지연에 민감한 대규모 센서네트워크에서 지연시간 보장을 위한 알고리즘

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A Latency-Secured Algorithm for Delay-Sensitive Large-Scale Sensor Networks

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요 약

센서네트워크가 넓은 영역에서의 환경 감시 혹은 u-City에서의 정보전송 등에 이용될 경우 노드 개수는 많이 증가하게 된다. 이 때 발생하는 문제점 중 하나는 역방향 전송 지연시간이 급격하게 늘어난다는 점이다. 이 논문에서는 대규모 센서네트워크에서 역방향 패킷의 지연시간을 최소화할 수 있는 알고리즘을 제시하였다. 지그비 방식과 비교할 때 에너지 소비는 지그비와 거의 비슷하면서도 지연시간을 90% 이상 줄일 수 있음을 확인하였다.

Key Words : Sensor Network, Latency, Beacon, Energy Consumption, MAC Protocol

ABSTRACT

When a sensor network is used for monitoring environments in large area or transmitting information in a u-City the number of nodes becomes very large. One of the problems with this application is the increased time delay, especially in reverse direction. In this paper, we propose a new algorithm that can minimize the latency of reverse packet in large sensor network. Analysis shows that the proposed scheme can reduce the latency by more than 90% when compared to Zigbee, while the energy consumption is maintained.

Ⅰ. Introduction

Wireless sensor network (WSN) is a distributed system composed of many battery-powered sensor nodes and the main function of it is monitoring environments by collecting and transmitting information from each node. The main challenges of WSN are coverage, latency, energy consumption and correct information gathering. Nowadays as the coverage of WSN becomes larger the number of sensor nodes as well as the number of hops is increased. With the increase of hops in ad-hoc based WSN the transmission time delay is also increased. This delay is admitted in the WSN that monitors slowly changing parameters. However, the delay becomes critical when the WSN is used in carrying delay sensitive parameters such as fire alarm, security information or emergent images. One of the most fundamental ways to reduce the time delay is to avoid collisions so that neighboring nodes do not transmit at a time[1]. Some medium access control (MAC) protocol is used to provide the collision free transmission of data from source node to the coordinator. Many

※ 본 연구는 한국연구재단 (2009-0083890) 및 국민대학교 교내연구비 지원으로 수행되었음.
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논문번호 : KICS2010-01-009, 접수일자 : 2010년 1월 7일, 최종논문접수일자 : 2010년 5월 10일

researchers have developed different MAC protocols to solve the time delay as well as energy dissipation problem.

It is observed that with S-MAC about 4 seconds are needed to deliver data from a source node to the coordinator that is 4 hops apart in linear type WSN when duty cycle is set to 10% and data traffic load is low[1],[2]. Increasing the load would double the time delay, which is not tolerable in delay sensitive applications. In DMAC[3], the duty cycle is adjusted adaptively depending upon the traffic load in the network by varying the number of active slots. It utilizes a data gathering tree and data prediction structure specific to sensor network applications to achieve both latency efficiency and energy saving. In TMAC[4], a radio interference range which is larger than the transmission range is used to activate all nodes in the network at a time. If any node enters into active mode then many nodes in the interference range remain active unnecessarily for a long period leading to energy waste. Adaptive S-MAC[5] reduces the latency, but cannot solve the multi-hop latency problem since only two hop transmission is executed in a time frame. LE- MAC[6] introduced a 'traffic aware early wake-up (T-wakeup)' scheme where the CTS (Clear to Send) signal is used to wake up a node from sleep period. Here the sink node transmits the CS (Carrier Sensing) signal and switches the node state. The number of hops that data can be transmitted in a single time frame is decided by the extension of the CS range, which decides the latency.

This paper presents a latency secured MAC, as a new protocol explicitly designed for beacon-enabled large WSNs. The main objective of this protocol is to reduce the time delay in delay sensitive networks. This protocol considers two different states at each sensor node, i.e., active state and sleep state. In active state sensor nodes are able to transmit or receive data. In sleep state nodes can't communicate with their neighboring nodes, and don't respond to RTS/CTS signal. These active and sleep times are maintained by using a timer at each node.

Ⅱ. Related Works

Various WSN MAC protocols have been developed to reduce energy consumption of sensor nodes as well as to reduce latency. S-MAC[1] is a popular WSN protocol that maintains periodic listen and sleep in each time frame to reduce the energy consumption of idle listening period. No doubt periodic listen and sleep saves energy efficiently, but at the cost of high latency which is undesirable in delay sensitive networks. It also needs SYNC (Synchronization) packet transmission from the coordinator to multiple hops, requiring much energy to cover large sensor networks.

The basic operation of typical S-MAC is shown in Fig. 1. SYNC packet is transmitted in the beginning of the time frame, then source node

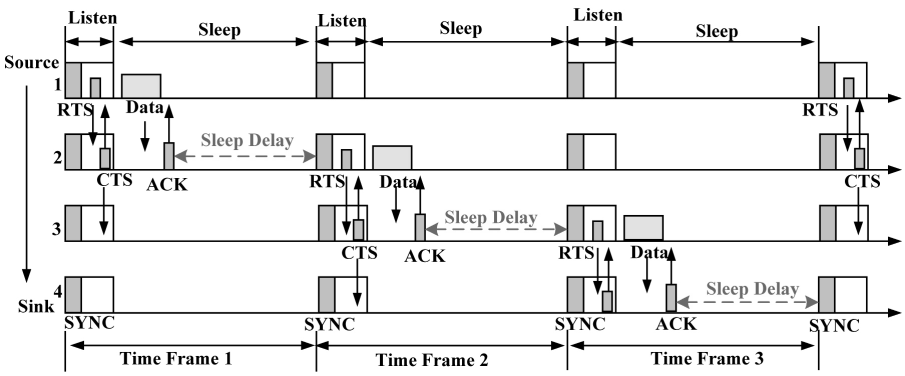

Fig.1. Operation of typical S-MAC

1 and the nearest parent node 2 exchange RTS/CTS signals and immediately transmit data packets while node 3 is in sleep state to save energy. For further data transmission from node 2 to its parent node 3 it should wait until the next time frame, which requires a large time delay. In order to reduce this delay adaptive S-MAC[5] is proposed. It allows two hops transmission in a frame by waking up the third node using a vector timer. In Fig. 2, it is shown that both node 2 and 3 receive data in the first time frame but node 4 should wait until the next time frame. Therefore, this protocol reduces the number of time frames by half compared with S-MAC.

LE-MAC[6] is a useful approach for reducing sleep delay in multiple hops. Its performance depends on the ability of CS range, which is normally not more than the twice of actual transmitting or receiving range[7]. In this respect, LE-MAC proposed up to 4-hop transmission in a single time frame as shown in Fig. 3. If the total hops in a network is more than 4, then it requires another time frame. The performance of this scheme also is restricted by CS range and SYNC signal transmission distance.

Zigbee[8] is a well acceptable protocol that provides an efficient algorithm to avoid data collision and excessive energy consumption in large sensor network. This protocol uses periodic listen and sleep cycle to avoid idle listening and

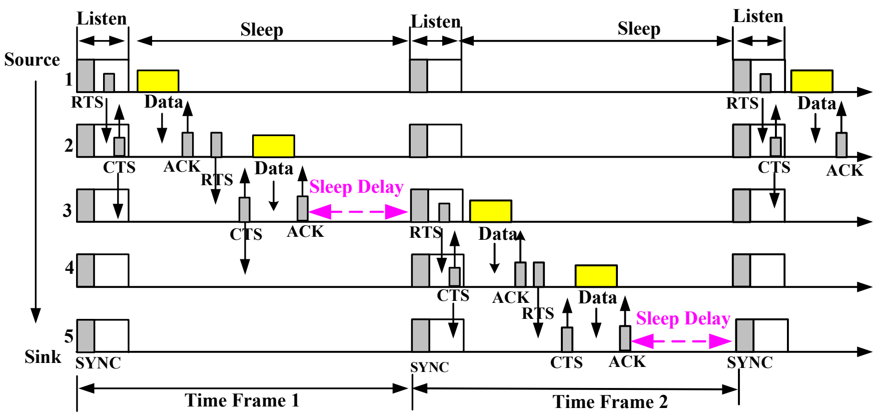

Fig.2. Operation of adaptive S-MAC

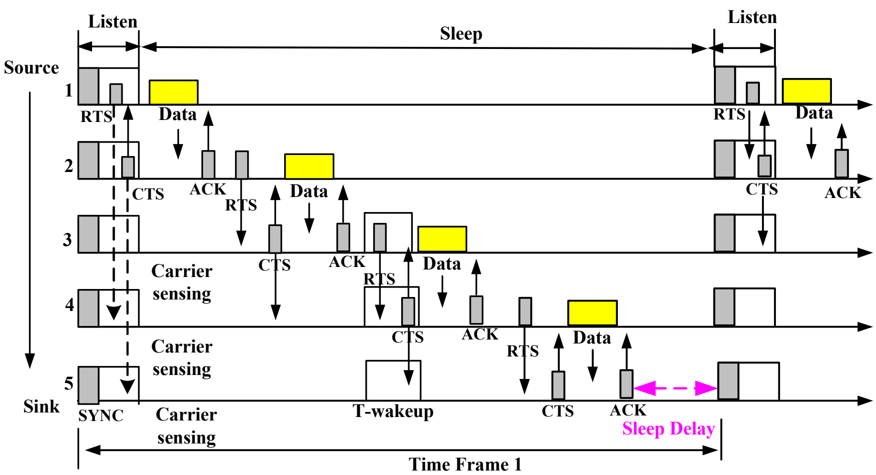

Fig.3. Operation of LE-MAC

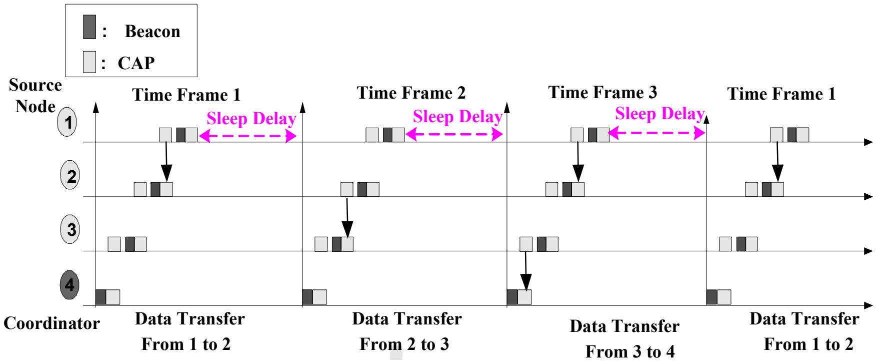

Fig.4. Operation of Zigbee

to increase the battery life, but the latency is still undesirable for the delay sensitive large networks. As in the typical S-MAC protocol, the required number of time frames is directly proportional to the number of hops in the network as shown in Fig. 4.

Ⅲ. Principles of the Proposed Protocol

The main objective of the proposed protocol is to modify the existing beacon-enabled Zigbee to reduce the time delay, maintain the energy efficiency, avoid collision and minimize the idle listening. To achieve all of these goals we consider the beacon signal to initiate the time frame which is composed of transmitting time, receiving time and sleep time. Performance of the proposed latency-secured (LS) MAC protocol is compared with those of the existing ones.

3.1 Latency Secured (LS) MAC protocol

In this scheme all reverse transmissions are completed in a single time frame as shown in Fig. 5. In the first stage, the coordinator node transmits a beacon signal which is followed by forward data. The beacon includes network information such as frame structure, total hop number, wake-up time, node connection, etc. Each node receives the beacon from the nearest parent node and forwards data successively, and then enters into a waiting time, which is a sleep state. After waking up, each node responds to the RTS from their children nodes by CTS and then receives reverse data. After transmitting reverse data, each node enters into a sleep state until the next time frame. The optional ACK

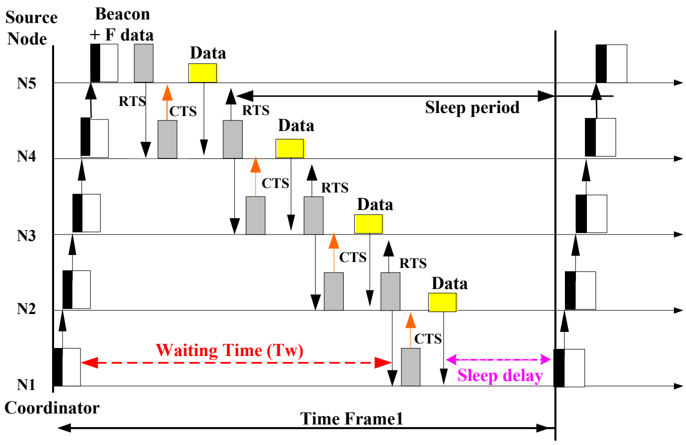

Fig.5. Operation of LS-MAC

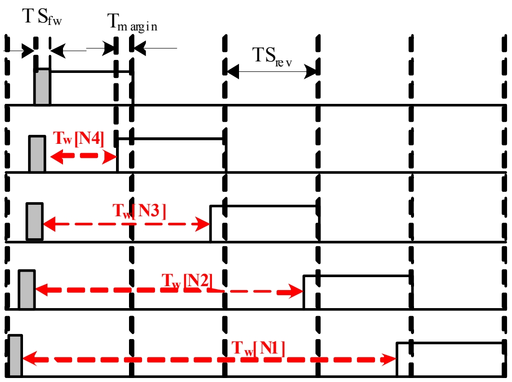

Fig.6. Illustration of waiting time

(Acknowledgement) signal is not used in this protocol. The RTS signal from the receiver is used instead to notify the successful reception. Suppose that node N4 in Fig. 5 receives data from its child node N5 and sends a RTS signal to its parent node N3. Then, this RTS is also received by node N5 and is regarded as ACK signal.

The waiting time between forward and reverse transmission is decided by the hop number as shown in Fig. 5. Active time of each node is fixed, which is called a time slot. Receiver nodes should wake up before the end of the previous time slot as shown in Fig. 6 to prepare the reception and it is called a time margin.

Therefore, the waiting time of k'th hop can be described as in equation (1).

$$T_W(k) = (N_{hop} - k) \times (TS_{fw} + TS_{rev}) - T_{margin} \quad (1)$$

where N_{hop} is the maximum hop number, TS_{fw} the forward time slot, and TS_{rev} the reverse time slot. Since both TS_{fw} and TS_{rev} are fixed, the waiting time can be defined for each node only if the hop number is given. Fig. 7 shows the sequence of reverse transmission in the proposed LS-protocol. As shown in the figure, each node waits until all its children nodes' response before starting its reverse transmission toward the parent node.

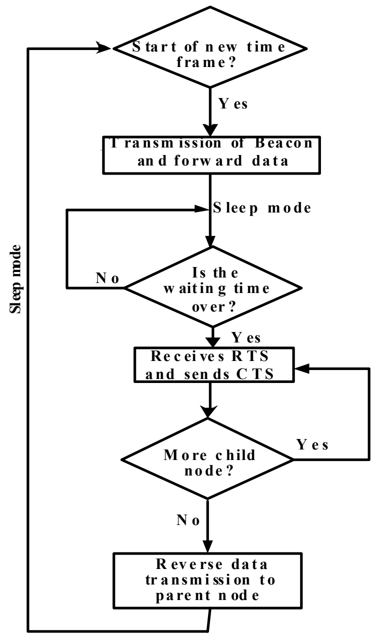

Fig.7. Flow chart of LS algorithm

3.2 Analysis of Latency

In this section, latency of the proposed scheme is compared with those of Zigbee, typical S-MAC, adaptive S-MAC and LE-MAC. Time frame consists of active period and sleep period as shown in Fig. 8.

Data measured in sleep period must be buffered until the next beacon signal. This time delay is called queuing time, t_q. As done in [5],[6] we assume that the queuing time happens only at the source node. For delay calculation this queuing time is added to the actual data transmission time which depends on packet size, data rate, number of hops, physical distance between two data transmitting nodes, and protocol delay. Sleep time, t_{sl} is the period between the completion of transmission and the beginning of the following time frame.

Therefore, the total delay of N-hop Zigbee is:

$$D(N) = t_q + (N)\, T_{frame} - t_{sl} \quad (2)$$

where $T_{frame} = t_{backoff} + t_{tx} + t_b + t_{sl}$, $t_{backoff}$ is the average delay due to contention, t_{tx} the

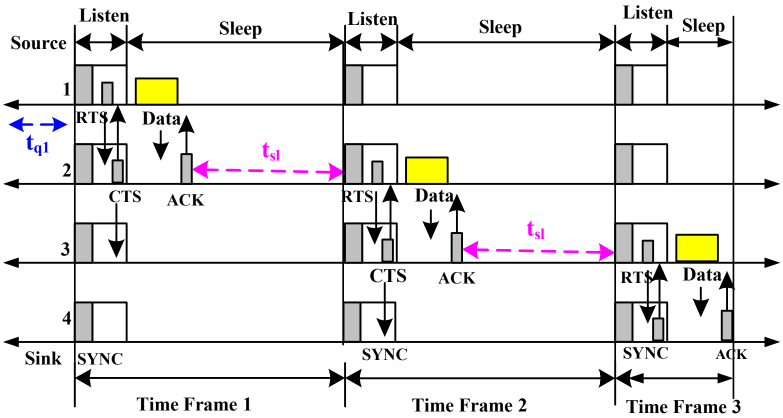

Fig.8. Definition of each parameter in a time frame

transmission time of data packet across one hop which includes RTS and CTS time, and t_b the beacon time.

The total delay for N-hop typical S-MAC is:

$$D(N) = t_q + (N)\,T_{frame} - t_{sl} \tag{3}$$

where $T_{frame} = t_{backoff} + t_{tx} + t_{sl}$. The S-MAC latency is similar to that of Zigbee except the beacon time t_b.

The total delay for N-hop adaptive S-MAC is:

$$D(N) = t_q + \lceil N/2 \rceil\, T_{frame} - t_{sl} \tag{4}$$

where $T_{frame} = 2(t_{backoff} + t_{tx}) + t_{sl}$ because a packet can traverse up to 2 hops in one time frame. Sleep period, t_{sl} , is the remaining time after 2-hop transmission in one time frame.

The total delay for N-hop LE-MAC is:

$$D(N) = t_q + \lceil N/K \rceil\, T_{frame} - t_{sl} \tag{5}$$

where $T_{frame} = K(t_{backoff} + t_{tx}) + t_{sl}$ because a packet can traverse up to K hops in one time frame depending upon the CS range. In eqs. (2)-(5) t_{sl} is deducted because sleep time in the last time frame is not counted in latency as in Fig. 8.

In the proposed LS protocol, packets can transmit up to N hops continuously in a single time frame. The total delay of N-hop LS is:

$$D(N) = t_q + N(t_{backoff} + t_{fw} + t_{rev}) \tag{6}$$

where t_{fw} includes the beacon time and forward data transmission time, and t_{rev} is the reverse data transmission time per hop.

Note that although the composition of time frame differs for each MAC, the count of it is important since the major part of it is sleep time. By comparison of (2)-(6) it is observed that N-hop Zigbee and typical S-MAC requires N time frames, Adaptive S-MAC N/2 time frames, LE-MAC N/K time frames while LS requires only a single time frame.

3.3 Analysis of Energy Consumption

Energy consumption is another important constraint of a large WSN. Many schemes have been proposed to reduce the energy consumption. Although the main objective of our study is to secure minimized latency in large WSNs, energy should be controlled also. Energy consumption is dependent on modes: in active mode, nodes are able to transmit and receive data while in sleep mode, all transmissions are halted. Therefore, energy consumption in sleep mode is neglected. Hence, the total energy consumption for N-hop LS is expressed as:

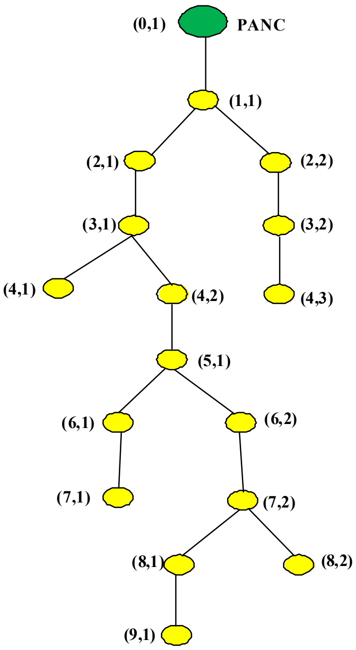

Fig.9. Network model of the simulation

$$E_T = n\{P_t \times T_t + P_r(T_a - T_t)\} \quad (7)$$

where n is the number of nodes in the network, P_t the power consumption per second in transmission time, T_t the transmission time, P_r the power consumption per second in reception or idle time, and T_a the active time which is dependent on the duty cycle and time frame.

Ⅳ. Performance Evaluation

Latency and energy consumption are calculated for various types of protocols explained in section III. A 9-hop non-symmetrical network with 16 source nodes and one coordinator as shown in Fig. 9 is considered for the simulation. Two dimensional numbering is used to represent each node: the first digit represents hop number and the second one the node number in a particular hop. Considering that the reverse data carries multiple measurement data while forward data includes only network information, all sensor nodes are assumed to generate 100-byte reverse data packets in each time frame while 50-byte forward packets are broadcasted. In addition, 20-byte beacon packets, reflecting the super frame structure of Zigbee, are used. The time frame is set to 1 second and duty cycle, the ratio of active period over the time frame, is assumed to be 10% for each node. We consider the queuing time t_q as the random delay between 0 and 1 second since transmission occurs once in a time frame. We also consider the total active time as the combination of t_{rev}, t_{fw}, t_b, and idle time, all of which are dependent on the packet size. Collision is not considered in this simulation since the generated packet size is very small compared to each time frame. Distance between nodes is fixed at 40 meter as in [5],[6] and data rate is considered to be 1 Mbps. It is assumed that data transmission consumes 24.75 mW while data reception or idle mode requires 13.5 mW[9].

The average latency is obtained for different hop distances of the network model shown in Fig. 9. Fig. 10 shows that the latency of the LS protocol is much smaller than those of the other protocols. Although latency of LE-MAC is nearly close to the proposed scheme in small hop distances, the difference becomes larger as the hop number is increased. Fig. 11 shows the average latency for the proposed LS-MAC protocol with different packet sizes. It is found from this figure that the reverse packet has more

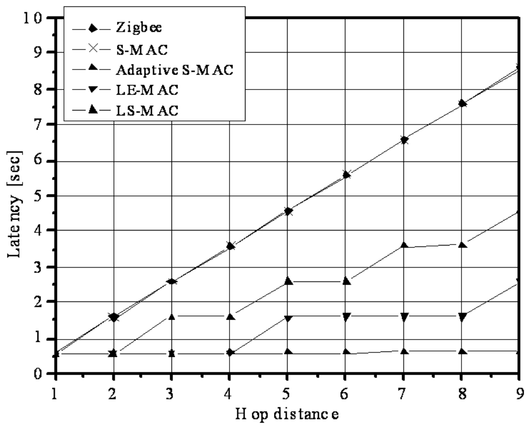

Fig.10. Average latency for 1 sec. time frame and 10% duty cycle

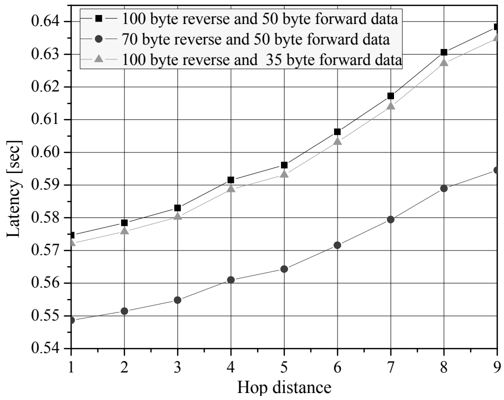

Fig.11. Comparison of average latency for different reverse and forward data

effect than forward packet, and this is due to that the forward transmission is broadcasting. If the network structure is more complicated and packet generation is more frequent, then the difference of delay for different packet sizes will be larger.

Fig. 12 shows the energy consumption of the example network when the time frame is 1 second and the duty cycle is 10%. All nodes are assumed to generate data once in a time frame. The energy consumption at each hop distance means the cumulative energy required up to that hop number. It is shown that a little more energy is consumed in the proposed LS-MAC, which is caused by the 5 byte time margin illustrated in Fig. 6. However, this increase is nearly negligible. Energy consumption among various protocols is very similar[6] since it is the transmission energy

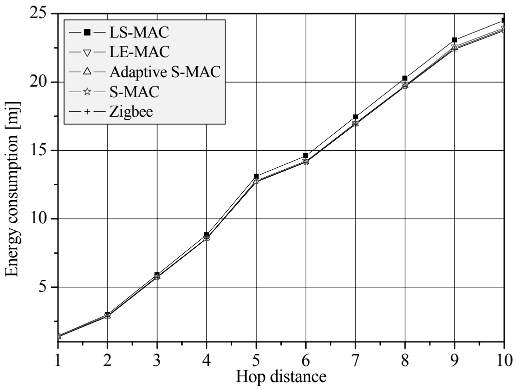

Fig.12. Energy consumption for the 9-hop network of Fig. 9 with 1 second time frame and 10% duty cycle

that differs among protocols, but the difference between them is quite small compared to the energy consumed in the receiving time.

Therefore, it can be concluded from the analysis that the proposed LS-MAC protocol can reduce the latency while maintaining the energy consumption level.

Ⅴ. Conclusions

In this paper, we present a new MAC protocol that can effectively reduce the latency of reverse data in beacon-enabled large wireless sensor networks. Unlike existing protocols, the proposed LS-MAC can complete all the reverse transmission within one cycle. Therefore, this protocol can be applied to a time-sensitive large sensor network. Since the worst case delay scenarios are considered, the practical delay will be less than the one given in this paper. On the other hand, the energy consumption in the proposed scheme is very much similar to those of other existing protocols.

In summary, the proposed algorithm has potential than all other existing MAC in large sensor network in terms of latency and energy consumption.

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