Turkish Journal of Electrical Engineering & Computer Sciences

http://journals.tubitak.gov.tr/elektrik/

Research Article

Turk J Elec Eng & Comp Sci
(2013) 21: 812 – 824

doi:10.3906/elk-1108-14

An event-driven WSN MAC protocol design based on active node and dynamic time slot allocation

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Received: 04.08.2011 • **Accepted:** 21.12.2011 • **Published Online:** 03.05.2013 • **Printed:** 27.05.2013

Abstract: The unique features of wireless sensor networks (WSNs) make them suitable for a wide range of applications in many different areas. However, with many of the protocols and algorithms used in traditional wireless networks, it is usually neither feasible nor possible to apply them directly to WSNs due to the strict resource constraints of tiny sensor nodes. Moreover, application-specific approaches for communication protocols are usually imposed since WSN applications have distinct requirements. In this study, event-driven WSN applications, where a number of sensor nodes are randomly and densely deployed in remote and difficult to reach locations, are targeted. In such applications, energy efficiency and latency are crucial design parameters since replacing or recharging the batteries of sensor nodes is extremely difficult, and any sensed data should be transmitted eventually. Considering this aspect, conventional time division multiple access-based medium access control (MAC) protocols are not well suited, although there are a few MAC protocols specifically designed for event-driven WSNs. In this paper, we introduce a MAC protocol, named modified bit-map–assisted (M-BMA), for event-driven WSN applications, designed by employing a new active node determination method (ANDM) and dynamic time slot allocation approach. Utilizing the proposed ANDM, we present that the M-BMA well supersedes its classical counterpart, offering up to approximately 49% better energy usage as well as up to about 68% fewer message delays.

Key words: WSN, MAC, active node, dynamic time slot allocation

1. Introduction

A wireless sensor network (WSN) is a collection of a number of low-power, low-cost, multipurpose sensor nodes communicating wirelessly over a short distance. The unique features of WSNs, such as ease of installation, self-organizing, and simple maintenance requirements, make them suitable for a wide range of applications in many different areas ranging from military to health applications and from disaster relief to industrial applications [1,2]. These widespread applications can be categorized into 4 groups in terms of data delivery, as continuous, event-driven, query-driven, and hybrid [3]. In the continuous applications, sensed data should be transmitted periodically to the sink [4]. However, sensor nodes sensing the specific phenomena or measurement values defined previously should send the data immediately in event-driven ones. Hence, the application requirements are so different that application-specific designs are necessary. This paper mainly focuses on the event-driven type of WSNs.

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Some examples of event-driven WSN applications are forest fire detection systems [5,6], intrusion detection systems [7], and sniper localization [8]. Since there is no need to gather data continuously in these kinds of applications, keeping the number of sensor nodes for sending data to a minimum is required to prolong the network lifetime. Specifically, in applications where a large number of sensor nodes are randomly and densely deployed in remote and difficult-to-reach networking environments, replacing the sensor batteries is extremely difficult, even impossible. Thus, energy efficiency becomes one of the most crucial WSN design criteria. Another key issue in event-driven WSN applications is the event of interest to be reported within the shortest possible time. Keeping communication delays to a minimum in some given limits is also critically important for this kind of application, since the sensed data should be transmitted as soon as possible in event-driven WSN applications for fast decision making.

A WSN's performance relies on how its sensor nodes share the communication medium efficiently and fairly [9]. Medium access control (MAC) protocols assist in arranging when and how the sensor nodes access and then utilize the transmission medium [10]. Because of the characteristic properties of WSNs, MAC protocols designed for traditional wireless networks cannot be applied to WSNs directly. MAC protocols for WSNs can be classified into 2 groups, namely schedule-based and contention-based [10]. However, there are a few hybrid protocols combining the advantageous features of both of them [11,12]. Schedule-based MAC protocols are more energy efficient than contention-based ones. Since frequency division multiple access protocols require extra circuit design and code division multiple access protocols have to cope with high computation complexity, they are not well suited to WSNs. Consequently, most of the schedule-based protocols developed for WSNs are a version of time division multiple access (TDMA) [13].

Conventional TDMA protocols are more suitable for continuous observation-based WSN applications since it is assumed that each WSN node always has data to send. For the event-driven WSN applications in which a specific phenomenon observation or a given parameter measurement should take place, the necessity of introducing new MAC protocols to be developed has arisen due to the fact that the sensor nodes might not always have data to transfer. In the literature, there are some MAC protocols specifically designed for the event-driven WSN applications mentioned in Section 2.

In this paper, large-scale event-driven WSNs with dense node deployment are targeted as the application area. A new generic content-based scheduling approach, the active node determination method (ANDM), which determines active nodes, is proposed. Moreover, a TDMA-based MAC protocol, named the modified bit-map–assisted (M-BMA), is developed using the ANDM to demonstrate the benefits of the ANDM. The results are compared to those of the fundamental BMA protocol in terms of energy efficiency and latency.

2. Background

Traditional TDMA-based MAC solutions are not well suited for event-driven WSN applications since every node might not always have data to send. In the literature, there are some MAC protocols specifically designed for such applications. The event-driven TDMA (ED-TDMA) [14] is an energy efficient MAC protocol developed for event-driven WSNs. It consists of rounds including the set-up and steady-state phases. After clustering and time synchronization in the set-up phase, the steady-state phase has n variable length TDMA frames. When a WSN node needs to transmit data, it sends a request at the beginning of the frame and waits for the slot allocation from the cluster head (CH). The ED-TDMA protocol basically improves the channel utilization by changing the TDMA frame length according to the number of source nodes and reduces the length of TDMA schedule packets to decrease the schedule overhead.

The BMA [15,16] is a basic MAC protocol designed for event-driven WSN applications. The operation of the BMA is also divided into rounds, including the set-up and steady-state phases. The cluster is formed in the set-up phase and then the steady-state phase begins. The steady-state phase consists of the contention period, data transmission period, and idle period, as illustrated in Figure 1. It is fundamentally based on allocating data time slots to only source nodes. In the well-known BMA protocol [16], each WSN node is given a 1-bit time slot to report the CH, whether it has data to send or not. A node with data to transmit, called a source node, initially sends 1 bit to the CH. A nonsource node, without data to transmit, leaves its own 1-bit time slot unused. Thus, the CH distinguishes the source nodes and prepares and broadcasts the time slot allocation schedule according to this knowledge. Finally, while nonsource nodes fall directly asleep, source nodes transmit their sensed data during their allocated time slots.

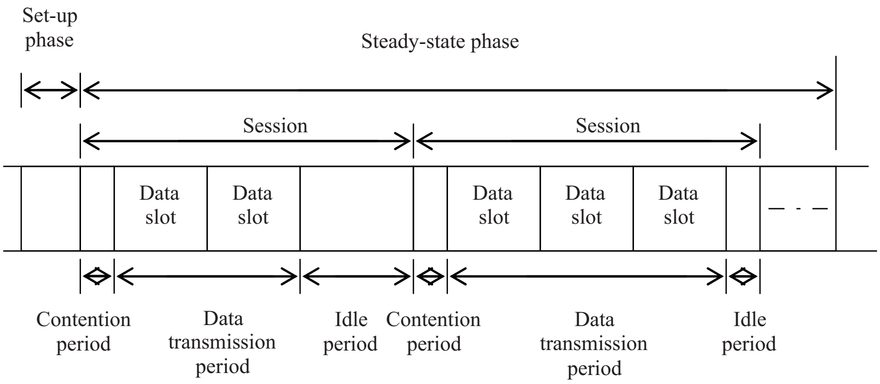

Figure 1. A single round for the BMA protocol [16].

The parameters used in the mathematical expressions in the rest of the paper for both the BMA and proposed M-BMA protocols are given in Table 1.

Table 1. Parameters used in the mathematical expressions.

P_t	Power consumption in transmit mode
P_r	Power consumption in receive mode
P_i	Power consumption in idle mode
T_d	Time required to send/receive a data packet
T_c	Time required to send/receive a control packet
T_{ch}	Time for the CH to transmit a control packet in BMA
E_{sn}	Energy consumption of a source node
E_{non-sn}	Energy consumption of a nonsource node
E_{ch}	Energy consumption of the CH
E_N	Energy consumption of a member node to receive a control packet
N	Number of member nodes
n	Number of source nodes
m	Number of active nodes
p	Probability of being a source node (source node ratio)
p'	Probability of being an active node (active node ratio)
l	Number of frames

It is supposed that a cluster consists of a CH and N member nodes (non-CH) and the energy consumption is calculated over one round with k sessions/frames. n_i represents the number of source nodes in the ith session/frame. The Bernoulli trial is used to calculate the probability of a node to send the data. Accordingly, as p is the probability, the number of source nodes in a frame as given by [16]:

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

Therefore, the expectation of the total number of source nodes in a round is expressed as [16]:

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

As given in [17], the energy consumption of a source node consisting of "$P_rT_{ch} + P_tT_c + (N-1)P_iT_c$" in the contention period and "P_tT_d" in the data transmission period for the BMA protocol can be calculated as follows:

$$E_{sn} = P_rT_{ch} + P_tT_c + (N-1)P_iT_c + P_tT_d. \tag{3}$$

The energy consumption of a nonsource node in the contention period of the BMA protocol is given by [17]:

$$E_{non-sn} = P_rT_{ch} + NP_iT_c. \tag{4}$$

The CH energy consumption consists of "$nP_rT_c + (N-n)P_iT_c + P_tT_{ch}$" in the contention period and "nP_rT_d" in the data transmission period [17], and it is given as:

$$E_{ch} = n(P_rT_c + P_rT_d) + (N-n)P_iT_c + P_tT_{ch}. \tag{5}$$

Finally, the total energy consumption during a round [17] in the BMA protocol is given as:

$$\begin{aligned} E_{BMA} \;\; = \;\; & l[n(P_tT_c + (N-1)P_iT_c + P_tT_d + P_rT_{ch}) + (N-n)(NP_iT_c + P_rT_{ch}) \\ & +n(P_rT_c + P_rT_d) + (N-n)P_iT_c + P_tT_{ch}]. \end{aligned} \tag{6}$$

The average packet latency [16] in the BMA protocol is given by:

$$L_{BMA} = \frac{NT_c + T_{ch} + nT_d}{n}. \tag{7}$$

3. Proposed M-BMA protocol design stages

In this section, first, our new ANDM is expressed. The proposed MAC protocol utilizing it is then explained in detail and the flowcharts related to it are given.

3.1. Active node determination method

Some MAC protocols especially designed for event-driven WSN applications just allocate TDMA time slots to source nodes, but they do not concern data redundancy, resulting in useless data transmission originating from the same application region. Based on the idea that gathering similar data from the same region simultaneously does not provide an additional contribution for the evaluation of the event/situation, the fundamental motivation of this study is to reduce data redundancy and, consequently, optimize energy consumption and latency by assigning a time slot to only one of the source nodes, all with the same data sensed and to be sent. To this end, a generic content-based scheduling approach [18] has been developed and named ANDM.

In event-driven WSNs, a source node is the node sensing any predetermined measurement (temperature, humidity, pressure, etc.) or event depending on the application requirements. Since many nodes are deployed randomly and are densely close to the phenomenon in this kind of application, the neighbor nodes might sense and want to transmit the same data. As the main objective of these applications is to obtain data from the field, there is no purpose in getting the same data from more than one sensor node. This data redundancy causes both energy waste and latency increase.

Instead of all of the source nodes sending data in these kinds of event-driven WSN applications, allowing only one of the source nodes with the same data to transmit is called ANDM. The source node allowed to transmit is defined as the active node. The ANDM is based on assigning a data slot to only one of the source nodes with the same data. For this purpose, before preparing the time slot schedule, the CH compares the differences in the data received from the all of the source nodes and assigns a data slot to just one of them, which sends the same difference data. Thanks to this method, only small-sized difference data are transmitted in the data slots, utilizing the content-based scheduling.

A forest fire detection WSN application is considered to exemplify the ANDM. Before deployment, the sensor nodes are set with a predetermined temperature threshold value, which might be an incipient fire indication. A large number of sensor nodes are randomly and densely deployed by a plane over the forest, and clusters are formed by a set of sensor nodes. Nodes that do not sense a temperature value equal to or above the predetermined threshold value do not send any data. If the predetermined temperature threshold is set to 50 $^\circ$C, the sensor nodes that measure below 50 $^\circ$C do not send any data. The sensor nodes whose measurements are equal to or above 50 $^\circ$C are called source nodes. The current temperature measurement values are rounded off. Each source node computes the difference between the threshold and its current temperature measurement. Assume that the measurement values of 5 source nodes are 51, 55, 55, 60, and 58 $^\circ$C. They send 1 (0001_2), 5 (0101_2), 5 (0101_2), 10 (1010_2), and 8 (1000_2), respectively, to the CH as their obtained difference data. The CH compares the data, determines that 2 of them have the same difference data, and assigns a data slot to only 1 of these 2 source nodes, because getting the same data from the same region does not provide any extra information for the evaluation of the event. In contrast to this simple example, there might be more than 2 source nodes with the same temperature measurement. Regardless of the number, the CH assigns a data slot to only one of them. In this example, the number of source nodes is 5 but the number of active nodes is 4. The probability of the resolution loss is out of this paper's scope and can be further studied later. During the determination of the active nodes, some criteria could be considered such that the source node is the one closer to the CH or with more remaining energy, etc. In this paper, we do not introduce any restrictions in order to focus on the generic aspect of the ANDM.

The ANDM is a generic approach that can be adapted to any TDMA-based MAC protocol. The proposed M-BMA is a MAC protocol developed by applying the ANDM to make the benefits of the ANDM clear. It has some directions in common with the BMA, so we prefer calling it M-BMA rather than giving it a new name. In the M-BMA protocol, every node has its mini-slots before the data transmission period, as in the BMA. However, these mini-slots are arranged in the 4 bits required for the ANDM, which are used to report the presence of difference data at a source node in the M-BMA, while each mini-slot in the BMA is only 1 bit long to inform the CH that a source node has data to send.

3.2. The M-BMA protocol details

The proposed protocol is named the M-BMA since it originates from the fundamental BMA protocol. The M-BMA protocol consists of rounds including both a set-up phase and a steady-state phase, as in the other classical schedule-based MAC protocols (Figure 2). In the set-up phase, a CH is chosen and then the cluster is formed according to a given clustering mechanism. After that, the steady-state phase begins. It is divided into k sessions and each session has 3 different periods, namely contention, data transmission, and idle. The contention period looks like the one in the BMA protocol. However, source nodes send the difference data between the predefined threshold and the measurement values instead of transmitting 1 bit in the BMA protocol. For this purpose, each node is assigned a 4-bit slot. In the BMA protocol, it is known that there are N slots in a cluster with N member nodes, since each node is assigned a 1-bit slot during the contention period. On the other hand, in the M-BMA protocol, 4N slots are required to allocate 4 bits to each node for transmitting the difference data in the N-node network. The source-to-CH control message is only 1 bit long in the BMA protocol; the control packet includes this 1-bit control message plus other MAC level overhead information [16]. Considering the fact that the content of the control packet is unknown and it has already N bits, the remaining 3N bits are added to the control packet length. This increment causes extra overhead, although the M-BMA still remains advantageous as it provides better results than the BMA protocol, as explained in Section 4.

The nodes that sense equal or higher values than the threshold value are called source nodes. The source nodes transmit difference data in their 4-bit slots to the CH during the contention period and the nonsource nodes remain in the idle mode within their allocated 4-bit slots. Consequently, the CH not only knows all of the source nodes, but also knows all of the source nodes with the same data and assigns time slots to the WSN nodes according to this knowledge. The CH compares the difference data from the source nodes, determines the same ones, and assigns a time slot to only one of them. For instance, if 2 or more source nodes have the same data, the CH allocates the time slot to just 1 of them. In this selection, some criteria might be considered, such as the node closer to the CH or the node with more remaining energy. In this paper, there is a simple assumption for the selection criteria in order to not lose focus on the MAC design.

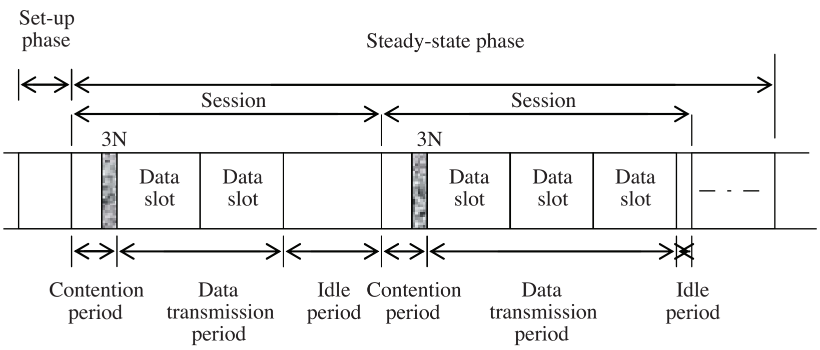

Figure 2. A single round for the M-BMA protocol.

The flowchart related to the operation of the CH in the M-BMA protocol is presented in Figure 3a. First of all, the clustering algorithm is determined and the cluster is formed. In the flowchart, an algorithm name is not given considering the fact that any clustering algorithm could be employed in it. On the other hand, it is assumed that the clustering algorithm in the low-energy adaptive clustering hierarchy [19] is used, as in the BMA protocol, owing to the similarities between the BMA and M-BMA protocols. After that, the system enters the steady-state phase. In the contention period of the steady-state phase, the CH allocates 4-bit slots to all of its member nodes. The CH then waits for the difference data coming from the source nodes, and following the comparison of the data, it broadcasts the schedule in which the time slots allocated to the nodes with different data are included. After aggregating the data packets, the CH sends the abstract packet to the sink or base station.

The flowchart for the operation of a cluster member is shown in Figure 3b. After the set-up phase, each member node waits for the TDMA-like schedule, in which 4-bit slots for every node are assigned by the CH. During each contention period, all of the member nodes have to turn on their radios. Unless a node is a source node, it leaves the slot empty and goes into sleep mode. If it is source node, it transmits the difference data and waits for the data slot allocation schedule. In a case where the node is not assigned a data slot, it goes into sleep mode. Otherwise, it is chosen as an active node; it transmits the data during its allocated slot and then goes into sleep mode.

The proposed M-BMA protocol improves energy efficiency, especially designed for cluster-based event-driven WSN applications [20].

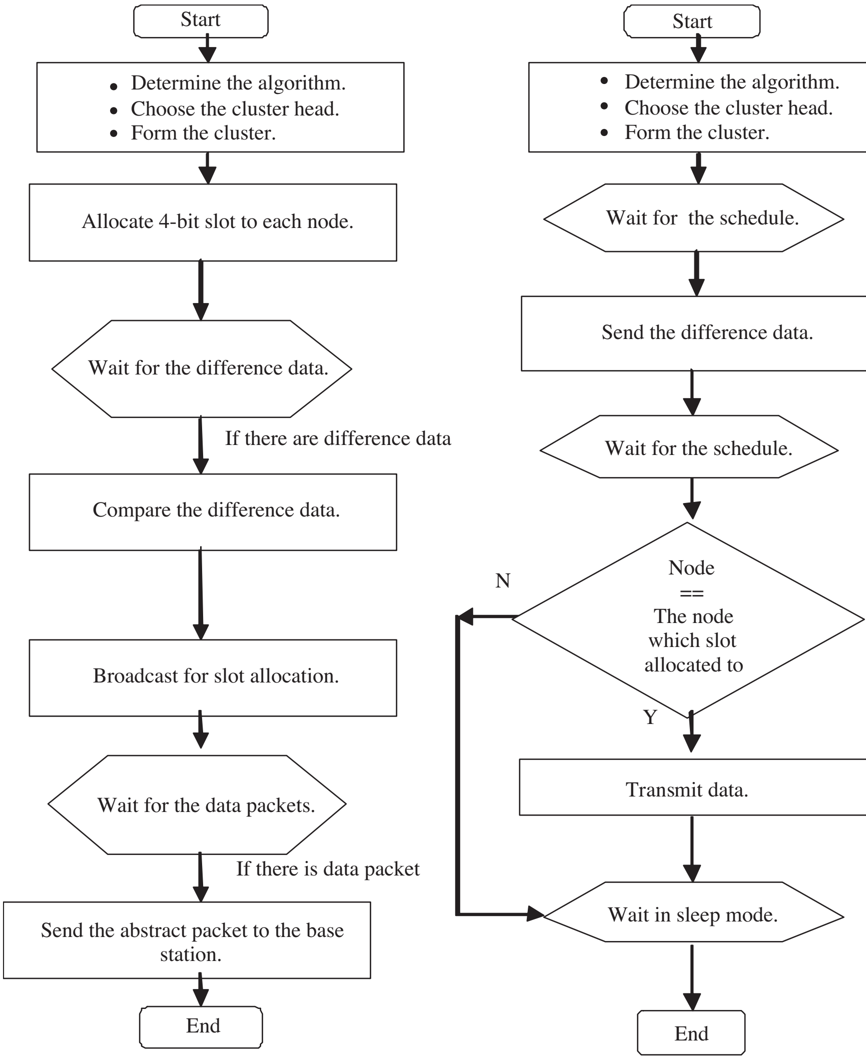

Figure 3. a) Flowchart for the CH; b) flowchart for a cluster member.

4. Evaluation of the proposed M-BMA protocol

In this section, the M-BMA protocol is analyzed in terms of its energy efficiency and latency. First, energy consumption expressions are given for the M-BMA protocol and then the energy consumption values of the BMA and M-BMA protocols are compared with respect to their source node ratios. Moreover, the latency comparisons of the BMA and M-BMA protocols are given in the next subsection. Data for Rockwell's wireless integrated network sensors (WINS) model [21], used in the numerical analysis as in [16], is given in Table 2. The energy consumption of the nonactive nodes in the sleep mode is ignored.

Table 2. Data for Rockwell's WINS model [21] used in the numerical analysis.

Parameter	Value
Transmit power (P_t)	462 mW
Receive power (P_r)	346 mW
Idle power	330 mW
Data transmit rate	24 kbps
Data packet	250 bytes
Control packet	18 bytes

4.1. Energy efficiency analysis

Recharging or changing the batteries of WSN nodes is difficult or costly in applications, as many of them are deployed in remote locations [22]. Therefore, the first objective of a WSN application design is to prolong the lifetime of its nodes and thus the network. Considering this fact, a comparative energy efficiency analysis of the proposed M-BMA is presented in detail in this subsection.

As listed in Table 1, m represents the number of active nodes and is given as:

$$m = np' \tag{8}$$

where p' is the active node ratio and n is the number of source nodes.

The energy consumption of a source node includes "$P_r(T_{ch}+$ (3N / data rate)) + (N –1)$P_i(T_c+$ (3N / data rate)) + $P_t(T_c+$ (3N / data rate))" in the contention period and "P_tT_d" in the data transmission period, and E_{sn} can be calculated as follows:

$$\begin{aligned} E_{sn} &= P_r(T_{ch} + (3N/\text{data rate})) + P_t(T_c + (3N/\text{data rate})) \\ &\quad +(N-1)P_i(T_c + (3N/\text{data rate})) + P_tT_d. \end{aligned} \tag{9}$$

During total energy consumption calculation for the M-BMA protocol, it is assumed that there are n source nodes in the contention period and m of them are active nodes in the data transmission period.

On the other hand, a nonsource node energy consumption in a frame is expressed as:

$$E_{non-sn} = NP_i(T_c + (3N/\text{data rate})) + P_r(T_{ch} + (3N/\text{data rate})). \tag{10}$$

The CH energy consumption includes "mP_rT_d" and "$nP_r(T_c+$ (3N / data rate)) + (N – n)$P_i(T_c+$ (3N / data rate)) + $P_t(T_{ch}+$ (3N / data rate))", and thus E_{ch} is calculated as:

$$\begin{aligned} E_{ch} &= nP_r(T_c + (3N/\text{data rate})) + mP_rT_d + (N-n)P_i(T_c + (3N/\text{data rate})) \\ &\quad +P_t(T_{ch} + (3N/\text{data rate})). \end{aligned} \tag{11}$$

Considering the above expressions, for the proposed M-BMA protocol, the total energy consumption in a round is calculated as below:

$$\begin{aligned} E_{M-BMA} &= l[n\{P_t(T_c + (3N/\text{data rate})) + (N-1)P_i(T_c + (3N/\text{data rate})) \\ &\quad + P_r(T_{ch} + (3N/\text{data rate}))\} + mP_tT_d + (N-n)\{NP_i(T_c + (3N/\text{data rate})) \\ &\quad + P_r(T_{ch} + (3N/\text{data rate}))\} + nP_r(T_c + (3N/\text{data rate})) + (N-n)P_i(T_c + (3N/\text{data rate})) \\ &\quad + mP_rT_d + P_t(T_{ch} + (3N/\text{data rate}))]. \end{aligned} \tag{12}$$

The variation in energy consumption with respect to the ratios of source and active nodes is given in Figure 4. Energy consumption increases with the increment of both the source node and active node ratios. However, the ANDM has a reduction effect on the energy consumption. For example, if the source node ratio is 50%, the energy consumption value is 1.26 without the ANDM. If the active node ratio is 50%, the energy consumption value for the same example is 0.93. When the active node ratio increases, the energy consumption expectedly increases as well. While the active node ratio is equal to 100%, all of the source nodes are also active nodes. However, this is an extreme situation for an event-driven WSN with dense deployment. Thus, it is concluded that the ANDM has a positive impact on the reduction of energy consumption.

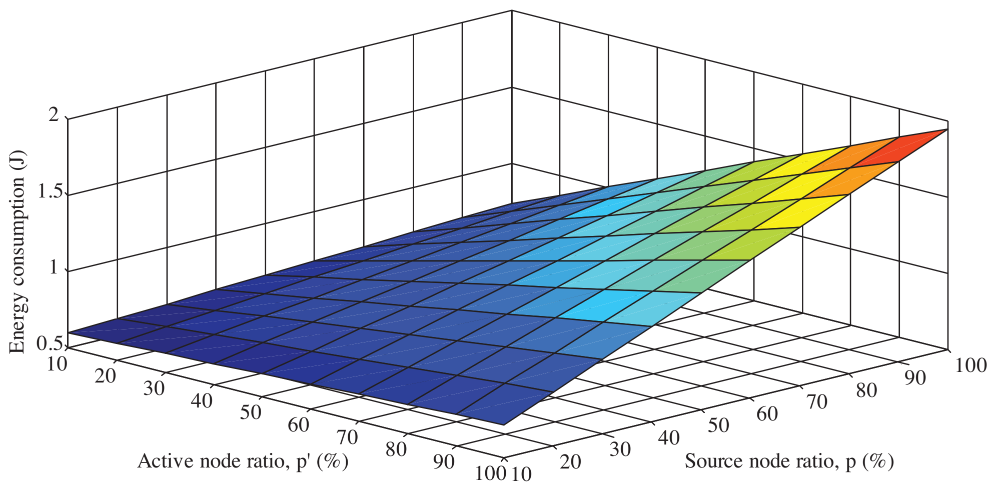

Figure 4. Energy consumption versus the ratios of the source and active nodes.

The graphs of the energy consumption versus the source node ratio (p) for the active node ratios (p' = 0.25, 0.5, 0.75, 1) 25%, 50%, 75%, and 100% are given in Figure 5, where the number of frames (l) and the number of member nodes (N) are assumed as 2 and 10, respectively. It is shown that the M-BMA consumes less energy than its counterparts compared to p' = 0.25 in the first graph of Figure 5. When p' increases, the number of active nodes and the number of data slots allocated to them also increase. A case in which all of the source nodes have different data (the number of source nodes = the number of active nodes) is represented by p' = 1 in Figure 5. That is the worst case scenario for the M-BMA protocol application and it is also quite hard to come across such a situation for event-driven WSN applications with dense node deployment.

4.2. Latency analysis

Latency is defined as the time from a sender WSN node transmitting a data packet to the packet being received successfully by the receiver WSN node [16]. The importance of latency characteristically depends on the type of the application [10]. In event-driven WSN applications, latency is a crucial design parameter, and so data should be transmitted as soon as possible for vital decision making in the central unit of the designed system. Basically, a fewer number of nodes sending data means a lower latency result, as expressed in the following equation:

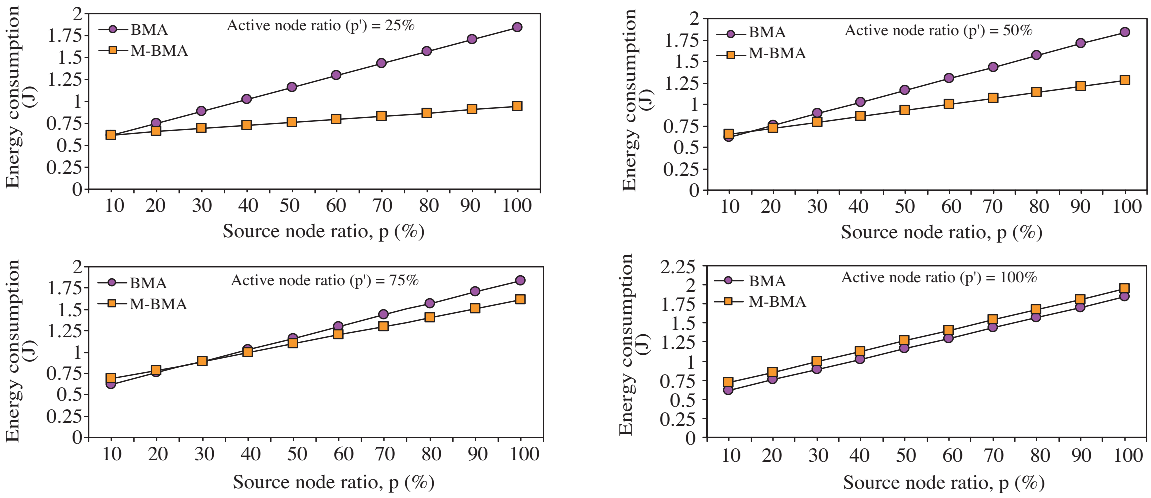

Figure 5. Energy consumption versus the ratio of source nodes (where p' = 0.25, 0.5, 0.75, and 1).

$$L_{M-BMA} = \frac{N[T_c + (3N/\text{data rate})] + [T_{ch} + (3N/\text{data rate})] + mT_d}{n}. \quad (13)$$

The average latency of the M-BMA protocol versus the ratios of the source and active nodes is given in Figure 6. Even if there is a relatively high latency for the low values of the source node ratio (i.e. less than 10%), the variation of the source node ratio has a horizontal line and does not have very much effect on the latency. However, the latency then increases, since the higher the number of active nodes is, the higher the number of the transmitting nodes is.

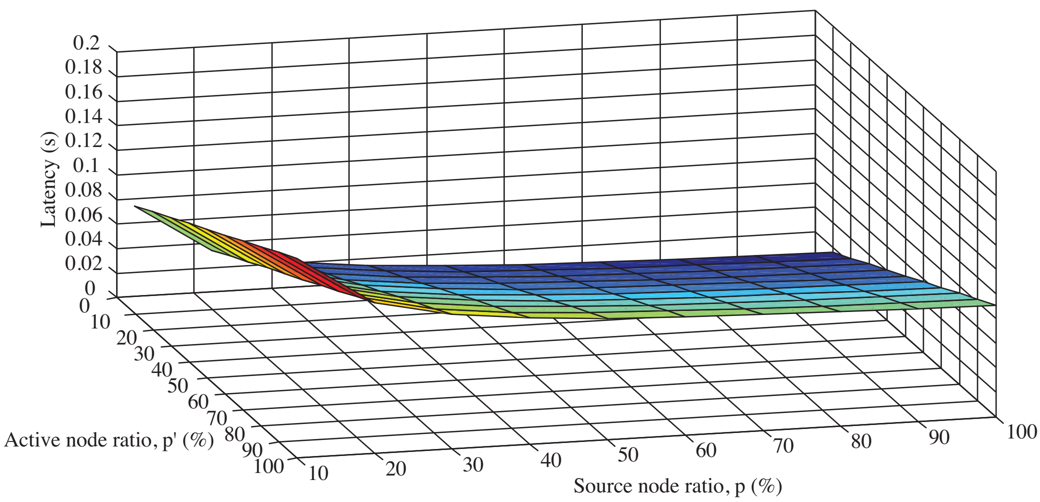

Figure 6. Average latency versus the ratios of the source and active nodes.

Average packet latency (L) results of the classic BMA and the proposed M-BMA protocols versus the source node ratio (p) are shown for different active node ratios (p' = 25%, 50%, 75%, and 100%) in Figure 7. The number of nodes (N) is assumed as 10. As seen in Figure 7, the 2 protocols have similar latencies for high p values. It is also shown that the latency of the M-BMA protocol is almost the same as that of the BMA protocol, even in the worst case for this approach, in which all of the source nodes have different data (p' = 100%). Although the BMA and M-BMA protocols have parallel tendencies, the latter has a lower latency as a consequence of the ANDM insertion. In the BMA protocol, all of the source nodes are assigned data slots; therefore, both the number of data slots and the latency are higher than that of the M-BMA, accordingly. On the other hand, the number of data slots allocated to the WSN nodes is much reduced by assigning slots to only active nodes in the M-BMA protocol. Thanks to the ANDM approach, evidently much lower latency results are obtained.

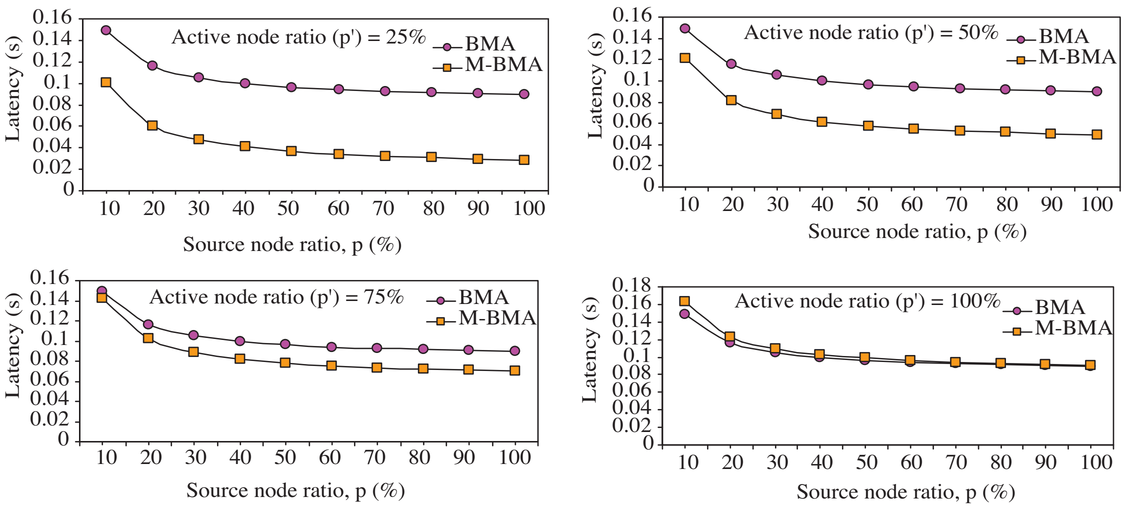

Figure 7. Average latency versus the ratio of the source nodes (where p' = 0.25, 0.5, 0.75, and 1).

5. Conclusions

In event-driven WSN applications, energy efficiency and latency reduction are crucial for prolonging the network lifetime and reporting data as soon as possible, respectively. For classical TDMA-based MAC protocols, the fewer the number of data slots used, the lower the energy consumption and latency achieved. Considering these facts, the new ANDM presented in this paper is an effective approach since it decisively reduces the data slots allocated.

In this paper, a new TDMA-based MAC protocol M-BMA was presented to discuss the ANDM in detail. In the M-BMA protocol, the contention period becomes larger than that of the BMA protocol, since the difference data are transmitted in 4-bit slots instead of 1-bit slots. Therefore, the energy consumption is meaningfully reduced and improved latency results can be obtained since the number of data slots allocated is decreased. The energy efficiency and latency performances of the M-BMA protocol are demonstrated by comparing them to the BMA protocol in terms of source and active node ratios.

The application of the ANDM developed in this paper can be straightforwardly extended to the other MAC protocols.

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