DISTRIBUTED TRANSMISSION PROTOCOL FOR LIFETIME MAXIMIZATION IN SENSOR NETWORKS

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ABSTRACT

This paper addresses the design of distributed transmission protocol for lifetime maximization in wireless sensor networks (WSNs). A dynamic protocol for lifetime maximization (DPLM) is proposed. This protocol exploits both the channel state information (CSI) and the residual energy information (REI) at each individual sensor. The principle of DPLM resembles the retirement planning strategy: be more opportunistic by prioritizing sensors with better channels for transmission when the network is young and more conservative by favoring sensors with more residual energy when the network is old. The asymptotic optimality of DPLM in terms of utilizing CSI is established analytically. The performance of DPLM is evaluated via simulations.

1. INTRODUCTION

In wireless sensor networks (WSNs), one of the critical operations is the information retrieval process in which sensor measurements are collected by access points (APs) to be used by the end user. Under the architecture of SEnsor Network with Mobile Access (SENMA) [1], the mobile APs initiate the data collection process by broadcasting beacon signals to activate sensors. Activated sensors then transmit, according to a transmission protocol, their data to the APs through a common wireless channel (see Fig. 1).

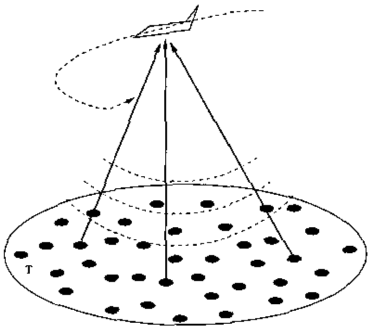

Fig. 1: Sensor network with mobile access point.

One of the challenging research topics on WSNs is to design energy-efficient information retrieval protocols. As shown in [2, 3], energy-efficient design can be formulated as an unconstrained or a constrained optimization problem. In the former, the design objective is to maximize the number of transmitted information bits per Joule under an implicit assumption that each sensor has an infinite amount of energy. The key to the unconstrained energy efficiency is the use of the channel state information (CSI). Specifically, transmission protocols should give higher priorities to sensors with better channels; sensors with poor channel realizations should save their energy, wait for their chances, and act when opportunities arise. This opportunistic strategy is first proposed by Knopp and Humblet [4] and later studied in [5–9].

On the other hand, the constrained formulation of energy efficiency aims at maximizing the network lifetime under the assumption that each sensor is powered by a nonrechargeable battery with a finite amount of energy. Many researchers have realized that lifetime maximizing schemes should exploit the residual energy information (REI) of each sensor. Various sensor placement schemes, routing and transmission protocols [10–12] that utilizes REI have been proposed.

[13] is perhaps the first work to reveal that both CSI and REI are key parameters for lifetime maximization in wireless networks with fading. Since the sensor with the best channel may not be the sensor with the most residual energy, lifetime maximizing protocols rely on an optimal tradeoff between CSI and REI [13]. A distributed transmission protocol that exploits both CSI and REI is proposed in [13]. Referred to as the max-min approach, the protocol proposed in [13] maximizes the minimum residual energy in each data collection. As a consequence, the probability that the network dies is minimized in each data collection.

The max-min protocol proposed in [13] is static with respect to the network age: the weight of CSI over REI (and vice versa) remains the same over the span of the network

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lifetime. The lack of adaptation to the network age limits the performance of the max-min protocol. In this paper, we propose a dynamic protocol for lifetime maximization (DPLM) that trades off CSI and REI according to the age of the network. The principle of DPLM resembles the retirement planning strategy: be more opportunistic by prioritizing sensors with better channels for transmission when the network is young and more conservative by favoring sensors with more residual energy when the network is old. As a consequence of the dynamic nature of this protocol, DPLM is asymptotically optimal in terms of utilizing CSI as demonstrated by our analysis. Simulation results show that DPLM provides significant performance gain in terms of lifetime.

2. SYSTEM MODEL

2.1. Network and Radio Model

Consider a sensor network with N nodes deployed for monitoring certain phenomenon. In each data collection, M samples from these N sensors are retrieved by a mobile AP where M is determined by the underlying application and the QoS requirement. Due to node redundancy, we generally have $M \ll N$. Realizing that sensors experience different channel fading and have different residual energy, we seek the answer to the following question: which M sensors should be chosen to transmit their measurements so that the network lifetime is maximized. In order to gain insights and simplify the presentation, we assume $M = 1$. The extension of the proposed protocol to general cases is, however, straightforward.

We assume that sensor measurements are in the form of equal-sized packets. The channel between the mobile AP and a sensors follows a block fading model with the block length equal to the transmission time of one packet. Let s_i denote the i-th sensor in the network where $i = 1, \ldots, N$. Let $c_i(l)$ be the channel gain of s_i during the l-th data collection and $e_i(l)$ the residual energy of s_i at the beginning of the l-th data collection. For simplicity, we will often write e_i and c_i instead of $e_i(l)$ and $c_i(l)$ when referring to a arbitrary data collection. The energy required for s_i to transmit its packet to the AP during the l-th data collection is given by

$$E_r^{(i)}(l) = E_c + \frac{\overline{E}}{c_i(l)} \tag{1}$$

where E_c is the energy consumed in the transmitter circuitry, and $\overline{E}$ is the required transmission energy to achieve an acceptable received signal-to-noise ratio (SNR) at the AP in the absence of (small-scale) channel fading. Generally, $\overline{E}$ depends on the path-loss of the channel, and we have assumed that sensors are at approximately the same distance to the mobile AP. Clearly, the better the channel gain $c_i(l)$, the smaller the required transmission energy $E_r^{(i)}(l)$.

2.2. Lifetime Definition

We assume that each sensor is powered by a non-rechargeable battery with E_0 initial energy. A sensor is considered dead if its residual energy drops below the transmitter circuitry energy consumption E_c, *i.e.*, it does not have enough energy for transmission under any channel condition. The lifetime $\mathcal{L}$ of the sensor network is defined as the number of data collections until any sensor in the network dies (the first death) or no sensor has enough energy for transmission (the first failure in data collection), whichever occurs first. After the network dies, the total unused energy E_w left in the network is wasted.

In [14], a general formula for the network lifetime is derived. This lifetime formula holds independently of the lifetime definition, the network architecture and protocol, channel fading characteristics, and energy consumption model. Applying this formula to the current network setting, we obtain the expression for the average network lifetime $\mathcal{L}$ as,

$$\mathbb{E}[\mathcal{L}] = \frac{NE_0 - \mathbb{E}[E_w]}{\mathbb{E}[E_r]} \tag{2}$$

where $\mathbb{E}[E_w]$ is the expected unused energy in the network when it dies and $\mathbb{E}[E_r]$ the expected reporting energy consumed by sensor nodes in a randomly chosen data collection.

The following notations are adopted in the remaining paper. Let $\vec{E} = (e^{(1)}, e^{(2)}, \ldots, e^{(N)})$ be the ordered residual energy profile of the sensors at the beginning of one data collection where $e^{(1)} \geq e^{(2)} \geq \ldots \geq e^{(N)}$. Define $\Delta(\vec{E}) = (\delta_1, \delta_2, \ldots, \delta_{N-1})$ where $\delta_i = e^{(i)} - e^{(i+1)}$ and $\eta(\vec{E}) = (\eta_1, \eta_2, \ldots, \eta_{N-1})$ where $\eta_i = \frac{e^{(i)} - e^{(i+1)}}{e^{(i+1)}}$ as, respectively, the absolute and the relative dispersiveness of the residual energy profile $\vec{E}$. For two equal-length vectors $\vec{x} = (x_1, x_2, \ldots, x_N)$ and $\vec{y} = (y_1, y_2, \ldots, y_N)$, we say $\vec{x} \geq \vec{y}$ if $x_i \geq y_i$ for all i. The step function is denoted by $U(x)$, *i.e.*, $U(x) = 1$ if $x \geq 0$ and $U(x) = 0$ otherwise.

3. THE DYNAMIC PROTOCOL FOR LIFETIME MAXIMIZATION (DPLM)

3.1. The Protocol

From (2), we can see that reducing $\mathbb{E}[E_r]$ and $\mathbb{E}[E_w]$ leads to prolonged network lifetime. To reduce $\mathbb{E}[E_r]$, the sensor with the best channel should be scheduled for transmission in each data collection. To reduce $\mathbb{E}[E_w]$, however, the sensor with the most residual energy should be favored in order to balance energy consumption among sensors. Since channel realizations are independent of the residual energy, an optimal tradeoff between CSI and REI needs to be achieved for lifetime maximization.

Realizing that maintaining small dispersiveness of the residual energy profile is crucial only toward the end of the network lifetime, we propose a dynamic transmission protocol that adaptively trades off CSI and REI according to the age of the network. Specifically, the proposed protocol DPLM selects the sensor which requires the least portion of its residual energy for the current transmission, *i.e.*, the sensor s_i is selected in the l-th data collection if and only if

$$\frac{e_i(l)}{E_r^{(i)}(l)} \geq \frac{e_j(l)}{E_r^{(j)}(l)}, \quad \text{for any } s_j. \tag{3}$$

That is, the sensor which is able to transmit the most number of times under the current channel conditions is allowed to transmit in the current data collection. Our DPLM can be readily implemented in a distributed fashion with the aid of the opportunistic carrier sensing scheme [9,13] by allowing each sensor to choose its transmission backoff time according to the following local metric

$$\gamma_i = g(c_i, e_i) = \frac{e_i}{E_c + \frac{\overline{E}}{c_i}}. \tag{4}$$

3.2. The Dynamic Nature and Asymptotic Optimality

Next, we show the dynamic nature of DPLM by comparing the probability that DPLM selects the sensor with the best channel or the most residual energy under different network residual energy profiles $\vec{E}$. For simplicity, we assume that the channel gains associated with different sensors are identically and independently distributed

Theorem 1 *DPLM adaptively trades off CSI and REI according to the relative dispersiveness $\eta(\vec{E})$ of the sensor residual energy profile. Specifically, as $\eta(\vec{E})$ increases, the probability of selecting the sensor with the best channel decreases while the probability of selecting the sensor with the most residual energy increases. That is,*

$$\begin{aligned} &\eta(\vec{E}_1) \leq \eta(\vec{E}_2) \\ &\quad \Rightarrow \Pr\{\textit{pick } c^{(1)}|\vec{E}_1\} \geq \Pr\{\textit{pick } c^{(1)}|\vec{E}_2\}; \quad &(5a) \\ &\quad \textit{and } \Pr\{\textit{pick } e^{(1)}|\vec{E}_1\} \leq \Pr\{\textit{pick } e^{(1)}|\vec{E}_2\}. \quad &(5b) \end{aligned}$$

Proof: To prove Theorem 1, we derive the probability that DPLM picks the sensor with the best channel $c^{(1)}$ and the probability that DPLM picks the sensor with the most residual energy $e^{(1)}$ for a given residual energy profile $\vec{E}$ as

$$\begin{aligned} \Pr\{c^{(1)}|\vec{E}\} = \sum_{i=1}^{N} \int_0^1 \prod_{l=1}^{i-1} F_c \left[\frac{1}{\frac{e^{(l)}}{e^{(i)}} \left(\frac{1}{x} + E_c\right) - E_c} \right] \\ \times F_c^{N-i}(x) dF_c(x), \end{aligned} \tag{6}$$

and

$$\begin{aligned} \Pr\{e^{(1)}|\vec{E}\} = \int_0^1 \prod_{l=2}^{N} \left\{ F_c \left[\frac{1}{\frac{e^{(l)}}{e^{(1)}} \left(\frac{1}{x} + E_c\right) - E_c} \right] \right. \\ \left. \times \chi_x + (1 - \chi_x) \right\} dF_c(x) \end{aligned} \tag{7}$$

where $\chi_x = U\left(xE_c - \frac{e^{(l)}}{e^{(1)} - e^{(l)}}\right)$ and $F_c(x)$ is the cumulative distribution function (cdf) of the i.i.d. channel gain. As the relative difference of the sensor residual energy $\eta(\vec{E})$ increases, the ratio of any two residual energy $\frac{e^{(l)}}{e^{(i)}}$ increases, where $1 \leq l \leq i \leq N$. Hence, the probability of picking the best channel $c^{(1)}$ decreases as $\eta(\vec{E})$ increases. Since the cdf $0 \leq F_c(x) \leq 1$, the probability of picking the most residual energy $e^{(1)}$ increases as $\eta(\vec{E})$ increases.

□□□

Since the total amount of energy $\sum_{i=1}^{N} e^{(i)}$ left in the network indicates the network age, the dynamic nature of DPLM with respect to the network age can be readily seen from the following corollary.

Corollary 1 *For the same absolute dispersiveness $\Delta(\vec{E})$ of the sensor residual energy profile, DPLM adaptively selects the sensor according to the total residual energy $\sum_{i=1}^{N} e^{(i)}$ in the network. Specifically, $\forall \epsilon > 0$,*

$$\Pr\{\textit{pick } c^{(1)}|\vec{E}\} < \Pr\{\textit{pick } c^{(1)}|\vec{E} + \epsilon\}; \tag{8a}$$

$$\Pr\{\textit{pick } e^{(1)}|\vec{E}\} > \Pr\{\textit{pick } e^{(1)}|\vec{E} + \epsilon\}. \tag{8b}$$

Proof: This corollary can be shown by noticing that for the same absolute dispersiveness of the sensor residual energy $\Delta(\vec{E})$, the relative dispersiveness $\eta(\vec{E})$ increases as the total energy $\sum_{i=1}^{N} e^{(i)}$ increases.

□□□

This corollary shows that when the network is young, DPLM is more likely to pick the sensor with the best channel. When the network becomes older, the probability that DPLM selects the sensor with the best channel decreases while the probability that DPLM selects the sensor with the most residual energy increases.

Recall that the optimal transmission protocol under the unconstrained formulation is to allow only the sensor with the best channel to transmit. Let us call this opportunistic protocol as the CSI-only protocol and denote its average reporting energy consumed in a data collection as E^*. Clearly, E^* is a lower bound on the reporting energy consumed in a data collection. One would expect that a good protocol under the constrained formulation should approach this optimal protocol under the unconstrained formulation when the constraint on the initial energy becomes less restrictive, *i.e.*, $E_0 \to \infty$. As demonstrated by Theorem 2, DPLM possesses this desirable property. It is asymptotically optimal in terms of utilizing CSI.

Theorem 2 *Assume that realizable channel gains are bounded below*[1]. *We have,*

$$\lim_{E_0 \to \infty} \mathbb{E}[E_r] = E^*, \tag{9}$$

where E^* is the average reporting energy achieved by enabling the sensor with the best channel for transmission in each data collection.

A proof of Theorem 2 can be found in [15]. As shown in the simulation examples in Section 4, the convergence of the average reporting energy $\mathbb{E}[E_r]$ in DPLM to the minimum value E^* is fast. The average reporting energy in DPLM approaches E^* even for small E_0 that allows a sensor to transmit, on the average, only 5 to 10 times (see Fig. 3).

4. SIMULATION EXAMPLES

This section compares the performance of different distributed transmission protocols [13]. The "arbitrary" protocol randomly picks a sensor for transmission in each data collection. The REI-only protocol selects the sensor with the most residual energy in each data collection. In all the figures, we normalize the required reporting energy in the absence of channel fading ($\bar{E} = 1$) and assume the (normalized) transmitter circuitry energy consumption is $E_c = 0.01$. We have also included the energy $E_{es} = 0.001$ consumed in channel acquisition for protocols utilizing CSI. The channel fading is assumed to be i.i.d. Rayleigh distributed.

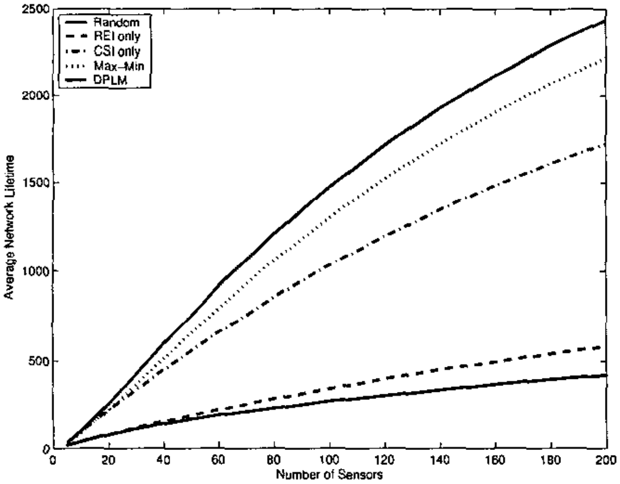

Fig. 2: Comparison of the average network lifetime of different transmission protocols with different number of sensors. $E_0 = 5$.

Fig. 2 compares the network lifetime $\mathbb{E}[\mathcal{L}]$ of different transmission protocols. As the number N of sensors increase, the network lifetime $\mathbb{E}[\mathcal{L}]$ increases, but the rate at which $\mathbb{E}[\mathcal{L}]$ increases diminishes. As expected, the random protocol performs the worst. The transmission protocols exploiting CSI (such as the CSI-only, Max-Min and DPLM protocols) outperform those without CSI (such as the random and REI-only protocols). DPLM outperforms all the available schemes and its performance gain increases as N increases.

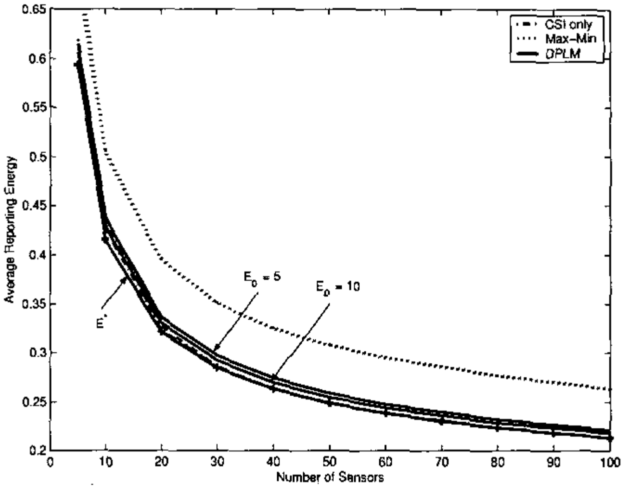

Fig. 3: Comparison of the average transmission energy consumed in each data collection of different transmission protocols. $E_0 = 5, 10$.

Fig. 3 compares the average reporting energy $\mathbb{E}[E_r]$ of different transmission protocols with CSI. As the number of sensors increases, the average reporting energy decreases and so does the rate of decreasing. As the initial energy E_0 increases, the average reporting energy $\mathbb{E}[E_r]$ of Max-Min and CSI-only protocols remains almost the same while that of DPLM decreases. The Max-Min protocol requires more energy in each data collection than CSI-only and DPLM. The average reporting energy $\mathbb{E}[E_r]$ of DPLM approaches the minimum value E^* when the initial energy E_0 increases. We notice that the $\mathbb{E}[E_r]$ of DPLM is close to the minimum value E^* even when E_0 is small: a sensor can only transmit, on the average, 5 or 10 times until it dies.

Fig. 4 demonstrates the dynamic nature of DPLM. As the age of the network (in terms of number of data collections performed) increases, the probability that DPLM picks the sensor with the best channel decreases while the probability of picking the sensor with the most residual energy increases. That is, DPLM is more opportunistic by favoring the sensor with the best channel for transmission when the network is young and more conservative by favoring the sensor with the most residual energy when the network is

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[1] This is equivalent to say that the transmission power of sensors is bounded above.

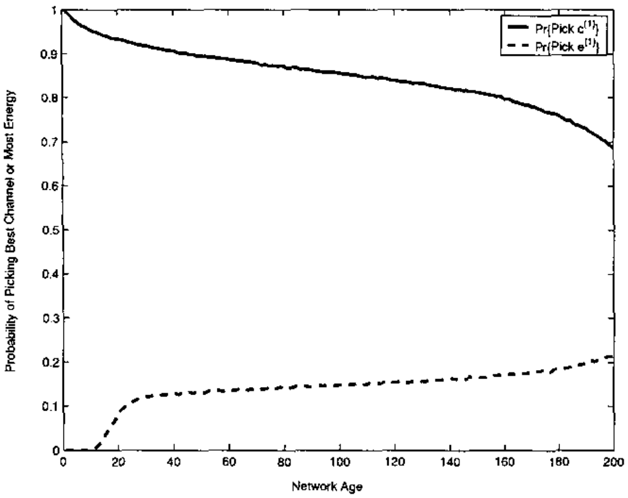

Fig. 4: The probability that DPLM selects the sensor with the best channel or the most residual energy. $E_0 = 10, N = 10$.

old.

5. CONCLUSION

In this paper, we propose a dynamic transmission protocol for lifetime maximization in sensor networks. Referred to as DPLM, the proposed protocol selects the sensor that requires the least portion of its residual energy for the current transmission. We demonstrate analytically that DPLM adaptively selects the sensor according to the age of the network. It is more aggressive to reduce the reporting energy by prioritizing the sensor with the best channel when the network is young and more conservative to balance the network residual energy by favoring the sensor with the most residual energy when the network is old. As the initial energy goes to infinity, the average reporting energy of DPLM approaches the minimum value achieved by selecting the sensor with the best channel in each data collection. Simulation results show that DPLM outperforms existing protocols and its performance gain increases as the number of sensors increases.

6. REFERENCES

[1] L. Tong, Q. Zhao, and S. Adireddy, "Sensor Networks with Mobile Agents," in *Proc. 2003 Intl. Symp. Military Communications*, (Boston, MA), Oct. 2003.

[2] J. Wiesselthier, G. Nguyen, and A. Ephremides, "Energy-aware wireless networking with directional antennas: the case of session-based broadcasting and multicasting," *IEEE Trans. on Mobile Computing*, vol. 1, no. 3, pp. 176–191, 2002.

[3] J. Wiesselthier, G. Nguyen, and A. Ephremides, "Resource management in energy-limited band-limited, tranceiver-limited wireless networks for session-based multicasting," *Computer Networks*, vol. 39, pp. 113–131, 2002.

[4] R. Knopp and P. Humblet, "Information capacity and power control in single cell multi-user communications," in *Proc. Intl Conf. Comm.*, (Seattle, WA), pp. 331–335, June 1995.

[5] D.N.C.Tse and S.V.Hanly, "Multiaccess Fading Channels : I Polymatroid Structure, Optimal Resource Allocation and Throughput Capacities," *IEEE Trans. Information Theory*, vol. 44, pp. 2796–2815, November 1998.

[6] I.E.Telatar and S.Shamai, "Some information theoretic aspects of decentralized power control in multiple access fading channels," in *Proc. Info. Theory and Networking Workshop*, (Piscataway, NJ), pp. 23–23, 1999.

[7] X.Qin and R.Berry, "Exploiting Multiuser Diversity for Medium Access Control in Wireless Networks," in *IEEE INFOCOM*, (San Francisco, CA), 2003.

[8] S. Adireddy and L. Tong, "Exploiting Decentralized Channel StateInformation for Random Access," *IEEE Trans. Info. Theory*, Feb 2005.

[9] Q. Zhao and L. Tong, "Opportunistic Carrier Sensing for Energy Efficient Information Retrieval in Sensor Networks," *to appear in EURASIP Journal on Wireless Communications and Networking*, 2005.

[10] J. Chang and L. Tassiulas, "Energy conserving routing in wireless ad-hoc networks," in *Proc. of IEEE INFOCOM*, 2000.

[11] Q. Xie, C. Lea, M. Golin, and R. Fleischer, "Maximum Residual Energy Routing with Reverse Energy Cost," in *Proc. IEEE Globecom*, 2003.

[12] O. Younis and S. Fahmy, "HEED: a hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks," *IEEE Trans. Mobile Computing*, vol. 3, pp. 366–379, 2004.

[13] Y. Chen and Q. Zhao, "Maximizing the Lifetime of Sensor Network Using Local Information on Channel State and Residual Energy," in *Proc. of the 39th Conference on Information Science and Systems*, March 2005.

[14] Y. Chen and Q. Zhao, "On the lifetime of wireless sensor networks," *submitted to IEEE Communication Letters*, May 2005.

[15] Y. Chen and Q. Zhao, "Applying Retirement Planning Strategy to Sensor Networks: Dynamic MAC for Lifetime Maximization," *to be submitted*, May 2005.