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Design and implementation of enhanced IEEE 802.15.4 for supporting multimedia service in Wireless Sensor Networks

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ABSTRACT

Recently, there has been a growing demand to incorporate multimedia content delivery over the Wireless Sensor Networks (WSNs). This feature could not only enhance several existing applications in the commercial, industrial, and medical domains, but could also spur an array of new applications. However, the efficient gathering of still images, audio, and video information in WSNs imposes stringent requirements on the throughput and energy consumption. Most wireless communication standards with high or moderate data throughputs do not focus primarily on energy efficiency. The IEEE 802.15.4 WPAN standard provides a widely accepted solution for low-cost and low-power wireless communication, with a potential to cater to many types of application scenarios. IEEE 802.15.4 MAC includes features such as its dual operational modes (Non-Beacon-enabled mode/Beacon-enabled mode), which make this standard more attractive for providing multimedia services over the networked sensors. Its Beacon-enabled mode can conserve energy by using the RF sleep mechanism, but it is limited by the lower data throughput. On the other hand, the Non-Beacon-enabled mode can offer higher data throughput but at the expense of significant energy consumption, mainly due to the idle listening problem. In order to overcome these issues, we propose an enhancement to IEEE 802.15.4, named *TEA-15.4*, which adaptively adjusts the active period based on traffic information. To detect data traffic in the network, the proposed scheme utilizes two techniques: Arbitrary Traffic Signal (ATS) and Traffic Time-Out (TTO). By utilizing these two techniques, the proposed TEA-15.4 can not only support enough data throughput to carry out multimedia communications, but also offer lower energy consumption for the sensing device in WSNs. For performance evaluations, we implement our proposed scheme and the IEEE 802.15.4 full-standard on the TinyOS. Based on the results gathered from testbed experiments and the TOSSIM simulator, TEA-15.4 is shown to be a suitable mechanism for Wireless Multimedia Sensor Networks (WMSNs).

1. Introduction

Many believe that Wireless Sensor Networks (WSNs) [1] are an indispensable part of the latest wave that will revolutionize the way we do computing today. WSNs will enable our transition from the notion of "personal computing" to a technology infrastructure that allows us to integrate computing into the environment, a concept coined as "pervasive and embedded computing" [2,3]. In this scenario, multimedia data with multiple modalities, such as still image, audio, and video, may be more influential than a large amount of conventional data observed and gathered from the physical environment. Consequently, the scope of its applicability and functionality goes beyond what traditional applications, such as habitat and

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healthcare monitoring, target tracking and military surveillance, and home automation and control, have to offer. With multimedia communication support, a new array of applications would be possible, where technology is envisioned to become more personal, for example the Healthcare Personal Area Network (PAN) [4]. Following the hallmarks of personal computing (i.e., inexpensive, small, and simple), a distinctive feature of such ad hoc wireless networks is the availability of limited power supply.

Applications that support multimedia communications would further exacerbate the situation, demanding lower latency and higher communication efficiency as well. Recently, there has been a growing need for research efforts to provide multimedia services over WSNs [4–6]. These survey papers have categorically argued for new techniques at each layer of the network protocol stack to cope with the foreseen challenges associated with the Wireless Multimedia Sensor Network (WMSN). In the context of contention-based channel access schemes, more emphasis was put on the needs for energy-aware and adaptive duty cycle calculations that could meet the foremost concerns of energy conservation without sacrificing data throughput and delay.

Most wireless communication standards with high or moderate data throughputs do not focus primarily on energy efficiency. However, the IEEE 802.15.4 Wireless Personal Area Network (WPAN) standard [7,8] provides support for low-cost and low-power wireless connectivity among resource limited devices. The IEEE 802.15.4 Physical (PHY) and Medium Access Control (MAC) specifications promise to cater to diverse performance requirements from a wide spectrum of applications [9,10,18,19]. The IEEE 802.15.4 MAC includes the features like low-duty cycle operation and self-organization for WPANs. These features make this standard more attractive for providing multimedia services over the networked sensors.

Akyildiz et al. [5] advocated for the suitability of a multi-tier, scalable network architecture consisting of heterogeneous elements for WMSNs. These heterogeneous elements provide an efficient cost-performance mix by employing less expensive and resource-constrained scalar sensors and high power superior elements such as image sensors. These elements send multimodal sensing data to a cluster head designated for performing resource intensive processing. This architecture is illustrated in Fig. 1.

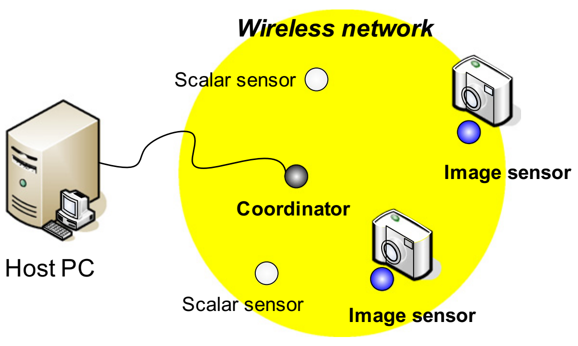

Fig. 1. A general Wireless Multimedia Sensor Network (WMSN) architecture.

For scalar sensors, conserving energy is critical because they generate data traffic at lower rates. The IEEE 802.15.4 MAC achieves low-duty cycle operation, termed the "Beacon-enabled mode," based on the RF sleep mechanism. On the other hand, image sensors demand higher data throughput in order to transmit the bulk of multimedia traffic. In this case, the Non-Beacon-enabled mode would be the preferred choice, since it operates without any sleep mechanism. Unfortunately, the operational mode is decided by the coordinator during the network initialization, forcing the IEEE 802.15.4 to support only one mode at a time. Consequently, this makes it difficult to meet both goals, i.e., the higher energy efficiency and data throughput in the original IEEE 802.15.4.

In this paper, we propose a novel scheme, named "Traffic and Energy Aware IEEE 802.15.4 (TEA-15.4)" to reduce energy consumption and improve data throughputs in the current IEEE 802.15.4 standard by utilizing data traffic information. In the proposed TEA-15.4, a coordinator can adaptively adjust the active period according to the data traffic information of the associated devices in the Beacon-enabled mode. When the data traffic load is low, the active period is decreased to reduce energy consumption caused by the idle listening [11,12]. On the other hand, for higher data traffic, the active period is extended close to that of the Non-Beacon-enabled mode to improve the data throughput. In order to detect the traffic information, TEA-15.4 employs two techniques. The first mechanism is based on Arbitrary Traffic Signal (ATS) and the second utilizes Traffic Time-Out (TTO). The ATS scheme is designed to detect an arbitrary traffic frame or its collision signal that indicates the existence of data traffic, whereas the TTO scheme utilizes a time-out mechanism to detect data traffic information of the associated devices. These two mechanisms are periodically performed during the sentinel duration, i.e., a special epoch for detecting the traffic information as decided by the coordinator.

The main contributions of our work are as follows: first, we have proposed a novel solution for improving IEEE 802.15.4 performance with the adaptive active duration via two data traffic indication schemes (that is, ATS and TTO). Second, we have designed and implemented a real sensor platform and its camera module for testbed experiments of the Wireless Multimedia Sensor Networks. Finally, for performance evaluations, we have implemented our proposed scheme, as well as the original IEEE 802.15.4 full-standard, into the TinyOS [28]. Moreover, we have designed and implemented a new wireless propagation model and RF physical stack for simulations in the TOSSIM [29].

The rest of the paper is organized as follows: in Section 2, we give a brief overview of the IEEE 802.15.4 standard and a summary of related works. In Section 3, our motivation is described with some experimental results on the IEEE 802.15.4 protocol stack, and our WMSN test-bed implementation details are introduced. Section 4 explains our enhanced TEA-15.4 protocol and its sub-schemes, which include the proposed traffic indication mechanisms in detail. Section 5 presents extensive performance evaluations of the proposed scheme and its comparison with the original IEEE 802.15.4 standard. Finally, we conclude the paper in Section 6.

2. Background and related works

2.1. A brief overview of the IEEE 802.15.4 standards

The IEEE 802.15.4 based network supports two operational modes: *Non-Beacon-enabled* and *Beacon-enabled* modes. In the Non-Beacon-enabled mode, the basic medium access mechanism is the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). A Clear Channel Assessment (CCA) is carried out before transmitting on the channel. If the channel is not clear, it waits for a random amount of time before the retransmission is tried. The communication among devices in this mode consumes more energy because of the lack of periodic listen/sleep coordination. In the Beacon-enabled mode, a coordinator (also called a PAN coordinator) is allowed to manage a superframe structure, bounded by beacon frames. Each beacon frame is sent by the coordinator at regular intervals. Such intervals are called *beacon intervals*, each of which consists of an active period and an optional inactive period, as shown in Fig. 2. The active period is also called the *superframe duration*, and is further divided into two parts: the Contention Access Period (CAP) and the Contention Free Period (CFP). The CAP uses the slotted CSMA/CA mechanism for channel access, whereas the CFP is the scheduled TDMA mechanism managed by the coordinator. Normal data traffic or control messages are transmitted during the CAP, whereas QoS-required traffic is exchanged during the CFP. Note that in order to simplify explanation of our proposed solution, we consider CAP traffic only.

All devices synchronize themselves with the superframe schedule of the coordinator and try to communicate based on the slotted CSMA/CA mechanism during the active period. In the inactive period, nodes are allowed to enter a sleep state to conserve energy. The length of the beacon interval (BI) and the superframe duration (SD) are defined as follows:

$$BI = aBaseSuperframeDuration \times 2^{BO} \quad (1)$$

$$SD = aBaseSuperframeDuration \times 2^{SO} \quad (2)$$

where *aBaseSuperframeDuration* is defined as the *base slot duration* (= 60*symbols*) multiplied by the *number of superframe slots* (= 16). Two parameters, the Beacon Order (BO) and the Superframe Order (SO), are determined by a coordinator and included in the beacon frame. Their ranges are defined as $0 \leqslant SO \leqslant BO \leqslant 15$, such that the value for SO should not be larger than the BO.

2.2. Related works

Studies on IEEE 802.15.4 can be largely categorized either as simulation-based or analytical modeling oriented.

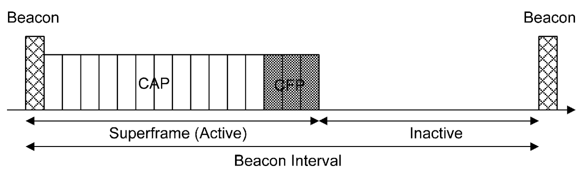

Fig. 2. Superframe structure in the IEEE 802.15.4 Beacon-enabled mode [7].

Those falling into the first category include [14–19]. Zheng and Lee [14] presented detailed simulation results covering several general features of the IEEE 802.15.4, including association, slotted/un-slotted CSMA behavior, and direct/indirect data transmission. In this comprehensive study, they discussed various performance and simulation parameters under a variety of different simulation scenarios. A similar study was carried out in [15], with a concentration on the Beacon-enabled mode in the star topology. Mario et al. [16,17] introduced the duty cycle adaptation schemes based on the communication frequency and traffic monitoring. The authors reported energy savings via a runtime adjustment of protocol parameters, namely BO (Beacon Order). Additionally, a number of papers have evaluated the 802.15.4 performance with respect to certain applications [18,19]. In these papers, the authors investigated its performance in the healthcare environment. The main focus was on the study of scalability and energy efficiency with different parameters related to the medical and the WBAN (Wireless Body Area Networks) contexts.

Works based on analytical modeling are described in [20–25]. Broadly, these papers investigated energy consumption, latency, and data throughput performance of the IEEE 802.15.4 with a number of conditions such as saturated or unsaturated networks and Beacon-enabled or Non-Beacon-enabled modes.

Related work also includes research efforts to support multimedia content delivery over the IEEE 802.15.4 based networks. Pekhteryev et al. [26] tested image transmission using a hardware-based implementation of the IEEE 802.15.4 standard. For the MAC protocol, they utilized a CSMA/CA based multiple access scheme. However, their work did not propose any enhancement to the standard in the context of the multimedia data transfer. Therefore, the issues regarding a tradeoff between energy efficiency and network throughput in WPAN have largely remained unexplored. More recently, Burda and Wietfeld [27] demonstrated the possibilities of sending voice messages using IEEE 802.15.4 networks. In this work, the CFP/Guaranteed Time Slots (GTS) structure in the Beacon-enabled mode was used to allow voice transmission over the network. The contention-free medium access by using GTS slots can offer the reserved bandwidth to some of the selected nodes. However, the scheme does not assure enough bandwidth to support streaming service because the number of GTS slots in the IEEE 802.15.4 is limited to a maximum of seven slots. Moreover, in order to cater to the latency issues due to the longer GTS return time, it should select a smaller BO value. Consequently, it has a drawback in terms of energy efficiency because the smaller BO value results in a shorter inactive period. To the best of our knowledge, none of the mentioned works specifically address the idle listening, data throughput, latency issues and the possible solutions in great depth to provide the multimedia communication over an IEEE 802.15.4 based WPAN.

3. Motivation via the real tests in IEEE 802.15.4 based WMSNs

As mentioned earlier, the two operational modes of the IEEE 802.15.4 have a tradeoff between energy consumption and data throughput. In this section, we will perform tests on the IEEE 802.15.4 based WMSN testbeds to discuss their drawbacks. Based on the results obtained, the need for new solutions is then emphasized and motivated.

3.1. The software stacks for the IEEE 802.15.4 implementation

In order to test the IEEE 802.15.4 standard, we implemented its full software stacks with 48 primitives on TinyOS [28]. TinyOS is the most popular operating system for Wireless Sensor Networks, and runs on various custom hardware platforms. Many protocols and systems have been implemented on TinyOS. However, the IEEE 802.15.4 protocol stack has not been implemented in TinyOS yet. Our implemented IEEE 802.15.4 stack can provide both Non-Beacon-enabled and Beacon-enabled modes. The following list shows our implemented interfaces for providing the IEEE 802.15.4 standard in the TinyOS:

- MCPS_SAP interface: To support the transport of network data units (NSDUs) to MAC sub-layer (5 primitives).
- MLME_SAP interface: To allow the transport of management commands between network and MLME (30 primitives).
- PD_SAP interface: To support the transport of MPDUs between peer MAC sub-layer entities (3 primitives).
- PLME_SAP interface: To allow the transport of management commands between MLME and PLME (10 primitives).

For the network and address assignment protocol, we developed the ZigBee tree network and its distributed address assignment scheme in our IEEE 802.15.4 codes. The implementation of the ZigBee network and IEEE 802.15.4 stacks is one of the important contributions in our work. However, in this paper, we focus more on the IEEE 802.15.4 stacks and their start topology.

3.2. Camera sensor embedded ZigbeX platform

For real tests of the IEEE 802.15.4 based WMSNs, we utilized a new smart sensor device called the ZigbeX [30]. ZigbeX is equipped with a low power microprocessor (Atmega 128 [31]) and a narrow-band RF device (CC2420 radio transceiver [32]), which can support physical-layer functionalities of the IEEE 802.15.4 standard. Based on this RF chip, we can make use of the ZigbeX platform as the IEEE 802.15.4 testbed. It is 40 mm × 70 mm in size and is powered by two 1.5 V AA batteries. To add additional hardware, the ZigbeX has a 50 pin connector which is directly connected to the Atmega 128 microprocessor. ZigbeX can be equipped with various optional sensor boards through this 50 pin connector. Fig. 3 shows the ZigbeX platform and its corresponding block diagram.

To enable image capture, we designed a new camera module based on the C328 chip [33]. This module was connected to the 50 pin connector of ZigbeX and controlled by the Atmega 128 microprocessor. The C328 camera module has a Serial Interface (UART) and the JPEG CODEC compression engine to provide low-cost and low-powered image captures. A user can select among seven different color types and four image sizes (80 × 640 ~ 640 × 480) through TinyOS programming.

The captured JPEG file by the camera module is fragmented into 64 bytes units, and these are sent to the ZigbeX's microprocessor (i.e., Atmega 128) through the UART interface. On receiving the fragmented JPEG frame, the ZigbeX attempts to transmit it to the coordinator using the IEEE 802.15.4 protocol stack and the CC2420 RF transceiver. After a successful transmission, the ZigbeX requests the next fragmented frame from the camera module.

Given the resource-constrained hardware, the sink node does not perform reassembly of the fragmented frames. Instead, it forwards the fragmented frames, received over the wireless medium, to the PC connected through the UART interface. The user can view the JPEG image using a simple application that runs on the PC, which performs reassembly of the fragmented frames. In order to view the image, captured by the camera module, we developed a new picture viewer program using the Window MFC API. The program reassembles the fragmented frames in order to make a single JPEG file, and displays the image. Fig. 4 shows the connection layout between the camera device and the coordinator.

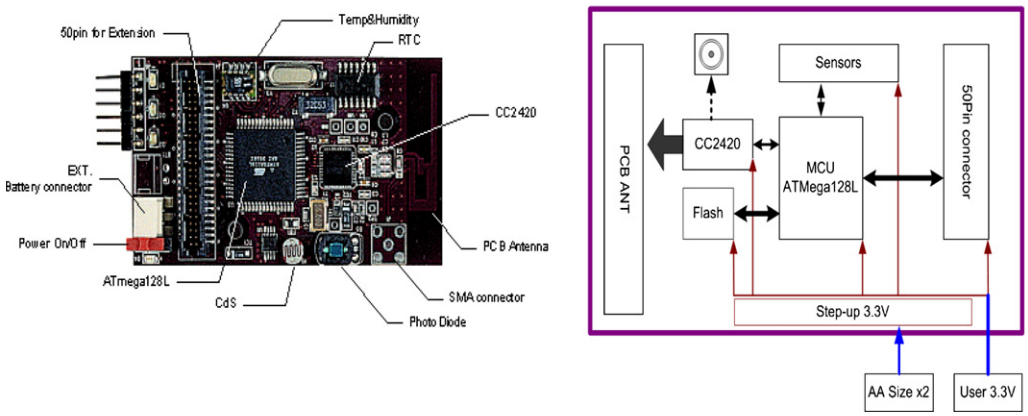

Fig. 3. The real sensor platform: ZigbeX.

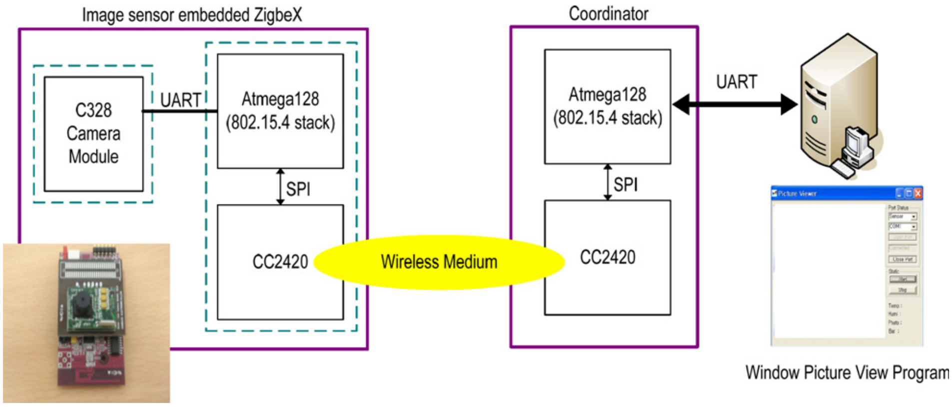

Fig. 4. Connection layout between the camera device and coordinator.

3.3. Experimental environments and results in the IEEE 802.15.4 based WMSNs

The following are the details regarding our testbed setup. It was used to carry out performance evaluation of the image and sensing services based on the IEEE 802.15.4.

- Six ZigbeX devices were deployed, in the star topology as shown in Fig. 5.
- One device was chosen as the coordinator (also, a sink) while the others acted as the associated general devices. Among the general devices, one device was equipped with the camera module (i.e., an image sensor) and other devices simply operated as the general sensing nodes (i.e., scalar sensors).
- The devices attempted to associate with the coordinator during the first 5 seconds.
- Each experiment lasted for 100 seconds, including the initialization and association time.
- Once an association was done, the device having a camera module attached tried to continuously transmit the fragmented image frame to the coordinator while other devices transmitted their sensing data every 10 seconds.
- We evaluated the number of transmitted JPEG files received and the energy consumption of four general sensor devices during 100 seconds, averaged over five test results.

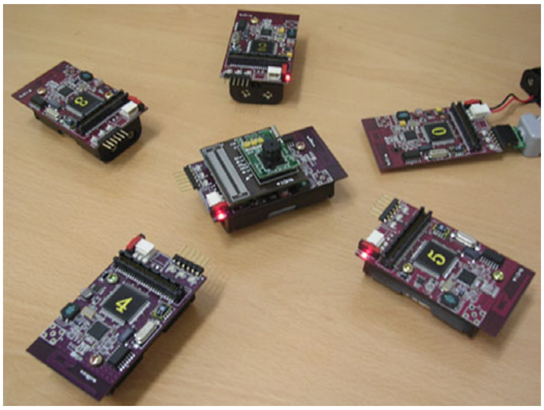

Fig. 5. Picture of the experimental testbeds.

The first set of experiments was performed for the IEEE 802.15.4 Non-Beacon-enabled mode. The BO (Beacon Order) value of the coordinator (nodeID 0) was set to 15 – this designated the network to operate in the Non-Beacon-enabled mode. In this mode, JPEG and sensing frames are transmitted without the sleep mechanism. Over 100 seconds, 64 JPEG files (averaged 15,480 bps) were successfully received at the coordinator and were reassembled by the picture viewer program. However, the energy consumed at the other four sensing devices was reported to be very high (nearly 5 W). The higher data throughput was achieved at a cost of significant energy consumption, mainly because of the idle listening by the sensing nodes.

Secondly, to evaluate the performance of the IEEE 802.15.4 Beacon-enabled mode, we set the BO and SO (Superframe Order) values of the coordinator to 8 and 5, respectively. Here, the BO value was chosen as the middle one in its possible range (0–15). Our selection of the middle value was based on an intuitive observation. Thus, too large values of the BO parameter could result in longer latency due to a longer beacon interval, whereas too small BO values could result in more frequently generated beacon packets. Therefore, we simply set the BO parameter to the middle value of 8. In our experimental testbed settings, another parameter SO was chosen to obtain approximately a 10% duty cycle. Note that the possible values of the SO are limited to those less than the BO value (i.e., $0 \leqslant SO \leqslant BO \leqslant 15$) for maintaining the inactive period in the beacon interval. Actually, the SO parameter dictates the active duration of the superframe structure, and thus the duty cycle. For example, the SO values of 3–7 (when the BO value is 8) can be interpreted as the duty cycles of 3.125%, 6.25%, 12.5%, 25%, and 50%, respectively. We set the SO value to 5 in order to yield a duty cycle close to 10%. This is based on the observation that most of existing energy efficient MAC protocols, such as S-MAC [12], were tested with the duty cycle set to 10%.

In the Beacon-enabled mode, devices try to transmit their frames in the superframe duration only, and go to sleep state during the inactive duration. Therefore, the four

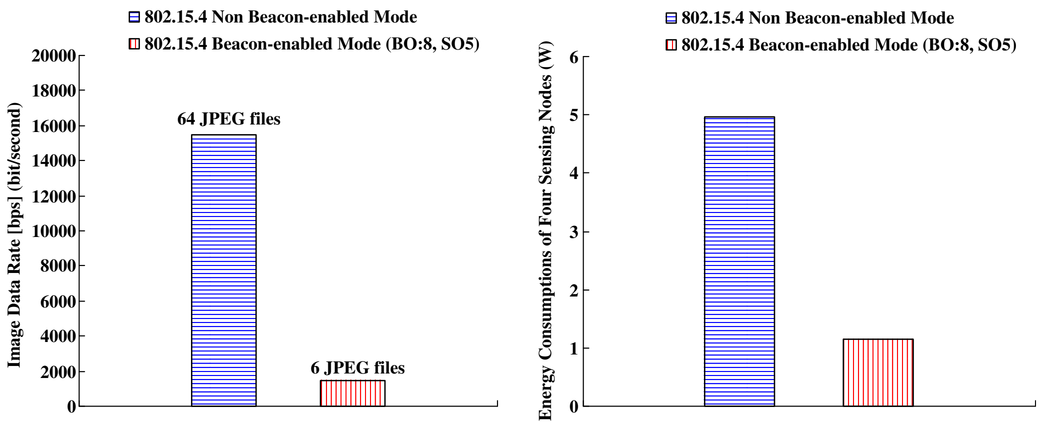

Fig. 6. Experimental results in 802.15.4 Non-Beacon-enabled and Beacon-enabled modes: *Image data rate, Number of received JPEG files, and Energy consumption.*

sensing devices in this mode consumed less energy than the Non-Beacon-enabled mode, but the number of JPEG files received was reduced because the active duration for transmitting fragmented JEPG frames is limited by the SO value. Since we set the BO and SO values to 8 and 5, respectively, the superframe duration was just 1/8 of a beacon interval. Moreover, periodic beacon transmissions also reduced the actual active duration for frame transmissions. Over 100 seconds, only six JPEG files (averaged 1440 bps) were successfully received by the coordinator. However, the energy consumed by the other four sensing devices was very low (nearly 1.1 W), as compared with the Non-Beacon-enabled mode. Fig. 6 shows the image data rate, number of received JPEG files, and energy consumption results in these two scenarios.

Based on the results given above, we can say that for general sensing devices with low data traffic, it is better to operate in the Beacon-enabled mode for the sake of reducing energy consumption. Conversely, for the camera device with high data traffic, it is better to operate in the Non-Beacon-enabled mode to provide more stable image transfer. Since the IEEE 802.15.4 mode is decided by the beacon frame generated by the coordinator, the network could only operate in either a Beacon-enabled or Non-Beacon-enabled mode. Therefore, it is hard to satisfy diverse performance requirements for applications with various data traffic types. These observations motivated us to study a new adaptive superframe duration mechanism based on the data traffic information, where we can satisfy both energy consumption and data throughput requirements to provide combined sensing and image data transmission over the IEEE 802.15.4 based WMSNs.

4. TEA-15.4: the enhanced version of IEEE 802.15.4 for multimedia services

To reduce energy consumption and improve data throughput, the proposed TEA-15.4 scheme adaptively adjusts the active period based on the data traffic information. In this section, we explain two techniques for detecting traffic presence, and then introduce how the active duration is adjusted in the IEEE 802.15.4 Beacon-enabled mode. In our description, we use the term *sentinel duration* to refer to a special epoch for detecting the traffic information.

4.1. The proposed traffic indication mechanisms for the TEA-15.4 protocol

In this subsection, we explain the two traffic indication techniques utilized in the proposed TEA-15.4 scheme in detail.

4.1.1. The Arbitrary Traffic Signal (ATS) scheme

In the IEEE 802.15.4 Beacon-enabled mode, nodes can transmit their data frames during the active period only. Therefore, any data frames generated during the inactive period remain stored in the queue buffer, and their transmissions are postponed until the next beacon interval. In the proposed ATS scheme, upon detecting the pending data traffic in its queue, a node tries to send an arbitrary data frame to its coordinator during the sentinel duration. Based on the received arbitrary data frame or signal, the coordinator can be informed of the existence of data traffic from the nodes. In scenarios where there are several nodes having pending traffic, more than one arbitrary data frame generated by these nodes may collide. This collision, however, may also signal the existence of data traffic information. The ATS scheme determines whether data traffic exists or not by checking the channel state (Idle or Busy) during the sentinel duration. The physical stack of the IEEE 802.15.4 standard provides the Clear Channel Assessment (CCA) function to check the channel states. The coordinator then adjusts its active period, based on the arbitrary data frame or its collision by referring to the CCA function. Fig. 7 shows the arbitrary traffic frame format. Our ATS scheme utilizes a general data frame format as the arbitrary traffic frame with a data payload of 0, making it compatible with the original IEEE 802.15.4 MAC.

We propose the following equation to calculate the sentinel duration, which is the special epoch for detecting the traffic information for the ATS scheme, by referring to the

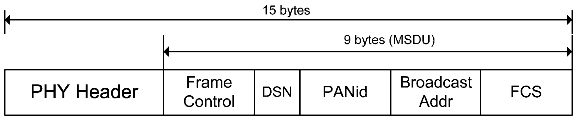

Fig. 7. Frame structure of arbitrary traffic frame.

values defined in the IEEE 802.15.4 standard. The sentinel duration (T_{ATS}) for ATS can be expressed as follows:

$$T_{ATS} = L_{ATS}/DataRate + T_g \quad (3)$$

where L_{ATS}, *DataRate* and T_g represent the length of an arbitrary data frame (= 15 bytes), data transmission symbol[1] rate, and guard time (to deal with the synchronization error), respectively. Since the *DataRate* is defined as 4 bits/symbol in the standard (2.4 GHz frequency band); $L_{ATS}/DataRate$ is calculated as 30 symbols. Considering the guard time of 10 symbols, we set T_{ATS} to 40 symbols. Given that the CCA detection time is eight symbols by the standard, the ATS scheme can check up to five CCAs during T_{ATS}.

The rationale behind using the ATS frame for traffic indication, instead of trying to send the pending frames, has two implications. First, the pending data frame uses the random backoff of CSMA/CA; thus devices need to wait longer in order to decide whether the data traffic exists or not. Conversely, the ATS frames are transmitted without backoff, making its sentinel duration shorter than that of the TTO scheme (as explained in the next section), where pending data frames are transmitted directly. Secondly, it is stated that the ATS scheme uses a general data format with zero payloads. This decision makes our scheme compatible with the original IEEE 802.15.4, without introducing any new control frame for traffic indication purposes.

Nodes having pending traffic check the first CCA function before transmitting their arbitrary traffic frame. If the first CCA is busy, they assume that some other node is currently transmitting a data frame from the previous sentinel duration, and therefore do not generate their arbitrary traffic frames to prevent collisions. Given that all the CCAs are detected as idle during the sentinel duration, the ATS concludes that there is no data traffic. On the other hand, if one of the CCA becomes busy from the arbitrary traffic frame or its collision, the ATS scheme decides otherwise. The proposed ATS will not be carried out during the GTS slots in order not to disturb the GTS data traffic.

4.1.2. The Traffic Time-Out (TTO) scheme

The second traffic indication technique utilizes the time-out mechanism, and therefore excludes any arbitrary traffic frame generation. At the start of sentinel duration, nodes having data traffic start to transmit their data frame based on the slotted CSMA/CA, similar to the original IEEE 802.15.4. In order to check for the existence of data traffic, the TTO scheme waits for the general packet frame's signal during the maximum contention period. This mechanism is inspired by the way TA timeout of T-MAC [13] works to shorten the active period with an adaptive timer. Thus, we have utilized the TTO to detect traffic in order to adjust

[1] Symbol means the time unit utilized in the IEEE 802.15.4 standard [7].

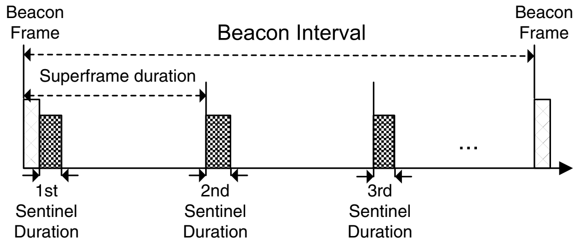

Fig. 8. Performing sentinel durations in a beacon interval.

the active duration of IEEE 802.15.4 for saving energy as well as improving data throughput. We propose the following equation to calculate the sentinel duration for the TTO scheme by referring to the values defined in the IEEE 802.15.4 standard. The sentinel duration (T_{TTO}) for TTO scheme can be calculated as

$$T_{TTO} = (2^{BE} - 1) \times aUintBackoffPeriod \quad (4)$$

where BE is the back-off exponent value (its maximum value is 5) utilized to define the contention window size, and *aUintBackoffPeriod* is defined as 20 symbols in the IEEE 802.15.4 standard; therefore, T_{TTO} is calculated as 620 symbols. As a transmitted packet should appear within the maximum 620 symbols, the TTO scheme can detect the existence of traffic information within this duration. If one of the CCA becomes busy during T_{TTO}, the TTO scheme decides that there is data traffic. However, if no data is generated during T_{TTO}, nodes decide that there is no traffic in this active period and enter into the sleep mode. Since the TTO scheme transmits no additional traffic indicator frames, it is consistent with the original IEEE 802.15.4 MAC without any conflict and control packet transmission overheads.

Since T_{TTO} is greater than that of T_{ATS}, nodes tend to remain in the active mode longer to detect traffic presence, resulting in energy consumption. Furthermore, in the lower data traffic scenarios, where fewer traffic indicator frames are generated, the ATS scheme is more efficient than the TTO scheme. However, the ATS's throughput may be slightly less than the TTO's, in the case of higher data traffic. The reason behind is that the ATS scheme utilizes the sentinel duration for transmitting arbitrary traffic frames, making the duration for transmitting general frames reduced. However, the performance gap between them is small compared to the original IEEE 802.15.4.

4.2. Adaptive active duration

Our TEA-15.4 utilizes the ATS and TTO techniques to detect the presence of any pending data traffic at devices. In the TEA-15.4, nodes having no data traffic to send are not required to continuously maintain an active state even when they are operating in their superframe duration. The sentinel duration is periodically performed with a length equivalent to the superframe duration in a single beacon interval, as shown in Fig. 8. In the proposed scheme, since the SO value is set to be smaller than the BO value, several occurrences of sentinel duration can be performed in one beacon interval.

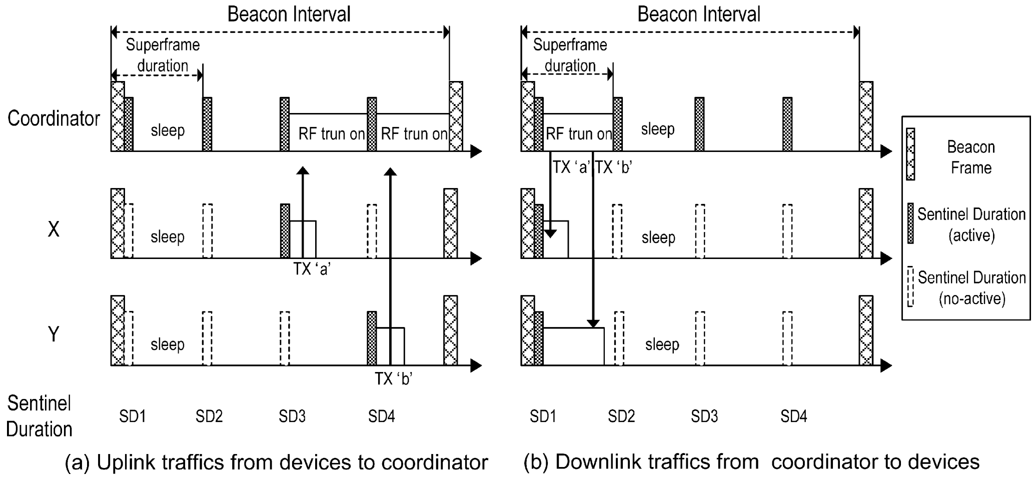

Fig. 9. Examples of the adaptive active duration in TEA-15.4.

At the start of the sentinel duration, if a node finds pending data traffic in its queue buffer, it tries to convey the traffic information to its coordinator by using either the ATS or TTO technique. Upon detecting traffic presence from nodes at some sentinel duration, the coordinator maintains an active RF state to receive the data frames until the next sentinel duration. If there is no data traffic at some sentinel duration, the coordinator and the nodes enter or continuously maintain the sleep state accordingly. Nodes can continuously carry out the sentinel duration so that the pending data traffic can be transmitted to the coordinator even after the superframe duration is over. In this way, data throughput can be increased and latency decreased during the high data traffic load. Fig. 9 shows operations of the adaptive active duration scheme in the TEA-15.4. In this example, we set the SO and BO values to 3 and 5, respectively.

First, we describe the uplink scenario (Fig. 9a). At the first sentinel duration (SD1), nodes check the pending data traffic. Since there is no data traffic at the nodes, they enter the sleep state. In this example, a new packet '*a*' is generated at node *X* in between SD2 and SD3. Therefore, node *X* wakes up at SD3 and sends its traffic information to its destination (i.e., the coordinator) using either ATS or TTO. At SD3, the coordinator is now aware of the traffic information of node *X*, so it continuously turns on its RF interface for receiving the data until the next sentinel duration. However, node *Y* (thus, an associated device) remains in the sleep state at SD3, because it is neither a coordinator nor has traffic to send. Similarly, when node *Y* has a new packet '*b*' in between SD3 and SD4, the traffic information is informed at SD4 and its transmission is performed after SD4. In this case, node *X* continuously maintains the sleep state because it has no data traffic.

Now, let us describe the downlink scenario shown in Fig. 9b. We assume that a coordinator has packets '*a*' and '*b*' for the nodes *X* and *Y*, respectively. At the start of the beacon interval, the coordinator inserts this traffic information into the beacon frame according to the IEEE 802.15.4 standard [7], and forwards it to the nodes. Upon receiving the beacon frame, nodes *X* and *Y* become aware of the fact that the coordinator has some pending traffic for them, so they prepare the data request command to receive data frame from the coordinator. Here, nodes *X* and *Y* should periodically carry out sentinel duration until they receive pending data traffic from the coordinator. At SD1, nodes *X* and *Y* try to transmit a data request command to the coordinator because downlink is the indirect transmission [7]. The coordinator can transmit its packets '*a*' and '*b*' to nodes *X* and *Y* in between SD1 and SD2 after receiving the data request command. At the start of SD2, both nodes *X* and *Y* maintain their sleep state because they have already received pending traffic from the coordinator. If the new data packet is generated by some node, its transmission proceeds in a similar fashion to that illustrated in Fig. 9a. Based on this adaptive active duration of TEA-15.4, image sensors can transmit the multimedia traffic during a total beacon interval, and scalar sensors can continuously maintain sleep state except for transmission of the sensing data traffic.

5. Performance evaluation

5.1. An experimental study using real sensor platforms

In order to evaluate our proposed TEA-15.4 scheme, we implemented it on the TinyOS and tested it with the experimental setup as explained in Section 3.3. We utilized the TTO traffic indication scheme for the real testbed evaluation. The performance of the ATS scheme was evaluated by a simulation study (Section 5.2).

The hardware limitation of real sensor platforms (i.e., CPU clock and processing power) may cause imperfect time synchronization even among local/one-hop neighboring sensor nodes. Therefore, the utilization of a slow-clock microprocessor requires some guard time to avoid beacon interval or sentinel duration miss in star topologies. As our experimental study suggests, the guard time of 4 ms is long enough to resolve the above problem for both IEEE 802.15.4 and our scheme. When the Beacon-Enabled mode or our proposed scheme is applied to multi-hop network

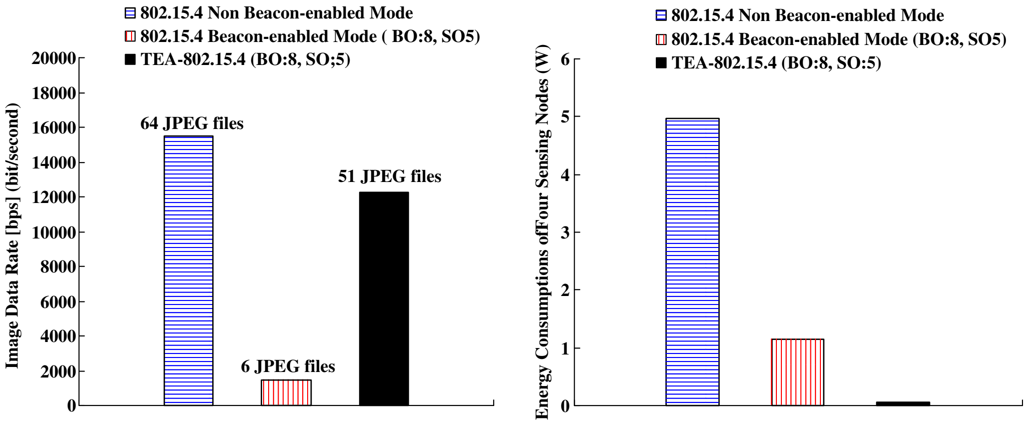

Fig. 10. Experimental results in the TEA-15.4 and 802.15.4 Non-Beacon-enabled/Beacon-enabled modes: *Image data rate, Number of received JPEG files, and Energy consumption*.

topologies, they should be combined with some beacon scheduling mechanisms [37,38] for the global time synchronization among multi-hop nodes. We will consider applying our schemes to the multi-hop network scenarios in future works.

5.1.1. Experimental results with image transfer in the TEA-15.4 based WMSNs

As explained in Section 3.3, we set the BO and SO values of the coordinator to 8 and 5, respectively. The sentinel duration is periodically repeated as the unit of superframe duration in the Beacon-enabled mode. Fig. 10 shows the results of image data rate, number of received JPEG files, and energy consumption in the TEA-15.4 based WMSNs. Over 100 s, 52 JPEG files (12240 bps) successfully arrived at the coordinator. The number of JPEG files is smaller than in the Non-Beacon-enabled mode because of periodic beacon transmission, synchronization problems, and delay to perform sentinel durations. However, in terms of energy consumption, our protocol shows the best performance because a general device maintains its active status only when new traffic is generated. Based on the experimental results (Fig. 10), the proposed TEA-15.4 can conserve the significant amount of energy while maintaining a sufficiently high throughput.

5.1.2. Experimental results with simple streaming transfer in the TEA-15.4 based WMSNs

To evaluate the streaming services over the proposed TEA-15.4 based networks, we built a simple streaming application that continuously generates data packets of the largest possible size permitted in the standard.[2] The testing topology and environments are the same as described in the previous subsection (except that the image sensor node is now replaced by the streaming application). For this reason, the energy consumption of four ordinary nodes are comparable to that of previous testing results; however, the data rates (bps) observed by the sensor node with a streaming application are changed. Fig. 11 shows

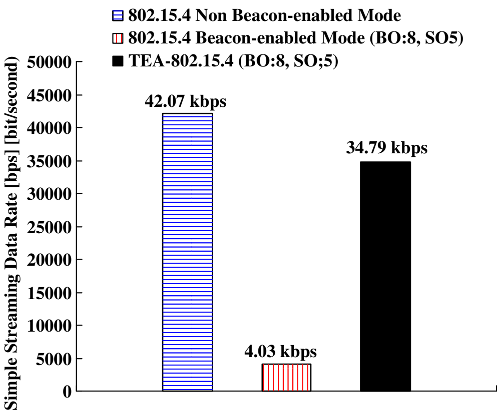

Fig. 11. Experimental results in the proposed TEA-15.4 scheme and the IEEE 802.15.4 Non-Beacon-enabled/Beacon-enabled modes: *Streaming data rate* (bps).

the data rate of three protocols at the coordinator that receives data from the sensor with the streaming application, averaged over five test runs. The graph for the TEA-15.4 shows that it achieves an average of 34.79 kbps. Therefore, we conclude that our scheme can also support the low voice coding standards such as G.729a (with 8 kbps) and ARM (with 4.75–12.2 kbps).

5.2. A simulation study using TOSSIM

5.2.1. Simulation environments

We evaluate the performance of the TEA-15.4 protocol and compare it with the IEEE 802.15.4 Non-Beacon-enabled mode and Beacon-enabled mode by using TOSSIM [29]. TOSSIM is a widely used sensor network simulator for TinyOS sensor networks. One of the merits of TOSSIM is that the whole system and network source codes of TinyOS for the real sensor platforms can be directly utilized in the virtual simulation. Therefore, users can easily test and debug their applications, routing, and MAC protocols on the assumption that numerous sensor nodes are deployed.

Unfortunately, IEEE 802.15.4 cannot be directly simulated and tested on the current version of TOSSIM because

[2] IEEE 802.15.4's maximum packet size is defined as 127 bytes: MAC header (25 bytes), NWK header (8 bytes) and DATA payload (94 bytes).

its RF physical stack is based on the old RF transceiver model (i.e., CC1000 [34]). To overcome this limitation, we implemented the new RF physical stack [35] in TOSSIM, referred to as the CC2420 RF chip [32], which includes the IEEE 802.15.4 physical characteristics. Our physical stack can not only transmit data at 250 kbps, but also can detect CCA (Clear Channel Assessment), RSSI (Receive Signal Strength Indicator), and LQI (Link Quality Indication) based on the two-ray ground pass loss model [36]. Moreover, a user can change the transmission power from 0 dBm to −25 dBm and select radio channels from 11 to 26. Based on the new RF physical stack, we can now utilize the modified version of TOSSIM as the performance evaluation tool for our proposed scheme.

In our simulation model, we evaluated the performance of our scheme in the star topology. One device was chosen as the coordinator while the other devices acted as the associated image sensor or scalar sensor. The data frame size was set to 64 bytes. The total simulation time was 400 s, and the energy consumption model used 13.5 mW, 24.75 mW, and 15 uW in receiving, transmitting, and sleep, respectively, as given in [12]. We assume that all nodes are already associated with the coordinator and that all data traffic is generated in 350 s. The scalar sensor nodes sense and transmit their sensing data every 10 s, similar to the implementation scenario, and the image sensor's traffic is generated every 0.1 s. The 0.1 s traffic generation times show enough performance to simulate camera traffic during the simulations. The BO value for Beacon-enabled mode and our schemes was set as 8. We simulated four protocols (i.e., 802.15.4 Non-Beacon-enabled mode, 802.15.4 Beacon-enabled mode, TEA-15.4 with the ATS, TEA-15.4 with the TTO), by varying three simulation parameters: (1) number of camera devices, (2) the SO values, and (3) the number of nodes. The metrics used for our simulation study were as follows:

- *Aggregate Throughput*, defined as the sum of received data frame bytes at the coordinator during simulation time.
- *Delivery Ratio*, defined as the ratio of the number of arrived packets and generated packets during simulation time.
- *Average Latency*, computed as the average delay incurred when the packet travels from the device to the coordinator.

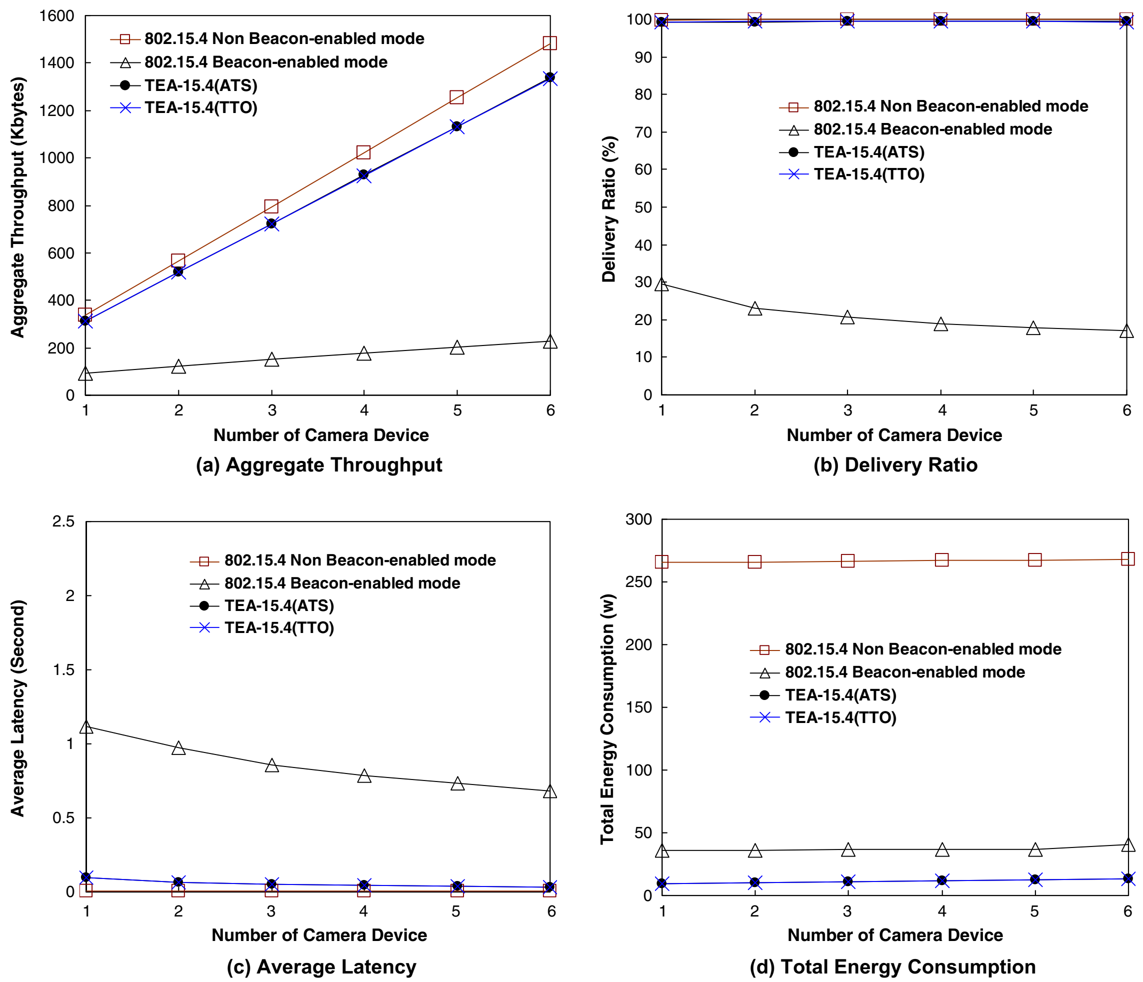

Fig. 12. Results for various numbers of image sensors with SO = 5, BO = 8 and nodes = 50.

- *Total Energy Consumption*, defined as the energy consumed by all the devices, including image sensors and scalar sensors, during the simulation time.

5.2.2. Simulation results

For the first set of results, we have simulated four protocols with a various number of image sensors (from 1 to 6). In these simulations, the number of nodes was set to 50 and the values for the SO and BO were 5 and 8, respectively.

Fig. 12 plots the values for different performance matrices as the function of number of image sensors. In terms of the aggregate throughput, which is shown in Fig. 12a, even though the 802.15.4 Non-Beacon-enabled mode gives the best result, our ATS and TTO based TEA-15.4 schemes performed equally well. The performance gap between them seems to be caused by the transmission of beacon frames and the delay to check traffic information for the sentinel duration. However, the 802.15.4 Beacon-enabled mode gives a very low throughput because of its fixed active duration. Therefore, in terms of data throughput, the IEEE 802.15.4 Beacon-enabled mode is not likely suitable for carrying multimedia over sensor networks.

This throughput result leads to better performance of the 802.15.4 Non-Beacon-enabled mode, and our schemes in terms of delivery ratio as well (Fig. 12b). However, the high data traffic by image sensors limits the 802.15.4 Beacon-enabled mode from transmitting the total generated traffic within the superframe duration. The data remains queued in the buffers until the end of the simulation time or is dropped due to the buffer overflow, resulting in a lower delivery ratio. On the other hand, since the IEEE 802.15.4 Non-Beacon-enabled mode and proposed schemes are capable of processing much more data transmissions than the Beacon-enabled mode, their delivery ratios are higher than those of the Beacon-enabled mode. For the given simulation scenario, both the ATS and TTO schemes maintain nearly 100% delivery ratio.

Fig. 12c shows the average latency of four different protocols. The IEEE 802.15.4 Non-Beacon-enabled mode shows the best result in this metric, as well. As expected, our TEA-15.4 can transmit data frames with a lower latency than the 802.15.4 Beacon-enabled mode because

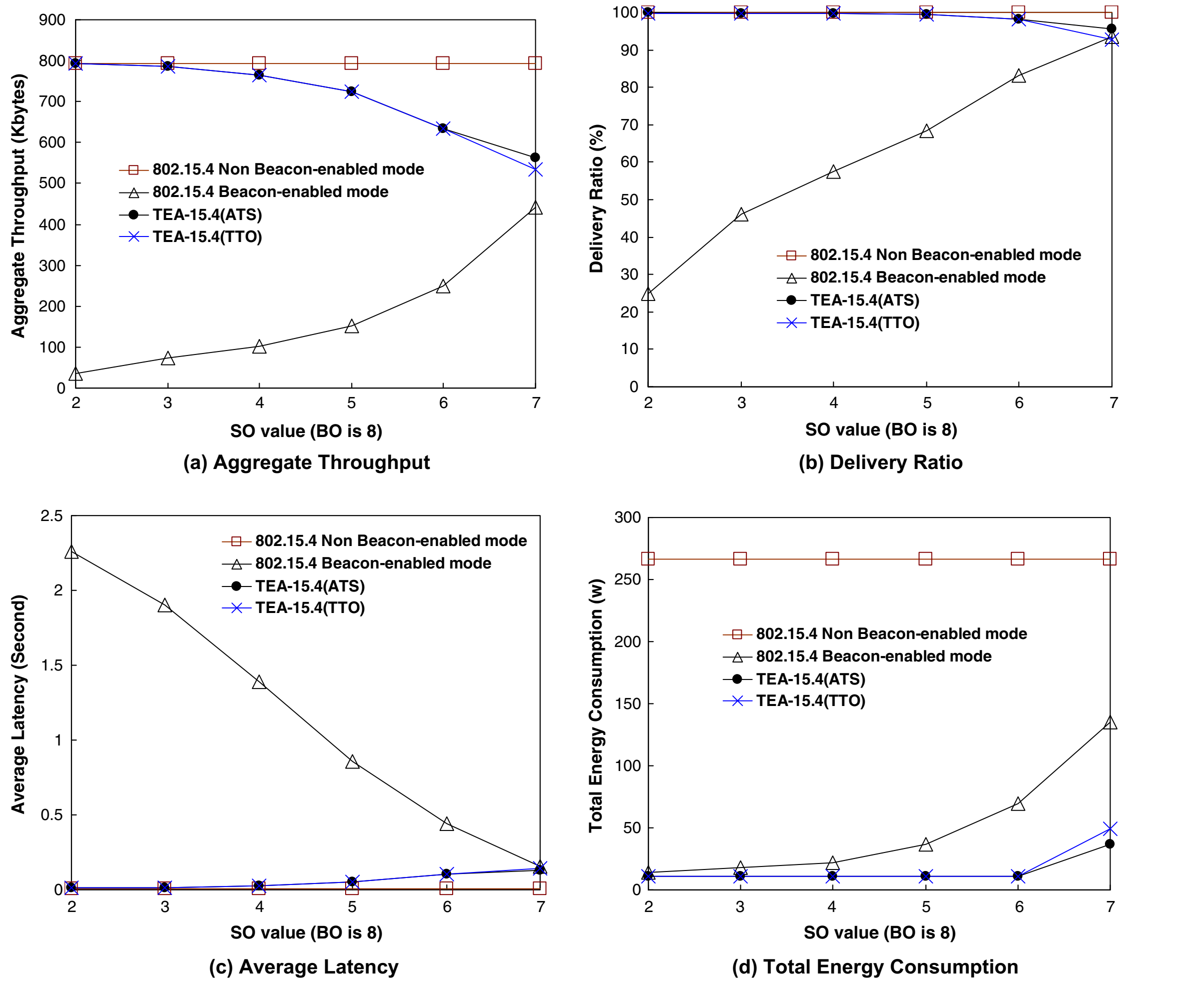

Fig. 13. Results for various SO values with BO = 8, scalar sensors = 50, and image sensors = 3.

our schemes check data traffic information during every sentinel interval. This shows that our proposed schemes are appropriate for delivery/delay sensitive applications.

Fig. 12d shows the total energy consumption of the four protocols. Our proposed schemes can reduce the idle listening problem by adjusting the active duration. Therefore, the scalar sensor nodes having low data traffic can save energy in the proposed TEA-15.4 while other protocols' nodes should maintain an active RF state always or in the full superframe duration. In particular, the Non-Beacon-enabled mode's energy consumption is very high because it has no sleep mechanism. Referring to Fig. 12a and d, we can observe that the proposed schemes not only provide better data throughput but also consume less energy. Therefore, our proposed scheme is a suitable protocol for the WMSNs.

For the second set of simulation results, we varied the values for SO from 2 to 7. The SO values significantly influenced the throughput and energy consumption in our schemes because the period of sentinel duration is set based on the superframe duration. In this simulation, the BO value, the number of scalar sensor nodes, and the number of image sensor nodes are fixed as 8, 50, and 3, respectively.

Fig. 13 shows the performance results with various SO values. Since the 802.15.4 Non-Beacon-enabled mode is not influenced by the BO, its performance is same for all the SO values. In the 802.15.4 Beacon-enabled mode, its active duration increases as the value for SO increases. Therefore, as the SO value approaches the BO value, the Beacon-enabled mode consequently performs similar to the Non-Beacon mode. As shown in Fig. 13a–d, the Beacon-enabled mode's performance in terms of aggregate throughput, delivery ratio, average latency, and total energy consumption approaches that of the Non-Beacon-enabled mode as the SO value grows. In TEA-15.4, as the value for SO increases, the interval of sentinel duration increases as well because we have set the sentinel interval duration to the superframe duration. In our scheme, a node checks for the data traffic during each sentinel duration, but it is possible that the nodes lose, the sentinel interval, or some data is generated right after the sentinel interval is

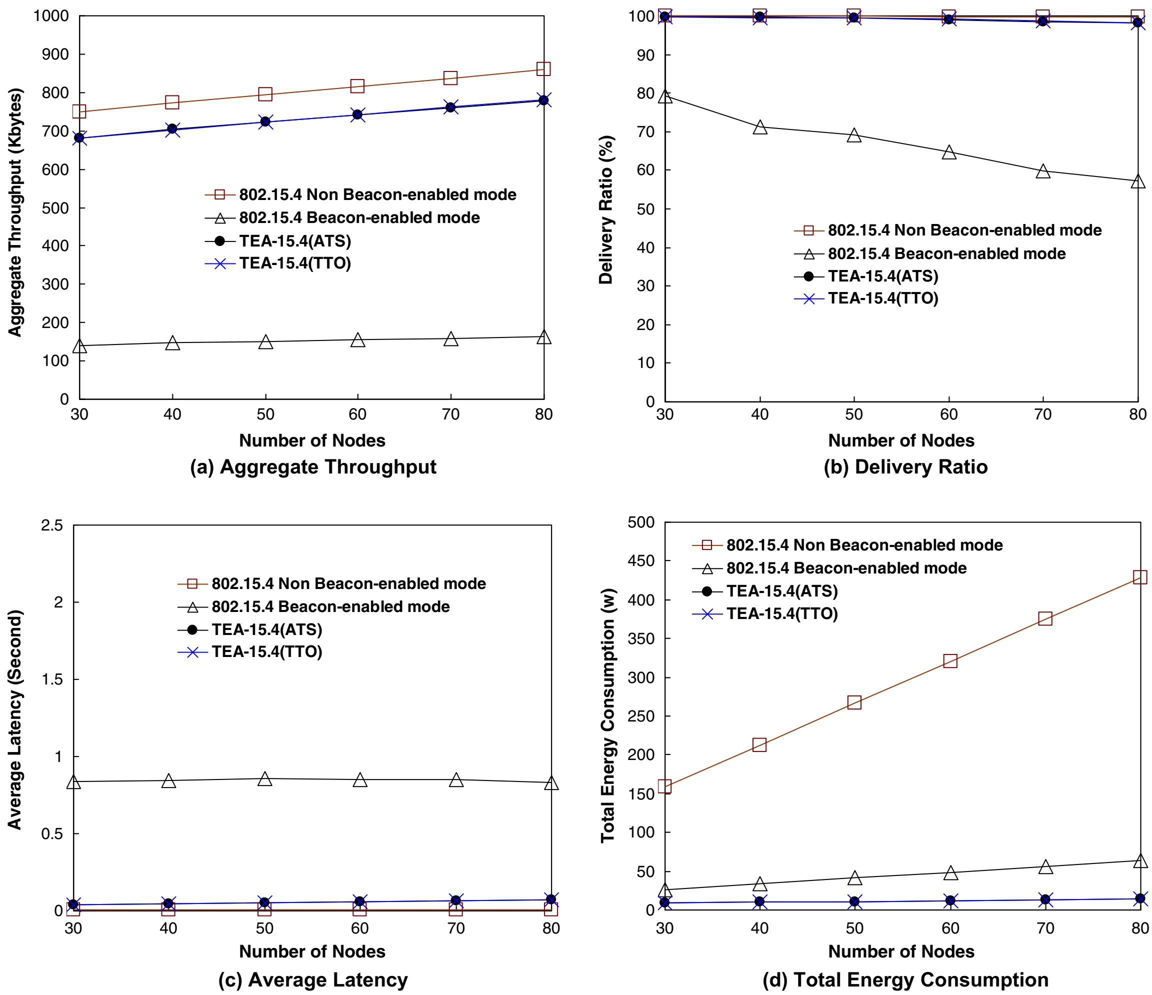

Fig. 14. Results for various network sizes with SO = 5, BO = 8, and image sensors = 3.

over. In this case, the nodes should wait until the next sentinel duration to transmit data traffic. Therefore, the performance of the proposed TEA-15.4 scheme (also in terms of the aggregate throughput, delivery ratio, average latency, and total energy consumption) degrades slightly as the value for SO increases, mainly because its sentinel duration is also extended. The graphs in Fig. 13 show that our TEA-15.4 with the ATS/TTO schemes has very good performance when the SO values are less than 5.

For the final set of simulation results, we varied the number of nodes from 30 to 80. In these simulations, since the number of image sensors is fixed at three, the number of scalar sensors is varied. Therefore, this scenario is similar to simulating the original wireless sensor network, which is influenced by conventional sensing data traffic. The values for SO and BO are 5 and 8, respectively.

Fig. 14 shows the performance results with various numbers of nodes. As the number of nodes increase, the conventional sensing data traffic also increases. In terms of the aggregate throughput, delivery ratio, and average latency, as shown in Fig. 14a–c, our proposed schemes continuously perform better than the IEEE 802.15.4 Beacon-enabled mode. Furthermore, its performance is quite comparable with another counterpart, the IEEE 802.15.4 Non-Beacon-enabled mode. At the same time, our TEA-15.4 scheme is shown to consume less energy than the other protocols because of its adaptive active duration, as shown in Fig. 14d. Again, based on these simulation results, we argue that our scheme is a suitable protocol for both multimedia and conventional WSNs.

6. Conclusions

Over the years, the IEEE 802.15.4 standard has made a reputation as a prominent technology, with the potential to cater to many types of application scenarios. Moreover, advancements in image technology encourages combining image data with conventional sensing data to leverage existing Wireless Sensor Networking applications. However, multimedia communication over resource-constrained networked sensors imposes a new set of challenges, where higher data throughput with lower latency is demanded without compromising energy efficiency.

In this paper, we have proposed an enhancement to IEEE 802.15.4, named "TEA-15.4 (Traffic and Energy Aware IEEE 802.15.4)", to provide multimedia communications in WSNs. The proposed scheme adaptively adjusts the active duration in the Beacon-enabled mode based on the data traffic information. This information is conveyed to the PAN coordinator during a special epoch, *sentinel duration*, via two traffic indication mechanisms, the ATS (Arbitrary Traffic Signal) and the TTO (Traffic Time-out). We implement our proposed scheme and the IEEE 802.15.4 full-standard on the TinyOS. Based on the results, gathered from real testbed experiments using the ZigbeX sensor platforms and comprehensive simulations using the TOSSIM simulator, we show that the proposed TEA-15.4 scheme is capable of achieving significantly higher energy conservation than the original IEEE 802.15.4 protocol, while providing sufficient data throughput to transport multimedia data such as images and streaming. Our experiments also demonstrate the suitability of our work to handle both multimedia and conventional WSNs. The theoretical analysis of capacities, stability, and fairness will be the focus of important future work.

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