ENERGY-AWARE DATA-CENTRIC MAC
FOR APPLICATION-SPECIFIC SENSOR NETWORKS

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ABSTRACT

We propose an energy-aware data-centric MAC protocol for application-specific large sensor networks. Referred to as Opportunistic Type-Based Medium Access (O-TBMA), the proposed protocol adopts the principle of cross-layer design that integrates application layer (detection and estimation) performance measure with physical layer communications, medium access control, and signal processing. Focusing on maximizing energy efficiency and network lifetime, we investigate data-centric medium access strategies and develop opportunistic transmission schemes that incorporate information on sensor channel state and residual energy.

Key Words: Data-centric MAC. Sensor network lifetime.

1. INTRODUCTION

1.1. Cross-Layer Design for Application-Specific Sensor Networks

Contemporary network science focuses primarily on the general, not the application specific. It is then only natural that the prevailing approach to networking is a modular and layered approach, not an integrated approach. For example, the role of signal processing has been relegated to the two ends of the protocol stack: establishing and maintaining links at the physical layer and encoding and representing source information at the application layer. Such a layered strategy is one of the reasons that has led to the phenomenal success of the Internet and the cellular network.

In this paper, we take a viewpoint that classical methodologies developed for general purpose data networks, ad hoc or cellular, are not adequate for application-specific sensor networks; what has been fundamental to the success of the Internet—the layered architecture and design—may in fact be a hindrance to efficiency for application-specific networks.

Consider, for example, sensor networks deployed for target detection and tracking, environmental monitoring, or the detection of a specific chemical compound. For such applications, network performance will be measured not by data rate at the link level, nor by the throughput over the network; such metrics for general data networks do not necessarily translate to a performance measure suitable for signal detection and estimation. For application-specific sensor networks, performance should be measured by application-defined metrics: the miss detection probability, the false alarm rate, the network lifetime for performing these tasks, and the energy efficiency for target detection, tracking, and estimation.

1.2. Energy-Aware Data-Centric MAC

We consider the problem of delivering measurements from a large number of sensor nodes to a mobile access points [1] or a cluster head/gateway node. We aim at a distributed MAC protocol that maximizes the network lifetime while maintaining a global estimation performance specified by the application layer.

Referred to as Opportunistic Type-Based Multiple Access (O-TBMA), the proposed protocol incorporates channel state information and sensor residual energy for lifetime maximization. Differing from conventional user-centric MAC such as TDMA, CDMA, and FDMA, O-TBMA is data-centric. Specifically, simultaneous transmissions from a large number of sensors are orthogonalized based on their measurements, allowing the delivery of the type or the empirical measure which is a sufficient statistic for parameter estimation. Furthermore, sensors are chosen for transmission based on their channel state and residual energy, leading to prolonged network lifetime while maintaining a given level of estimation performance.

1.3. Related Work

The problem of estimation over multiaccess channel has been formulated and a Type-Based Multiple Access scheme proposed by Mergen and Tong [2–4] and, independently by Liu and Sayeed [5, 6]. Works prior to TBMA, *e.g.,*Chamberland and Veeravalli [7], and Chan *et al.* [8], assumed that each sensor is allocated an orthogonal channel to transmit its observation as in TDMA, FDMA or CDMA. Earlier work on distributed detection and fusion usually do not assume the presence of multiaccess interference. See, *e.g.,* [9–12] and references therein.

The idea of incorporating channel state information into multiaccess was first proposed by Knopp and Humblet [13] and further developed in [14–20]. These approaches all focus on data rate or throughput instead of energy efficiency or network lifetime. The use of the residual energy information in lifetime maximizing protocols has been considered in [21–28]. In [29–31], both channel state and residual energy are used in the design of MAC protocols for network lifetime maximization. Differing from this paper, however, the definition of network lifetime employed in [29, 30] is decoupled from the performance measure specified by the application layer.

2. PROBLEM STATEMENT

Suppose that we have a network of N sensors observing $\mathbf{x} = (x_1, \cdots, x_N)$ drawn from a certain joint distribution $p(\mathbf{x}; \theta)$. The classical detection and estimation problem is to make an inference about θ based on $\mathbf{x}$.

We now add one layer of networking to this problem by assuming that sensors have to deliver their measurement $\mathbf{x}$ to the access point or gateway node through a noisy multiaccess channel. Consider the schematic shown in Figure 1 in which N sensors in the network obtains measurements $\{x_i\}_{i=1}^N$. Among these N sensors, M sensors are chosen to communicate the measurement to the access point. A chosen sensor i delivers its measurement by transmitting a signal $s_i(t; x_i)$. The access point receives a mixture of transmissions from these M sensors

$$z(t) = \sum_i y_i(t) + v(t), \quad y_i(t) = s_i(t; x_i) * h_i(t), \quad (1)$$

where $h_i(t)$ is the channel fading process, and $v(t)$ the additive noise. Given that sensor data $\mathbf{x}$ are drawn jointly from a parametric distribution $p(\mathbf{x}; \theta)$, the estimation problem at the access point is to estimate θ from $z(t)$ so that the mean square error is no larger than ζ

$$\mathbb{E}(|\hat{\theta} - \theta|^2) \le \zeta. \quad (2)$$

Our goal here is to design a MAC protocol governing the choice of multiaccess signaling $s_i(t; x_i)$ and the sensor selection so that the network lifetime is maximized while maintaining the estimation requirement given by (2).

To prolong the network lifetime, it is clear that we should minimize the number M of data samples to be collected (thus minimize the number of transmissions). We thus tackle this problem in two steps: (i) design the multiaccess signaling $s_i(t; x_i)$ that leads to the minimum number M_* of data samples required for a given estimation performance ζ; (ii) design a sensor selection scheme that chooses M_* sensors with desired properties for lifetime maximization.

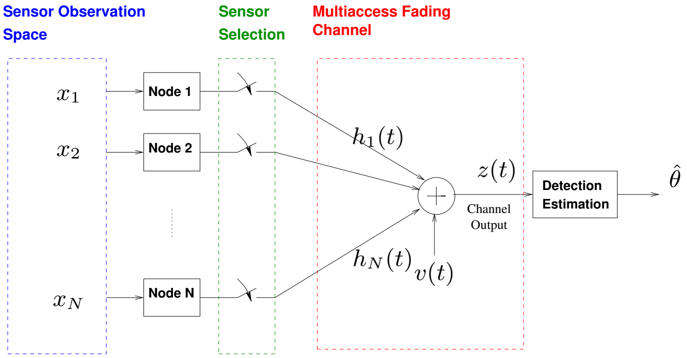

Fig. 1: Transmission through a multiaccess fading channel.

3. THE OPTIMAL MULTIACCESS SIGNALING

Consider first the ideal scenario that the access point has direct access to M data samples $\{x_i\}$, and each x_i is a discrete random variable drawn i.i.d. from probability mass function

$$\mathbf{p}_\theta = (p_\theta(1), \cdots, p_\theta(k)).$$

In this case a fundamental limit on estimation performance is given by the Cramér-Rao bound (CRB) [32]

$$\mathbb{E}\{(\hat{\theta} - \theta)^2\} \ge \frac{1}{MI(\theta)}, \quad (3)$$

where

$$I(\theta) = \sum_{i=1}^{k} \frac{(dp_\theta(i)/d\theta)^2}{p_\theta(i)} \quad (4)$$

is the Fisher information.

In [2–4], a type-based medium access (TBMA) protocol was proposed based on the observation that the the *type* or the empirical measure [33, 34] is a sufficient statistic for estimation. Suppose that the measurement x_i assumes a value from a finite alphabet $\mathcal{X}$ of size k. The type of $\mathbf{x}$ is the k-dim probability vector $\tilde{\mathbf{p}} = \frac{1}{M}(\mathcal{N}_1, \cdots, \mathcal{N}_k)$, where $\mathcal{N}_j$ is the number of nodes that observe j.

Consider the ideal conditions when all sensors are synchronized and there is no fading, *i.e.*, $h_i(t) = 1$. Let

$$\{u(t; 1), \cdots, u(t; k)\}$$

be a set of orthonormal waveforms, one for each possible measurement value. The received signal at the access point is

$$z(t) = \sum_{j=1}^{k} \mathcal{N}_j u(t; j) + v(t). \quad (5)$$

Suppose that the access point passes $z(t)$ through the bank of matched filters $\{u^*(-t; 1), \cdots, u^*(-t; k)\}$ and samples their output at $t = 0$. In this case, signals corresponding to the same data measurement add coherently, and the received signal vector, scaled by $\frac{1}{M}$, converges to the sufficient statistic $\tilde{\mathbf{p}}$ in distribution. It has been shown in [2–4] that TBMA is asymptotically efficient and the convergence to the CRB is fast. Thus, the signaling scheme based on this data-centric orthogonalization is asymptotically optimal in terms of minimizing the number of data samples required for a given estimation performance. Approximately, the number M of data samples required by the TBMA scheme is

$$M \approx \frac{1}{\zeta I(\theta)}, \tag{6}$$

where $I(\theta)$ is the Fisher information given in (4).

4. ENERGY-AWARE DATA-CENTRIC MAC

Using the multiaccess signaling given by the TBMA scheme, we need to collect M data samples in each data collection to achieve the required estimation performance. The next question we need to address is which M sensors in the network should be selected for transmission to prolong the network lifetime.

4.1. Network Lifetime

The definition of network lifetime is application specific. For the problem we consider here, network lifetime is given by the time span during which the targeted level of estimation performance can be maintained: $\mathbb{E}[(\hat{\theta}-\theta)^2] \leq \zeta$. Assume that the application layer requires an estimate of θ at a certain rate λ. Sensors are then required to take measurements and deliver their data at rate λ. With a fixed initial energy E, a sensor dies after a finite period of time. To achieve an MSE no larger than ζ, the number of sensors alive has to be no smaller than M. The network lifetime $\mathcal{L}(\mathcal{T})$ for a particular transmission scheme $\mathcal{T}$ is then determined by the first time when the number of sensors alive goes below M.

The first crucial step is to obtain a characterization of network lifetime. For a network with N sensors, and each sensor with E_0 Joules of initial energy, it has been shown recently in [29, 35] that

$$\mathcal{L}(\mathcal{T}) = \frac{NE_0 - \mathbb{E}[E_{\text{w}}(\mathcal{T})]}{\mathbb{E}[E_{\text{d}}(\mathcal{T})]} \tag{7}$$

where $\mathcal{T}$ denotes a specific transmission scheme, $E_{\text{d}}(\mathcal{T})$ the total energy consumed in a randomly chosen data collection, and $E_{\text{w}}(\mathcal{T})$ the amount of unused energy when the network dies, both are random variables depending on specific realizations. We have assumed, without loss of generality that $\lambda = 1$.

4.2. Two Key Factors: Channel State and Residual Energy

We isolate two crucial factors that affect network lifetime $\mathcal{L}$. From (7), it is obvious that we should minimize the total transmission energy $\mathbb{E}(E_{\text{d}}(\mathcal{T}))$ in each data collection. This means that we should choose sensors with better channel realizations so that less transmission energy are needed to achieve the targeted SNR at the access point. Therefore, the transmission scheme $\mathcal{T}$ should be a function of the channel state, which motivates the proposed opportunistic transmission scheme described below.

To minimize $\mathbb{E}(E_{\text{w}}(\mathcal{T}))$, $\mathcal{T}$ should be such that the energy across sensors is utilized in some balanced way. To this end, the transmission scheme should also be a function of sensor residual energy: sensors with more energy left should have higher priority to transmit. This is the second key parameter that needs to be incorporated in the transmission protocol $\mathcal{T}$.

4.3. Opportunistic Data-Centric MAC

The key innovation is an opportunistic transmission scheme that exploits both channel state information and residual energy. Let h_i and e_i denote, respectively, the channel realization and the residual energy of sensor i at the beginning of a particular data collection. Assume first that each sensor has the perfect knowledge of h_i. In this case, the channel effects can be mitigated at the transmitter and the TBMA strategy described in the previous section can be applied directly [3].

As stated above, to minimize the transmission energy, we should favor sensors with better channel realizations. To reduce the used energy left in the network when the network dies, however, the sensor with higher 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 the channel state information (CSI) and the residual energy information (REI) needs to be achieved for lifetime maximization.

We formulate the problem by introducing a concept of energy efficiency index γ_i which is a function of sensor i's channel gain $c_i \triangleq |h_i|^2$ and residual energy e_i

$$\gamma_i = g(c_i, e_i). \tag{8}$$

In each data collection, M sensors with the largest energy efficiency indexes are chosen for transmission. The problem of transmission protocol design is thus reduced to the design of the function $g(\cdot)$.

We consider here defining the energy efficiency index γ_i as the ratio of sensor i's residual energy e_i to the required transmission energy $E_{\text{tx}}(c_i)$ given its current channel gain c_i.

$$\gamma_i = \frac{e_i}{E_{\text{tx}}(c_i)}. \tag{9}$$

In another word, sensors whose current transmissions require the least with respect to their residual energy are enabled for transmission. This transmission protocol, first proposed in [36], is shown to be adaptive to the network age [30]. Specifically, this protocol is more opportunistic by favoring sensors with better channels when the network is young and more conservative by favoring sensors with more residual energy when the network is old. Shown in Figure 2 are simulation results on the lifetime performance of this transmission protocol for a given estimation performance. Compared to protocols that utilize solely the channel station information or the residual energy information, the proposed protocol provides improved performance in network lifetime.

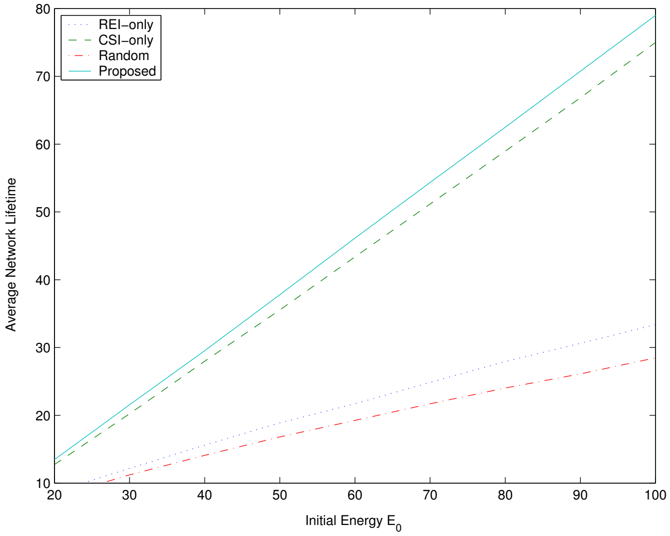

Fig. 2: Lifetime performance comparison (initial energy measured by the average number of transmissions).

5. CONCLUSION

In this paper, we propose a data-centric MAC protocol for application-specific sensor networks. By exploiting two physical layer parameters: channel state and residual energy, the proposed protocol prolongs the network lifetime while maintaining a given level of estimation performance specified by the application layer.

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] G. Mergen and L. Tong, “Estimation Over deterministic multiaccess channels,” in *Proceedings of the 42nd Allerton Conf. on Communications, Control, and Computing*, (Monticello, IL), Sep.28-Oct.01 2003.

[3] G. Mergen and L. Tong, “Estimation over multiaccess channels.” submitted to IEEE Trans. on Signal Processing, July 2004.

[4] G. Mergen and L. Tong, “Sensor–Fusion center communication over multiaccess fading channels,” in *Proc. IEEE ICASSP*, (Philadelphia, PA), March 18-23 2005.

[5] K. Liu and A. M. Sayed, “Asymptotically optimal decentralized type-based detection in wireless sensor networks.” ICASSP’04 presentation slides, May 19 2004.

[6] K. Liu and A. M. Sayed, “Optimal distributed detection strategies for wireless sensor networks,,” in *42nd Annual Allerton Conf. on Commun., Control and Comp.*, Oct. 2004.

[7] J.-F. Chamberland and V. V. Veeravalli, “Asymptotic results for decentralized detection in power constrained wireless sensor networks,” *IEEE JSAC Special Issue on Wireless Sensor Networks*, 2004.

[8] B. Chen, R. Jiang, T. Kasetkasem, and P. Varshney, “Fusion of decisions transmitted over fading channels in wireless sensor networks,” in *Conference Record of the Thirty-Sixth Asilomar Conference on Signals, Systems and Computers*, Nov. 2002.

[9] R. Viswanathan and P.K.Varsheny, “Distributed Detection with Multiple Sensors: Part II -Advanced Topics ,” *Proceedings of the IEEE*, vol. 85, pp. 54–63, Jan. 1997.

[10] R.S.Blum, S.A.Kassam, and H.V.Poor, “Distributed Detection with Multiple Sensors: Part II-Advanced Topics,” *Proceedings of the IEEE*, vol. 85, pp. 64–79, Jan. 1997.

[11] V. V. Veeravalli, T. Basar, and H. V. Poor, “Decentralized sequential detection with a fusion center performing the sequential test,” *IEEE Trans. Inform. Theory*, vol. 39, pp. 433–442, Mar. 1993.

[12] P. K. Varshney, *Distributed Detection and Data Fusion*. New York, NY: Springer, 1997.

[13] 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.

[14] R. Cheng, “Optimal transmit power management on a fading multiaccess channel,” in *Proceedings of Information Theory Workshop*, (Haifa, Israel), June 1996.

[15] 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.

[16] S.V.Hanly and D.N.C.Tse, “Multiaccess Fading Channels: Part II : Delay Limited Capacities ,” *IEEE Trans.*

Information Theory, vol. 44, pp. 2816–2831, November 1998.

[17] 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.

[18] P.Viswanath, D.N.C.Tse, and R.Laroia, "Opportunistic Beamforming using Dumb Antennas," *IEEE Trans. Information Theory*, vol. 48, pp. 1277–94, June 2002.

[19] S.Sanghavi and B.Hajek, "Adaptive Induced Fluctuations for Multiuser Diversity," in *Proc. Intl. Symp. Information Theory*, (Lausanne, Switzerland), pp. 450–450, July 2002.

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

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

[22] A. Shankar and Z. Liu, "Maximum Lifetime Routing in Wireless Ad-hoc Networks," in *Proc. of IEEE INFOCOM*, 2004.

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

[24] R. Kannan, L. Ray, R. Kalidindi, and S. Iyengar, "Max-Min Length-Energy-Constrained Routing in Wireless Sensor Networks," in *Proc. of the 1st European Workshop on Wireless Sensor Networks*, Jan. 2004.

[25] O. Younis and S. Fahmy, "Distributed clustering in adhoc sensor networks: A hybrid, energy-efficient approach," in *Proc. of IEEE INFOCOM*, 2004.

[26] Z. Ignjatovic, M. Perillo, W. Heinzelman, and M. Bocko, "An energy conservation method for wireless sensor networks employing a blue noise spatial sampling technique," in *Proc. of the third international symposium on Information processing in sensor networks*, 2004.

[27] J. Chang and L. Tassiulas, "Maximum Lifetime Routing in Wireless Sensor Networks," *IEEE/ACM Transactions on Networking*, vol. 12, pp. 609–619, August 2004.

[28] C. Cress, S. Yang, and M. Sudit, "Energy efficient data retrieval for networked multi-mode wireless sensors," in *Proc. of the 1st ACM international workshop on Performance evaluation of wireless ad hoc, sensor, and ubiquitous networks*, (Venezia, Italy), Oct. 2004.

[29] 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.

[30] Y. Chen and Q. Zhao, "Distributed Transmission Protocol for Lifetime Maximization in Sensor Network." to appear in Proc. of IEEE SPAWC, June 2005.

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

[32] J. Shao, *Mathematical Statistics*. Springer, 1999.

[33] I. Csiszár, "The method of types," *IEEE Trans. Information Theory*, vol. 44, p. 2505, October 1998.

[34] T. Cover and J. Thomas, *Elements of Information Theory*. John Wiley & Sons, Inc., 1991.

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

[36] Q. Zhao, "On the use of channel state for energy efficient information retrieval in sensor networks," in *Proc. of IEEE ICASSP*, March 2005.