}[P(a_k)] = 1$. It is noted that our power control strategy converts fading channels to additive white Gaussian noise channels with a gain of $\alpha$. Thus, the error exponent of our scheme achieves the Chernoff information which is the best achievable one in a class of the Bayesian detectors that are a function of the local observation data, $\mathbf{X}$ and $L$ [7], [13], [14].

Applying the power control policy to (3), the empirical distribution can be written by

$$
\mathbf{T} = \alpha [N_0 \ N_1 \ \cdots \ N_{M-1}]^T + \mathbf{w}',
$$

where $\mathbf{w}' = [w_0' \ w_1' \ \cdots \ w_{M-1}']^T$. With a growing number of deployed sensors in WSNs, even for a high threshold value $\tau$, we can still find enough number of sensors with their channel gains larger than the threshold. Additionally, these higher channel gains also cause a large $\alpha$ to satisfy the individual power constraint of sensor nodes. In consequence, it is expected that larger $\alpha$ boost the inherent array gain of TBMA, and noise in (11) becomes negligible. We use the LLR test in (4) as a fusion rule using the empirical distribution in (11).

For given power control policy, the objective function in (6) becomes a monotonically decreasing function with growing $\tau$ since both the average number of activated sensors, $L$ and the activation probability, $p_T(\tau)$ decrease as $\tau$ increases. Thus, the optimal $\tau$ is the largest value satisfying (7) for given $P(a_k)$. To find the optimal threshold, we will characterize the DEP in terms of $\tau$ for a binary quantization in the following subsection.

### A. Detection Performance

In general, the DEP of the LLR fusion in (4) may not be derived in a closed form, but we can obtain a simple expression to evaluate numerically for $M = 2$.[1] Thus, we focus on a binary quantization case for the Bayesian setup and derive the DEP of the proposed scheme. We further assume that 1) $p_{b_0}(1) = p_{b_1}(0)$ are less than 0.5 (i.e., symmetric observation channels), and 2) two hypotheses are equally likely.

Since the number of activated sensors in our scheme is a random variable depending on the threshold, the average detection probability can be obtained as the sum of binomial probabilities as follows:

$$
\bar{p}_d = \sum_{L=0}^{N} \binom{N}{L} (p_T(\tau))^L (1 - p_T(\tau))^{N-L} p_d(L),
$$

where $p_d(L)$ is the average detection probability conditioned on $L$ activated sensors.

To calculate the probability $p_d(L)$, we should take both observation and communication channels into account. Suppose that $L$ sensors are activated and $k$ sensors amongst them transmit the waveform $\psi_1$ to the FC. Since we assume that the observation channel is binary symmetric, the probability that the FC decides $\theta_1$ is computed by $\Pr\{T_0 < T_1 | N_1 = k\}$ from the LLR in (4). According to (11), the pdfs of $T_0$ and $T_1$ are $\mathcal{N}(\alpha (L-k), \sigma^2)$ and $\mathcal{N}(\alpha k, \sigma^2)$, respectively. Thus,

$$
\Pr\{T_0 < T_1 | N_1 = k\} = \Pr\{T_1 - T_0 > 0 | N_1 = k\}
$$

$$
= Q \left( \frac{\alpha (L-2k)}{\sqrt{2\sigma}} \right),
$$

where $Q(t) = \frac{1}{\sqrt{\pi}} \int_{t}^{\infty} \exp \left( \xi^2/2 \right) d\xi$. Then, we finally obtain the probability of $p_d(L)$ which is given by

$$
p_d(L) = \sum_{k=0}^{L} \Pr\{T_0 < T_1 | N_1 = k\} \Pr\{N_1 = k | \theta_1\},
$$

[1] Since we assume i.i.d. fading channels, we drop the user index, $\ell$ for the sake of simplicity.
where \( \Pr \{ N_1 = k|\theta_1 \} = \left( \frac{L}{k} \right) p_{\theta_1}^k (1) p_{\theta_1}^{L-k} (0) \) is the probability that \( k \) sensors choose \( \theta_1 \) and \( L-k \) sensors choose \( \theta_0 \) when \( \theta_1 \) is true. Following the same approach, we can also compute the average false alarm probability \( \bar{p}_f \):

\[
\bar{p}_f = \sum_{L=0}^{N} \left( \frac{N}{L} \right) (p_T (\tau))^L (1 - p_T (\tau))^{N-L} p_f (L), \tag{15}
\]

where \( p_f (L) = \sum_{k=0}^{L} \Pr \{ T_0 < T_1 | N_1 = k \} \Pr \{ N_1 = k|\theta_1 \}. \)

Substituting (12) and (15) into the given DEP constraint, the threshold \( \tau \) for achieving a given DEP can be found by numerical evaluations.

IV. SIMULATION RESULTS

In this section, we present numerical and Monte Carlo simulation results of our proposed opportunistic TBMA scheme. For simulations, we assume that the observation channels have a pmf with \( p_{\theta_0} (1) = p_{\theta_1} (0) = 0.2 \) and the communication channels are zero mean complex Gaussian with unit variance (i.e., \( \mathcal{CN} (0, 1) \)). The weighting factor in DEP, \( \delta \) is set to 0.5.

For comparisons, we consider the type-based random access (TBRA) scheme proposed in [9] where the sensors are randomly activated with probability \( \lambda \) regardless of CSI. To make the comparisons fair, we assume that the activated sensors in TBRA also have perfect knowledge of their CSI. However, unlike our proposed scheme where the minimum channel gain is lower bounded by \( \tau > 0 \), it is possible for some of randomly selected sensors to have vanishing channel gains, \( a \ll 1 \), which requires unbounded transmit power. Thus, we cannot apply the same power control policy in (10). Instead, we apply another well-performed one in [6] as follows:

\[
P (a) = \begin{cases} 
\frac{1}{\bar{a}}, & 0 \leq a \leq \infty, \\
\frac{1}{P_0}, & \text{otherwise}
\end{cases}
\tag{16}
\]

where \( P_0 \) is a constant satisfying the power constraint, \( \mathbb{E}_a [P(a)] = 1 \). Furthermore, we compare our scheme with the coherent combining of TBMA and TBRA without a power control rule (i.e., \( P (a) = 1 \forall a \)). The performance of the noiseless communication links (i.e., \( w = 0 \) in (2)) are also provided as lower bounds.

In this setup, we first compare our opportunistic TBMA scheme with the TBRA scheme in terms of the DEP. Fig. 2 presents numerical and simulation results of the DEP in a range of activation probability, \( p_T \) for different \( N \) and SNR = 0dB. We see that channel-aware TBMA schemes outperform TBRA schemes regardless of power control strategies. Note that all schemes in Fig. 2 satisfy \( \mathbb{E}_{a_T} [P(a_T)] = 1 \), and we can say that the proposed TBMA scheme consumes energy in the most efficient way. In particular, the DEP of opportunistic TBMA scheme with power control is the same to that of the noiseless case.

We now present the average number of activated sensors satisfying a given DEP constraint as a measure of energy consumption of WSNs which is of our main interest in this paper. Figs. 3 and 4 depict analytical and simulation results of the activation probability as a function of SNR for various values of DEP. In case of the TBRA scheme, we find an optimal \( \lambda \) by trial and error to achieve the given DEP. It is shown that both TBRA and proposed TBMA schemes with/without the power control strategies approach the lower bounds in the high SNR regime due to the inherent array-gain of TBMA [6], [7], [8]. However, we are more interested in the low SNR regime since sensors are power limited devices. We find that the proposed TBMA scheme outperforms TBRA at all SNR values and becomes more outstanding as SNR decreases. For DEP = 0.01 and SNR = -10dB in Fig 3 (Fig. 4), the proposed scheme with the power control needs an activated ratio of 33% (7%) but TBRA with/without the power control need 53% (13%) and 59% (15%), respectively. This performance gap will contribute to reducing the total energy consumed by sensors and making the lifetime of WSNs longer.

In Fig. 5, we show the results of evaluations of activation ratio at different sizes of WSNs (50 \( \leq N \leq 500 \)). Although the
proposed scheme shows better performance (smaller activation ratio) in all cases, performance superiority is more significant at low SNR, -15dB. It should be noted that with growing $N$, the proposed scheme seems to lose the performance superiority. This stems from the fact that as $N$ grows, the number of activated sensors ($L$) in TBRA also becomes big enough for the multiuser diversity to work. Although the performance gap in Fig. 5 looks smaller in percentage-wise as $N$ grows, the difference of the number of selected sensors $L$ for both schemes stays almost the same. For example, in the range of $200 \leq N \leq 500$, the proposed TBMA and TBRA with the power controls respectively activate about 15 and 39 sensors on the average.

V. CONCLUSION

In this paper, we proposed a new channel-aware TBMA scheme to exploit the multiuser diversity in large WSNs for better energy efficiency. In the proposed scheme, each sensor opportunistically accesses to the FC with/without a power control strategy according to its channel condition, thereby energy is consumed in an efficient way. Our simulation results confirmed that the proposed approach can significantly save the transmission energy comparing with the random selection scheme, TBRA, where sensors are activated regardless of their communication channel qualities. We quantified the performance improvements of the proposed scheme by comparisons at different values of DEP, SNR and numbers of sensors in WSNs. We found that the proposed scheme provided significant energy saving in the low SNR region where most of power-limited sensors are working.

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