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Maximizing the Lifetime of Sensor Network Using Local Information on Channel State and Residual Energy

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Abstract —

This paper investigates the lifetime of a sensor network employing different distributed transmission protocols. We show that the network lifetime depends on not only the initial energy of the sensors and the number of sensors but also the average transmission energy and the average residual energy in the network after the lifetime expires. We thus propose a new distributed transmission scheme which utilizes the local information on both the channel state and the residual energy of a sensor node. Simulation results show that our new scheme achieves better lifetime performance than other available schemes.

I. Introduction

One of the critical operations in sensor networks is the process in which data collected by sensor nodes are retrieved by an access point (AP) to be used by the end-user. We consider SEnsor Network with Mobile Access (SENMA), a network architecture proposed in [1]. As illustrated in Fig. 1, during the information retrieval operation, a mobile access point broadcasts a beacon to activate sensors in certain area. Activated sensors then transmit, according to a transmission protocol, their data to the AP through the common wireless channel.

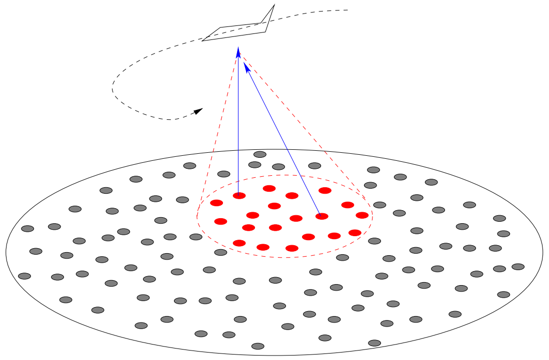

Fig. 1: Sensor network with mobile access point.

Knopp and Humblet [2] showed that the optimal transmission scheme in terms of maximizing the sum capacity under an average power constraint is to enable only the sensor with the best channel to transmit. It is shown in [3, 4] that this opportunistic (with respect to the channel state) scheme is also optimal in energy efficiency measured in information bits per Joule when the cost in channel acquisition is negligible. Focusing solely on minimizing the energy consumed in each transmission, however, this purely opportunistic scheme is not optimal in terms of the network lifetime. We show in this paper that the network lifetime depends on not only the average transmission energy but also the residual energy left in the network after the lifetime expires (this amount of energy is thus wasted). Aiming at a better balance between the average transmission energy and the average wasted energy, we propose a new distributed transmission scheme which utilizes the local information on both the channel state and the residual energy at each individual sensor. Simulation results show that our new scheme outperforms the picking best channel scheme when the number of sensors is large.

There is a growing body of literature on the study of sensor network lifetime. Majority of existing work is on the analysis of network lifetime for a given network architecture and transmission protocols. See [5–9] and references therein. In [10,11], transmission protocols are proposed for sensor networks under the performance measure of energy efficiency which does not take into account of the hard constraint of the limited energy at each sensor.

The rest of the paper is organized as follows. Section II describes the network model and defines the lifetime. In Section III, we present the distributed transmission protocol via carrier sensing. In Section IV, we analyze the network lifetime under different transmission schemes and propose a new protocol which achieves better lifetime performance. Simulation results that compare the lifetime of different transmission schemes are provided in Section V while Section VI concludes this paper.

II. Network Model and Lifetime

We consider a sensor network with N sensors, each powered by a battery with E_{in} initial energy. Without loss of generality, we assume that in each data collection, every sensor has an equal-sized data packet to be transmitted to the AP. In each data collection, one of these N sensors is enabled to transmit its data packet to the AP. The questions we seek to answer are (i) which sensor should be enabled for transmission so that the network lifetime is maximized; (ii) how to design a distributed transmission protocol to enable the sensor with desired property.

Sensors transmit their data to the AP through a flat and slow faded channel with Rayleigh distributed envelop statistics. We assume that the channel fading during one data packet remains the same. Since the distance from the sensor to the AP is usually much larger than that among the sensors, the path loss is almost the same for all the sensors. Hence, in the absence of Rayleigh fading, the energy E_{nf} required to transmit one data packet with an acceptable received signal-to-noise ratio (SNR) at the AP is approximately the same for all the sensors. The total energy required for the k-th sensor to transmit its data packet during the l-th data collection is thus given by

$$E_{tx}^{(k)}(l) = E_c + \frac{E_{nf}}{\gamma_k(l)} \tag{1}$$

where E_c is the energy consumed in the transmitter circuitry and $\gamma_k(l)$ is the channel gain associated with the k-th sensor during the l-th data collection. For Rayleigh fading, $\gamma_k(l)$ is exponentially distributed with (normalized) mean 1. Then the average transmission energy for one data packet is given by

$$\mathbb{E}(E_{tx}) = E_c + E_{nf}\mathbb{E}\left(\frac{1}{\gamma_s(l)}\right) \tag{2}$$

where $\mathbb{E}(x)$ denotes the average of x and $\gamma_s(l)$ is the channel gain associated with the transmitting sensor during the l-th data collection.

Let $e_k(l)$ $(k = 1, 2, \ldots, N)$ denote the remaining energy of the k-th sensor at the beginning of the l-th data collection. A sensor is considered dead if its residual energy drops below the energy consumption E_c of the transmitter circuitry, *i.e.,* it does not have enough energy for transmission under any channel condition. We consider the network nonfunctional when the first sensor in the network dies or no sensor has enough energy for transmission during a data collection, whichever occurs first. The lifetime LT of the sensor network is then defined as the number of data collections until the network becomes nonfunctional, *i.e.,*

$$\begin{aligned} LT = \min\{l-1\,|e_k(l) < E_c \text{ for any } k = 1, 2, \ldots, N \\ \text{or } e_k(l) < E_{tx}^{(k)}(l) \text{ for all } k = 1, 2, \ldots, N\}, \end{aligned} \tag{3}$$

where $E_{tx}^{(k)}(l)$ is defined in (1).

After the lifetime expires, the total unused energy of the sensors in the network is wasted. Hence, the wasted energy is given by

$$E_w = \sum_{k=1}^{N} e_k(LT+1). \tag{4}$$

Appendix A shows that the average lifetime of the network can be written in terms of the average transmission energy $\mathbb{E}(E_{tx})$ and the average wasted energy $\mathbb{E}(E_w)$ as

$$\overline{LT} = \frac{NE_{in} - \mathbb{E}(E_w)}{\mathbb{E}(E_{tx}) + NE_{es}} \tag{5}$$

where E_{es} is the energy consumed by one sensor in channel estimation which is zero for transmission schemes that do not require the channel state information (CSI). From (5), we see that for networks with fixed N and E_{in}, the network lifetime depends on both $\mathbb{E}(E_{tx})$ and $\mathbb{E}(E_w)$. Transmission protocol that solely minimizes the average transmission energy $\mathbb{E}(E_{tx})$ is not optimal in maximizing the network lifetime. To maximize the network lifetime, the transmission protocol should strike a balance between $\mathbb{E}(E_{tx})$ and $\mathbb{E}(E_w)$ by taking into account both the channel state and residual energy of each sensor.

III. DISTRIBUTED TRANSMISSION VIA CARRIER SENSING

In this section, we focus on the design of a distributed transmission protocol which is capable of enabling a sensor with a particular local property. In the next section, we study which local property should be used to determine the transmitting sensor so that the network lifetime is maximized.

In [3,4,11], a distributed transmission protocol named opportunistic carrier sensing is proposed for energy efficient information retrieval in the sensor networks. The goal of this opportunistic scheme is to enable the sensor with the best channel to transmit based solely on the local CSI. To achieve this, this scheme incorporates the local CSI into the backoff strategy of carrier sensing. Specifically, after each sensor measures its channel gain γ_k using the beacon of the AP, it chooses a backoff time τ_k based on a predetermined function $f(\gamma)$ which maps the channel state to a backoff time and then listens to the channel. A sensor will transmit with its chosen backoff delay if and only if no one transmits before its backoff time expires. If $f(\gamma)$ is chosen to be a strictly decreasing function[1] of γ as shown in Figure 2, this opportunistic carrier sensing will ensure that only the sensor with the best channel transmits.

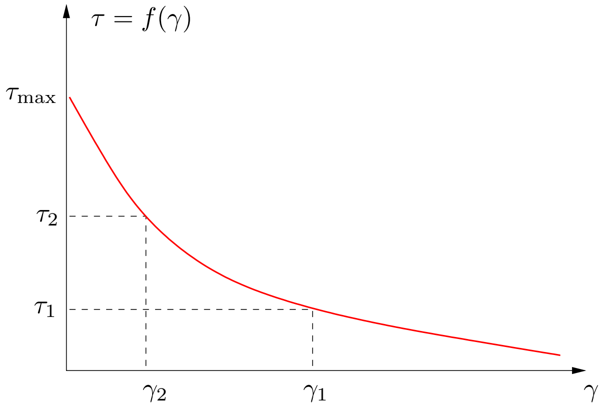

Fig. 2: Opportunistic carrier sensing.

The idea of opportunistic carrier sensing, first proposed in [10,12], provides a distributed solution to the general problem of finding maximum/minimum. Replacing the channel gain with other metrics, we are able to select the sensor with the maximum/minimum desired metric. Specifically, after each sensor computes the predefined metric $y_k = g(x_1, x_2, \ldots, x_n)$ based on its own state characterized by parameters $x_1, x_2, \ldots, x_n$ (for example, these parameters can be channel gain, residual energy, distance to a reference point, data property, QoS of its measurement), it maps its metric y_k to a backoff time τ_k using a predetermined decreasing function $f(y)$ and then listens to the channel. When the propagation delay among sensors is negligible, the sensor with the maximum metric will seize the channel.

With the above approach, the problem of designing the optimal distributed transmission protocol in terms of the lifetime performance reduces to the problem of finding the proper metric $g(x_1, x_2, \ldots, x_n)$, with which the network lifetime is maximized. As mentioned in the Section II, the network lifetime depends on both the transmission energy and the residual energy of the sensors. Thus, a metric $g(\gamma_k, e_k)$ which takes into account both the channel gain γ_k and the residual energy e_k is desired.

IV. LIFETIME ANALYSIS

In this section, we investigate the network lifetime under different distributed transmission protocols. We propose a

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[1] When the propagation delay is negligible, $f(\gamma)$ can be any decreasing function. When the delay is significant, however, $f(\gamma)$ needs to be designed judiciously to maintain the performance of the opportunistic carrier sensing. In [11], a backoff function $f(\gamma)$ is constructed and graceful performance degradation demonstrated with respect to propagation delay.

new transmission protocol which utilizes both the channel states and the residual energy of the sensors.

IV.A Transmission Protocols without CSI

The simplest transmission protocol is to arbitrarily pick a sensor to transmit, *i.e.,* the metric $g(\gamma_k, e_k)$ is a random variable independent of γ_k and e_k.

A better scheme can be obtained by taking into account the remaining energy of each sensor. Intuitively, the sensor with the most residual energy is less likely to die after the transmission. Hence, picking the sensor with the most residual energy will decrease the probability that the whole network dies and thus increase the lifetime of the network. The k-th sensor is selected during the l-th data collection if the residual energy of the k-th sensor is greater than any other sensors whose remaining energy is sufficient for the current transmission, *i.e.,*

$$\begin{aligned} &e_k(l) \geq e_j(l) \text{ for all } j \\ &\text{subject to } e_j(l) \geq E_c + \frac{E_{nf}}{\gamma_j(l)}. \end{aligned} \tag{6}$$

In Appendix B, we show that this scheme of enabling the sensor with the most residual energy minimizes the average dynamic range of the network residual energy, *i.e.,* it aims at maintaining a uniform energy profile among sensors. This scheme can be implemented using the carrier sensing approach (see Section III) with metric

$$g(\gamma_k, e_k) = e_k(l). \tag{7}$$

IV.B Transmission Schemes with CSI

With the aid of CSI, we can decrease the average transmission energy $\mathbb{E}(E_{tx})$ and thus increase the network lifetime. The most straightforward transmission scheme is to pick the sensor with the best channel to transmit so that the average transmission energy $\mathbb{E}(E_{tx})$ is minimized. That is, the k-th sensor is selected during the l-th data collection if it requires the minimum transmission energy among the sensors which have enough energy for the current transmission, *i.e.,*

$$\begin{aligned} &\gamma_k(l) \geq \gamma_j(l), \quad \text{for all } j \\ &\text{subject to } e_j(l) \geq E_c + \frac{E_{nf}}{\gamma_j(l)}. \end{aligned} \tag{8}$$

The picking best channel scheme can be implemented using the carrier sensing approach with metric

$$g(\gamma_k, e_k) = \gamma_k(l). \tag{9}$$

Note that the picking most energy scheme aims solely at minimizing $\mathbb{E}(E_w)$ by taking into account the residual energy while the picking best channel scheme focuses entirely on minimizing $\mathbb{E}(E_{tx})$ by utilizing the CSI. Neither scheme is optimal in terms of maximizing the network lifetime (see Fig. 3).

We propose a new distributed transmission protocol which takes into account both the CSI and the residual energy. Specifically, in the l-th data collection, sensor k is enabled for transmission if AFTER this data collection, sensor k has the most residual energy. In another word, this new scheme maximizes the minimum residual energy among all sensors in each data collection, *i.e.,* the k-th sensor is enabled during the l-th data collection if

$$e_k(l) - \frac{E_{nf}}{\gamma_k(l)} \geq e_j(l) - \frac{E_{nf}}{\gamma_j(l)}, \quad \text{for any } j = 1, \ldots, N. \tag{10}$$

Our new scheme can also be implemented using the carrier sensing approach with metric

$$g(\gamma_k, e_k) = e_k(l) - \frac{E_{nf}}{\gamma_k(l)}. \tag{11}$$

Comparing (11) to (7) and (9), we can see that this new scheme takes into consideration both the channel condition and the residual energy of the sensors. It maximizes the minimum sensor residual energy in the network at each data collection.

V. Simulation Examples

This section compares the lifetime performance of different transmission schemes. In all the figures, the transmission energy required to achieve an acceptable SNR in absent of fading is $E_{nf} = 1$ unit energy. All the other energy quantities are normalized by E_{nf}. The circuitry energy consumption and the channel estimation energy consumption are $E_c = 0.01$ and $E_{es} = 0.001$, respectively.

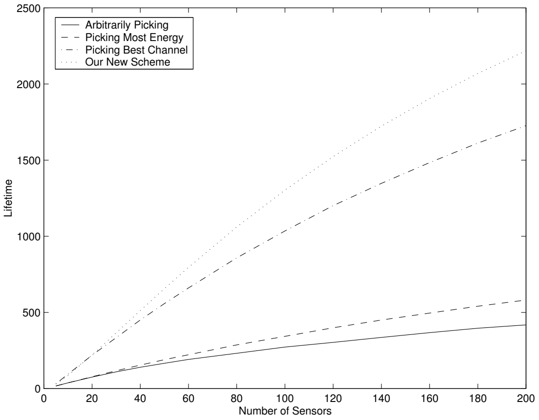

Fig. 3: Comparison of the network lifetime. $E_{in} = 5$.

Fig. 3 compares the lifetime of the networks employing different transmission schemes. As expected, the arbitrarily picking scheme performs the worst. The picking most energy scheme outperforms the arbitrarily picking scheme. As the number of sensors N increases, the performance gain of the picking most energy scheme over the arbitrarily picking scheme increases. The network lifetime of the transmission schemes with CSI increases much more rapidly than those without CSI as N increases. The CSI improves the lifetime of the network. The picking best channel scheme is not optimal in the sense of maximizing network lifetime. Our new scheme outperforms the picking best channel scheme when the number of sensors N is large. As N increases, the performance gain of our new scheme over the picking best channel scheme increases.

Fig. 4 compares the average transmission energy of our new scheme to that of the picking best channel scheme. The average transmission energy remains almost the same as the initial energy E_{in} increases. As the number of sensors N increases, the average transmission energy decreases and so does the rate of decreasing. Compared to the picking best channel scheme, the additional transmission energy required in our scheme diminishes as the number of sensors increases (see the lower plot in Fig. 4 which demonstrates the different in average transmission energy).

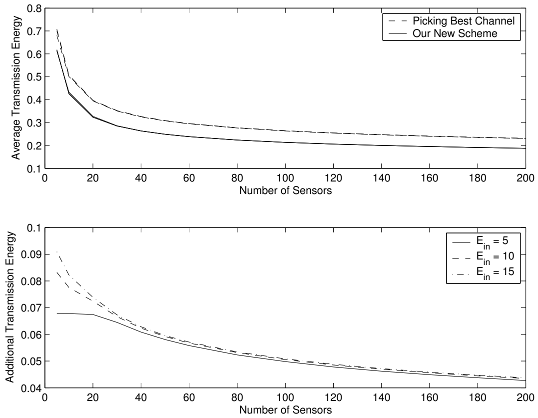

Fig. 4: Comparison of the average transmission energy with different initial energy $E_{in} = 5, 10, 15$.

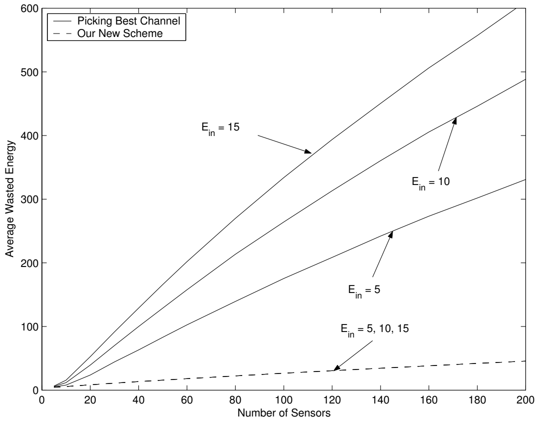

Fig. 5: Comparison of the average wasted energy with different initial energy $E_{in} = 5, 10, 15$.

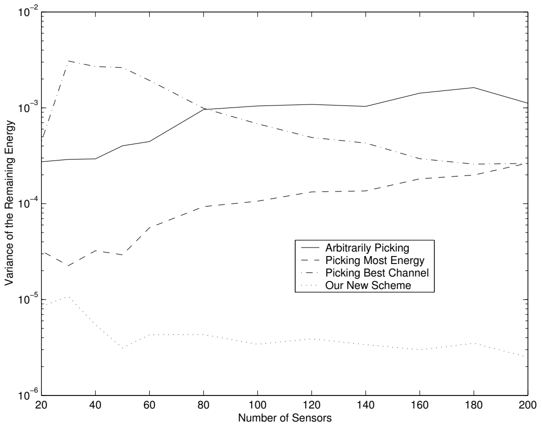

Fig. 6: The variance of the remaining energy. $E_{in} = 10$

Fig. 5 compares the average wasted energy of our new scheme to that of the picking best channel scheme. As the initial energy E_{in} increases, the average wasted energy $\mathbb{E}(E_w)$ of our new scheme remains the same while that of the picking best channel increases. As the number of sensors N increases, the average wasted energy $\mathbb{E}(E_w)$ of the picking best channel scheme increases much more rapidly than that of our new scheme. Combining Figs. 4 and 5, we find that as the number of sensors N increases, the additional transmission energy required in our new scheme decreases and the additional wasted energy in the picking best channel scheme increases. From (5), we can see that the lifetime of our new scheme outperforms that of the picking best channel as the number of sensors increases, which can also be seen from Fig. 3. Hence, transmission scheme which minimizes the average transmission energy is not optimal in terms of the network lifetime. Transmission schemes which take into consideration both the transmission energy and the residual energy of the sensors are desired to achieve longer lifetime.

Fig. 6 plots the variance of the remaining energy of the sensors after the lifetime expires. The variance of the remaining energy in our new scheme is much smaller than the other three schemes, which indicates that the remaining energy of our new scheme approaches uniform distribution. This observation agrees with our expectation that less energy is wasted in our scheme after the lifetime expires. On the other hand, lager variance of the other three transmission schemes indicates that the remaining energy of the sensors fluctuate widely, which results in more wasted energy.

VI. Conclusion

This paper investigated the lifetime performance of different transmission schemes for the information retrieval operation in sensor networks. We showed that the network lifetime depends on both the average transmission energy and the average remaining energy in the network after the lifetime expires. Picking the sensor with the best channel is no longer an optimal scheme in the sense of maximizing the lifetime. We thus proposed a new transmission scheme which utilizes both the CSI and the residual energy of the sensors. Simulation results showed that our new scheme outperforms the available schemes when the number of sensors in large.

We notice that the metric (11) used in the proposed protocol equally weights the required transmission energy and the residual energy of the sensor. Metrics with different weighting factors are studied in our forthcoming paper [13].

Appendix A

We use the frequency interpretation to prove the expression for the average network lifetime (5). Let $lt^{(k)}$ and $e_w^{(k)}$ be the network lifetime and the wasted energy of the k-th trial. Let $e_{tx}^{(k)}(l_k)$ be the transmission energy for the l_k-th data transmission during the k-th trial, where $1 \leq l_k \leq lt^{(k)}$. By the conservation of energy, we obtain

$$NE_{in} = \sum_{l_k=1}^{lt^{(k)}} (NE_{es} + e_{tx}^{(k)}(l_k)) + e_w^{(k)}. \tag{12}$$

Summation of (12) over M trials yields

$$MNE_{in} = \sum_{k=1}^{M} \sum_{l_k=1}^{lt^{(k)}} (NE_{es} + e_{tx}^{(k)}(l_k)) + \sum_{k=1}^{M} e_w^{(k)}. \tag{13}$$

As the number of trials M goes to infinity, the sample mean approaches the expected value. We can re-write (13) as

$$\begin{aligned} NE_{in} &= \left(\frac{1}{M}\sum_{k=1}^{M} lt^{(k)}\right)\left(NE_{es} + \frac{\sum_{k=1}^{M}\sum_{l_k=1}^{lt^{(k)}} e_{tx}^{(k)}(l_k)}{\sum_{k=1}^{M} lt^{(k)}}\right) \\ &\quad + \frac{1}{M}\sum_{k=1}^{M} e_w^{(k)} \qquad (14) \\ &= \overline{LT}(NE_{es} + \mathbb{E}(E_{tx})) + \mathbb{E}(E_w) \end{aligned}$$

where

$$\lim_{M\to\infty} \frac{1}{M}\sum_{k=1}^{M} lt^{(k)} = \overline{LT}, \qquad (15)$$

$$\lim_{M\to\infty} \frac{1}{M}\sum_{k=1}^{M} e_w^{(k)} = \mathbb{E}(E_w), \qquad (16)$$

$$\lim_{M\to\infty} \frac{\sum_{k=1}^{M}\sum_{l_k=1}^{lt^{(k)}} e_{tx}^{(k)}(l_k)}{\sum_{k=1}^{M} lt^{(k)}} = \mathbb{E}(E_{tx}). \qquad (17)$$

Eq. (5) follows directly from (14).

Appendix B

Suppose that $e_1 \geq e_2 \ldots \geq e_N$ are the remaining energy of the sensors after the l-th data collection and e_{tx} is the expected energy that is required to transmit one data packet. Let Δe and Δe_k denote the expected energy difference among the sensors after the transmission of the the sensor with the most energy and after that of the k-th sensor, respectively.

- When $e_1 - e_{tx} \geq e_2$, $\Delta e = e_1 - e_{tx} - e_N$. Since $e_1 \geq e_k$, $e_k - e_{tx} \leq e_2$ and $\Delta e_k \geq e_1 - e_N \geq \Delta e$. When $e_N \leq e_1 - e_{tx} \leq e_2$, $\Delta e = e_2 - e_N$. Since $e_1 \geq e_k$, $e_N \leq e_k - e_{tx} \leq e_2$ and $\Delta e_k = e_1 - e_N \geq \Delta e$.
- When $e_1 - e_{tx} \leq e_N$, $\Delta e = e_2 - e_1 + e_{tx}$. Since $e_1 \geq e_k$, $e_k - e_{tx} \leq e_N$ and $\Delta e_k = e_1 - e_k + e_{tx} \geq \Delta e$.

Hence $\Delta e \geq \Delta e_k$. That is, the picking most energy scheme tries to reduce the difference among the residual energy of the sensors.

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