XY-MAC: a Short Preamble MAC with Sharpened Pause for Wireless Sensor Networks

Abstract—**Short preamble MAC protocols such as X-MAC use a series of consecutive short preamble packets with pauses between them which refer to as a strobed preamble. This allows the target receiver to send an ACK packet during those pauses to stop the preamble transmission. In this way, the average length of transmitted preamble is reduced, thus such protocols achieve lower latency of each hop and more energy saving. With pauses longer than the transmission of an ACK packet, the sampling period at receivers is increased significantly in strobed preamble protocols, which makes it suboptimal of energy efficiency in light traffic load networks. In this paper, the XY-MAC proposes a technique called early termination to sharpen the size of those pauses. With sharpened pauses, the sampling period at receivers can be set very short to acquire a high level of energy efficiency. A set of experiments has been held to compare with X-MAC. The results show that the duty cycle can be reduced to 30% to 50% of X-MAC under various traffic loads. The lower traffic loads are, the better XY-MAC performs.**

Index Terms—**Wireless Sensor Networks, Medium Access Control, Energy Efficiency, Sharpened Pause**

I. Introduction

Wireless sensor networks often consist of quantities of sensor nodes deployed in a large area for information collection. Sensor nodes are interconnected via wireless in an ad-hoc way. Sensor nodes are mostly battery powered in wireless sensor networks. The battery power is very limited due to the small size of sensor nodes. Also it will be very difficult to charge or replace batteries for such a large amount of sensor nodes. So the main challenge of Wireless sensor networks is how to establish a reliable network under strict energy constraints.

In most scenarios of wireless sensor network applications, sensor nodes in Wireless sensor networks generate low traffic load, thus the channel is expected to be idle most of time. So idle listening is the most significant energy consumption under such circumstances [1]. Nodes drain out their batteries by continuously listening on the idle channel waiting for potential data frames. To reduce idle listening, a mechanism called duty cycling has been proposed. In duty cycling MAC protocol, sensor nodes periodically switch their radio between sleeping state and active state. A lower duty cycle can substantially reduce the energy consumption of wireless sensor networks.

In duty cycling MAC protocols, sensor nodes only wake up for a small active period and sleep most of time to mitigate idle listening. In order to guarantee packet transmission under low duty cycles, there are two typical approaches for sensor nodes to wake up on time for the upcoming packet. The first approach is synchronized which is adopted by SMAC [4], TMAC [5], etc. In these protocols, sensor nodes self-organized into several adjacent virtual clusters. Nodes within the same cluster keep a common active period to wake up concurrently to communicate with each other. However, to maintain synchronization of each cluster in a distributed way, extra overheads have been introduced. The second approach is asynchronous, which is usually refer to as preamble sampling. This mechanism is used in protocols such as BMAC [6]. If a data packet has been generated, the transmitter will send a preamble prior to the transmission of the data packet to wakeup the target receiver for the upcoming transmission. The length of the preamble should be longer than the period of the duty cycle of the target receiver to ensure that it can be awakened. Receivers sample the channel at each active period, and stay in receiving state if the transmission of the preamble is detected to receive the following data packets.

Although preamble sampling protocols are energy efficient under low traffic load by keeping a very low duty cycle without the requirement of synchronization overheads. The long preamble introduced by these protocols consumes extra energy. The transmitter keeps transmitting the whole preamble even if the target receiver has already been waked up. And the receivers have to receive half of the preamble in average. Short preamble MAC protocols such as MFP (Micro Frame Protocol) [3] and X-MAC [2] have been proposed to solve such problems. These short preamble MAC protocols employ a series of small packets, which are refer to as short preamble, to replace the continuous long preamble. Each short preamble packet usually carries an indicator of the upcoming data packets, such as the target receiver's address. In this way, reception of long preamble and unwanted data packets is avoided. Thus they save substantial energy compared to typical preamble sampling protocols.

In some short preamble MAC protocols such as MFP, the short preamble packets are transmitted continuously. Receivers simply switch its radio off after a successful reception of a short preamble and switch its radio on at the beginning of the data packet transmission according to the sequence number in the short preamble. So a full-length preamble will always be transmitted and all the receivers in one-hop range of the transmitter will be woken up. This makes it suboptimal in terms of energy efficiency. Another kind of short preamble MAC protocols such as X-MAC employs a strobed preamble which inserts pauses between consecutive short preamble packets. This allows the target receiver to send an ACK packet to stop the transmission of the remaining short preamble packets. In this way, the average preamble length has been reduced to approximate half of the period of the duty cycle of the target receiver. Thus such a mechanism reduces the number of unnecessary woken up receivers and latency of each data packet transmission. However, the sampling period at receivers should be longer than those pauses to correctly detect any ongoing transmission. Thus the performance of these protocols depends to a high grade on the length of those pauses.

In this paper, we propose XY-MAC, to eliminate the requirement of long sampling period introduced by the strobed preamble. The main idea of XY-MAC is to terminate those pauses at an early time by performing an ACK detection following by transmission of each short preamble. The result of the ACK detection will determine whether transmitter should stay in receiving state for the reception of an ACK packet or switch to transmitting state for the transmission of remaining short preamble packets. This can reduce the required sampling period at receivers greatly. Furthermore, we present two ways to detect the ACK packet: CCA (Clear Channel Assessment), which is a prompt way; Sync Word Detection, which is more reliable but extends the time spent on detecting the ACK packet. In broadcast communications, receivers of XY-MAC simply receive the short preamble packets without sending an ACK packet to ensure all receivers in the transmitter's range can be woken up by the strobed preamble. In this way, XY-MAC can simply adapt to broadcast communications with a countdown sequence number in short preamble packets without further modifications at the transmitter.

The rest of the paper is organized as follows. We discuss the related work in Section II. Section III presents the design of XY-MAC protocol. We describe the implementation of XY-MAC and give some measurements in Section IV. The performance of XY-MAC is evaluated through a set of experiments in Section V. Section VI concludes the paper.

II. RELATED WORK

Duty cycling MAC protocols can be divided into two categories: synchronized approaches which maintain a common active/sleep period and asynchronous approaches which are refer to as preamble sampling. [1] The preamble sampling protocols can be further classified as typical preamble sampling protocols and short preamble protocols. The representative protocols are discussed as below.

SMAC [4] is a milestone in this area. It provides a low duty cycle without requirement of precise synchronization of sensor networks. The basic idea of SMAC is that nodes concurrently wake up to communicate with each other in a virtual cluster with a loose synchronization. Nodes in a virtual cluster keep a common active/sleep schedule, while border nodes keep both virtual clusters' active/sleep schedule. The main drawback of SMAC is that the duty cycle is predefined and constant, which reduces the energy efficiency under variable traffic load.

TMAC [5] is an improvement of SMAC, whose main idea is to adaptively change the length of active period by enabling nodes to turn off their radio during active period when no further traffic is expected. In this way, TMAC is traffic adaptive and more energy efficient especially under low traffic load. A problem called early sleep is introduced by TMAC, as it partially breaks the synchronizations in a virtual cluster. This problem increases latency in multi-hop network.

The main energy waste of MAC protocols which maintain a common active/sleep period is the overheads introduced by synchronization. And the performance of these protocols is poor in low traffic case, since most nodes wake up without receiving any valuable packet but wasting a lot of energy on synchronization overheads. Therefore, Preamble sampling MAC protocols have been proposed for networks with low traffic loads.

BMAC [6] is a typical preamble sampling protocol which requires none synchronization effort among sensor nodes. All sensor nodes in BMAC have independent active/sleep schedules. A preamble larger than the sleeping period of receivers is transmitted prior to data packets. Sensor nodes sample the channel during the active period, and return to sleep if the channel is sensed idle. Once the channel is asserted as busy, nodes will stay in receiving state for the upcoming data packet. Such a mechanism called preamble sampling significantly reduces the energy consumption by eliminating overheads of synchronization and is energy efficient under low traffic load. The main disadvantage of BMAC is that a full length preamble should always be transmitted, all receivers in range will be woken up and receive the remaining preamble half of total length in average.

WiseMAC [7] is another typical preamble sampling protocol, which eliminates the transmission of a full length preamble by memorizing the active/sleep schedule of neighboring nodes. In this way, WiseMAC can reduce the number of irrelative woken up receivers and the average length of received preamble at each receiver. However, in WiseMAC, receivers still have to receive the remaining preamble. Also, there is no performance improvement in broadcast communications.

There are two main problems of typical preamble sampling protocols. One is that receivers will not know whether the data packet is worth receiving until the whole data packet has been received. The other is the reception of the useless long remaining preamble. These two problems degrade the energy efficiency of typical preamble sampling MAC protocols. In this case, short preamble MAC protocols have been proposed to solve such problems.

Micro Frame Protocol [3] is a short preamble MAC protocol, which uses a series of short preamble packets to replace a continuous long preamble. Each short preamble packet contains a sequence number field to indicate when the data will be transmitted. The short preamble packet also contains an indicator of the data packet such as destination address. When a short preamble packet is successfully received by a receiver, the receiver can make a decision from the indicator whether the oncoming data packet is worth receiving. Although MFP reduces the average received preamble length and eliminates the unnecessary reception of the data packet. A full length preamble is still need to be transmitted and all the receivers in the transmitter's radio range will be woken up. This consumes extra energy and leads to larger latency.

X-MAC [2] is another kind of short preamble MAC protocol, which uses a strobed preamble by inserting short pauses between preamble packets. These short pauses enable the target receiver to send an early ACK to stop the transmission of remaining short preamble packets. In this way, X-MAC achieves more energy saving and reduces the latency at each hop by reducing the average preamble length. The main deficiency of X-MAC is that the short pauses are not "short" enough indeed. Since those pauses in X-MAC are designed long enough to receive an entire ACK packet. Sampling period at receivers, which should be longer than the pauses, is increased. This degrades the energy efficiency of X-MAC, especially under light traffic load networks. [1]

III. DESIGN OF XY-MAC

The ultimate goal of XY-MAC is to reduce the sampling period at receivers to achieve more energy efficiency. Although the use of a strobed preamble reduces the average length of transmitted preambles for lower latency and energy efficiency, it increases the sampling period at receivers to an intolerable length by inserting pauses between short preamble packets. XY-MAC aims at sharpening the length of those pauses to acquire an acceptable sampling period at receivers. With such a motivation, a mechanism called early termination is presented.

A. Early Termination

With a purpose of receiving an ACK packet from the target receiver, the original length of pauses in current short preamble protocols is designed larger than the duration of an ACK packet reception. In fact, only one ACK packet from the target receiver is expected for each unicast communication. So there is no contention for the transmission of the ACK packet, and the target receiver could send an ACK packet to inform the transmitter immediately after a successful reception of a short preamble packet. The ACK packet should be sent even if the target receiver does not intend to receive the data packets. Therefore, most of these pauses are just a waste of time and energy without receiving anything but noise. Through above analysis, we can see that the length of those pauses may be reduced with some proper mechanisms.

In XY-MAC, in order to sharpen those pauses, the transmitter performs an ACK detection following each short preamble transmission when it enters the listening period. The ACK detection does not need to receive the whole ACK packet, but to sample the channel or check the reception of a packet sync word, to determine whether an ACK packet is transmitted (Methods for ACK detection will be discussed later). If the ACK detection returns a negative result, the transmitter terminates the listening period immediately and switches its radio to transmitting state for the transmission of the remaining short preamble packets. This mechanism is called early termination. On the other hand, a positive result of the ACK detection indicates that the target receiver has successfully received a short preamble packet and is transmitting an ACK packet back to the transmitter. In this case, the transmitter should stay in receiving mode to adapt its listening period long enough to guarantee the reception of the ACK packet.

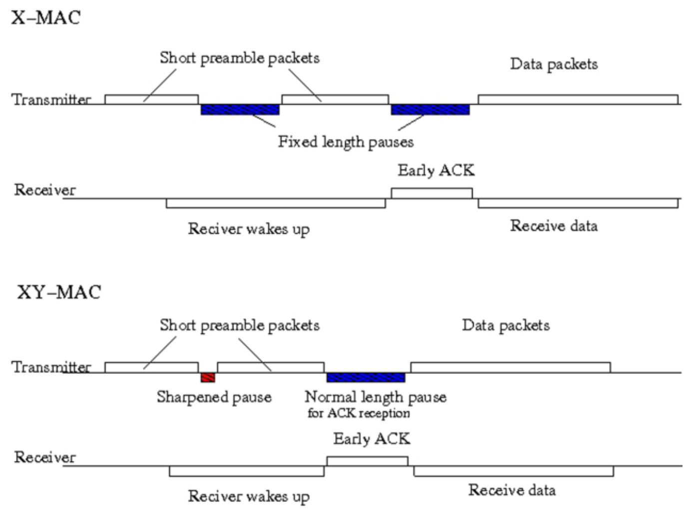

Fig. 1. Mechanism of XY-MAC compared with XMAC.

Fig. 1 illustrates how XY-MAC works with early termination compared to X-MAC with fixed length pauses. With these sharpened pauses, XY-MAC efficiently reduces the required length of sampling period at receivers. Thus it achieves more energy efficiency, especially under low traffic load.

B. Approaches of ACK Detection

There could be many approaches for ACK detection, in XY-MAC, two main approaches are employed: CCA (Clear Channel Assessment) and Sync Word Detection.

CCA is the major approach to detect the channel status, busy or idle. The thresholding based CCA is a poor technique as it may lead to many false positives, which let the transmitter's radio keep on receiving state until timeout. If the target receiver wakes up at this very moment, it may miss the current transmission. The CCA based on outlier detection proposed in BMAC [6] improves the performance by distinguishing valid packets from noise when none outlier is found, as the probability for a valid packet to have outliers is extremely low.

The sync word detection approach can be easily used on radio transceivers that have a function to detect packet sync word such as CC2500 [8]. A packet transmission will be asserted when a sync word of the packet is received. In this way, the transmission of an ACK packet can be detected at an early time of the transmission. So in sync word detection, the transmitter waits for a certain interval, which is related to preamble quality threshold and sync word qualifier in CC2500, and check whether the packet transmission is asserted to detect the ACK packet. Furthermore, the length of pauses between short preamble packets can be automatically adapted by the hardware while using this sync word detection. When a packet transmission is asserted during the ACK detection, the transmitter should stay in receiving state until the packet transmission is de-asserted, which indicates the end of the packet in common case. In case the address check fails during the reception of the packet, the packet transmission will also be de-asserted to stop the listening period of the transmitter. The transmitter catches out the failure at receiving the ACK packets and continues to transmit the following short preamble packets. This reduces the cost of false positives.

From above, we can see that ACK detection based on sync word detection is more reliable than based on CCA. But the interval of sync word detection, which should be longer than the transmission time of preamble bits (typical 4 bytes) and sync word (typically 2 bytes), slightly increases the length of pauses between short preamble packets.

C. Adapting to Broadcast

Short preamble protocols using a strobed preamble are more energy efficient for unicast communications, since it do not need a full-length preamble that wakes up all receivers in range. But in case of broadcast communications, when a full-length preamble should always be performed, short preamble protocols such as MFP save more energy by eliminating redundant reception of broadcast packets. To achieve better performance in broadcast communications, XY-MAC adds a sequence number field in short preamble packets for broadcast packet transmissions. Unlike MFP, the sequence number is countdown to indicate the number of remaining short preamble packets. In this way, even if neighboring receivers have different duty cycles, each receiver can learn the time when data packets will be transmitted from this sequence number. Once successfully receiving a short preamble packet, receivers simply turn off their radio and return to sleep instead of sending an ACK packet to transmitter to ensure all receivers in transmission range can be woken up. Receivers that intend to receive the broadcast packet will wake up again at the estimated start time of data packet transmission. A broadcast packet is acknowledged when the former transmitter receives a short preamble packet of the same broadcast packet from receivers.

TABLE I
CURRENT CONSUMPTION OF EACH STATE

State	Typical Current Consumption	Measured Current Consumption
Radio Sleep (with WOR)	Approximate 10uA	N/A
Radio Receive (at sensitivity limit)	17.3mA	17.6mA
Radio Receive (above sensitivity limit)	14.9mA	14.5mA
Radio Transmit (at -12dBm output power)	11.1mA	11.7mA
MCU Active	3mA	2.9mA
MCU Sleep	1 uA	N/A

Typical Current Consumption are given in CC2500 [8] and MSP430 [9] datasheets.

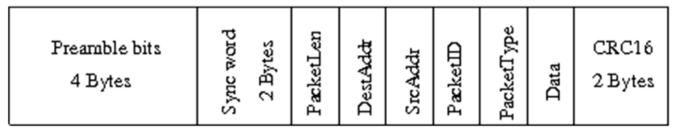

Fig. 2. Frame structure of XY-MAC packets.

IV. IMPLEMENTATION

A. Hardware Platform

To evaluate the performance of XY-MAC, we have implemented the protocol on wireless sensor nodes with an mcu of TI MSP430, and a CC2500 radio. The CC2500 operates in 2.4GHz ISM and SRD frequency band, with a configurable data rate up to 500 kBaud.

B. System Parameters

The current consumption of CC2500 in different state is shown in Table I. We use an oscilloscope to measure the voltage drop of a 17 Ohm resistor on the power supply cable to get the current consumption. We use 2-FSK with a bit rate of 20 kbps. The output power is configured as -12dB. A sleeping period of 500 ms is chosen for all receiving nodes and the max preamble length is 1.2 times to sleeping period to ensure the target receiver can be successfully woken up. We choose the CCA approach for ACK detection, thus the time spent on ACK detection is approximate 1.5 ms, while a sampling period of 2 ms is adopted at receivers.

We also implement X-MAC as a comparison protocol. The fixed length of pauses of X-MAC is set to 10 ms, while the sampling period at receivers is set to 12 ms accordingly.

C. Frame Structure

The frame structure of short preamble packets and ACK packets are is shown in Fig. 2. Preamble bits and Sync word are inserted by hardware automatically, and can be configured through registers. There are three types of packets in current implementation: Short preamble packet, ACK packet, and Data packet. The length of data field varies for different packet types. Broadcast is not supported in current implementation.

The total length of a short preamble packet is 14 bytes, which is the same as an ACK packet. Under a bit rate of 20 kbps, the transmission time of these two kinds of packets are both 5.6 ms.

D. Current Consumption

The current consumption measured by oscilloscope through the voltage drop of a 17 Ohm resistor is shown in fig. 3 to fig.6. The current over time reflects the state switching of the radio transceiver. Therefore, we can see exactly how the protocol works through this intuitive way. Fig. 3 and Fig. 4 illustrate the transmission of short preamble packets of X-MAC and XY-MAC separately. In Fig. 3, each low current level indicates the transmitting period of a single short preamble packet. While each high current level indicates that the radio transceiver is in receiving state and performing ACK detection with input at sensitivity limit. The mcu sleeps during the transmitting period and keeps reading the RSSI register on radio transceiver during the ACK detecting period. In Fig. 4, we can see that the radio transceiver is left in receiving state for 10 ms to receive the ACK packet from the target receiver. The mcu is in sleeping state in both transmitting and receiving period, while only wakes up at the end of receiving period to set up the next transmission of a short preamble packet. By comparing these two figures, we can see that the length of pauses between short preamble packets is sharpened greatly by XY-MAC using the early termination mechanism.

Fig. 5 shows a successful reception of an ACK packet from the target receiver. After transmission of a short preamble packet, the radio transceiver is switched to receiving state to perform an ACK detection. The channel is idle at first, after a very short interval while the receiver is processing the short preamble packet and generating an ACK packet, the target receiver begins to transmit an ACK packet to the transmitter, and the channel is busy then. We can capture this procedure from the variation of current consumption, since the current consumption of the radio transceiver is different in receiving state with input at sensitivity limit from well above sensitivity limit. After a successful reception of an ACK packet from the target receiver, the transmitter stops the transmission of remaining short preamble packets. In order to present the transmission of the ACK packet more clearly, the following data packet transmission has been omitted in the source code temporarily. So the transmitter and the receiver just switch off their radio and enter sleeping state after the ACK transmission. Fig. 6 shows an active period of a sensor node when the channel is clear, the sampling period of XY-MAC is approximate 2 ms, which greatly reduces the duty cycle to an acceptable level. Note that due to hardware limitation, the wake up time before entering receiving state is about 1.5ms. Also we perform a synthesizer calibration at the end of each active period, which takes approximate 700 us. So, in total, the active period is about 5 ms.

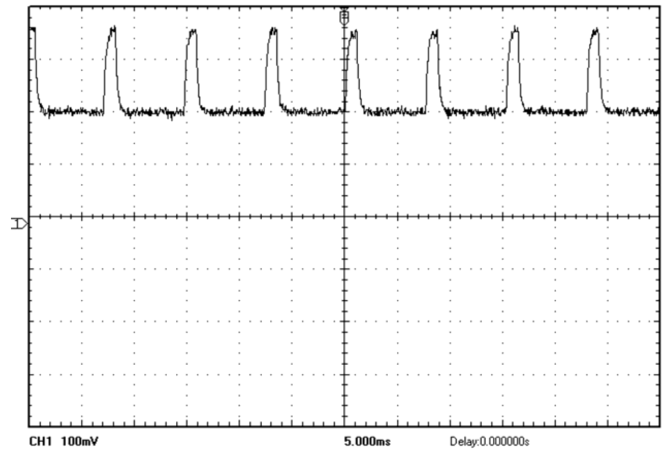

Fig. 3. Transmission of short preamble packets in XY-MAC

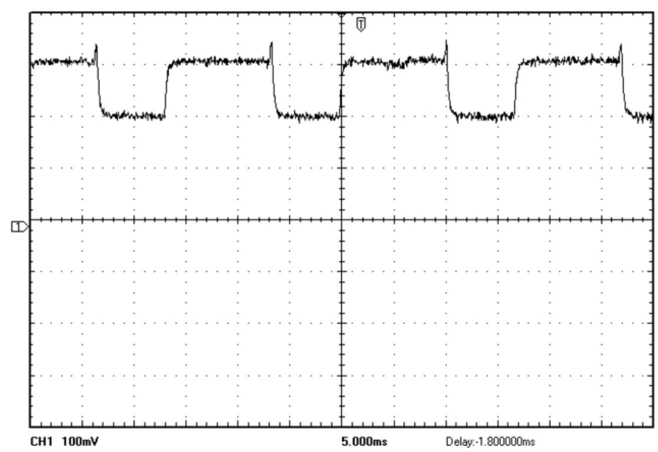

Fig. 4. Transmission of short preamble packets in X-MAC

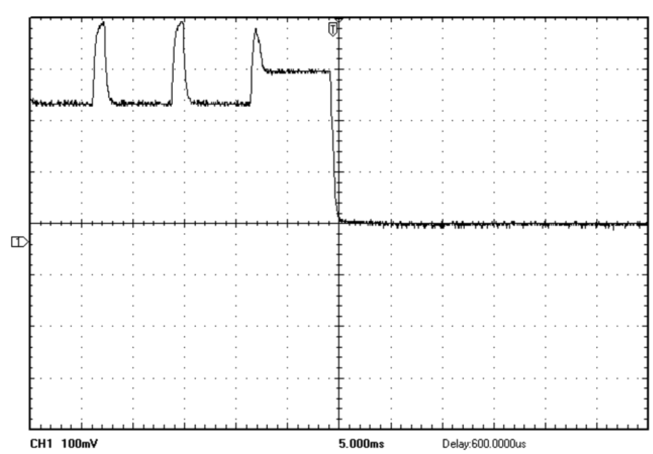

Fig. 5. The transmitter terminates the remaining transmission of short preamble packets when an ACK packet from the target receiver is successfully received.

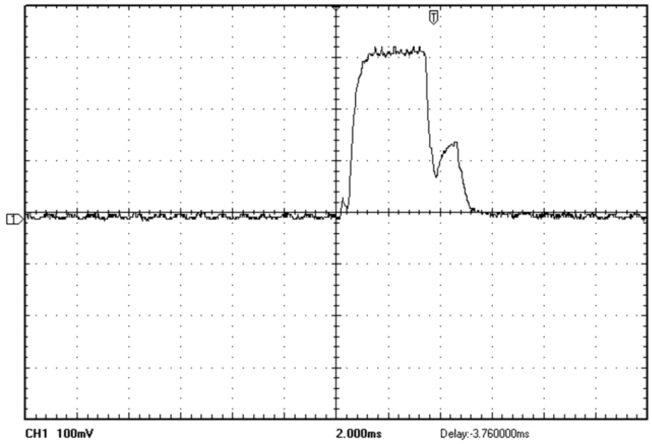

Fig. 6. Sampling period at receivers

V. Experimentation and Evaluation

A. Experimentation Settings

A set of experiments are carried out on a star topology network containing seven receivers and a unique transmitter. The packet interval at the transmitter varies from 1 second to 10 seconds. The destination address of data packets periodically varies from receiver 0 to receiver 6.

B. Duty Cycle under Various Traffic Loads

We show that the duty cycle changes under various traffic loads of XY-MAC and X-MAC separately in this experiment. We can draw from Fig. 7 that the duty cycle of XY-MAC is reduced to about 30% to 50% of the duty cycle of X-MAC under the same traffic load. The duty cycle of X-MAC under a packet interval of 1 second is 4.74%, while in XY-MAC, the duty cycle reduces to 2.77% with the same packet interval at the transmitter. Duty cycles of X-MAC and XY-MAC are 3.21% and 1.21% when packets are generated every 10 seconds, respectively. The duty cycle of XY-MAC is almost in the range of 1% to 2%, this leads to substantially energy saving at sensor nodes.

C. Duty cycles under low traffic loads

Fig. 8 illustrates the ratio of duty cycles of these two protocols. From this figure, we can clearly see that the ratio declines when lighter traffic loads are adopted. This indicates that under low traffic loads, XY-MAC outperforms X-MAC in terms of energy efficiency by reducing the duty cycle to a very low level. With a packet interval of 10 seconds, the average duty cycle of XY-MAC is only 37.81% of that of X-MAC. This means that the lifetime of receivers of XY-MAC will be about three times longer than those of X-MAC under such traffic load.

We can see from the result of the experiment that, with the early termination mechanism, the duty cycle of short preamble MAC protocols using strobed preamble can acquire very low duty cycle, even in lightly loaded networks.

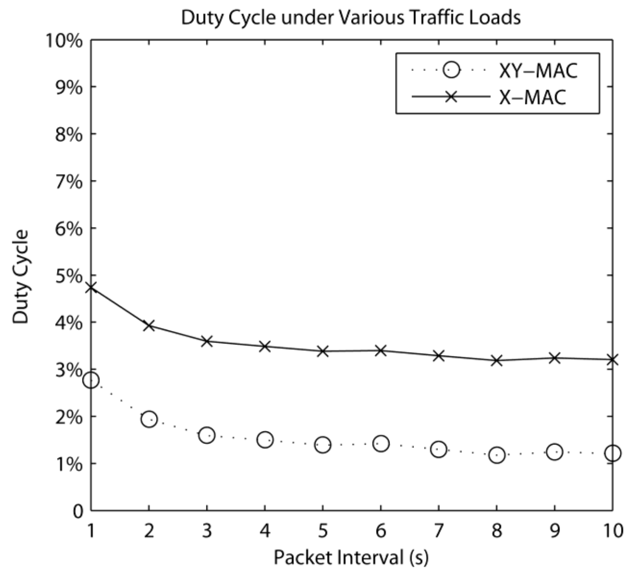

Fig. 7. Compare duty cycle of XY-MAC with X-MAC under various traffic loads.

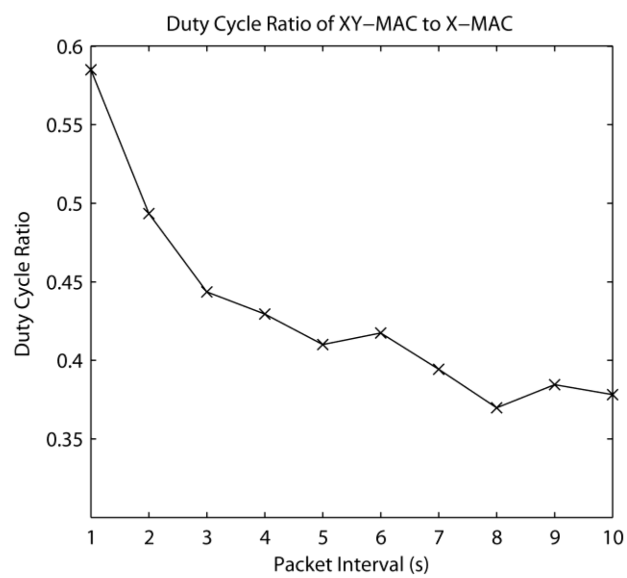

Fig. 8. Duty cycle ratio of XY-MAC to X-MAC

VI. Conclusion

Short preamble MAC protocols for wireless sensor network with strobed preamble can be hardly refer to as energy efficient. Because they increases sampling periods at receivers by introducing pauses between short preamble packets. The contribution of XY-MAC is to sharpen those pauses to achieve a lower duty cycle at receivers. In this way, short preamble MAC protocols with strobed preamble can be more energy efficient, even in low traffic networks.

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