A Latency MAC Protocol for Wireless Sensor Networks

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Abstract

This paper proposes a MAC protocol called the Latency MAC (LMAC) protocol for wireless sensor networks. The proposed LMAC protocol aims at minimizing the power consumption caused by the idle listening problem through enlarging the data collection time. This study examines the latency constraint in wireless sensor networks and studies the tradeoff between extra latency and energy-efficiency. In the process of trading latency for energy-efficiency, there are many restrictions. Thus, this study analyzed these limitations and then tries to achieve the best tradeoff between latency and energy-efficiency according to these limitations. By increasing the arrival prediction accuracy of data packets, the simulation results show that the LMAC protocol indeed help the sensor nodes to consume less energy, especially for the wireless sensor networks with loose latency constraints or light traffic load.

Keywords: *MAC Protocol, Wireless Sensor Networks, LMAC*

1. Introduction

Wireless sensor networks are used in various applications such as environment monitoring, animal behavior tracking, factory controlling, homeland security, military detecting, etc. Data flow direction and energy constraint are the major difference between wireless sensor networks and the traditional ad hoc networks. In wireless sensor networks, there are some special nodes which are called sinks. Sinks are the destinations of data packets and every sensor nodes transmit the sensed data to the sink. Thus, the data flow in wireless sensor networks is generally one-way traffic to sinks from all sensor nodes except some protocol control data packets or communication occurred between sensor nodes. Energy-efficiency is a critical issue in most wireless networks, especially in wireless sensor networks where sensor nodes are usually operated by battery in cheaper hardware devices and will not be maintained for a long time after the network topology is established. In general, wireless sensor networks demand a longer life time protocol than that of other wireless networks. The other constraints such as data latency and transmission rate are less concerned. Therefore, we try to enhance energy-efficiency by sacrificing these less important factors.

Some special topology architectures and critical energy-efficiency constraint in wireless sensor networks, most of the popular ad hoc network protocols like IEEE802.11 can not be used in wireless sensor network. There are many various wireless sensor network-oriented protocols developed, such as hardware devices wake-up radio [6], energy-efficiency MAC protocols [2, 9, 10, 12], and energy-efficiency routing protocols [1, 8], etc.

There are some major energy wastage problems in wireless sensor networks. The first problem is idle listening. While a node is waiting and listening for possible incoming packets, the energy is wasted when there is no such packet. The second one is overhearing. When a node receives a packet which does not belong to it, the energy is also wasted. The third problem is control packet overhead. Some protocol will request nodes exchange information periodically to maintain the schedule scheme or topology. The control packets flowing in nodes will increase energy consumption too.

Another energy-efficiency problem in wireless sensor network is unbalance consumption of energy. That is, the nodes that are closer to sink nodes will be busier than other nodes. Therefore, their energy consumption will be heavier than others. Actually, there is one more energy inefficiency problem: collision. In current research, most of wireless network protocols use the RTS/CTS scheme so the collision effect has been minimized.

There are two major directions of MAC protocol design in wireless network: contention based and TDMA based protocols [10]. Contention based protocols like IEEE 802.11, whose major energy wastage source is idle listening due to the uncertainty of when the packets will arrive, have to be aware of the network condition to gain the access right of transmission. This energy wastage is very difficult to overcome in this kind of design. In addition, contention based protocol will also cause the problem of overhearing. In TDMA based protocols, the major energy inefficiency results from idle listening and control packet overhead. The idle listening energy wastage is caused by missing prediction. And the sensor nodes have to keep exchanging control packets to maintain their schedule synchronized. Latency plays different roles in different oriented wireless sensor networks. In most data collection type wireless sensor networks, latency is an unimportant issue but in some special purpose system such as fire alarm network, human health monitoring system, the latency is the most important constraint. Thus, the tradeoff between latency and energy-efficiency does not suit for all kind of wireless sensor networks.

This paper proposed a MAC protocol called the Latency MAC (LMAC) protocol. In order to increase the energy efficiency, the LMAC protocol sacrifices some packet latency to reduce the energy wastage of idle listening, and to increase the accuracy of the prediction for packets incoming. As a result, the wireless sensor networks can significantly reduce the energy wastage for idle listening through the help of the LMAC protocol.

Some related MAC protocol designs and comparisons were discussed in Section 2. The design and some analysis of the LMAC protocol are presented in Section 3. In section 4, we showed the simulation results and comparisons among the LMAC, the SMAC and the PMAC protocols.

2. Related Works

In [4] has shown the energy consumption of contention based MAC protocol is too huge and is not appropriate in wireless sensor networks due to the energy wastage caused by idle listening. SMAC uses the wake/sleep duty cycle scheme to reduce energy consumption. It replaces the state of idle listening with sleeping in general wireless network to achieve energy efficiency. TMAC [9] tries to improve SMAC by using a time out scheme to further reduce the idle listening wastage. DMAC [2] uses an improved staggered sleeping cycle to reduce data latency of SMAC. PMAC generates a pattern for each sensor node via network traffic history. The sensor nodes will exchange patterns and make out a real schedule of sleep plan. There are many researches [3, 7, 11] have discussed the tradeoff between latency and energy. In [3, 7], the authors focus mostly on the modeling analysis and offline schedule like real time scheduling. In [11], authors purposed a tree structure with offline and online schedules but the schedules required the antenna to support two different transmit ranges.

One problem of data packets arrival time prediction is the sensor nodes will suffer some levels of penalty for missed prediction because the protocols will schedule certain operations for this arriving data packet such as wake up or notify the next node to be ready to receive this data packet. PMAC generates patterns via past traffic conditions, but the traffic load might be unstable and cause the patterns unfit the current traffic. In schedule-based MAC protocol, the problem is when a node is wake-up and listening, there might have no packet incoming or sent out from the buffer. In S-MAC-like protocols, the incoming rate does not be considered, instead, a sensor node wakes up every fixed period to check if there are packets incoming or sent out. What S-MAC can do is nothing but adapted the sleep duty cycle to fit the environment setup.

3. The LMAC Protocol

3.1. Overview of LMAC Protocol

In an extreme case, a sensor node could minimize the energy wastage by sleeping for a very long time and waking up for a short time. It receives all the data from previous nodes and then sends them out in the duration of wake-up. Obviously, this method can totally avoid the idle listening wastage but it will cause the data out of date and the buffer overflowing. In the LMAC protocol, the scenario is similar. Every sensor node will store a certain number of data packets which are either received from the neighboring nodes or sensed by the sensor node in buffer for a certain time length.

As we describe above, a protocol can predict the arrival time of packets, but the prediction accuracy can not be 100%. Let $P_n(T)$ be the possibility of n data packets arrived in T time units. If each data packet possesses similar possibility to arrived in each time unit, according to traditional probability theory, we have

$$P_n(T) \approx \frac{(\lambda T)^n}{n!} e^{-\lambda T} \tag{1}$$

According to equation (1), if the sensor nodes assume that the arrival rate of the incoming packets is λ, then the missing rate is $P_0(1/\lambda)$ whose value is about 0.36. Once a sleep schedule is generated according to this prediction then the idle listening will occur every 3 sleep cycles in average. However, if the sensor nodes assume that the arrival rate of the incoming packet is $\lambda/2$, the missing rate is reduced to 13%. One of the benefits of extending sleep cycle is that we greatly reduce the energy wastage caused by idle listening but we might suffer the additional data latency.

The LMAC protocol also predicts the time of incoming packets but does not treat them as true incoming events. The goal of the proposed scheduling scheme is to determine the sleep cycle and the transmission number to the neighbors. Every sensor node calculates two parameters for scheduling: *Doze* and *Bulk*. *Doze* stands for how many time slots a sensor node will sleep. *Bulk* represents the number of data packets that a sensor node will try to transmit *at most* after waking up from sleeping. *Doze* parameter stands for a sensor node will transmit data packets every *Doze* time slots. Every sensor node need to calculate its own *Doze* and *Bulk* according to the *Doze* and *Bulk* parameters of the children nodes. After the schedule is generated, every sensor node will transmit at most *Bulk* data packets every *Doze* time slots. While a sensor node sleeping within this *Doze* period, the sensor node will still wake up and receive its children's data if its children are waking up from the sleeping and ready to send out of data packets.

$$A(i,T)=\begin{cases}\text{Receive Data} & \text{if } \forall j \in C(i),\ T \bmod Doze_j \le \left\lceil \dfrac{Bulk_j}{P_m} \right\rceil \\ \text{Transmit Data} & \text{if } T \bmod Doze_i \le \left\lceil \dfrac{Bulk_i}{P_m} \right\rceil \\ \text{Sleep} & \text{otherwise} \end{cases} \quad (2)$$

Equation (2) above shows the action a sensor node N_i will perform at time T. In equation (2), P_m stands for the maximal number of data packets can be transmit within one time slot and $C(i)$ is the set of children nodes of node N_i. Node N_i will wake up and receive data when its children N_j is waking up after sleeping $Doze_j$ time slots. And node N_i will wake up to transmit data to its next node when node N_i has slept $Doze_i$ time slots. A sleep schedule example with *Doze* parameter is given in figure 1. After the initial schedule has been generated, we can calculate the data latency for this initial schedule and then adjust the schedule to fit the latency constraint.

3.2. Time Synchronization

Since every sensor node knows when its neighbors will wake up, and knows the maximal number of transmission within this wake-up period. The idle listening problem has been solved because we increase the possible transmission within each wake-up period. Time synchronization is an unavoidable overhead for TDMA or time slot based MAC protocols. In the LMAC protocol, the time synchronization action is performed at the beginning of each active time slot as shown in figure 2. T_{tx} stands for the time length required to complete a data transmission, including the contention window CW, RTS, CTS, DATA, and ACK. Except for time synchronization, a sensor node only executes 3 actions in a time slot. A sensor node will either remain in sleep when there is no transmission on schedule or wake up if its previous nodes have transmission on schedule. Receiving and sending transmission can be operated in the same time slot. The number of transmission within one time slot depends on the time unit of arrival rate, network bandwidth, and data packet size.

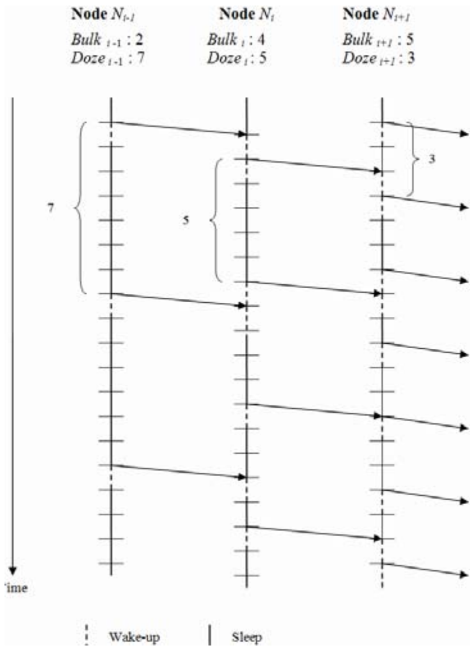

Figure 1. Sleep and wake-up states of sensor nodes in LMAC protocol

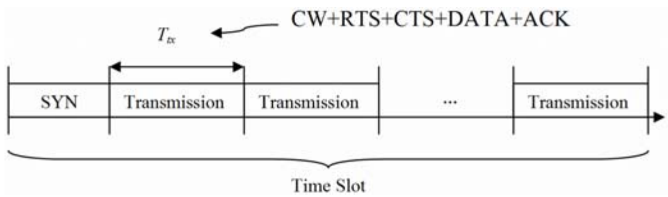

Figure 2. Contents of Time Slot

3.3. Details of Sleep Schedule in the LMAC Protocol

Bulk and Doze Parameters: In order to achieve the goal we state above, we have to define the algorithm to initiate *Doze* and *Bulk* parameters for all sensor nodes. In a Poisson arrival system, the maximal *Bulk* number of a sensor node is limited by many causes such as buffer size of a sensor node, network bandwidth, data packet size, etc. The *Bulk* stands for the number of data packets a sensor node will transfer *at most* within one sleep cycle. As a result, the *Bulk* number was bounded by the transmission time of each data packet. *Doze* parameter indicates the sleep time of a sensor node before it sends out data. When a sensor node is sleeping for *Doze* time length, it will still wake up to receive data there its children nodes are ready to transmit data.

Transmission Rate Constraint: A sensor node has to transmit *Bulk* data packets within the *Doze* sleep cycles. Since both the receiving and transmitting actions might happen in the same time slot, the expected bandwidth is only half of the bandwidth.

$$\mathrm{D}oze_k \geq 2 \times \frac{Bulk_k}{P_m} \tag{3}$$

Buffer Overflow Constraint: The LMAC protocol can not guarantee the buffer is overflow-free no matter how big it is. What we can do is just setting an overflow probability threshold and controlling the overflow probability under this threshold. For a sensor node, the numbers of incoming data from children nodes are determined, so we only have to investigate the relations between the remaining buffer space and self-sensed data packets. Let the buffer size of node N_k be $Buffer_k$ and let $C(k)$ stand for all the children nodes connected to node N_k. The remaining buffer space b_k is that $Buffer_k$ takes away the maximal possible arrival data within the $Doze_k$ sleep cycles. The value of b_k can be calculated by equation (4) and the overflow probability with buffer size b_k can be estimated by equation (5).

$$b_k = Buffer_k - \sum_{j \in C(k)} Bulk_j \times \left\lceil \frac{Doze_k}{Doze_i} \right\rceil \tag{4}$$

$$P([\text{Overflow}_k]) = 1 - \sum_{j=0}^{b_k} \frac{(\lambda_k \times Doze_k)^j}{j!} e^{(-\lambda_k \times Doze_k)} \tag{5}$$

Latency Constraint: If a sensor network has a data latency restriction, we will consider the latency for the leaf nodes only because the leaf nodes have the largest data latency in all nodes. For a data packet been transmitted to the sink from a leaf node, it will suffer the following latency factors: carrier sense latency, backoff latency, sleep latency, queuing latency, and transmission latency [12]. Carrier sense latency indicates that the sensor node performs the carrier sense action. Backoff latency is that when a sensor node fails on carrier sense, it will redo the carrier sense action after a random short time period. When the sensor node is in sleep, it will not transmit the self-sensed data packet or received immediately. The waiting time between data packet arrival and transmission is sleep latency. The queuing latency indicates the waiting time of a data packet in buffer from beginning transmission to being delivered. The transmission latency is the time required to transmit a packet out and it depends on the network bandwidth. Comparing to other latency factors, carrier sense latency and backoff latency are smaller and we can ignore them.

Let $P(k)$ be a set of nodes including all the ancestor nodes connected to node N_k, i.e. all the nodes will pass the data packets which are sensed by node N_k to sink. The expected latency includes sleep latency, queuing latency, and transmission latency. $W(k)$ is the average queuing time for data packets in node N_k.

$$E(L_k) = \frac{1}{2} Doze_k + W(k) + T_{tx} + \sum_{i \in P(k)} \left(\frac{1}{2} Doze_i + \frac{1}{2} Bulk_i \times T_{tx} + T_{tx} \right) \tag{6}$$

In order to confront the latency constraint, we should calculate the worst case of latency and use it as the upper bound.

$$L_k = Doze_k + W(k) + T_{tx} + \sum_{i \in P(k)} \left(Doze_i + Bulk_i \times 2T_{tx} + 2T_{tx} \right) \tag{7}$$

After the above restrictions are considered, we can finally study the relation between *Bulk* and *Doze.* For the node k, $Bulk_k$ must be greater than the number of possible arrival data packets within $Doze_k$ or the buffer will overflow.

$$Bulk_k \geq \sum_{i \in C(k)} \left(\frac{Doze_k}{Doze_i} \times Bulk_i \right) + (\lambda_k \times Doze_k) \tag{8}$$

If the number of data packets in buffer is less than *Bulk*, a sensor node can turn off radio and stop everything to sleep after transmitting all the data packets in buffer. On the other hand, if the number of data packets in buffer is greater than *Bulk*, it has to wait for the next time slot.

Initial Scheduling: After understanding all the restrictions and relations of *Bulk* and *Doze,* we can generate an initial schedule for networks. A series graphics in figure 3 has shown the schedule initiate diagram step by step. Firstly, we have every sensor node use its "following node number" as the initial *Bulk* number as shown in figure 3(b). Since we have got every node an initial *Bulk* number, we can calculate its *Doze* parameter by (8) as shown in figure 3(c). After generating every node's *Doze* parameter, we can calculate the latency for the leaf nodes by using equation (7). If the latency has not reached the limit of the system, we will adjust the *Doze* by equation (7). After the new *Doze* parameters are attained, we can re-adjust the *Bulk* parameters. Then we get a sleep and transmission schedule to fit the latency constraint as shown in figure 3(d).

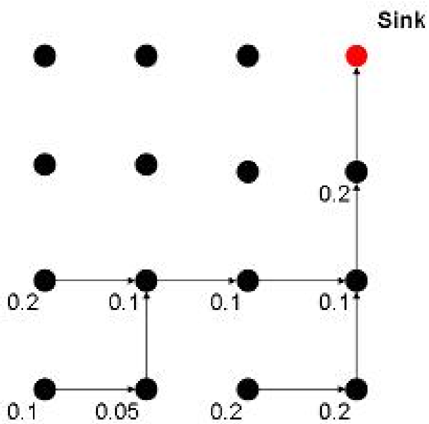

Figure 3(a). Arrival Rate

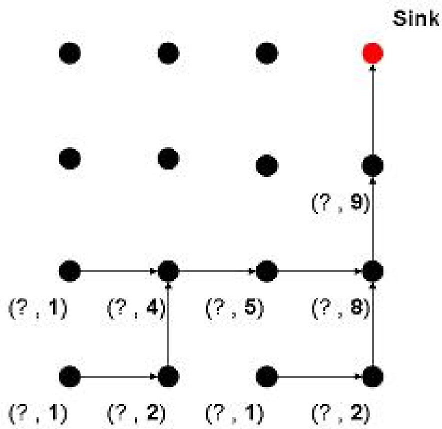

Figure 3(a). Arrival Rate

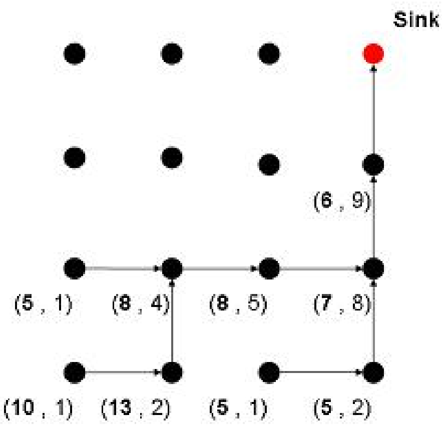

Figure 3(c). Initial Schedule

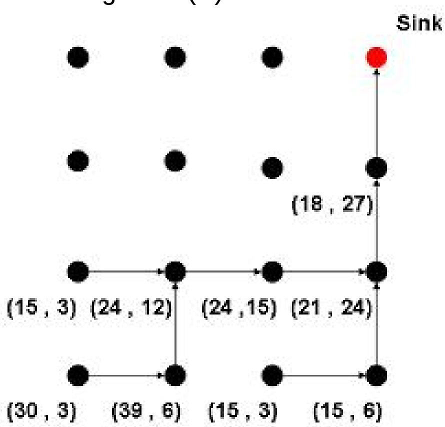

Figure 3(d). Final Schedule fits Latency Constraint

Table 1. Simulation Setup Parameters

Parameter	Value
Sending Power	0.25 w
Receiving Power	0.2 w
Idle Power	0.1 w
Simulation Time	1000 secs
Poisson Arrival Time Unit	100 ms
Bandwidth	20 kbps
Data Packet Size	20 bytes

3.4 Optimization

The scheme we describe above in setting initial *Bulk* parameters is just one basic option. In a system with a loose latency constraint, we can give some nodes higher initial *Bulk* numbers in order to optimize the energy-efficiency. There is one more energy-efficiency problem we stated earlier: unbalanced energy consumption. A sensor node closer to the sink will consume more energy than that far away from the sink because the data flow will pass through more frequently. [5] We can slightly reduce the unbalanced energy consumption by giving heavy load sensor node more initial *Bulk* number.

3.5 Traffic Adaptation

In the LMAC protocol, we have to know the arrival rate and the latency constraint to generate schedule for every sensor node. After initial and optimal operations, the schedule is fixed and will be performed periodically. If any events happen to this network topology such as sensor nodes running out of battery, sensor nodes' arrival rate being changed, one of sensor nodes is broken in the middle of the network chain, etc. What we have to do is just re-scheduling the network chain from the changed nodes to sink. All other nodes does not connect to those changed nodes will not be affected. However, the energy-efficiency performance of the LMAC protocol will decrease and not be optimal anymore.

4. Simulation and Performance Comparison

In this section, we simulate the LMAC protocol and compare it with SMAC and PMAC in different metrics. The simulation topology is a square mesh network with different sizes. The simulation is running on NS2 2.3.1. Our simulations will focus on some specific features: energy consumption on different traffic loads, and latency constraint over different number of sensor nodes. The setup parameters are shown in Table. 1.

In figure 4, we compared the total energy consumption under different numbers of sensor nodes (average arrival rate 0.05) over a mesh network. In this simulation, there are no certain data sources. Instead, every sensor node will sense data and forward it to the sink. The total energy consumption of LMAC protocol is 28% of that of SMAC when the network size is small. However, when the network size is larger, the total energy consumption of the LMAC protocol is 59% of that of SMAC. The difference of energy consumption is smaller because there are too many data packets flowing in the network. Thus, no matter when a sensor node wakes up, there are a lot of data packets ready to be sent in buffer. In figure 5, only the leaf nodes on the left and bottom edges will sense data over a grid network topology. In this setup, we can clearly see that the energy consumption of the LMAC protocol is much less than that of SMAC and PMAC. The total energy consumption of the LMAC protocol is 23% of that of SMAC and 50% of that of PMAC when the traffic load is small. In figure 6, we show that the energy consumption of the busiest sensor node in the network. In figure 7, we show the total energy consumption under different arrival rate. The energy consumption of the LMAC protocol is smaller more when the arrival rate is small. The performance difference is more obvious when the source nodes are only leaf nodes on edges. In figure 8, we show the total energy consumption under different latency constraints. The LMAC protocol indeed consumes less energy when the latency constraint is bigger. But when the latency constraint is larger than a threshold, the total energy consumption of the LMAC protocol is fixed because the idle listening caused by inaccurate prediction no longer exists. Or the other restrictions such as buffer size, transmission rate will bound the minimal energy consumption.

5. Conclusion

This paper considers the reasons causing idle listening and tries to avoid them by sacrificing latency to increase the arrival prediction accuracy. The LMAC protocol outperforms energy-consumption over SMAC and PMAC under a loose latency constraint and a light traffic load in wireless sensor network environment. It can operate successfully in high traffic load and high latency constraint as well.

In a light traffic load scenario, prediction-based protocols and constant sleep wakeup schedule protocols will suffer more from idle listening due to the uncertainty of incoming data. The LMAC protocol prevents the uncertainty by increasing the length of sleep cycles to guarantee the existence of transmissions when a sensor node wakes up. This method greatly reduces the total energy consumption. Moreover, in a loose latency constraint network environment, the LMAC protocol can use the extra latency to increase the prediction accuracy.

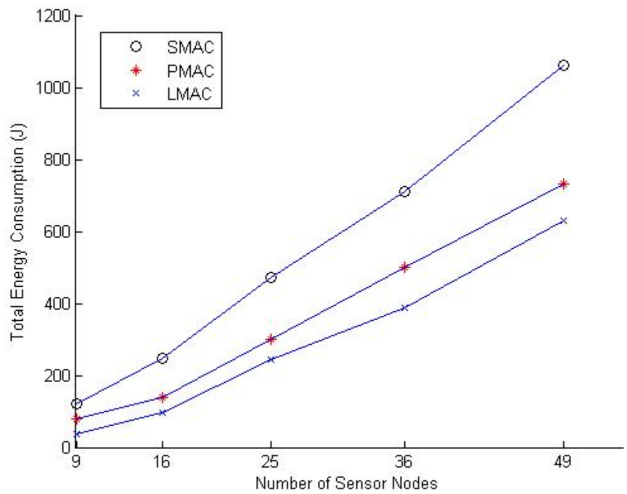

Figure 4. Total energy consumption under different numbers of sensor nodes

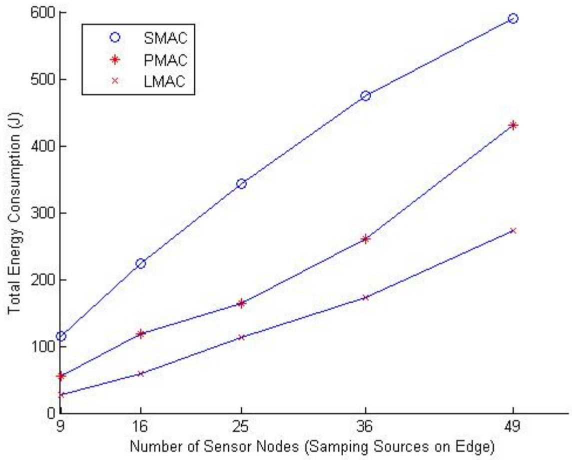

Figure 5. Total energy consumption under different numbers of sensor nodes & Source Nodes on Edge

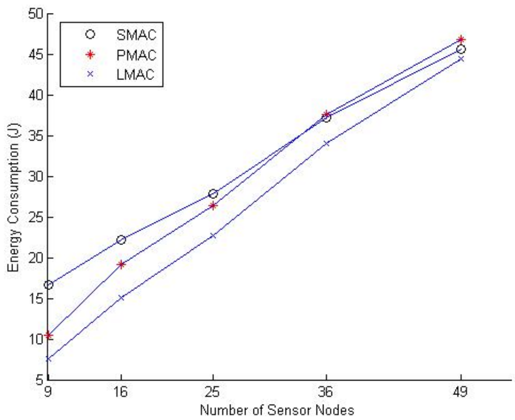

Figure 6. Energy consumption of the busiest sensor node under different numbers of sensor nodes

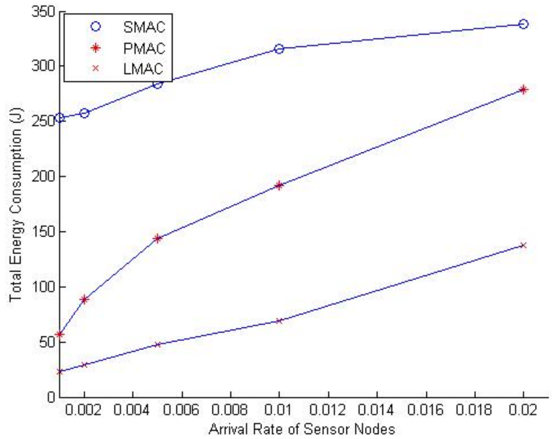

Figure 7. Total energy consumption under different arrival rates

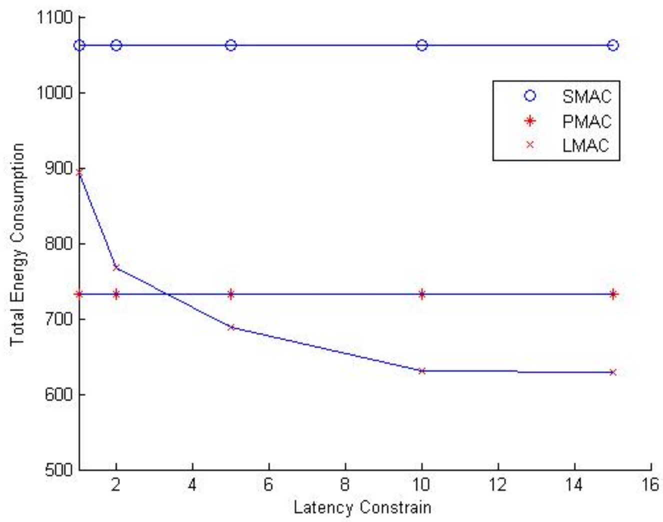

Figure 8. Total energy consumption under different latency constraint

Table 2. Extra energy consumption compared to the LMAC protocol under different numbers of nodes

MAC Protocol / Numbe of Nodes	PMAC	SMAC
9	122.22%	243.43%
16	42.86%	155.82%
25	21.78%	92.73%
36	29.06%	84.18%
49	16.34%	68.73%

Table 3. Average energy consumption per packet under different arrival rates

MAC Protocol / Arriva Rate	LMAC	PMAC	SMAC
0.001	0.0189	0.0460	0.2044
0.002	0.0235	0.0718	0.2079
0.005	0.0382	0.1161	0.2293
0.01	0.0558	0.1548	0.2546
0.02	0.1113	0.2250	0.2730

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