An Energy-Aware Approach for Event-Driven Multimedia Data Acquisition in WMSNs

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Abstract. In context-aware monitoring and control applications, multimedia data generated by multimedia sensors at a critical moment have to be delivered to a server reliably with tight time constraint. However, it is challengeable to process those data using a wireless multimedia sensor network with limited resources in terms of energy, bandwidth and processing power. Therefore, in this paper, we propose an energy-aware approach to deliver those event-driven bursty data in a reliable and timely manner by exploiting the advantage of slot scheduling technique and channel allocation. Our approach enables the concurrent transmission of a burst of multimedia data in order to shorten the multimedia data acquisition time and reduce the energy consumption. The simulation results show that the proposed approach can satisfy the requirements of multimedia applications in terms of data acquisition time and energy consumption compared with other approaches.

Keywords: WMSNs · Multimedia data · Slot scheduling

1 Introduction

A wireless multimedia sensor network (WMSN) for a context-aware monitoring and control application usually consists of several scalar sensors that report the readings from environment to a server periodically and multiple multimedia sensors that generate and transmit a burst of multimedia data (or bursty data) such as still image or video on demand only when a critical event occurs. Due to the limited bandwidth and energy of a sensor node, it is challengeable to design a protocol that can satisfy the tight time constraint and the reliability of multimedia data transmission in such a critical moment.

Various TDMA-based media access control (MAC) protocols such as TreeMAC [1], I-MAC [2], RRMAC [3] have been proposed for reliable and real-time data transmission in WMSNs. However, these protocols were basically designed for periodic data acquisition, they may not be suitable for transmitting bursty data with the time constraint reliably. In addition, for an efficient bursty data transmission with the traditional MAC protocols, the complex slot scheduling algorithm may be required and/or the wasted energy consumption of the sensor nodes is inevitable since sensor nodes may still remain active or idle listening state during the duration of bursty data transmission.

Y. Chen and T. Q. Duong (Eds.): INISCOM 2017, LNICST 221, pp. 131–141, 2018.
https://doi.org/10.1007/978-3-319-74176-5_13

Recently, some approaches have been proposed to support the transmission of bursty data in WMSNs. Multimode Hybrid Medium Access Control (MMH-MAC) [4] can support bursty traffic in dynamic networks with the use of slot reuse technique. BurstMAC [5] which relies on the TDMA and multi-channel mechanism is proposed to enhance the network performance and prolong the network lifetime. Advertisement-based Time-division Multiple Access (ATMA) [6] reserves transmission slots by using the CSMA technique and manages the reservation of nodes in an energy-efficient way by making the use of the nature of bursty traffic to reduce the energy consumption of nodes. However, it may not be suitable for dealing with multi-hop bursty traffic and may also suffer from the funneling effect problem when applying in a tree-based network. iQueue-MAC [7] is proposed to deal with bursty traffic by using a hybrid mechanism: CSMA/CA is used in light traffic load while TDMA is used in case of bursty traffic to provide better throughput with support of the multi-channel technique. An optimized low energy adaptive clustering hierarchy (Op-LEACH) [8] allows the nodes with bursty data to get more transmission slots which are released by the nodes without having data during the bursty data transmission. However, this passive way of acquiring slots cannot guarantee the delivery of bursty data in a timely manner. An approach in [9] tries to reduce transmission collision and thus transmits bursty data efficiently by allocating the different channels to the nodes in underwater sensor networks. This approach is complicated by dealing with channel allocation problem, multi-channel hidden terminal problem and missing receiver problem.

The aforementioned MAC protocols mostly deal with the periodic scalar data in general, while they try to transmit bursty data using slot scheduling when necessary. Accordingly, they have difficulty in predicting the amount of time to transmit bursty data since they do not take the time constraint of bursty data into account in designing a slot scheduling and transmission method. In order to solve such kind of problems, the approach in [10] reserves a particular path from an active multimedia node to the sink and then assigns dedicated slots for the nodes along the path for the bursty data transmission. However, without using the slot reuse technique may cause more latency under high traffic load conditions. Therefore, to reduce the bursty data collection time, the approach in [11] uses a channel-slot allocation scheme where the vertically two-hop away nodes along the reserved path are allowed to transmit data simultaneously either if they are located outside of their transmission range or the transmissions of those nodes are performed on different channels. However, this approach requires very tight time synchronization and it only achieves high performance in a long treesize network.

Taking into consideration the requirements of multimedia data applications and the above problems discussed so far, we propose an energy-aware approach with the aim of delivering bursty data in a reliable and timely manner. In this approach, the optimal path from active multimedia nodes to the server is set up with the consideration of bandwidth requirement for multimedia data transmission. Only the nodes along the optimal path will involve transmitting multimedia data, the other nodes get into a sleep state during multimedia data acquisition for conserving energy. Moreover, to shorten the bursty data transmission time, we exploit an efficient scheme that collects the bandwidth demand of the network and then assigns a number of dedicated slots to corresponding nodes based on their demands in an optimal way. Hence, the bursty data are delivered safely to the server in a contention-free manner while satisfying the tight time constraint of multimedia applications. The evaluation results indicate that the proposed approach improves the application performance significantly.

In what follows, the system model is described in Sect. 2. We present the principle design of the proposed approach in Sect. 3. Section 4 covers the performance evaluation. Finally, we make concluding remarks in Sect. 5.

2 System Model

In this paper, we consider a typical model for the safety monitoring and control (SMOCS) system which consists of one server and multiple sinks for collecting data readings from sensors in the network. Typically, there are two types of sensor nodes: *Ordinary sensor* (e.g. gas, heat, light, and humidity) and *multimedia sensor* (equipped with a camera module for taking a still image or video of a monitored object). An ordinary node (*ON*) senses data from environment and sends it to the server periodically. The server collects and then analyzes the data to judge whether a critical event has occurred or not. In case that a critical event is detected in a particular area, the server and/or sink sends a command to request the multimedia node (*MN*) in that spot to send a still image or video stream of the monitored object to confirm the critical situation. In that case, an *MN* with active camera module is called an active multimedia node (*AMN*).

Figure 1 illustrates a typical network model for WMSNs. There are multiple trees where each tree originates at a sink and then connects to other nodes via wireless link to form a tree-topology network. A wireless link can be disrupted due to node failure, battery depletion, or the effect of hard industrial environment. If a node belongs to a specific tree, it is called as a tree-node and the corresponding link is called a tree-link.

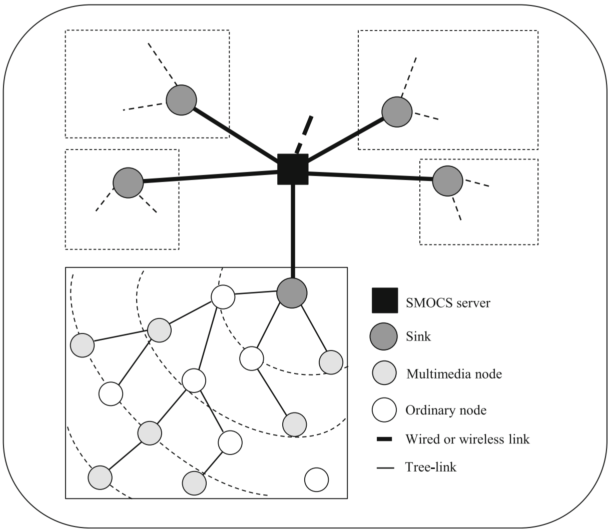

Fig. 1. An example of SMOCS system model

3 Principle Design of the Proposed Approach

3.1 Protocol Operation

The proposed protocol begins with the initial contention period (*ICP*), followed by the MAC Operation period and the multimedia data acquisition period (*MDAP*), as illustrated in Fig. 2.

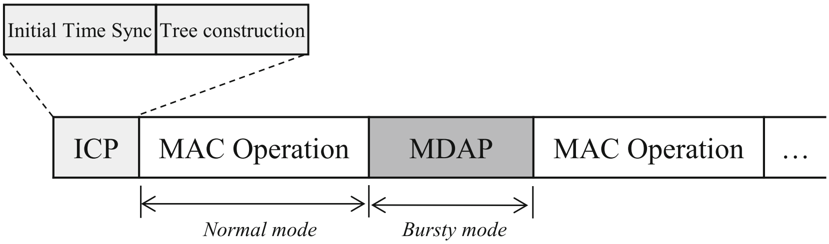

Fig. 2. The structure of the proposed approach operation

In the ICP, a tree is initially constructed and then time synchronization is performed. In this approach, every sensor node works in either of two modes: *normal mode* or *bursty mode*. A node operates in a normal mode in the MAC operation period which follows the ICP. In this mode, sensor nodes can report data readings to the sink periodically by using one of existing MAC protocols. When an abnormal situation is perceived, the sink starts the MDAP by sending a request of multimedia data to a specified multimedia sensor. Then, every node switches to bursty mode for sending or forwarding bursty data. In this paper, we do not explain the protocol operation in the normal mode and limit our discussion to the acquisition of event-driven multimedia data in the bursty mode.

For more convenience, the following notations are used in the rest of the paper as shown in Table 1.

Table 1. Some notations used in the paper

Notation	Definition
$D(i)$	A set of descendant list of node i
$T(i)$	T(i) = D(i) $\cup$ {i}
$C(i)$	A set of children of node i
$mIDs(i) = \{x \mid x \in T(i) \wedge x = MN\}$	A set of multimedia nodes in the subtree of node i
$mIDs^A(i) = \{x \mid x \in T(i) \wedge x = AMN\}$	A set of multimedia nodes in the subtree of node i
η_i	The number of packets generated by node i
S_i	A sending bandwidth demand of node i
R_i	A receiving bandwidth demand of node i
B_i	Total bandwidth demand of node i

3.2 Tree Construction

At the initialization, all nodes cooperate to build a tree which is rooted at the sink (as shown in Fig. 1). A link (i, j) is said to be *reliable* if node i can transmit a packet to node j successfully when there is no interference. Then, we can construct a robust tree such that every tree-link is bi-directionally reliable (*B-reliable*) [2].

Tree construction is initiated by an *advertisement* (*ADV*) message issued by the sink which is the only tree member at the initialization stage. Upon receiving the *ADV* message, an orphan that has a *reliable link* joins the sink by sending a *join request (JREQ)* message. A sending node attaches a set of its neighbors with a reliable link in the *ADV* message or the *JREQ* message so that the receiver can determine whether it has a *B-reliable* link to the sender or not. Upon receiving *JREQ*, the member sends a *join response* (*JRES*) message and takes the orphan as its child if the corresponding link between them is *B-reliable*. When the orphan receives *JRES*, it takes the member as its parent. Another orphan who has overheard *JREQ* can take the same procedure to become a member if its corresponding link is *B-reliable*. If an orphan overhears *JREQs* from multiple members with *B-reliable* links, it pairs with a member that has the shortest distance to the sink. During the operation time, if a certain node detects the failure of the link to its parent, it tries to find one neighbor that can provide the *B-reliable* link and shortest distance to the sink and then joins that node by sending *JREQ*.

3.3 Data Transmission Model and Our Motivation

In the previous work [12], a sharable slot is allocated to each level of a tree, starting from the nodes at the highest level down to those at the lowest one, and then data transmission is performed progressively in the level-order fashion (as shown in Fig. 1). Accordingly, interference or contention is narrowed down to the nodes located at the same level. However, within a sharable slot, those nodes also have to compete against other sibling nodes for data transmission, thereby increasing latency and network overhead when traffic load goes high. To overcome this problem, in our approach, instead of using a big sharable slot, a small fixed slot is assigned to each node dedicatedly. The proposed approach is twofold. *First*, for the nodes belonging different sibling groups, a dedicated channel is allocated to each parent node to receive data from its children (which is done by the distributed channel allocation scheme presented in [9]). *Second*, for the nodes within the same sibling group, each node is assigned a number of dedicated slots proportional to its bandwidth demand.

Figure 3 illustrates the operation of the proposed approach. Two different sibling groups belonging to two different parent nodes (e.g. x and y) work on different channels (channel X and channel Y, respectively), therefore channel contention can be narrowed down to a group of sibling nodes having the same parent. It is obvious that the fewer sibling nodes in the level of the tree, the less competition in channel access.

Suppose that a node x has m children, thus it has a sibling group, represented as $S(x) = \{x_1, x_2, \ldots, x_m\}$. By using a scheduling algorithm, each node in $S(x)$ is assigned a number of distinct slots for data transmission based on their bandwidth requirements. Note that, since two sibling groups work on different channels, their scheduled slot time can be overlapped each other, thereby contributing to reducing latency significantly.

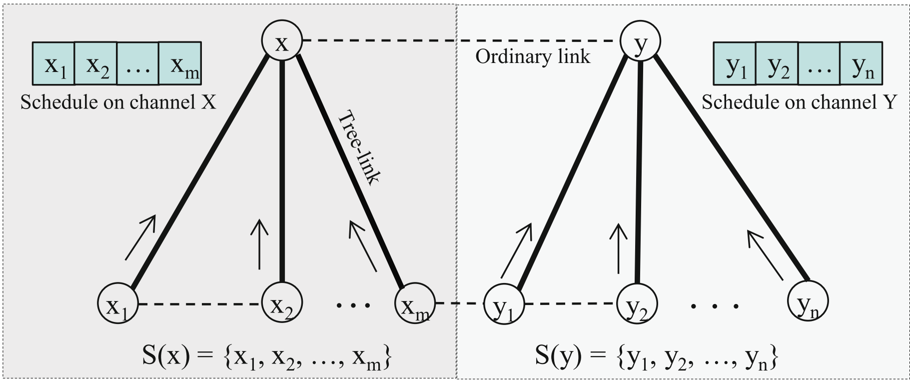

Fig. 3. Data transmission model.

3.4 Event-Driven Multimedia Data Acquisition

In this section, we describe the operation of the proposed approach for the acquisition of multimedia data in the bursty mode.

Initially, upon detecting an abnormal event in the monitoring field, the sink *S* starts the multimedia path setup phase by sending a special message, called a multimedia data request message (*MREQ*), to the specified multimedia node(s) in that area. When receiving *MREQ*, an intermediate node, if it found that the target multimedia node locates in its subtree, will forward *MREQ* toward the target *MN* node; otherwise, *MREQ* will be discarded. Then the process is continued until *MREG* reaches the target *MN* nodes. Upon receiving MREQ, an *MN* becomes active (called *AMN*) and then sends resource reservation request message (*RRREQ*) to the sink with the information of its bandwidth demand. The intermediate node located on the path from the *AMN* to the sink becomes the forwarding node and then forwards *RRREQ* to the upstream node until it reaches the sink. Upon receiving *RRREQ*, the sink responds to the resource request by broadcasting a resource reservation response (*RRRES*) message. Every node, except for the leaf nodes, needs to rebroadcast *RRRES*.

Note that *RRRES* contains the information of the slot schedule for every node locating on the multimedia transmission path. Therefore, upon receiving *RRRES* from the sink, the *AMN* starts sending its bursty data within the duration of the MDAP according to the assigned schedule. The intermediate nodes located on the path from the *AMN* to the sink need to forward those bursty data, whereas the others get into a sleep state to conserve bandwidth and energy. The structure of some messages used in the path setup phase is shown in Table 2.

Table 2. Multimedia path setup message structure

Path setup message	Description
$MREQ = (mIDs(s))$	*Multimedia data request message*
$RRREQ(i) = (\eta_i, S_i, R_i)$	*Resource reservation request message*
$RRRES(i) = (mIDs^A(i), MDAP)$	*Resource reservation response message*

During the multimedia path setup phase, based on each node's bandwidth demand, the sink produces a slot scheduling which defines the time that a node is allowed to work on. As shown in Eq. (1), bandwidth demand B_i of a node i consists of two parts: (i) *sending-bandwidth demand* S_i which corresponds to the number of necessary slots for sending all data packets in its subtree $T(i)$, and (ii) *receiving-bandwidth demand* R_i which corresponds to the number of required slots for collecting data from its children. Therefore, the bandwidth demand B_i can be presented as follows:

$$B_i = S_i + R_i \tag{1}$$

where S_i and R_i are determined by:

$$S_i = \sum\nolimits_{k \in T(i)} \eta_i \tag{2}$$

$$R_i = \begin{cases} \left(\sum\nolimits_{x \in C(i)} S_x\right) + max\{R_x \mid x \in C(i)\} & \text{where } C(i) \neq \emptyset \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

As discussed in Sect. 3.3, data transmission is performed according to the parent-children relationship in the tree. In fact, if two nodes have the same parent, they cannot send data at the same time because of the physical characteristic of a wireless transceiver. However, two distinct nodes can receive data from their children in parallel if no interference between two pairs of data transmissions. Therefore the receiving bandwidth demand of a node is determined as the sum of the sending-bandwidth demands of its children and the maximum of the receiving-bandwidth demand of its children as shown in Eq. (3).

Figure 4 shows an example of the multimedia path setup phase. The network topology consists of one sink S, five multimedia nodes (*nodes 1, 3, 4, 6* and *7*) and three ordinary nodes. Suppose that in this example, the sink S only needs to get multimedia data from *nodes 4, 6* and *7*.

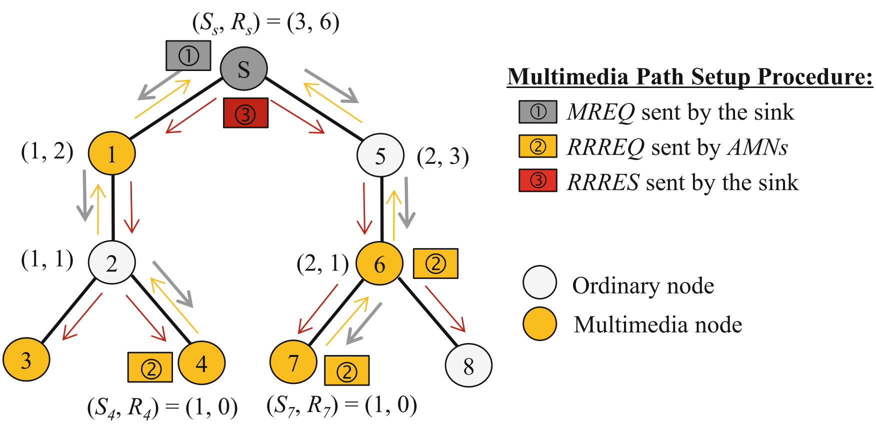

Fig. 4. An example of path setup procedure

Initially, the sink sends *MREQ* = {4, 6, 7} to notify that it wants to get data from nodes 4, 6, and 7. The intermediate nodes (1 and 5) forward *MREQ* toward its children until it reaches the destination. Upon receiving *MREQ*, nodes 4, 6 and 7 respond with *RRREQ* including the bandwidth demand for sending multimedia data. In this example, each *AMN* sends only one packet in each round.

In Fig. 4, node 7 sends *RRREQ* with $(S_{7,} R_7) = (1, 0)$ since it needs 01 slot for sending one data packet in each round, and no need slot for receiving since it has no children. Similarly, node 6 sends *RRREQ* with $(S_{6,} R_6) = (2, 1)$ since it needs to send two data packets (one is its own and the other is from its child) and receive one packet from its child (node 7). Finally, the sink needs totally 6 slots for receiving data from the network in each round of data collection.

4 Performance Evaluation

4.1 Simulation Setup

For performance evaluation, the proposed approach is compared with the slot demand-based path reservation (SDPR) approach [7], which has shown the good performance for bursty data transmission in WMSNs, by using the QualNet network simulator [13].

In the simulations, sensor nodes are static and randomly distributed in a square terrain of 100 × 100 (m^2). Since we consider the performance of bursty data acquisition, the performance metrics are evaluated based on that activity only. In each critical event, a burst of data has 100 data packets (each of 127 bytes) that are generated at a multimedia source node. A critical event is generated randomly in the network. Some key simulation parameters and values in the simulations are shown in Table 3.

Table 3. Simulation parameters

Parameter	Value
Default transmission power	−25 dBm (power level 3)
Sensor energy model	MicaZ
Path loss model	2-ray
Noise factor	10 dB
Slot size	6 ms
Dimensions	100 × 100 (m^2)
Simulation time	600 s
Number of nodes	1 sink; 25 sensor nodes
Data packet length	127 bytes
Bursty data load (each event)	100 packets

4.2 Simulation Results and Discussions

(1) Data Acquisition Time

In WMSNs, data readings from the monitored environment have to be reported to the sink or server within a specified time (*application deadline*). It means that the received data can be useless, even though it is received at the sink successfully. Therefore, in this paper, to evaluate whether a protocol can satisfy the requirement of the multimedia application, we use *data acquisition time* which is defined as the duration to send a burst of data packets from the multimedia source nodes to the sink.

Figure 5 compares the data acquisition time of the two protocols according to the variation of the number of AMNs which are requested to send multimedia data to the sink. We can see that two approaches have linearly increasing curves when increasing the number of AMNs. However, our proposed approach can achieve the better performance in term of data acquisition time and it can reduce the data acquisition time more than 30% compared with SDPR. Since the slot reuse technique is not used in SDPR, the transmission delay increases largely under the high traffic loads. However, our proposed approach allows two pairs of nodes to send data in parallel if they do not interfere with each other. Therefore, the data acquisition time is significantly reduced, thereby satisfying the tighter time constraint of multimedia applications.

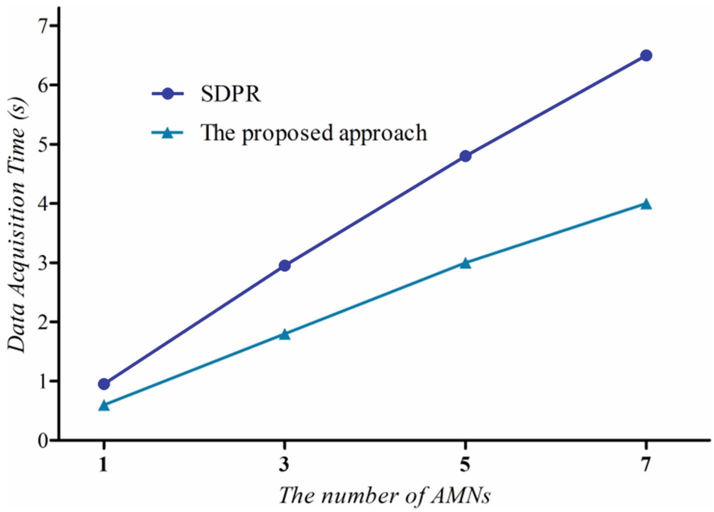

Fig. 5. Data acquisition time

(2) Energy Consumption

Energy is one of major concerns in WMSNs because of the difficulty in battery replacement, and therefore minimizing energy consumption of a sensor node is a main issue that needs to be considered [2]. A wireless transceiver of a node (e.g., CC2420 transceiver module in TelosB or Kmotes) usually consumes much more energy than the other components. Therefore, the operation of wireless transceiver should be controlled in an effective way to extend the network lifetime. For example, the radio should be in active state when processing data, and go to sleep state to conserve energy when having no data.

In this paper, we use *energy consumption* to evaluate how effectively a protocol spends energy in data transmission. Energy consumption can be calculated by measuring total energy consumed by all sensor nodes (except for the sink) and then dividing it by the total number of packets received at the sink.

Figure 6 shows the results of the two approaches in terms of energy consumption. We can see that the energy consumption in our proposed approach is much lower than the one in SDPR. Actually, to support for bursty data transmission, both approaches also reserve a path from the source of multimedia data to the sink. The other nodes which are outside of this path get into a sleep state to conserve energy. However, our approach can reduce the time to acquire multimedia data by allowing the concurrent data transmissions. As a result, the time of a node in active state is also reduced, thereby lowering the energy consumption significantly.

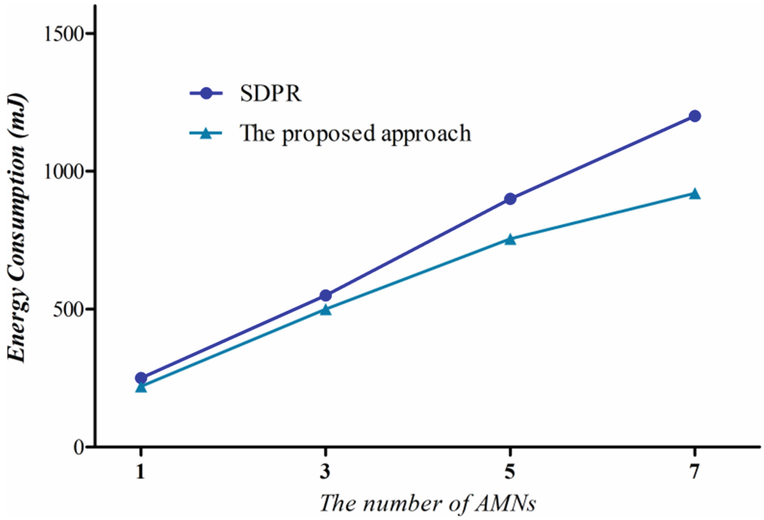

Fig. 6. Energy consumption per successfully received packet at the sink.

5 Concluding Remarks

In this paper, we propose an efficient approach for event-driven multimedia data acquisition in WMSNs that not only delivers bursty data reliably from the multimedia node to the sink, but also reduces bursty data acquisition time significantly by allowing the concurrent data transmission. Moreover, the network operation is fully controlled by the sink. The source node and the corresponding upstream nodes are assigned a number of slots enough for bursty data transmission while the others get into sleep state for saving energy. In this way, the source node can deliver bursty data packets to the sink successfully in a contention-free manner while satisfying the tighter time constraint of bursty data acquisition.

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