A Bit-Map-Assisted Energy-Efficient MAC Scheme for Wireless Sensor Networks

Jing Li and Georgios Y. Lazarou*

Telecommunication and Information Technology Laboratory (TITL)
Department of Electrical and Computer Engineering
Mississippi State University
glaz@ece.msstate.edu

ABSTRACT

The low-energy characteristics of wireless sensor networks (WSNs) pose a great design challenge for MAC protocol design. Recent studies have proposed different cluster-based MAC protocols. In this paper, we propose an intra-cluster communication bit-map-assisted (BMA) MAC protocol for large-scale cluster-based WSNs. BMA is intended for event-driven applications, where sensor nodes transmit data to the cluster head only if significant events are observed. In addition, we provide the energy and packet latency analytical models for BMA, conventional TDMA, and energy efficient TDMA (E-TDMA) when used as intra-cluster MAC schemes. Our results show that BMA is superior for the cases of low and medium traffic loads, relatively few sensor nodes per cluster, and relatively large data packet sizes. In addition, BMA performs better than the TDMA-based MAC schemes in terms of average packet latency.

Categories and Subject Descriptors

C.2.5 [**Computer-Communication Networks**]: Local and Wide-Area Networks—*Access Schemes*; C.4 [**Computer Systems Organization**]: Performance of Systems—*Modeling Techniques*

General Terms

Algorithms, Performance

Keywords

Wireless Sensor Networks, Energy-Efficiency, MAC Protocols

1. INTRODUCTION

Wireless Sensor Networks (WSN) typically consist of base stations and a number of wireless sensors. Each sensor is a unit with wireless networking capability that can collect and process data independently. Sensors are used to monitor activities of objects in a specific field and transmit the information to a base station.

Inexpensive sensors networked together have a wide variety of applications. One potential and significant application is homeland security. As another example, soil moisture measurements provide vital input data for a wide range of applications including weather and climate modeling, soil erosion management, geo-technical engineering, and optimization of farmland irrigation. For the U.S. Department of Energy, soil moisture measurements also are used to determine ground water movement and concentration for tracking and modeling contaminant plumes and leaks from waste tanks, landfills, and contaminated structures as well as nuclear testing and waste storage sites. DARPA and other military organizations are extremely interested in large-scale ad hoc networks that can be deployed with minimum amounts of installation (e.g., operational within minutes after being dropped from an airplane).

Medium access control (MAC) is used to avoid collisions by keeping two or more interfering nodes from accessing the medium at the same moment. This is essential to the successful operation of shared-medium networks. The unique characteristics of WSNs require an energy-efficient MAC that is quite different from traditional ones developed for wireless voice and data communication networks. The design of a MAC protocol for WSNs must consider the following factors:

- **Energy Efficiency:** Sensors have a limited energy supply and are usually deployed in a hostile environment. Recharging is almost impossible during the operation. Therefore, energy-efficient solutions are required for long-term applications.
- **Scalability:** Large-scale WSNs usually consist of tens of thousands of sensor nodes at least two orders of magnitude more sensors per router than conventional wireless networks. Highly localized and distributed solutions are required.
- **Dynamic and Autonomous Network Operation:** Sensors are often deployed and arranged in environments that are inaccessible to humans (e.g., dropped from an airplane into remote mountainous regions). The topology of a WSN changes frequently due to failures of the sensor nodes. Therefore, the protocols and algorithms should possess a self-organizing ability.

Clustering is a common distributed technique used in large- scale WSNs. Clustering solutions are often used with Time Division Multiple Access (TDMA)-based MAC schemes to reduce the cost of idle listening, [1],[2]. TDMA-based solutions usually perform

*This work was supported by the (US) Office of Naval Research (ONR) under Contract Number N00014-02-1-0623

IPSN'04, April 26–27, 2004, Berkeley, California, USA.

well under high traffic load conditions. With conventional TDMA, when a node has no data to send, it still has to turn on the radio during its scheduled slots. Under this condition, the node operates in Idle mode, which is an energy-consuming operation. In addition, conventional TDMA-based schemes perform well in terms of bandwidth efficiency and average packet latency when sensor nodes have always data to send. In addition, it is usually hard for TDMA schemes to change the time slot allocations and frame lengths dynamically according to the unpredictable variations of sensor networks.

In this paper, we propose an intra-cluster communication bit-map-assisted (BMA) MAC protocol for large-scale cluster-based WSNs. BMA is intended for event-driven applications, where sensor nodes transmit data to the cluster head only if significant events are observed. For these types of applications, we assume that the sensor nodes behave like Bernoulli traffic sources.

The major sources of energy waste are idle listening, collision, overhearing, and control packet overhead [3]. The radio of a sensor node can operate in four different modes: transmit, receive, idle, and sleep [4]. Idle listening dissipates considerable energy, almost equal to 50-100% of the energy consumed in receive mode [5]. A collision occurs when a transmitted packet is destroyed and retransmission is required. Overhearing refers to the condition that a node receives a packet sent to others. The control packet overhead is the energy consumed in transmitting the control packet. BMA reduces energy consumption due to idle listening and collisions.

In addition, in this paper, we provide energy and packet latency analytical models for BMA, conventional TDMA, and energy efficient TDMA (E-TDMA) when used as intra-cluster MAC schemes. With E-TDMA, nodes with no data to transmit keep their radios off during their allocated time slots.

The remainder of the article is structured as follows. Section 2 presents the related work. Section 3 discusses the BMA MAC solution in detail. Section 4 discusses the E-TDMA solution. Section 5 presents the analysis of the three MAC schemes as intra-cluster MAC schemes and provides some numerical evaluation results. Finally, the paper concludes with Sect. 6.

2. RELATED WORK ON CLUSTER-BASED MAC SCHEMES

MAC schemes for wireless networks are usually classified into two categories, contention-based and contention-free. Contention-based schemes are widely applied to ad hoc wireless networks because of simplicity and a lack of synchronization requirements. Such an example is the IEEE 802.11 wireless LAN standard, which is designed for minimum delay and maximum throughput. Traditional contention-based schemes require sensor nodes to keep their radios on to receive possible incoming messages. Therefore, such schemes are not energy-efficient due to idle listening.

Contention-free schemes, known as reservation-based or scheduling-based schemes, try to detect the neighboring radios of each node before allocating collision-free channels to a link. TDMA is an example of a contention-free scheme. Use of TDMA is viewed as a natural choice for sensor networks because radios can be turned off during idle times in order to conserve energy [1], [2], [6].

A cluster-based method, LEACH [2], applies TDMA within a cluster. The entire network is divided into non-overlapping clusters. There is a cluster head among each cluster. Instead of transmitting the data to the base station directly, the sensors send their data to the cluster-head. The cluster head relays the data to the global base station. LEACH randomly rotates the cluster head to distribute the energy consumption evenly among all sensors in the network. LEACH assumes all nodes have data to transmit to the cluster head at all times. Under this condition, TDMA scheduling uses the bandwidth efficiently.

The solution in [6] employs a ”super frame” time scheduling. A super frame is similar to a TDMA frame, which is comprised of a TDMA sub-frame, a BOOTUP sub-frame and an unused sub-frame assigned on demand. Sensor nodes enter in the BOOTUP mode immediately after being powered on and then search for new nodes to build links. During the TDMA period, sensors transmit local data and control signals to destination nodes. The unused period is assigned to specific applications to build a short-time local network. The structure of the super frame may change from epoch to epoch and different sub-frames of the super frame can be assigned to various transactions. However, the algorithm performs well only under specific conditions such as non-hierarchical architecture and no mobility. In addition, it is not bandwidth efficient.

PACT [1] combines an energy-efficient TDMA-based time schedule with passive clustering to reduce the overall energy consumption in large-scale WSNs. In the space domain, PACT applies the passive clustering structure to reduce the overall communication cost. There are three kinds of clustering status for a node: cluster-head, gateway, and cluster member. In the time domain, PACT applies the similar TDMA scheme as in Unifying Slot Assignment Protocol. PACT divides each TDMA frame into a control slot and a data slot. Each node turns on its radio during the control slots of a TDMA frame. Since the destination addresses of the node are included in the control packet, other nodes are scheduled to power down during the inactive period. Nodes pick up collision-free transmission slots according to the data slot assignment status specified in control packets.

3. BIT-MAP-ASSISTED (BMA) MAC

The main objective in designing the Bit-Map-Assisted (BMA) MAC protocol was to reduce the energy wastes due to idle listening and collisions while maintaining a good low-latency performance.

The operation of BMA is divided into rounds, as in LEACH [6]. Each round consists of a cluster set-up phase and a steady-state phase. A complete round is depicted in Fig. 1.

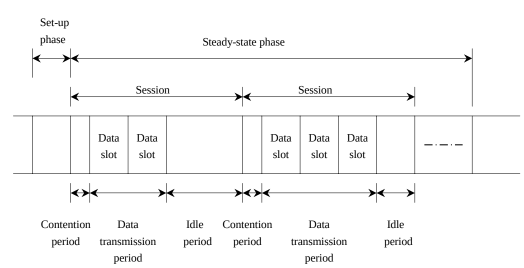

Figure 1: Illustration of a single round

3.1 Cluster Set-Up Phase

We assume a similar cluster formation algorithm as done in LEACH [2]. During the set-up phase, each node must decide whether it could become a cluster head based on its energy level. Elected cluster-heads broadcast an advertisement message to all other nodes claiming to be the new cluster-heads by using non-persistent CSMA. Next, each non-cluster head node joins the cluster in which communications with the cluster head requires the minimum amount of energy. Once the clusters are built, the system enters into the steady-state phase.

3.2 Steady-State Phase

The steady-state phase is divided into k sessions. The duration of each session is fixed. Each session consists of a contention period, a data transmission period and an idle period. Assuming that there are N non-cluster head nodes within a cluster, then the contention period consists of exactly N slots. Since each source node does not always have data to send, the data transmission period is variable. However, in each session, the data transmission period plus the idle periods is fixed to a constant (implementation) value. In this paper, we assume that all the data slots have the same size. Hence, the number of data slots in each session depends on the amount of data needed to be sent.

During each contention period, all nodes keep their radios on. The contention period follows a TDMA-like schedule: each node is assigned a specific slot and transmits a 1-bit control message during its scheduled slot if it has data to transmit; otherwise, its scheduled slot remains empty. A node with data to transmit is called a source node.

After the contention period is completed, the cluster head has complete knowledge of which nodes have data to transmit. The cluster head sets up and broadcasts a transmission schedule for the source nodes. After that, the system enters into the data transmission period, as shown in Fig. 1. If none of the non-cluster head nodes have data to send, the system proceeds directly to an idle period, which lasts until the next session. All source and non-source nodes have their radios turned off during the idle periods.

During the data transmission period, each source node turns on its radio and sends its data to the cluster-head over its allocated slot-time, and keeps its radio off at all other times. All non-source nodes have their radios off during the data transmission period.

When a session finishes, the next session begins with a contention period and the same procedure is repeated. The cluster head collects the data from all the source nodes and forwards the aggregated and compressed data to the base station. After a predefined time, the system begins the next round and the whole process is repeated.

4. ENERGY-EFFICIENT TDMA (E-TDMA)

With the basic TDMA MAC scheme, each round consists of a cluster set-up phase and a steady-state phase. The steady-state phase is divided into a contention period and k frames. During the contention period, the cluster-head builds a TDMA schedule and broadcasts it to all nodes within the cluster. There is one data slot allocated to each node in each frame. A node always turns on its radio during its assigned time slot regardless whether it has data to transmit or not. If it has not data to send, the node operates in *idle* mode, which is a high energy-consuming operation. E-TDMA extends the basic TDMA in order to reduce the energy consumption due to idle listening: when a node has no data to transmit, it keeps its radio off during its allocated time slots.

5. PERFORMANCE EVALUATION

5.1 Analysis

We assume that a clustered network has already been formed and there are N non-cluster-head nodes within a cluster. A round consists of k sessions/frames. There are n_i source nodes in the i_{th} session/frame. The event whether a node has data to transmit can be viewed as a Bernoulli trial. The possibility that a node has data to transmit is p. Therefore, n_i is a Binomial random variable, and

$$E[n_i] = Np = n \qquad i = 1, 2, \ldots, k. \tag{1}$$

Since the number of source nodes is independent from session/frame to session/frame, the expectation of the total number of source nodes in a round is:

$$E\left[\sum_{i=1}^{k} n_i\right] = \sum_{i=1}^{k} E[n_i] = kn. \tag{2}$$

The power consumption during the transmit mode, the receive mode, and the idle mode, are denoted by P_t, P_r, and P_i, respectively. The time required to transmit/receive a data packet is T_d seconds, the time required to transmit/receive a control packet is T_c seconds, and the time required for the cluster-head to transmit a control packet for BMA is T_{ch}.

5.1.1 BMA

All nodes keep their radios on during the whole contention period. Each source node transmits a control packet during its scheduled slot, and remains idle for $(N-1)$ slots. After receiving the transmission schedule from the cluster head, each source node sends its data packet to the cluster head over its scheduled time slot. Therefore, the energy consumption by each source node during a single session is:

$$E_{sn} = P_t T_c + (N-1) P_i T_c + P_r T_{ch} + P_t T_d. \tag{3}$$

Each non-source node stays idle during the contention period and keeps its radio off during the data transmission periods. Thus, over a single session, it consumes the following energy:

$$E_{in} = N P_i T_c + P_r T_{ch}. \tag{4}$$

During the contention period of the i^{th} session, the cluster-head node receives n_i control packets and stays idle for $(N-n_i)$ contention slots. During the following transmission period, it receives n_i data packets. Hence, the energy dissipated in the cluster-head node during a single session is

$$E_{ch} = n_i(P_r T_c + P_r T_d) + (N - n_i) P_i T_c + P_t T_{ch}. \tag{5}$$

Therefore the total system energy consumed in each cluster during the i^{th} session is:

$$E_{si} = n_i E_{sn} + (N - n_i) E_{in} + E_{ch}. \tag{6}$$

Each round consists of k sessions, thus the total system energy dissipated during each round is:

$$E_{round} = \sum_{i=1}^{k} E_{si}. \tag{7}$$

The average system energy consumed during each round is therefore

$$E = E\left[E_{round}\right] = E\left[\sum_{i=1}^{k} E_{si}\right] = k\left[nE_{sn} + (N-n)E_{in} + E_{ch}\right]. \tag{8}$$

We define the average packet latency (delay) as the average time required for a packet to be transmitted by a source node and received by the cluster-head. For BMA, the average packet latency is

$$L = \frac{NT_c + T_{ch} + nT_d}{kn}. \tag{9}$$

5.1.2 TDMA

During the contention period, the communication between the cluster-head and all other nodes is accomplished by using non-persistent CSMA. Suppose α is the throughput of non-persistent CSMA when there are N attempts per packet time. Each node transmits a control packet, and remains idle for the time $(N-1)\frac{T_c}{\alpha}$. Hence, the energy consumption by each node during the contention period is

$$E_n = \frac{P_t T_c}{\alpha} + (N-1)\frac{P_i T_c}{\alpha} + P_r T_c. \qquad (10)$$

The cluster-head node receives N control packets and dissipates the energy

$$E_{ch} = N P_r T_c + P_t T_c. \qquad (11)$$

Therefore, the total system contention energy dissipation can be shown to be

$$E_c = N\left[\frac{P_t T_c}{\alpha} + (N-1)\frac{P_i T_c}{\alpha} + P_r T_c\right] + N P_r T_c + P_t T_c. \qquad (12)$$

During the i^{th} frame, the energy dissipated in a source node is equal to $P_t T_d$. A non-source node turns and leaves on its radio during its scheduled time slot, and therefore, $P_i T_d$ Joules of energy are wasted. Also, during the i^{th} frame, the cluster-head consumes the following energy

$$E_{chi} = n_i P_r T_d + (N - n_i) P_i T_d. \qquad (13)$$

Hence, the system energy dissipated during the i^{th} frame is

$$E_{fi} = n_i P_t T_d + (N-n_i) P_i T_d + n_i P_r T_d + (N-n_i) P_i T_d. \qquad (14)$$

The total system energy dissipated during each round is computed as

$$E_{round} = E_c + \sum_{i=1}^{k} E_{fi}. \qquad (15)$$

The average system energy consumed during each round is hence

$$\begin{aligned} E &= E\left[E_{round}\right] \\ &= \left(\frac{N}{\alpha}+1\right) P_t T_c + \frac{N(N-1)}{\alpha} P_i T_c \\ &+ 2N P_r T_c + k\left[n P_t T_d + 2(N-n) P_i T_d + n P_r T_d\right] \qquad (16) \end{aligned}$$

The average packet latency is

$$L = \frac{\left(\frac{N}{\alpha}+1\right) T_c + kNT_d}{kn}. \qquad (17)$$

5.1.3 E-TDMA

In E-TDMA, a node with no data to send keeps its radio off during its allocated time slots. Thus, the average system energy dissipated in each round is:

$$\begin{aligned} E &= E\left[E_{round}\right] \\ &= \left(\frac{N}{\alpha}+1\right) P_t T_c + \frac{N(N-1)}{\alpha} P_i T_c \\ &+ 2N P_r T_c + k\left[n P_t T_d + (N-n) P_i T_d + n P_r T_d\right] \qquad (18) \end{aligned}$$

The average packet latency is as given in TDMA.

5.2 Numerical Results

We compare the performance of BMA, TDMA and E-TDMA as intra-cluster MAC schemes in terms of energy and average packet latency. The results are based on analytic computations. The comparison does not consider the possibility of bit-errors in the contention period. Figure 2 depicts the topology used in our evaluation: a cluster with N sensor nodes and one cluster head node.

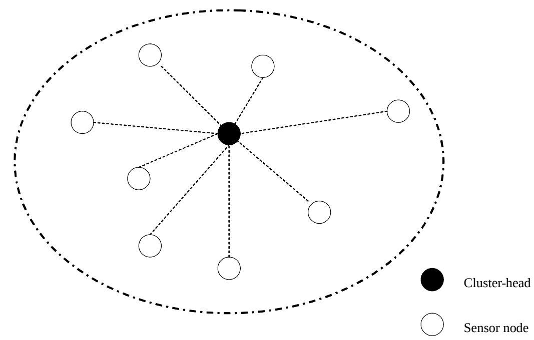

Figure 2: Ilustration of a single cluster with N nodes and 1 cluster head

There are two types of representative sensor nodes: Rockwell's WINS node and MEDUSA node [8]. The former represents a high-end sensor node, and the latter is an experimental sensor node. We use the WINS energy node model: the radio transceiver uses 462 mW for transmitting, 346 mW for receiving, and 330 mW for idle listening. The data rate is 24 kbps. Unless noted, we assume a data packet size of 250 bytes and a control packet size of 18 bytes. For TDMA and E-TDMA, we set α to 0.815 [10].

Figure 3 compares the three techniques in terms of the average packet latency. For large p, all three schemes have similar low average packet latencies. However, as p goes to zero, the average packet latency for both TDMA and E-TDMA grows exponentially, whereas for BMA, it stays relative low.

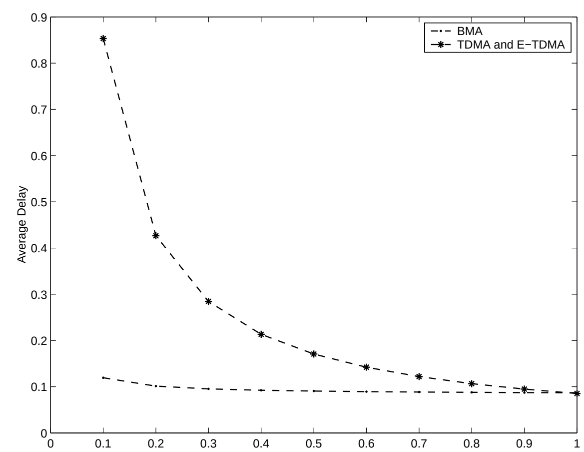

Figure 3: Average packet latency vs. p for the case of $N = 10$ and $k = 4$

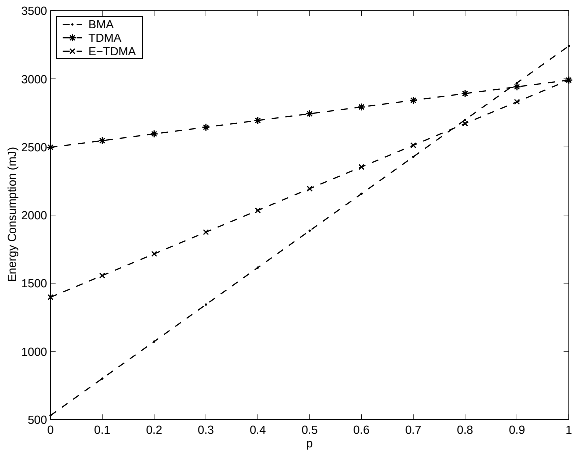

Figure 4: Average total cluster energy consumption vs. p for the case of $N = 10$ and $k = 4$

Figure 4 provides a comparison of the three intra-cluster MAC techniques in terms of the average total cluster energy consumption per round as a function of p for the case of $N = 10$ and $k = 4$. When p is less than about 0.75, BMA performs better than both TDMA and E-TDMA. The main energy conservation comes from avoiding idle listening. When p is above 0.75, the idle period is small and thus the energy cost from the contention periods outweighs the energy saving from the idle periods. Note that as p increases, the average idle period decreases. Thus, for p above 0.75, both TDMA schemes perform better. Note that for p less than 1, E-TDMA outperforms TDMA. The energy savings by E-TDMA relative to TDMA grow as p approaches zero.

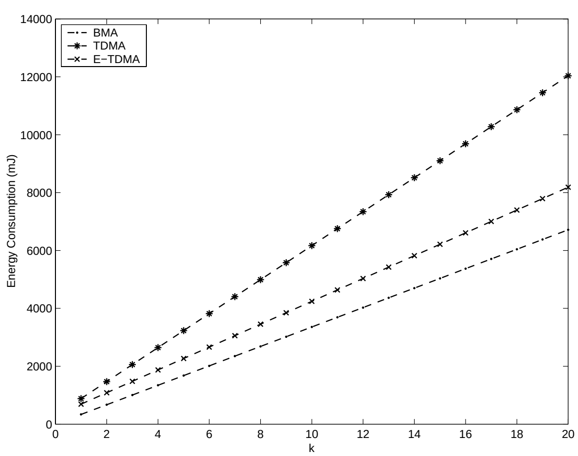

Figure 5: Average total cluster energy consumption vs. k for the case of $N = 10$ and $p = 0.3$

Figure 5 compares the three intra-cluster MAC schemes in terms of average total cluster energy consumption versus the number of sessions/frames per round for the case of $N = 10$ and $p = 0.3$. Clearly, for $k = 1$ to 20 sessions/frames/round, BMA is a much more energy conservative scheme than E-TDMA. Note that this is not true for all cases. This is illustrated in Fig. 6. That is, BMA performs better than E-TDMA for N and p relative small.

In Fig. 7, we illustrate the impact of the data packet size on the overall system energy consumption. For the case of N and p relative small, BMA performs better than the two TDMA scheme for large data packet sizes. This is due to the fact that in the BMA MAC scheme, the energy consumption in the contention periods becomes negligible compared to the total energy required to transmit large data packets (see Fig. 1). When data packet is less than 40 bytes long, both TDMA and E-TDMA outperform BMA.

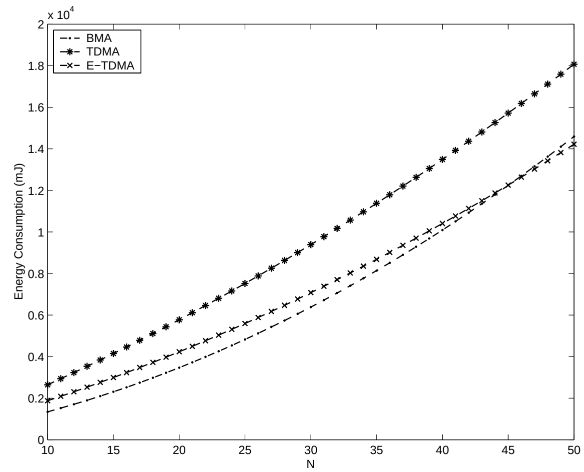

Figure 6: Average total cluster energy consumption vs. N for the case of $k = 4$ and $p = 0.3$

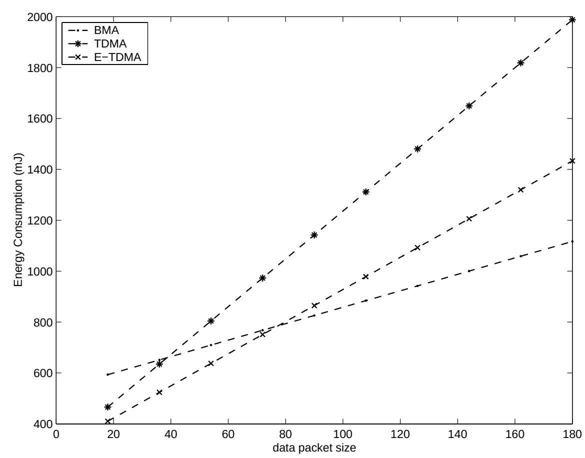

Figure 7: Average total cluster energy consumption vs. data packet length for the case of $N = 10$, $k = 4$ and $p = 0.3$

6. CONCLUSIONS

In this paper, we propose an intra-cluster communication bit-map-assisted (BMA) MAC protocol for large-scale cluster-based WSNs. BMA is intended for event-driven applications, where sensor nodes transmit data to the cluster head only if significant events are observed. Also, we provide analytic models for the energy and packet latency for BMA, conventional TDMA, and energy efficient TDMA (E-TDMA) when used as intra-cluster MAC schemes.

We compared BMA to conventional TDMA and E-TDMA, and demonstrated that:

- In terms of average packet latency, BMA is superior.

- In terms of energy efficiency, BMA performance heavily depends on the sensor node traffic offer load (parameter p), the number of sensor nodes within a cluster (parameter N), the data packet size and, in some cases, the number of sessions per round (parameter k). Based on the results presented in the paper, we conclude that BMA is superior for the cases of low and medium traffic loads, relatively few sensor nodes per cluster, and relatively large data packet sizes.

- The performance of BMA improves as the data packet size increases.

For most applications, p, N, k, and the data packet sizes can be controlled. For example, to keep p less than 0.5 and the data packet size large, sensor nodes could aggregate the sensing information from two or more events into one packet.

In addition, BMA and E-TDMA can be combined together to form a dynamically adaptive MAC scheme, where BMA is used in all the rounds that p is perceived to be small (or medium) and E-TDMA is used in all the rounds for which p is perceived to be large.

7. REFERENCES

[1] G Pei and C. Chien, "Low power TDMA in large wireless sensor networks," in Proc. MILCOM, 2001, vol. 1, pp. 347-351

[2] W. R. Heinzelman, A. P. Chandrakasan, and H. Balakrishnan, "An Application-Specific Protocol Architecture for Wireless Microsensor Networks," IEEE On Wireless Communications Trans., vol. 1, No. 4, Oct. 2002, pp. 660-670

[3] W. Ye, J. Heidermann, and D. Estrin, "An Energy-Efficient MAC protocol for Wireless Sensor Networks," in Proc. IEEE INFOCOM, 2002, vol. 3, pp. 1567-1576

[4] M. Stemm, and R. H Katz, "Measuring and reducing energy consumption of network interfaces in hand-held devices," IEICE Transactions on Communications, vol. E80-B, no. 8, pp. 1125-1131, 1997

[5] Y. Sankarasubramaniam, I. F. Akyildiz and S. W. McLaughlin, "Energy Efficiency based Packet Size Optimization in Wireless Sensor Networks," in Proc. of the First IEEE International Workshop on Sensor Network Protocols and Applications, Anchorage, Alaska, 2003

[6] K. Sohrabi and G. J. Pottie, "Performance of a novel self-organization protocol for wireless ad-hoc sensor networks," in Proc. Vehicular Technology Conference, 1999, vol. 2, pp. 1222 1226

[7] A. El-Hoiydi, "Aloha with preamble sampling for sporadic traffic in ad hoc wireless sensor networks," in Proc. IEEE International Conference on Communications, 2002, vol. 5, pp. 3418-3423

[8] V. Raghunathan, C.Schurgers, S. Park, and M. B. Srivastava, "Energy-aware wireless microsensor networks," IEEE Signal Processing Magazine, Mar. 2002, pp. 40-50

[9] S. Tanenbaum, Computer Networks, 4th ed. Upper Saddle River, NJ: Prentice-Hall, 1996

[10] L. Kleinrock and F. Tobagi, "Packet Switching in Radio Channels: Part I — Carrier Sense Multiple-Access Modes and Their Throughput-Delay Characteristics," IEEE Transactions on Communications, vol. 23, no. 12, pp. 1400-1416, 1975