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A cluster-based power-efficient MAC scheme for event-driven sensing applications ☆

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Abstract

In developing an architecture for wireless sensor networks (WSNs) that is extensible to hundreds of thousands of heterogeneous nodes, fundamental advances in energy efficient communication protocols must occur. In this paper, we first propose an energy-efficient and robust intra-cluster communication bit-map assisted (BMA) MAC protocol for large-scale cluster-based WSNs and then derive energy models for BMA, conventional TDMA, and energy efficient TDMA (E-TDMA) using two different approaches. We use simulation to validate these analytical models. BMA is intended for event-driven sensing applications, that is, sensor nodes forward data to the cluster head only if significant events are observed. It has low complexity and utilizes a dynamic scheduling scheme. Clustering is a promising distributing technique used in large-scale WSNs, and when combined with an appropriate MAC scheme, high energy efficiency can be achieved. The results indicate that BMA can improve the performance of wireless sensor networks by reducing energy expenditure and packet latency. The performance of BMA as an intra-cluster MAC scheme relative to E-TDMA depends on the sensor node traffic offer load and several other key system parameters. For most sensor-based applications, the values of these parameters can be constrained such that BMA provides enhanced performance.

Keywords: Wireless sensor networks; MAC protocols; Modeling; Energy efficiency; Latency

1. Introduction

Recent advances in sensor technology and wireless communication systems have prompted new research in the area of Wireless Sensor Networks (WSNs). Current state-of-the-art enables production of extremely small devices that can accommodate various sensing functions such as temperature, humidity, pressure, or acceleration, as well as on board communication means. The existence of communication capabilities allows these miniature devices to share and exchange information, thus forming wireless networks of sensors that consist of thousands of heterogeneous nodes performing various functions.

A fundamental barrier to achieving acceptable levels of performance in large-scale WSNs is energy

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efficiency [1–4]. Wireless sensors have limited energy supply and are usually deployed in environments where recharging is either impossible or too costly. For example, for a WSN solution to be feasible for archival institutions such as national museums, a battery operated sensor node, deployed within each exhibit, must have a lifetime of three years. National museums are usually very large, and therefore, tens of hundreds of thousands of sensors are needed to monitor the environment conditions in each exhibit.

Protocol design for WSNs has received far more attention than other design issues [1–3]. Protocol design attempts to improve energy efficiency by accepting a trade-off on other aspects of network performance, such as bandwidth efficiency, latency, and QoS [3]. Energy-aware networking protocols can provide larger energy consumption reduction than optimization of the hardware [2,3]. Algorithmic modifications can often result in significant energy savings [3]. It is well known that communication of data over wireless links consumes much more energy than sensing and data processing [2].

The energy efficiency requirements of WSNs pose a great challenge for Medium Access Control (MAC) protocol design. Recent studies have proposed several WSN-specific energy-efficient MAC schemes [5–9]. 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. Time Division Multiple Access (TDMA) is an example of a contention-free scheme.

The major sources of energy waste are idle listening, collision, overhearing, and control packet overhead [5]. The radio of a sensor node can operate in four different modes: Transmit, Receive, Idle, and Sleep [10]. Idle listening dissipates considerable energy, almost equal to 50–100% of the energy consumed in receive mode [11]. 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.

The use of TDMA-based MAC schemes is viewed as a natural choice for sensor networks because radios can be turned off during idle times in order to conserve energy [6–8]. In addition, dividing the sensor network into non-overlapping groups of nodes, a process referred to as clustering, is an effective method for achieving high levels of energy efficiency and scalability [12–17]. Clustering solutions are often combined with TDMA-based schemes to reduce the cost of idle listening [6,7].

A cluster-based method, LEACH [6], 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.

TDMA-based solutions usually perform well under high traffic load conditions. A high traffic load means all nodes always have data to transmit, which is not a natural behavior for event-driven applications. 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. The Energy-efficient TDMA (E-TDMA) extends the conventional TDMA 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. However, the cluster head has to keep on the radio during all the time slots. When there is no incoming packet during an idle time slot, the cluster head operates in the Idle mode and wastes energy. In addition, changing the time slot allocations and frame lengths dynamically according to the unpredictable variations of sensor networks is usually hard for TDMA-based schemes.

In this paper, we first propose an energy-efficient and robust intra-cluster communication bit-map assisted (BMA) MAC protocol for large-scale cluster-based WSNs and then derive two different energy analytical models for BMA, conventional TDMA, and energy efficient TDMA (E-TDMA) when used as intra-cluster MAC schemes. BMA is intended for event-driven sensing applications, that is, sensor nodes forward data to the cluster head only if significant events are observed. In addition, BMA has low complexity, its scheduling changes dynamically according to the unpredictable variations of sensor networks, and reduces the energy wastes due to idle listening and collisions while maintaining a good low latency performance. In addition, we construct simulation models and validate the analytic energy models with simulation measurements.

The remainder of this paper is structured as follows. Section 2 presents the BMA, the conventional TDMA and E-TDMA MAC scheduling schemes. Section 3 presents the analysis of the three MAC schemes as intra-cluster MAC schemes and provides the numerical evaluation and simulation results. Section 4 presents the conclusions and a summary.

2. Protocol description

2.1. BMA

The main objective in designing the Bit-Map-Assisted (BMA) MAC protocol is 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 by the top diagram in Fig. 1.

2.1.1. Cluster set-up phase

The cluster formation algorithm is identical to the one described in LEACH [6]. During the set-up phase, each node must decide whether it could

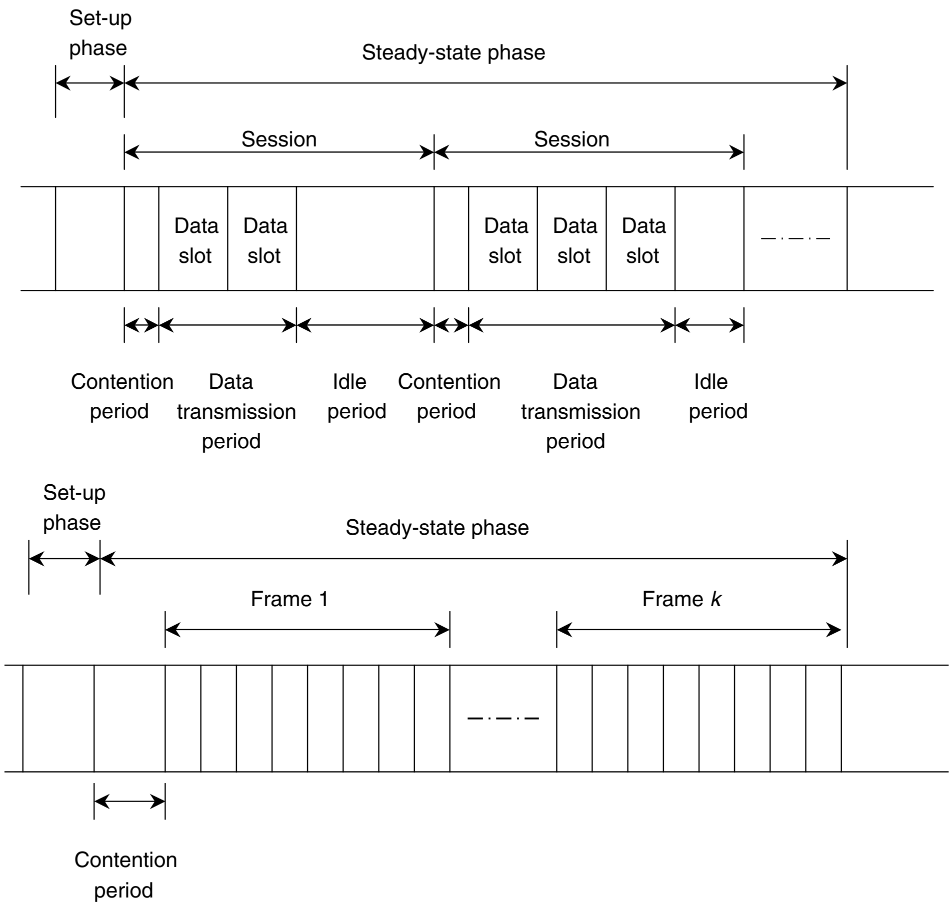

Fig. 1. The operations of BMA (top diagram) and TDMA (bottom diagram) are divided into rounds. The clusters are formed during the set-up phases. Each round ends after a predefined time and then the whole process is repeated.

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.

2.1.2. 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 knows all the nodes that 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 then forwards the aggregated and compressed data to the base station directly or via a multihop path consisted of cluster-heads. After a predefined time, the system begins the next round and the whole process is repeated.

2.2. Conventional TDMA and energy-efficient TDMA

Similarly, the operation of the conventional TDMA and energy-efficient TDMA (E-TDMA) schemes is divided into rounds. As shown by the bottom diagram of Fig. 1, each round consists of a cluster set-up phase and a steady-state phase.

2.2.1. Cluster set-up phase

The cluster set-up phase is exactly as in BMA.

2.2.2. Steady-state phase

The steady-state phase is divided into a contention period and k frames. The duration of each frame is fixed. During the contention period, all nodes keep their radios on. 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 with data to transmit is called a source node. 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.

With the basic TDMA scheme, a node always turns on its radio during its assigned time slot regardless whether it has data to transmit or not. If it has no 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.

When a frame finishes, the next frame begins 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.

3. Energy model development

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 ith session/frame. The event whether a node has data to transmit or not 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 $E[n_i] = Np = n,\ i = 1,2,\ldots,k$. 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

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

As done in [5,6], for simplicity we ignore the energy required to turn on the radio when a source node wakes up for transmission or reception of data or control packets. For very small packet sizes, this turn-on overhead can be significant. However, in almost all cases the packet sizes are big enough so that the transmission and reception of packets dominates the energy consumption over this radio turn-on overhead [3].

We develop two different energy models for evaluating the performances of BMA, conventional TDMA, and energy-efficient TDMA (E-TDMA). For simplicity, we assume error-free channels.

3.1. Energy model I

Energy model I describes the energy consumption as the multiplication of the power consumption and the operation time. 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. When a source node spends T seconds transmitting or receiving a packet, the energy dissipated is computed as: $E_{Tx}(T) = P_t T$, or $E_{Rx}(T) = P_r T$, respectively. The energy dissipated by the radio during an idle listening period of T seconds is expressed as: $E_I(T) = P_i T$.

We let T_d to be the time required to transmit/receive a data packet, T_c to be the time required to transmit/receive a control packet, and T_{ch} to be the time required for a BMA cluster-head to transmit a control packet.

3.1.1. 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 can be expressed as: $E_{sn} = P_t T_c + (N-1)P_i T_c + P_r T_{ch} + P_t T_d$.

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, the energy that it dissipates can be computed as: $E_{in} = NP_i T_c + P_r T_{ch}$.

During the contention period of the ith session, the cluster-head node receives n_i control packets and stays idle for $(N - n_i)$ contention slots. During the subsequent transmission period, it receives n_i data packets. Hence, the energy expended in the cluster-head node during a single session is given as: $E_{ch} = n_i(P_r T_c + P_r T_d) + (N - n_i)P_i T_c + P_t T_{ch}$. Therefore, the total system energy consumed in each cluster during the ith session is: $E_{si} = n_i E_{sn} + (N - n_i)E_{in} + E_{ch}$.

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

$$E_{round} = \sum_{i=1}^{k} E_{si}, \tag{2}$$

and hence, the average system energy expended during each round can be expressed as

$$E = E[E_{round}] = E\left[\sum_{i=1}^{k} E_{si}\right] = k[nE_{sn} + (N-n)E_{in} + E_{ch}]. \tag{3}$$

We define the average packet latency (delay) as the average time required for a packet to be generated by a source node and received by the cluster-head. For BMA, the average packet latency can therefore be computed as follows:

$$L = \frac{NT_c + T_{ch} + nT_d}{n}. \tag{4}$$

3.1.2. 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 $(N-1)\frac{T_c}{\alpha}$ seconds. Thus, the energy consumption by each node during the contention period is: $E_n = \frac{P_t T_c}{\alpha} + (N-1)\frac{P_i T_c}{\alpha} + P_r T_c$. The cluster-head node receives N control packets and transmits one. Hence, it expends the following energy: $E_{ch} = NP_rT_c + P_tT_c$. Clearly, the total system contention energy dissipation is: $E_c = NE_n + E_{ch}$.

During the ith frame, the energy dissipated in a source node is computed as: $E_{sn} = P_tT_d$. A non-source node turns and leaves on its radio during its scheduled time slot, and therefore, the energy wasted can be computed as: $E_{in} = P_iT_d$. Also, during the ith frame, the energy consumed by the cluster-head can be expressed as: $E_{ch} = n_iP_rT_d + (N - n_i)P_iT_d$. Hence, the system energy dissipated during the ith frame is

$$E_{fi} = n_iE_{sn} + (N - n_i)E_{in} + E_{ch} = n_iP_tT_d + (N - n_i)P_iT_d + n_iP_rT_d + (N - n_i)P_iT_d. \quad (5)$$

The total system energy expended during each round can be computed as follows:

$$E_{round} = E_c + \sum_{i=1}^{k} E_{fi}. \quad (6)$$

Thus, the average system energy consumed during each round is figured to be

$$\begin{aligned} E &= E[E_{round}] \\ &= \left(\frac{N}{\alpha} + 1\right)P_tT_c + \frac{N(N-1)}{\alpha}P_iT_c + 2NP_rT_c \\ &\quad + k[nP_tT_d + 2(N-n)P_iT_d + nP_rT_d]. \end{aligned} \quad (7)$$

Easily, the average packet latency can be shown to be

$$L = \frac{\left(\frac{N}{\alpha} + 1\right)T_c + kNT_d}{kn}. \quad (8)$$

3.1.3. E-TDMA

The total system contention energy dissipation is same as that of TDMA:

$$E_c = N\left[\frac{P_tT_c}{\alpha} + (N-1)\frac{P_iT_c}{\alpha} + P_rT_c\right] + NP_rT_c + P_tT_c. \quad (9)$$

In E-TDMA, during the ith frame, the energy dissipated by a source node is: $E_{sn} = P_tT_d$. A node with no data to send keeps its radio off during its allocated time slots. Therefore, $E_{in} = 0$. Also, during the ith frame, the cluster-head expends the following energy: $E_{ch} = n_iP_rT_d + (N - n_i)P_iT_d$. Thus, the system energy dissipated during the ith frame is easily found to be

$$\begin{aligned} E_{fi} &= n_iE_{sn} + (N - n_i)E_{in} + E_{ch} \\ &= n_iP_tT_d + n_iP_rT_d + (N - n_i)P_iT_d. \end{aligned} \quad (10)$$

Using (6), we can compute the total system energy dissipated during each round. Hence, the average system energy dissipated in each round is

$$\begin{aligned} E &= E[E_{round}] \\ &= \left(\frac{N}{\alpha} + 1\right)P_tT_c + \frac{N(N-1)}{\alpha}P_iT_c + 2NP_rT_c \\ &\quad + k[nP_tT_d + (N-n)P_iT_d + nP_rT_d]. \end{aligned} \quad (11)$$

The average packet latency is same as that of TDMA, and is given by (8).

3.1.4. Performance evaluation

Using the above energy models, we evaluated and compared the performance of BMA, TDMA and E-TDMA as intra-cluster MAC schemes in terms of energy consumption. In addition, we validated these analytic energy models with *ns-2* [20] simulations.

There are two types of representative sensor node models: Rockwell's WINS and MEDUSA [18]. The former represents a high-end sensor node, and the latter is used as an experimental sensor node. We used the WINS energy node model: the radio transceiver uses 462 mW for transmitting, 346 mW for receiving, and 330 mW for idle listening. For TDMA and E-TDMA, we set α to 0.815, as suggested in [19]. For each simulation experiment, we assumed that each node had 100 J of energy to expend.

We assumed that a clustered network had been formed and there were N non-cluster-head nodes and one cluster head node within each cluster. A single cluster is illustrated in Fig. 2. Each of the $n \leqslant N$ source nodes was transmitting data directly to the cluster head. All nodes were deployed randomly through out a 100 m × 100 m area. The node location patterns were generated using CMU's movement generator [21].

In all the simulation experiments, we employed UDP agents, since, in deriving the above energy models, we did not consider the dynamics of a TCP-like transport protocol. The maximum UDP segment size was set to 2 kB. We also assumed that each sensor node was equipped with an omni-directional antenna and we adopted the Two Ray Ground (d^4 power loss) propagation model [21].

We set the data rate to 2 Mbps and the data packet size to 1452 bytes, including a 52-byte

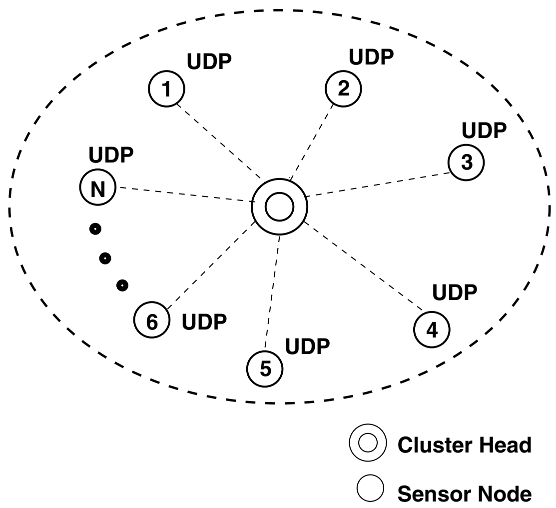

Fig. 2. An example of a single cluster with N nodes and one cluster head. In all simulation experiments, UDP is used as the transport protocol.

header. For BMA, the source to cluster head control packet size was set to 72 bytes, which contains a 20-byte payload and a 52-byte header.[1] All other control packet sizes were set to 152 bytes (100-byte payloads and 52-byte headers).

Fig. 3 compares the three intra-cluster MAC techniques in terms of the average intra-cluster energy consumption in a single round as a function of p, the probability of a sensor node having data ready to send, for the case of 20 non-cluster-head nodes ($N = 20$) and four sessions/frames per round ($k = 4$). For this case of system parameter values, BMA is shown to provide better performance than E-TDMA[2] for $p \leqslant 0.5$. The main energy conservation comes from avoiding idle listening.The energy savings by E-TDMA relative to TDMA grow as p approaches zero. In addition, it is evident from Fig. 3 that there is a close match between the simulation and analytic results.

Fig. 4 evaluates the performance of the three schemes in terms of the average intra-cluster energy expenditure per round as a function of k, the number of sessions/frames per round, for the case of $N = 20$ and $p = 0.3$. It is apparent that for these system parameter values, BMA delivers better performance than E-TDMA for small values of k. A similar behavior is also shown in Fig. 5, where the average intra-cluster energy consumption is plotted against the number of non-cluster-head nodes (N): for $p = 0.3$ and $k = 4$, BMA performs better than E-TDMA when $N \leqslant 30$. Again, the simulation results for these two cases closely match with the analytic results.

Fig. 6 illustrates the impact of the data packet size on the overall system energy consumption. For the case of $N = 20$, $k = 4$ and $p = 0.3$, BMA has better performance than E-TDMA when the data packet size is equal or greater than about 1000 bytes.

The performance of BMA relative to E-TDMA does not only depend on p, k, N, and data packet size, but it also greatly depends on the control packet size and other network factors. This is illustrated by Fig. 7. These performance curves were generated by changing the data rates to 24 kbps, the data packet sizes to 250 bytes, and the control packets to 18 bytes. For this system case scenario, BMA outperforms E-TDMA for $p \leqslant 0.75$ (with $N = 10$ and $k = 4$), $N < 40$ (with $k = 4$ and $p = 0.3$), and data packet size >80 bytes (with $N = 10$, $k = 4$, and $p = 0.3$). Surprisingly, in this case, the performance of BMA relative to E-TDMA improves as k increases.

Fig. 8 compares the three MAC techniques in terms of the average packet latency. For large p, all three schemes provide similar low latencies. However, as p goes to zero, the average packet latency for both classical TDMA and E-TDMA grows exponentially, whereas for BMA, it stays relative low.

3.2. Energy model II

Model II assumes a similar radio energy dissipation model as in [6]. Let E_{elec} (J/b) to represent the energy dissipated by the electronics for transmitting or receiving a 1-bit of data, and ε_{amp} (J/b/m^2) to denote the energy expended by the power amplifier at the transmitter for achieving an acceptable bit energy to noise power spectral density ratio (E_b/N_0) at the receiver. Then, when source node j transmits or receives a k-bit packet over distance d_j, the energy dissipated is computed using the following expressions: $E_{Tx}(k,d) = kE_{\text{elec}} + \varepsilon_{\text{amp}}kd^2$, or $E_{Rx}(k) = kE_{\text{elec}}$, respectively.

[1] Note that in BMA, the source-to-cluster-head control message is only 1-bit long. The 20-byte payload includes this 1-bit control message plus other MAC level overhead information. The 52-byte header is a default *ns-2* higher layer protocol overhead header. In an efficient BMA implementation, this control packet would probably be 20 or less bytes long.

[2] Since E-TDMA always outperform TDMA, it is enough to only compare BMA against E-TDMA.

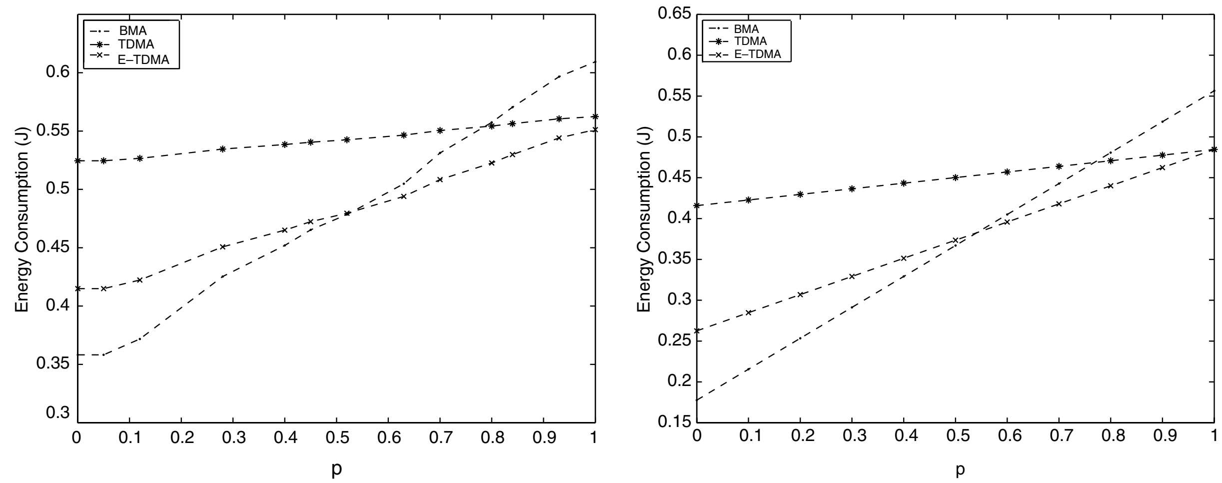

Fig. 3. Using Energy Model I, BMA is compared against TDMA and E-TDMA in terms of the average intra-cluster energy expenditure per round as function of p, the probability of a sensor node having data ready to send, for the case of 20 non-cluster-head nodes ($N = 20$) and four sessions/frames per round ($k = 4$). Left plot: simulation results, right plot: analytic results.

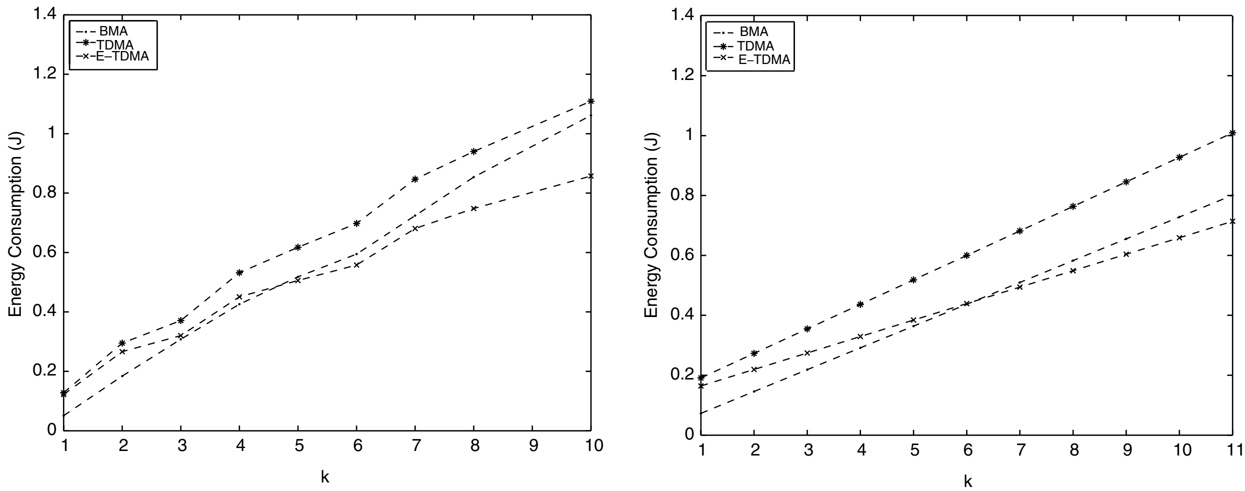

Fig. 4. Using Energy Model I, BMA is compared against TDMA and E-TDMA in terms of the average intra-cluster energy expenditure per round as function of k, the number of sessions/frames per round, for the case of 20 non-cluster-head nodes ($N = 20$) and $p = 0.3$, where p is the probability of a sensor node having data ready to send. Left plot: simulation results, right plot: analytic results.

In addition, to compute the energy expended during each idle listening period, we use the following: $E_{\mathrm{I}}(k) = \beta E_{Rx}(k)$. As mentioned earlier, during each idle listening mode, the radio dissipates 50–100% of the energy dissipated in the receiving mode [11]. Hence, β is the ratio of the energy dissipated in receiving mode to the energy dissipated in idle listening mode.

Let k_{c} be the normal control packet size, k_{d} be the data packet size, and d_j be the distance between node j and the cluster-head. We let $d_{\max}$ be the maximum distance between nodes and the cluster-head. Note that in BMA, the control packets sent by the source nodes to the cluster-head contain fewer bytes (1-bit control message plus packet header information) than the normal control packets. Hence, for BMA we use $k_{\mathrm{c_B}}$ to represent the source to cluster-head control packet size. Further, let T_{d} to be the time required to transmit/receive a data packet, T_{c} to be the time required to transmit/receive a normal

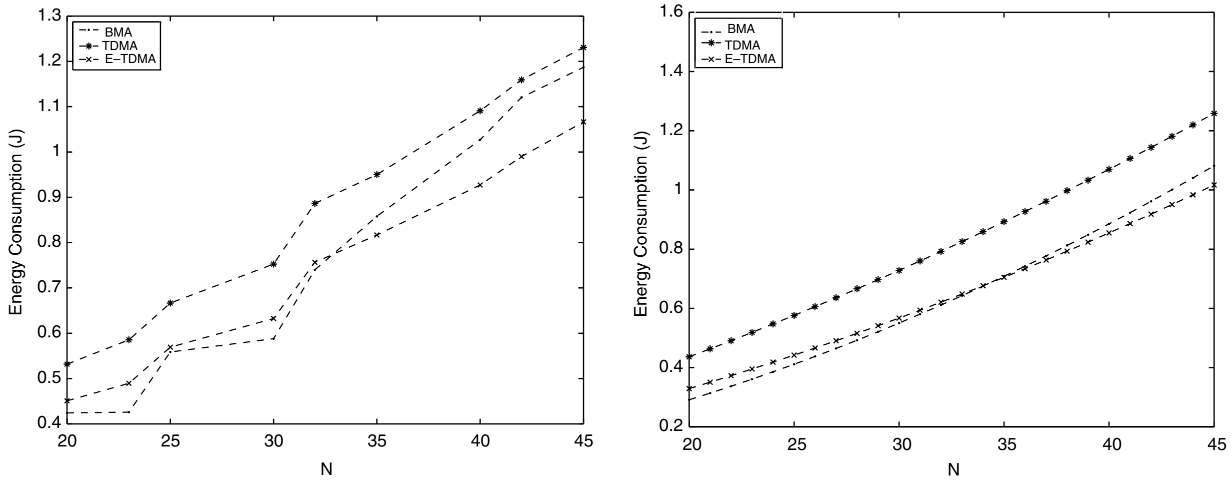

Fig. 5. Using Energy Model I, BMA is compared against TDMA and E-TDMA in terms of the average intra-cluster energy expenditure per round as function of *N*, the number of non-cluster-head nodes, for the case of four sessions/frames per round ($k = 4$) and $p = 0.3$, where *p* is the probability of a sensor node having data ready to send. Left plot: simulation results, right plot: analytic results.

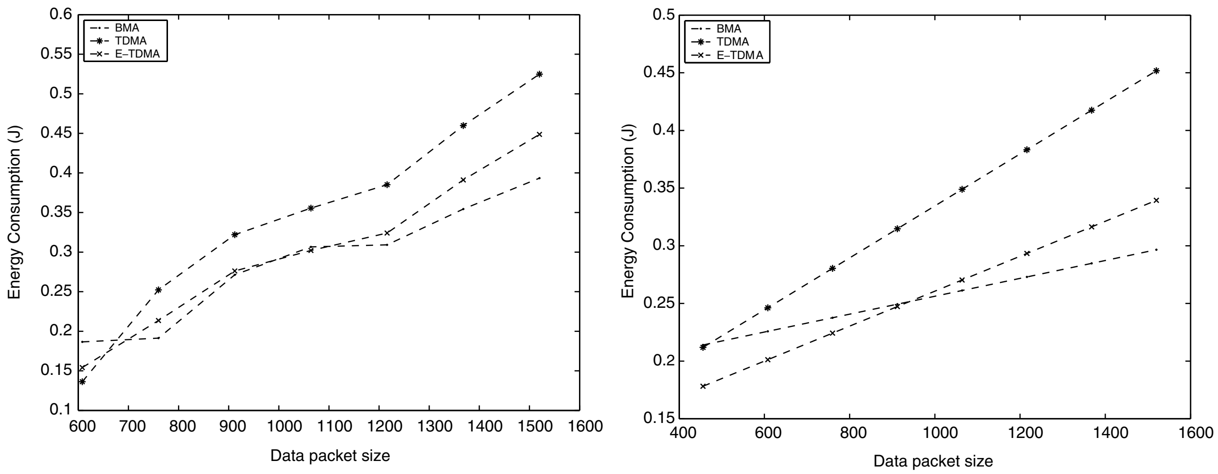

Fig. 6. Using Energy Model I, BMA is compared against TDMA and E-TDMA in terms of the average intra-cluster energy expenditure per round as function of *data packet size*, for the case of 20 non-cluster-head nodes ($N = 20$), four sessions/frames per round ($k = 4$), and $p = 0.3$, where *p* is the probability of a sensor node having data ready to send. Left plot: simulation results, right plot: analytic results.

control packet, and T_{c_B} the time required for a BMA source node to transmit a control packet.

3.2.1. BMA

The energy consumption by the *j*th source node during a single session can be expressed as: $E_{sn}(j) = E_{Tx}(k_{c_B}, d_j) + (N-1)E_I(k_{c_B}) + E_{Rx}(k_c) + E_{Tx}(k_d, d_j)$. Since each non-source node stays idle during the contention period and keeps its radio off during the data transmission periods, the energy it expends over a single session can be estimated as follows: $E_{in}(j) = NE_I(k_{c_B}) + E_{Rx}(k_c)$. 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 next transmission period, it receives n_i data packets. Thus, the energy dissipated by the cluster-head node during a single session is

$$E_{ch} = n_i E_{Rx}(k_{c_B}) + n_i E_{Rx}(k_d) + (N - n_i)E_I(k_{c_B}) + E_{Tx}(k_c, d_{max}), \quad (12)$$

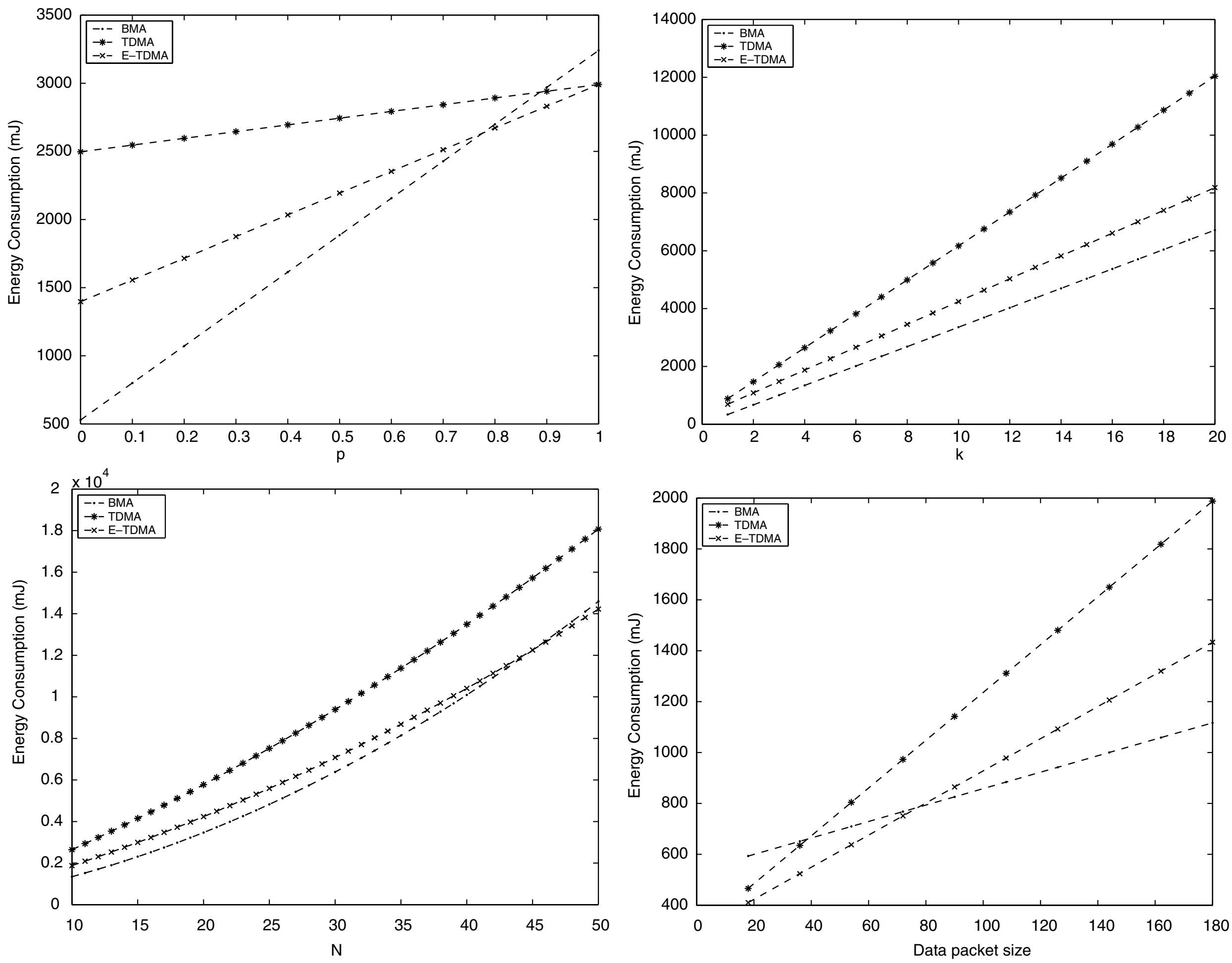

Fig. 7. Using Energy Model I, BMA is compared against TDMA and E-TDMA in terms of the average intra-cluster energy expenditure per round as function of p (top left, $N = 10$ and $k = 4$), k (top right, $N = 10$ and $p = 0.3$), N (bottom left, $k = 4$ and $p = 0.3$), and *data packet size* (bottom right, $N = 10$, $k = 4$, and $p = 0.3$).

and therefore, the total system energy consumed in each cluster during the ith session is

$$E_{\mathrm{si}} = \sum_{j=1}^{n_i} E_{\mathrm{sn}}(j) + \sum_{j=1}^{N-n_i} E_{\mathrm{in}}(j) + E_{\mathrm{ch}}. \tag{13}$$

Using (2) and the fact that each round consists of k sessions, we get the total system energy average system energy consumed during each round to be

$$E = E[E_{\mathrm{round}}] = E\left[\sum_{i=1}^{k} E_{\mathrm{si}}\right] = kE[E_{\mathrm{si}}]$$

$$= k\left[\sum_{j=1}^{n} E_{\mathrm{sn}}(j) + \sum_{j=1}^{N-n} E_{\mathrm{in}}(j) + E_{\mathrm{ch}}\right]. \tag{14}$$

The average packet latency can be easily determined as: $L = \frac{NT_{\mathrm{c_B}}+T_{\mathrm{c}}+nT_{\mathrm{d}}}{n}$.

3.2.2. TDMA

The energy consumption by the jth node during the contention period can be easily shown to be: $E_n(j) = \frac{1}{\alpha}E_{Tx}(k_{\mathrm{c}}, d_j) + \frac{N-1}{\alpha}E_{\mathrm{I}}(k_{\mathrm{c}}) + E_{Rx}(k_{\mathrm{c}})$. The cluster-head node receives N control packets and broadcasts one. Hence, $E_{\mathrm{ch}} = NE_{Rx}(k_{\mathrm{c}}) + E_{Tx}(k_{\mathrm{c}},d_{\max})$, and thus, the total system contention energy dissipation is given as,

$$E_{\mathrm{c}} = \sum_{j=1}^{N} E_n(j) + E_{\mathrm{ch}}$$

$$= \sum_{j=1}^{N} \frac{1}{\alpha}E_{Tx}(k_{\mathrm{c}}, d_j) + E_{Tx}(k_{\mathrm{c}}, d_{\max})$$

$$+ \frac{N(N-1)}{\alpha}E_{\mathrm{I}}(k_{\mathrm{c}}) + 2NE_{Rx}(k_{\mathrm{c}}). \tag{15}$$

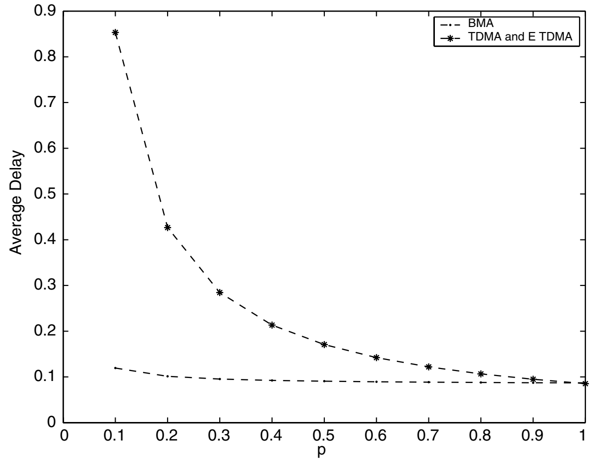

Fig. 8. Using Energy Model I, BMA is compared against TDMA and E-TDMA in terms of the average intra-cluster packet latency as function of p, the probability of a sensor node having data ready to send, for the case of 10 non-cluster-head nodes ($N = 10$) and four sessions/frames per round ($k = 4$).

During the ith frame, the energy expended by source node j is: $E_{sn}(j) = E_{Tx}(k_d, d_j)$. A non-source node turns and leaves on its radio during its scheduled time slot, even thought it has no data to send. Thus, $E_{in} = E_I(k_d)$. Further, during the ith frame, the cluster-head consumes the following energy: $E_{chi} = n_i E_{Rx}(k_d) + (N - n_i)E_I(k_d)$. Hence,

$$E_{fi} = \sum_{j=1}^{n_i} E_{sn}(j) + (N - n_i)E_{in} + E_{chi} = \sum_{j=1}^{n_i} E_{Tx}(k_d, d_j) + 2(N - n_i)E_I(k_d) + n_i E_{Rx}(k_d), \quad (16)$$

gives the system energy dissipated during the ith frame. Using (6), we get the average system energy consumed during each round to be

$$E = E[E_{round}] = E_c + kE[E_{fi}] = E_c + k\left[\sum_{j=1}^{n} E_{Tx}(k_d, d_j) + 2(N - n)E_I(k_d) + nE_{Rx}(k_d)\right]. \quad (17)$$

The average packet latency is as given in (8).

3.2.3. E-TDMA

The only difference of E-TDMA from TDMA is that with E-TDMA, a node with no data to send keeps its radio off during its allocated time slots. Thus, $E_{in} = 0$, and hence,

$$E_{fi} = \sum_{j=1}^{n_i} E_{Tx}(k_d, d_j) + (N - n_i)E_I(k_d) + n_i E_{Rx}(k_d). \quad (18)$$

Therefore, the average system energy dissipated in each round becomes

$$E = E[E_{round}] = E_c + k\left[\sum_{j=1}^{n} E_{Tx}(k_d, d_j) + (N - n)E_I(k_d) + nE_{Rx}(k_d)\right]. \quad (19)$$

Again, the average packet latency is as given in (8).

3.2.4. Performance evaluation

We again evaluated and compared the performance of BMA, TDMA and E-TDMA as intra-cluster MAC schemes using the Energy Model II and the same single cluster network model that was used in the performance evaluation of the Energy Model I and is shown in Fig. 2.

The system parameters were set to the following values: $E_{ele} = 50$ nJ/bit, $\varepsilon_{amp} = 10$ pJ/bit/m^2, $\beta = 0.8$, transmission rate = 1 Mbps, data packet size = 500 bytes, $\alpha = 0.815$, and normal control packet size = 25 bytes. For BMA, the source to cluster-head control packet size was set to 16 bytes. We let the distance between a node and the cluster-head to be a random variable uniformly distributed over the interval [10] meters.

Fig. 9 provides a comparison of the three intra-cluster MAC techniques in terms of the average intra-cluster energy expenditure per round as a function of p (top left), k (top right), and N (both bottom). BMA is shown to provide better performance than E-TDMA for $p \leqslant 0.7$ (with $N = 20$ and $k = 4$), $k \leqslant 14$ (with $N = 20$ and $p = 0.3$), and $N \leqslant 37$ (with $p = 0.3$ and $k = 4$). The main energy conservation comes from avoiding idle listening. When $p > 0.7$, 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 0.7, both TDMA schemes perform better. Obviously E-TDMA outperforms TDMA for all values of p. The energy savings by E-TDMA relative to TDMA grow as p approaches zero.

The bottom right plot of Fig. 9 demonstrates the impact of the data packet size on the performance

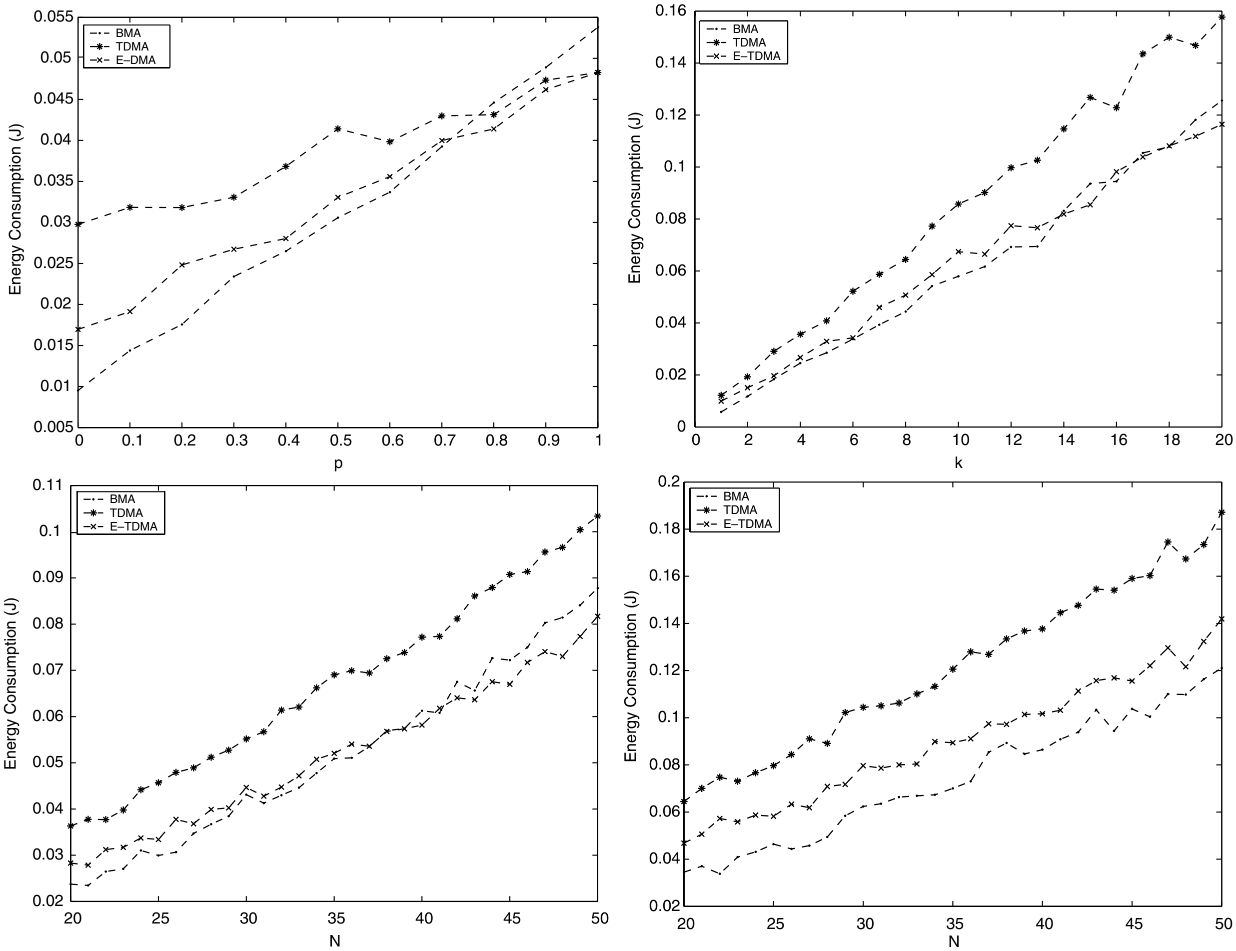

Fig. 9. Using Energy Model II, BMA is compared against TDMA and E-TDMA in terms of the average intra-cluster energy expenditure per round as function of p (top left, $N = 20$ and $k = 4$), k (top right, $N = 20$ and $p = 0.3$), N (bottom left, $k = 4$, $p = 0.3$, and *data packet size* = 500 bytes), and N (bottom left, $k = 4$, $p = 0.3$, and *data packet size* = 1000 bytes).

of BMA relative to E-TDMA: as the data packet increases, BMA delivers better performance than E-TDMA for much higher values of N. The energy performance curves vs. N that are shown in the bottom right plot of Fig. 9 were generated by increasing the data packet size from 500 bytes to 1000 bytes.

Fig. 10 illustrates the impact of the data packet size on the overall system energy consumption for the case of $N = 20$, $k = 4$, and $p = 0.3$. It shows that BMA performs better than the two TDMA schemes for large data packet sizes, and that the difference in performance grows as the data packet size becomes larger. This is due to the fact that in BMA, the energy consumption in the contention periods becomes negligible when compared to the total energy required to transmit large data packets.

The performance of BMA relative to TDMA and E-TDMA in terms of the average packet latency is the same as with Energy Model I.

4. Conclusion

Both theoretical analysis and simulation show:

- The energy performance of BMA, as an intra-cluster MAC scheme, relative to E-TDMA depends on the sensor node traffic offer load (parameter p), the data and control packet sizes, the number of sensor nodes within the cluster (parameter N), and, in some cases, the number of sessions per round (parameter k).
- BMA delivers better performance than E-TDMA for low and medium traffic loads (i.e., $0 < p \leqslant$

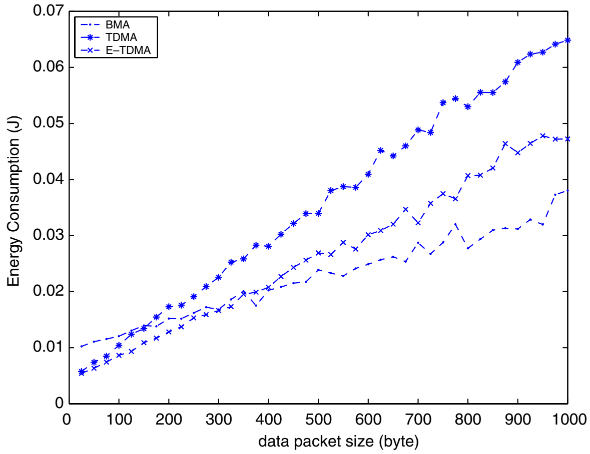

Fig. 10. Using Energy Model II, BMA is compared against TDMA and E-TDMA in terms of the average intra-cluster energy expenditure per round as function of *data packet size*, for the case of 20 non-cluster-head nodes ($N = 20$), four sessions/frames per round ($k = 4$), and $p = 0.3$, where p is the probability of a sensor node having data ready to send.

0.75) given large data packets, small control packets, and few cluster nodes.

- E-TDMA always provides better energy performance than conventional TDMA.
- BMA provides lower average packet latency than E-TDMA. For very high values of p, both schemes have similar average packet latencies. As p goes to zero, the average packet latency in E-TDMA grows exponentially, but in BMA stays relatively low.
- Both energy models provide similar results when used to compare the performance of BMA against TDMA and E-TDMA.

In most event-driven applications, the system parameters p, N, k, and the data packet size can be constrained such that BMA delivers a superior performance. For example, to keep p less than 0.5 and the data packet large, sensor nodes could aggregate their sensing information from two or more events into one packet. To keep the number of nodes within a cluster small, the whole network could be divided into a large number of clusters. The optimization process as described in [6] can be used to obtain the optimum number of clusters.

Both energy models can be extended by allowing the possibility of bit-errors occurrences during contention periods. A necessary extension to this work is to find the multidimensional system parameter regions in which we always have $0 < \frac{E_{\mathrm{BMA}}}{E_{\mathrm{ETDMA}}} < 1$.

4.1. Summary

We propose an energy-efficient, robust, and low latency intra-cluster communication bit-map-assisted (BMA) MAC protocol for wireless sensor networks. BMA is intended for event-driven sensing applications, that is, sensor nodes forward data to the cluster head only if significant events are observed. It is simple and uses a dynamic scheduling scheme.

In addition, we provide two energy models for BMA, conventional TDMA, and E-TDMA when used as intra-cluster MAC schemes. Using these energy models, we compared the performance of BMA against the performance of TDMA and E-TDMA. Results show BMA will improve the performance of wireless sensor networks by reducing energy expenditure and packet latency.

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