Dense Wireless Sensor Networks with Mobile Sinks

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Abstract— **We propose to develop wireless Sensor Networks with Mobile Sinks (MSSN), under high sensor node density, where multiple sensor nodes need to share one single communication channel in the node-to-sink transmission. Under the guideline of trading network energy consumption for the successfully retrieved packets, optimal and suboptimal transmission scheduling algorithms, which exhibit exponential and linear complexity respectively, are discussed under the desired application. The computer simulations show that the suboptimal algorithms perform nearly as good as the optimal one.**

I. Introduction

Sensor Networks with Mobile Sinks (MSSN) [1], [2] was proposed for two application areas, which are environment monitoring systems with high latency tolerance and intelligent-space. This new architecture features high energy-efficiency, because the multi-hop transmission of high volume data over the network is converted to single-hop transmission. Additional advantages of MSSN include infrastructure free, high security, and ease of implementation. We discussed the transmission scheduling algorithm TSA-MSSN [1] in a sparsely deploying network setup, where it is assumed that only one sensor node is communicating with the mobile sink on a given channel.

However, when the density of sensor networks increases, multiple nodes can be within the transmission range to the sink, and the assumption of a sparsely deploying setup no longer holds. When multiple radio channels are available, the sink can assign one such distinctive channel to any individual node. The TAS-MSSN can then operate on different channels respectively. However, when the number of nodes exceeds the number of channels, multiple nodes will need to share one channel. Thus, more complicated scheduling algorithms are needed.

Under different types of wireless networks, there are numerous works investigating the desired scheduling problem. Under cellular networks, from an information theoretic approach, [4] showed that, to maximize the total uplink capacity, it is sufficient to have only the user with the strongest channel to the base station transmit at any given time. Such power control scheme is known as multiuser diversity. Although strategies in [4] are optimal in the sense of capacity, in the service layer implementations, more QoS factors should be considered, such as fairness, delay, and connection admission control (CAC) [5]. In the area of sensor networks, the recent work on SENMA [10] studied the sensor network topology similar to MSSN, and proposed distributed scheduling algorithms. However, SENMA assumes a simple reachback sensor network, which differentiates it from the proposed MSSN.

Compared to the existing works, the MSSN is distinctive for the following considerations. In MSSN, the objective of the scheduling algorithm is to transmit all integrated/compressed information [6] stored on sensor nodes with the minimum energy consumption. Combined with the mobility of the sink, this guideline makes the system design different from the conventional wireless networks. More specifically, in the MSSN transmission scheduling, we exploit the tradeoff between the probability of successful information retrieval and the nodes energy consumption, under the delay limitations imposed by the sink mobility. Instead, in conventional wireless networks, "throughput" is generally emphasized, which is the number of the retrieved packets per second.

II. System Description and Optimal Algorithm

The optimal multiple nodes transmission scheduling algorithm (MTSA-MSSN) is an extension of the TSA-MSSN in [1]. Consider the sink having an estimation of its own current velocity and direction of mobility, which can be obtained from the Global Positioning System (GPS). MTSA-MSSN is run at the beginning of every communication time slot. One time slot is composed of the transmission of two different packets in sequence, which are the acknowledge (ACK) packet from the sink, and the data packet from the sensor nodes respectively. The obtained scheduling strategy can then be piggybacked on the ACK packets broadcasted by the sink to the associated sensor nodes. The ACK packets, on the other hand, also serve to acknowledge successful or failed data transmission in the previous time slot.

We do not assume the future mobility pattern is available at the sink. Instead, in MTSA-MSSN, we make two approximations. Let N denote the number of nodes sharing one communication channel. First, we assume that no new node is admitted to the channel until all N nodes have finished the transmission. Second, we estimate that the mobility of the sink maintains constant in future time slots. Both the two are realistic approximations, since the scheduling algorithm is run at the beginning of every time slot, where both the nodes and the sink mobility information are updated. As shown in the following, they generate a simplified system model as well.

A. System Description

Let $Range$ denote the communication range of the sensor node, which is assumed the same to all nodes. Let $\{\mathbf{L_1}, \ldots, \mathbf{L_N}\}$ denote the location of N sensor nodes respectively, which are assumed to be fixed throughout the transmission. At time slot i, let $\{K_n(i)|n = 1 \ldots N\}$ denote the number of packets awaiting transmission at node n. Assume the location, direction and speed of the sink are $\mathbf{L_s}(i)$, $\theta_s(i)$, $v_s(i)$ respectively. Then, the system state is composed of these $2N + 3$ parameters,

$$E(i) = \{\mathbf{L_s}(i), \theta_s(i), v_s(i), \mathbf{L_1}, \ldots, \mathbf{L_N}, K_1(i), \ldots, K_N(i)\}. \tag{1}$$

Let $D_n(i)$ denote the distance between the sink and the sensor node n, $n = 1 \ldots N$. Then, the communication channel gain for the node n can be modeled as [8],

$$G_n(i) = 10 \cdot \log(A) - 10\beta \cdot \log(D_n(i)) + \xi \ (dB), \tag{2}$$

where A is a constant decided by the antenna gain, β is the path loss exponent decided by the propagation environment, and ξ is a random variable under normal distribution $N(0, \sigma_\xi^2)$, indicating the shadowing effect.

At every time slot, we estimate that the mobility of the sink would be maintained as a constant when it passes through all the N circular regions, which are centered at $\mathbf{L_n}$ with the radius $Range$ respectively. Let $T_n(i)$ denote the estimated transmission time slots available for node n, $n = 1 \ldots N$. We have,

$$T_n(i) = \frac{\|\mathbf{L_s}(i) - \mathbf{L_{s\_out,n}}\|}{v_s(i) \cdot \Delta t}, \tag{3}$$

where $\Delta t = \frac{F_d + F_b}{R}$. F_d and F_b are the size of the data and ACK packets respectively. R is the transmission data rate. $\mathbf{L_{s\_out,n}}$ is defined as the point at which the sink goes out of the communication range of the sensor node n. Let,

$$T(i) = \max_{n=1 \ldots N} \{T_n(i)\}. \tag{4}$$

If i_0 denotes the current time slot, the series of estimated states can be defined as,

$$\hat{\mathbf{E}}(i_0) = \left\{\hat{E}(i_0), \hat{E}(i_0 + 1), \ldots, \hat{E}(i_0 + T(i_0) + 1)\right\}, \tag{5}$$

where $\hat{E}(i_0)$ is known as,

$$\hat{E}(i_0) = E(i_0). \tag{6}$$

Obviously, the size of each estimated state $\{\hat{E}(i), i_0 < i \le i_0 + T(i_0) + 1\}$ is decided only by $\{K_n(i_0)\}$, which is $\prod_{n=1}^{N}(K_n(i_0) + 1)$.

The supposed transmission strategy at a future time slot i, $i \ge i_0$, $\mathbf{S}(i)$ is decided by two parameters, $\mathbf{S}(i) = \{Node(i), P_t(i)\}$, where $Node(i) \in \{1 \ldots N\}$ denotes the ID of transmitting node in time slot i. $P_t(i)$ is, on the other hand, the transmission power at the sensor node $Node(i)$. We consider the transmission power is of discrete levels, and the number of optional levels is $Sizeof\{P_t\}$. Given $\hat{E}(i)$ and $\mathbf{S}(i)$, $\hat{E}(i + 1)$ is not related to any previous states before i. Thus, $\left\{\hat{E}(i)\right\}$ can be modelled as a Markov chain in time domain. Assuming that only one packet can be transmitted in one time slot, and every lost packet will be retransmitted in the next assigned slot, the state transferring probability function is here given by,

$$\begin{array}{l} P\left(\hat{E}(i+1)|\hat{E}(i), P_t(i), Node(i)\right) = \\ \begin{cases} P\hat{E}R(i), & \hat{K_n}(i+1) = \hat{K_n}(i), n = 1 \ldots N \\ 1 - P\hat{E}R(i), & \hat{K}_{Node(i)}(i+1) = \hat{K}_{Node(i)}(i) - 1, \\ & \hat{K_n}(i+1) = \hat{K_n}(i), for\ all\ n \ne Node(i) \\ 0, & others \end{cases} \\ i = i_0 \ldots i_0 + T(i_0) \end{array}, \tag{7}$$

where $P\hat{E}R(i)$ is the estimated packet error rate of transmission in future time slot i. Consider a BPSK modulated uncoded data packet and the sink is unaware of the shadowing effect ξ, $P\hat{E}R(i)$ can be written as [7],

$$P\hat{E}R(i) = 1 - \left(1 - Q\left(\sqrt{\frac{2P_t(i) \cdot D_{\hat{Node(i)}}(i)^{-\beta}}{\sigma_n^2}}\right)\right)^{F_d}, \tag{8}$$

where σ_n^2 is the noise power.

B. Optimal MTSA-MSSN Strategy

At current time slot i_0, the objective of MTSA-MSSN is to decide $\mathbf{S}(i_0)$ so as to maximize the number of successfully transmitted packets while minimizing the energy consumption. However, these two goals can not be achieved simultaneously. Similar as TSA-MSSN in [1], we search the optimal strategy $\mathbf{S}^*(E(i_0)) = \{Node^*(E(i_0)), P_t^*(E(i_0))\}$ by maximizing an utility function $J\left(\mathbf{S}(i_0), \hat{E}(i_0)\right)$,

$$\mathbf{S}^*(E(i_0)) = \arg\max_{\mathbf{S}(i_0)} \left\{J\left(\mathbf{S}(i_0), \hat{E}(i_0)\right)\right\}, \tag{9}$$

where,

$$\begin{array}{l} J\left(\mathbf{S}(i), \hat{E}(i)\right) = J\left(Node(i), P_t(i), \hat{E}(i)\right) = \\ \sum_{\hat{E}(i+1)} \max_{\mathbf{S}(i+1)} \left\{J\left(\mathbf{S}(i+1), \hat{E}(i+1)\right)\right\} \cdot \\ P\left(\hat{E}(i+1)|\hat{E}(i), P_t(i), Node(i)\right) - \frac{\lambda}{\max\{P_t(i)\}} \cdot P_t(i) \\ i = i_0, \ldots, i_0 + T(i_0) \end{array}. \tag{10}$$

In Eq.(10), λ is a coefficient deciding the tradeoff between the cost of energy consumption and the credit of successful packet transmission.

At the final state of the algorithm, $i = i_0 + T(i_0) + 1$, the utility function is decided only by the system state. The definition of $J\left(\hat{E}(i_0 + T(i_0) + 1)\right)$ is, however, application dependent. Suppose that each packet is equally credited, say "1", it can be defined as,

$$J\left(\hat{E}(i_0 + T(i_0) + 1)\right) = \sum_{n=1}^{N}\left\{K_n(i_0) - \hat{K_n}(i_0 + T(i_0) + 1)\right\}. \tag{11}$$

Because the size of the system state, $\prod_{n=1}^{N}(K_n(i_0) + 1)$, increases exponentially with the number of nodes N, the complexity of optimal algorithm also increases exponentially with N. To solve this, we further investigate suboptimal algorithms.

III. Suboptimal Algorithms

In developing suboptimal algorithms, the idea is to run TSA-MSSN (i.e. $N = 1$) algorithm individually for each node n, and combine the N individual strategies to decide the suboptimal multiple-access transmission strategy $\mathbf{S}^s(E(i_0))$. As presented in [1], the complexity of TSA-MSSN can be reduced to $O(1)$, when a feasible storage capability is available on the sink. The complexity of suboptimal algorithms equals to the N-time runs of TSA-MSSN with the same sized storage on the sink, which is $O(N)$.

A. Preprocessing: TSA-MSSN Runs

TSA-MSSN was detailed in [1]. At current time slot i_0, let $E_n(i_0)$ denote the system state on node n. After the preprocessing we obtain the TSA-MSSN power decision on each node, $\left\{P^*_{t,n}\left(E_n(i_0)\right)|n = 1 \dots N\right\}$. Suboptimal algorithms operate in different ways in deciding $Node^s\left(E(i_0)\right) \in \{1 \dots N\}$, and,

$$P^s_t\left(E(i_0)\right) = P^*_{t,Node^s(E(i_0))}\left(E_{Node^s(E(i_0))}(i_0)\right). \quad (12)$$

B. Suboptimal Algorithm I: Maximal Sensor Power Strategy

The strategy here is to choose the node with maximum $P^*_{t,n}\left(E_n(i_0)\right)$ as the transmitting node, that is,

$$Node^s\left(E(i_0)\right) = \arg\max_n \left\{P^*_{t,n}\left(E_n(i_0)\right)\right\}, \quad (13)$$

and $P^s_t\left(E(i_0)\right)$ is obtained through Eq.(12).

C. Suboptimal Algorithm II: Maximal Sensor Utility Strategy

Based on the TSA-MSSN preprocessing results, Maximal Sensor Utility Strategy (MSUS-MSSN) chooses the node with the maximal achievable TSA-MSSN utility summation, which is defined as,

$$\begin{aligned} U_n\left(E(i_0)\right) \quad = \quad & \textstyle\sum_{p=1;p\neq n}^{N}\left\{J_p\left(0, \hat{E}_p(i_0)\right)\right\} + \\ & J_n\left(P^*_{t,n}\left(E_n(i_0)\right), \hat{E}_n(i_0)\right) \end{aligned}. \quad (14)$$

We have,

$$Node^s\left(E(i_0)\right) = \arg\max_n \left\{U_n\left(E(i_0)\right)\right\}, \quad (15)$$

and $P^s_t\left(E(i_0)\right)$ is obtained through Eq.(12).

D. Implementation

To draw an analytical performance comparison between optimal and suboptimal algorithms is difficult. However, one should avoid a certain condition in suboptimal algorithms, where the TSA-MSSN power decision is zero for all node, which is,

$$P^*_{t,n}\left(E(i_0)\right) = 0, \quad n = 1 \dots N. \quad (16)$$

Under the condition, all suboptimal algorithms will keep every node sleeping in the current time slot i_0. The optimal MTSA-MSSM performs strictly better, since it avoids this restriction by jointly deciding the transmission over all N nodes. The condition can be avoided by running the channel selection algorithm for one specific node n only when it is active, i.e. $P^*_{t,n}\left(E_n(i_0)\right) > 0$. The criterion, on the other hand, also enhances the spectrum efficiency by keeping all the occupied channels busy. The details about implementations are omitted here for space saving, and can be found in [2].

IV. Simulations

The following simulations scenario is considered. The sink is passing through the sensor network region. The setup of communication parameters generally complies with IEEE 802.15.4 [3], and is listed in Table 1. The number of transmission power levels is set to 10, which is,

$$\begin{aligned} P_t(i) \in \{ \quad & -\infty, -32, -28, -24, -20, \\ & -16, -12, -8, -4, 0\} \ (dBm). \end{aligned} \quad (17)$$

λ, which is the parameter to decide the tradeoff between successful transmission and energy consumption, is set as “1”.

Table 1. Communication Parameters Setup

Parameter	Unit	Value
F_d	bit	128×8
F_b	bit	20×8
R	$bits/sec$	20000
β		3
A	dB	-31
$Range$	m	50
σ^2_n	dBm	-92
$v_s(i)$	m/sec	20

Simulations are performed to measure the energy consumption E_{all} and successfully transmitted packets P_{all} of MTSA-MSSN, MSPS-MSSN, and MSUS-MSSN respectively. In calculating the energy consumption, we however omit the RF circuits energy consumption, since it is the same for all algorithms. The definitions of E_{all} and P_{all} are thus,

$$E_{all} = \sum_{i=i_0}^{i_0+T(i_0)} P^r_t(i) \cdot \frac{F_d}{R}, \quad (18)$$

$$P_{all} = \sum_{n=1}^{N} \left\{K_n(i_0) - K_n(i_0 + T(i_0) + 1)\right\}, \quad (19)$$

respectively, where,

$$P^r_t(i) = \begin{cases} P^*_t(E(i)), & for \ \ optimal; \\ P^s_t(E(i)), & for \ \ suboptimal \end{cases}. \quad (20)$$

We assume two sensor nodes are sharing with one specific communication channel, which is $N = 2$. Without loss of generality, let $\mathbf{L_1} = [-5, 5]$, $\mathbf{L_2} = [0, -4]$, and $K_1(i_0) = K_2(i_0) = 10$. Set $\theta_s(i) = 0$. With $\mathbf{L_s}(i_0) = [22, 0]$, the sink passes through the circular communication region of the nodes. Fig. 1 & 2 plot the curve of E_{all} and P_{all} respectively when σ^2_ξ changes. The results are averaged over 500 Monte-Carlo runs.

The energy consumption E_{all} of MSPS-MSSN is much higher than the other two algorithms everywhere, however, it also has a higher P_{all} than others when σ^2_ξ is relatively small. Compared with MSPS-MSSN, the MTSA-MSSN and MSUS-MSSN offer a better tradeoff between energy consumption

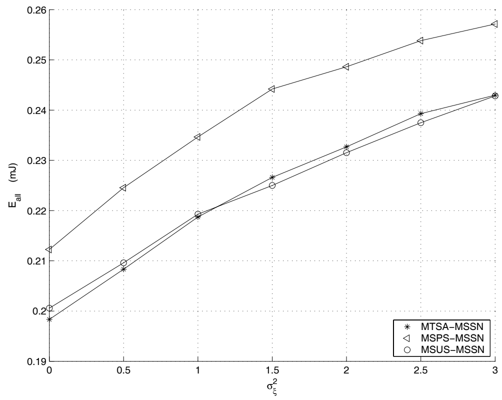

Fig. 1. Case I: total energy consumption E_{all} vs. σ_ξ^2

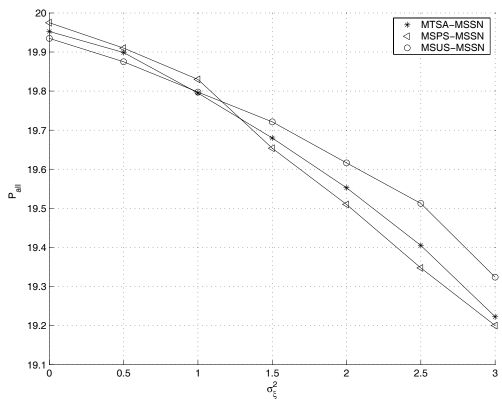

Fig. 2. Case I: successfully transmitted packets P_{all} vs. σ_ξ^2

and successful transmission rate. Although MTSA-MSSN is theoretically optimal and has a much higher complexity, the suboptimal MSUS-MSSN surprisingly performs at least as good as MTSA-MSSN in the simulation. When σ_ξ^2 is small, MTSA-MSSN outperforms MSUS-MSSN by a little, as shown in Fig. 1 & 2. However, when σ_ξ^2 become large, the suboptimal MSUS-MSSN is better than the optimal algorithm in both energy consumption and successful transmission rate. The result may seem to be abnormal at the first glance. This is, however, due to the fact that scheduling algorithms are unaware of the shadowing effect of the channel in Eq.(2). Suboptimal MTSA-MSSN chooses a higher transmission power level, which consumes more energy on one hand, enhances the probability of successful transmission on the other. Generally, suboptimal algorithms are efficient alternatives to the optimal one. Especially for the MSUS-MSSN, it performs as good as the optimal algorithm in terms of total energy consumption E_{all} and successful transmission rate P_{all}.

V. Conclusions and Discussions

In this paper, we have studied the operation of sensor networks with mobile sinks when multiple nodes share one communication channel during transmission. First, we have developed the optimal multi-node scheduling algorithm MTSA-MSSN. As the complexity of MTSA-MSSN increases exponentially with the number of nodes, we propose suboptimal algorithms based on the idea of running the single node scheduling algorithm TSA-MSSN individually on each node and then combining the results. The two suboptimal algorithms, MSPS-MSSN and MSUS-MSSN, exhibit complexity as low as $O(N)$. The performances of optimal and suboptimal algorithms are compared by means of computer simulations. The suboptimal algorithms achieve nearly the same performance as the optimal MTSA-MSSN.

It is interesting to compare the multiple access MSSN with the recently proposed SENMA [10], [11]. Although the two have similar network topology, they are of different types of networks. In MSSN, we assume certain signal processing capability on individual sensor nodes. The inter-node signal processing, e.g. [12], is considered implementable. SENMA, on the other hand, assumes a simple reachback sensor network, where the sensor nodes acquire the data and transmit it directly to the sink, with no inter-node signal processing. Moreover, the sink is dominant in MSSN, since deterministic scheduling is decided by the sink. SENMA is a sensor-nodes dominant network in the sense that random access scheduling is adopted. SENMA claims low complexity of the sensor nodes. MSSN, however, has higher efficiency and application specific flexibility [1], since the transmission of unnecessary correlated packets is avoided. The choice between the two should be dependent on the requirements of applications.

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