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ANALYSIS OF A POWER-SAVING MAC PROTOCOL IN SMART INTELLIGENCE SYSTEMS

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Abstract. *Reducing power consumption in smart intelligence systems for increasing the lifespan of battery-operated IoT devices is critical for stable system operation. To do this, a good power-saving Medium Access Control (MAC) protocol is needed. In this paper, we analyze a novel power-saving MAC protocol capable of reducing the power consumption of sensor devices. We conducted experiments to evaluate the operational efficiency of the power-saving MAC protocol in a real environment. Through the experiments, we find that the introduced power-saving MAC protocol can save power efficiently.*
Keywords: Power saving MAC, Smart intelligence system, Body sensor, Transmission power control

1. **Introduction.** In this Internet of Things (IoT) era, smart intelligence systems use wearable devices well-equipped with wireless body sensors to measure and analyze the day-to-day changes in a human's activities or health state. Because these devices are either appended within or on the human body, they are relatively small and have a limited battery life. These sensors, periodically measure a human's activities or health state and transmit data, thereby consuming numerous batteries; however, replacing these batteries often is challenging. Therefore, substantial research is being conducted on consuming energy efficiently and preserving batteries for longer [1-5].

For saving power of sensor devices and enlarging lifetime of wireless sensor networks, the Transmission Power Control (TPC) model and low power Medium Access Control (MAC) protocol are used. The TPC model comprises a control packet that adjusts the Transmission Power Level (TPL) when the sender node transmits data to the receiver node, thereby saving energy [6]. The low power MAC protocol prevents data transmission collisions and transmission delays between devices on the wireless sensor network; it alternates between the active state and sleep state to save energy [7].

However, there is no mechanism which supports both TPC and low power MAC mechanisms simultaneously. Therefore, in this paper, we introduce and analyze a power-saving MAC protocol which combines the TPC model and low power MAC protocol. This technique combines the asynchronous MAC protocol, known as the X-MAC protocol, and the TPC model for energy efficiency.

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2. **Power Saving Technologies.** To implement the TPC model, a closed loop mechanism is generally used. In a closed loop, the receiver node measures the RSSI and a suitable TPL is predicted based on that value for adjusting the transmission power to be transferred to the sender node via a control packet. Therefore, the control packet for delivering TPL should be transmitted regularly.

In the MAC protocol, energy is lost due to collisions, overhearing, control packet overhead, and idle listening [7]. For low power MAC, ample research is available on overcoming these drawbacks and using energy more efficiently [8,9]. These low power MAC protocols are broadly divided as: synchronous MAC protocols and asynchronous MAC protocols. In synchronous MAC protocols, the transmitting device and the receiving device are temporally synchronized to exchange data. When data are sent and received, all devices maintain an active state, and when data are not being sent and received, they maintain a sleep state. Typical synchronous MAC protocols are the Sensor-MAC (S-MAC) protocol [10] and the Timeout-MAC (T-MAC) protocol [11]. However, the synchronous MAC protocols require the synchronization mechanism which cause more energy consumption to transfer data.

In an asynchronous MAC protocol, the time between the devices is not synchronized, so control packets are not used that are periodically sent in synchronous MAC protocols for synchronization, and this can save additional energy. In an asynchronous MAC protocol, the receiving device maintains a sleep state and momentarily activates to detect if there is a wireless signal. At this point, if there is a wireless signal, the receiving device maintains an active state and receives the data. If there is no wireless signal, the receiving device returns to the sleep state. Each sending/receiving device maintains its own duty cycle for operation. Typical asynchronous MAC protocols include the Berkeley-MAC (B-MAC) protocol [12] and X-MAC protocol [13].

Especially, the X-MAC protocol uses a short preamble to resolve the energy consumption and delay problems caused by a long preamble. The short preamble of the X-MAC protocol contains the destination address, which is continuously sent for longer than the sleep time. The receiving device receives the preamble, and if the device is the destination, it prepares to receive data. If not, it returns to the sleep state and saves energy. Moreover, the receiving device sends early ACK packets about the short preamble to the transmitting device, so that it stops transmitting the preamble and the data transmission/reception is fast and hassle-free. In this manner, the X-MAC protocol uses the short preamble, the technique of inserting the destination into the preamble, and the early ACK technique to increase energy efficiency.

In this paper, we introduced and evaluated the MAC protocol that is a combination of the asynchronous X-MAC protocol and TPC mechanism in detail.

3. **Power-Saving MAC Protocol.** The introduced protocol is a hybrid of the X-MAC protocol and TPC model, which combines the X-MAC protocol's ACK packets and the TPC model's control packets. In the X-MAC protocol, the short preamble can be transmitted repeatedly until the receiver node enters the active state, but the introduced protocol has been modified to transmit the short preamble repeatedly until the RSSI value of the short preamble received by the receiver node is within the target RSSI margin.

Figure 1 shows the operating approach of the power-saving MAC protocol. In the protocol, the sender node repeatedly transmits a short preamble to the receiver node. When the receiver node enters an active state, the short preamble transmitted by the sender is received, and the preamble's RSSI value is measured, which is inserted in the early ACK packet, and the sender node is informed. The sender node receiving the early ACK packet extracts the RSSI value from the packet and determines whether this value is within the target RSSI margin. If the obtained RSSI value is higher than the target RSSI margin, the sender node uses the TPC algorithm to lower the TPL and retransmits

In the Sender Node:

Start:

Sending a short preamble until receiving an early ACK from the receiver node

When receiving an early ACK:

Extracting RSSI value from the received early ACK

If the RSSI value is within the target RSSI margin, then sending data packet.

Otherwise, calculating the new TPL using a TPC algorithm and sending a new short preamble with the new TPL up to the maximum retransmission count

In the Receiver Node:

When receiving a short preamble:

Measuring the RSSI value of the short preamble and sending it to the sender node through an early ACK packet

Figure 1. Power-saving MAC protocol [14]

the short preamble. Conversely, if the obtained RSSI value is lower than the target RSSI margin, the TPL is increased, and the short preamble is re-transmitted. The sender repeats this process until the RSSI value obtained from the early ACK packet is within the target RSSI margin or the number of times the short preamble has been retransmitted reaches the maximum retransmission count limit.

4. **Experiments.** We conducted the experiments using real sensor equipment with diverse power-saving TPC algorithms. Table 1 shows the experimental equipment and environmental variables used. The experiments used a CC1000 Radio module in a Cricket Mote manufactured by Crossbow [15]. The CC1000 Radio module has a 23-stage TPL [16]. In the experiments, the target RSSI margin was set at -85 dBm $\pm$ 5 dBm. Packets with received RSSI less than -120 dBm were treated as energy lost and 300 data packets were transmitted in each experiment. The experimenters attached the sender nodes to their backs and the receiver nodes to their chests. The experimenters' movements included standing, walking, and running. The experiment included indoor and outdoor locations. The experiment scenarios combined six situations (indoor/standing, indoor/walking, indoor/running, outdoor/standing, outdoor/walking, outdoor/running) for 30 cases conducted in one period. We assumed that one data packet was transmitted in 1 hour. Thus, we assumed that, each time the data was sent, the researcher could change his/her location and movement. The maximum number of times the short preamble could be sent

Table 1. Experimental parameters

Properties	**Values**
Radio protocol	Zigbee
Output power range	-8 to 10 dBm
Radio chip	CC1000
Target RSSI	-85 dBm $\pm$ 5 dBm
Minimum RSSI	-120 dBm
Number of packets	300
Sensor locations	Back/chest
Body movements	Standing/walking/running
Short preamble size	4 Bytes
Early ACK packet size	4 Bytes

before sending one data packet was set at eight. In the experiment, the MAX TPC algorithm is an algorithm that transmits all packets at the maximum TPL, and MIN TPC is an algorithm that transmits all packets at the minimum TPL.

Figure 2 shows the energy consumption and number of lost data for each TPC algorithm according to the transmission data size. In Figure 2(a), the size of the data packet transmitted by the sender node to the receiver node is 40 Bytes, and in Figure 2(b), the data packet size is 400 Bytes. When data size was small, the MAX TPC algorithm, which transmits data at the maximum TPL without adjusting the TPL, consumed the most energy, whereas, the MIN TPC algorithm, which transmits data at the minimum TPL, consumed the least energy. However, in the MIN TPC algorithm, approximately 40% of the total data was lost, and the energy waste due to retransmission was severe. Also, when the loss rate and the total energy consumption were compared, the TPC algorithm, which showed the best efficiency, was the ETPC algorithm, because this algorithm used the fewest short preambles indoors and outdoors, while standing, walking, or running, and in scenarios that combined all these situations. When data size was large, the MAX TPC algorithm continued to consume the maximum energy, and the MIN TPC algorithm consumed the least energy; however, it still demonstrated inadequate efficiency with over 40% loss rate. When data size was large, other algorithms, including Linear, Binary, Dynamic, and ETPC, showed similar energy efficiency results.

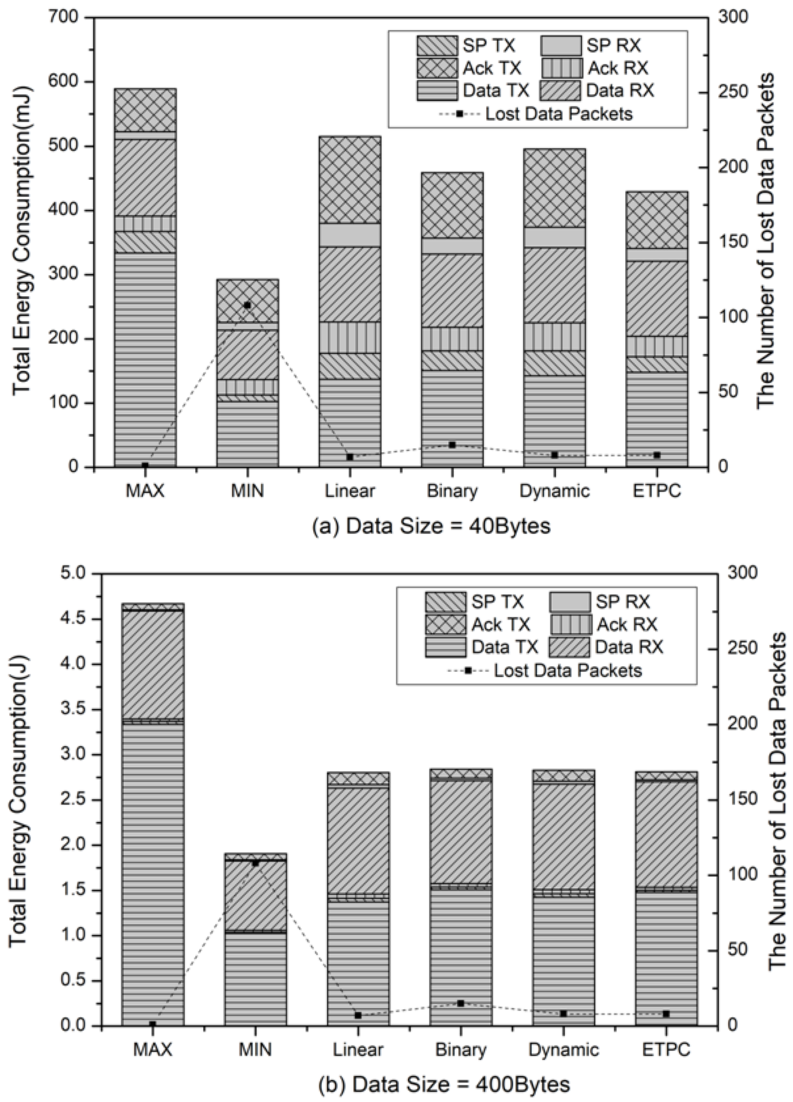

Figure 2. Energy consumption per TPC algorithms

The MAX and MIN TPC algorithms only send the short preamble and ACK packet once, similar to the X-MAC protocol. Other TPC algorithms use the power-saving MAC protocol and send/receive the short preambles and ACK packets repeatedly. Therefore, other TPC algorithms use more control packets than the MAX and MIN TPC algorithms. Therefore, the two graphs indicate that they use more energy for control packets. However, when they were compared for overall energy, the introduced technique consumed less energy. Thus, adjusting the TPL can greatly reduce energy efficiency.

Figure 2 shows that, when data size was small, the energy consumption ratio of the short preambles and the ACK packets was high. Conversely, when data size was large, the energy consumed by the short preambles and data packets was an infinitesimal part of the overall energy consumption, and the energy consumption ratio of the data packet transmission was overwhelmingly large. Therefore, when data size is small, the energy used for the short preambles significantly affects the overall energy, so the TPC algorithm, which uses few short preambles, is highly efficient. Therefore, as the size of the data becomes smaller, finding a suitable TPL with the minimum number of short preambles is essential. From the experiments, we can conclude that, when the data size was small, the ETPC algorithm was efficient, whereas the linear TPC algorithm and dynamic TPC algorithm used excessive short preambles and were inappropriate.

Figure 3 illustrates the number of lost data for each TPC algorithm. In these experiments, packets received at less than −120, −100, and −90 dBm were considered lost. When the loss standard was −120 and −100 dBm, the difference in the number of lost packets was insignificant. However, when the loss standard was −90 dBm, the Linear TPC algorithm was determined to have lost 66 packets.

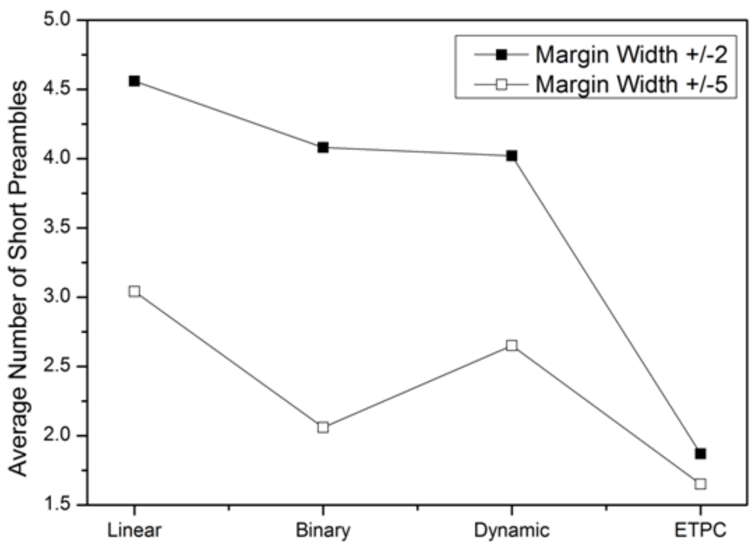

Figure 3. Number of lost packets

The experimental results indicate that the losses were lowest when the ETPC algorithm was chosen as the TPC algorithm, regardless of the loss standard. The ETPC algorithm determined the TPL through a linear equation having the target RSSI point as its objective, so most of the RSSI values were near the target RSSI point, and they continued to be in the target RSSI margin. However, the Linear, Binary, and Dynamic TPC algorithms make adjustments in stages to be in the target RSSI margin, rather than making the target RSSI point the objective, so there were several values not in the target RSSI margin but fluctuated around it. Thus, the ETPC algorithm had the fewer lost data packets than other algorithms.

In the experiments, the MAX and MIN TPC algorithms represent the performance of the pure X-MAC protocol. Therefore, we can say that the introduced power-saving MAC protocol cooperates well with diverse TPC algorithms and has better performance than the pure X-MAC protocol.

5. **Conclusions.** We introduced and analyzed a low power MAC protocol for efficiently transmitting data in a smart intelligence system. The protocol combined the X-MAC protocol's short preamble technique with a TPC model so that when short preambles are transmitted before transmitting data packets, TPC is performed to use the optimal power when transmitting data packets.

The experiments demonstrated that, in the protocol, the number of short preambles had a significant effect on the overall energy efficiency when the size of the transmitted data was small. Thus, the power-saving MAC protocol showed optimal performance when it used a TPC algorithm that uses few short preambles. When the size of the transmitted data was large, the energy used on the short preambles was smaller than the data energy; thus, there was no significant difference in efficiency between TPC algorithms. In this scenario, using several short preambles to find the appropriate TPL and transmit the data was useful, regardless of the TPC algorithm that was used. However, if enormous data is continuously transmitted with a high TPL, huge energy waste occurs, and if it is transmitted at a low TPL, the data loss rate becomes high, and loss can occur via retransmission. The experiments proved that the ETPC algorithm shows the best efficiency compared with other TPC algorithms.

In the future, we intend to conduct additional studies on low power MAC protocols that can transmit data more efficiently even when huge data is transmitted on a wireless body sensor network of smart intelligent systems.

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