L-MAC: Location-aware MAC Protocol for Wireless Sensor Networks

Jason Chen\textsuperscript{1}, Yang Xi\textsuperscript{2}

\textsuperscript{1}Samsung Research, USA
\textsuperscript{2}Quanzhou University of Information Engineering, China

Abstract

This paper presents the design, implementation and performance evaluation of a location MAC protocol, called L-MAC, for wireless sensor networks. L-MAC is a combination of TDMA and CSMA while offsetting the high overhead of time slot assignment by allocating the time slots to sensor nodes based on their location information. This design avoids high computation complexity of time slot assignment incurred by node mobility and node failure. The area which the wireless sensor network occupies is divided into blocks and each block is associated with an inter-block time slot and an intra-block time slot. In the inter-block time slot, the sensor nodes stay active and receive the packets from nodes outside of the block. In the intra-block time slot, the sensor nodes communicate with peer nodes in the same block under CSMA. Sensor nodes stay sleep in all other time slots unless they have traffic to send. L-MAC is implemented and evaluated in NS-2.

I. INTRODUCTION

A radio channel is able to provide a certain amount of channel capacity if the access to the channel is well coordinated in time, frequency, code and space domains. Medium access control (MAC) plays a key role in wireless sensor networks. A good MAC protocol can improve the performance of wireless sensor networks in several aspects, such as channel utilization, end-to-end delay, throughput and energy consumption.

A sensor node is extremely limited in power, computational capacities and memory. Due to these basic constraints, design of MAC protocols is generally different to design of traditional MAC protocols. Energy consumption minimization becomes the most important objective other than objectives such as throughput maximization, delay minimization and fairness. The major sources of energy waste in wireless sensor networks include collision, overhearing, control
overhead and idle listening. When collision happens, a transmitted packet is corrupted and has to be discarded, and the following retransmissions increase energy consumption. Overhearing refers to a node picks up packets that are destined to other nodes, while idle listening refers to a node listens to receive possible traffic that does not exist.

Typical MAC protocols include time division multiple access (TDMA), frequency division multiple access (FDMA), code division multiple access (CDMA), and contention-based protocols such as carrier sensing multiple access (CSMA). TDMA can avoid the collision by scheduling transmission of different sensor nodes in different time slots. However, TDMA has several other disadvantages. Firstly, algorithm for efficient time slot assignment is not trivial. It often requires a centralized node to find a collision-free schedule. Furthermore, developing an efficient schedule with a high degree of channel utilization is very hard. Secondly, TDMA needs time synchronization. High-precision synchronization leads to high control overhead and energy consumption. Thirdly, wireless sensor networks may experience frequency topology change because of time-varying channel, node movement, node failure and physical environmental changes. The dynamic topology requires time slot assignment to be updated in a timely manner, which also leads to high computation complexity and energy consumption. Lastly, channel utilization by TDMA is low in case the traffic is low.

CSMA is a common MAC protocol in wireless networks. It becomes popular because of its simplicity, flexibility and robustness. It does not require clock synchronization and global topology information. It handles the dynamic topology, such as node joining and node failure, without extra operations. The disadvantage of CSMA is collision. Collision can happen in any two-hop neighbors of a sensor node. While collision among one-hop neighbors can be greatly reduced by carrier sensing before transmission, carrier sensing does not work beyond one hop. This problem is also call hidden terminal problem, which can cause a serious throughput degradation especially in high data rate sensor applications. Although RTS/CTS mechanism can alleviate the hidden terminal problem, it also introduces high control overhead.

In this paper, we present a new location-based MAC protocol, called L-MAC, for wireless sensor networks. L-MAC is a combination of TDMA and CSMA while reducing the high overhead of time slot assignment by allocating the time slots to sensor nodes based on their location information. This design avoids high computation complexity of time slot assignment incurred by dynamic topology of wireless sensor networks, such as node mobility and node failure. In our design, the area of interest is divided into blocks with equal size and each block
is associated with an inter-block time slot and an intra-block time slot. Sensor nodes obtain their block ID by comparing their location and the block coordinates, then obtain their time slots. In inter-block time slot, the sensor nodes stay active and receive the packets from nodes outside of the block. In the intra-block time slot, the sensor nodes communicate with peer nodes in the same block under CSMA mechanism. Sensor nodes stay sleep in all other time slots unless they have traffic to send. Time slots are reused throughout the whole networks to reduce the packet delay. The reuse rule is designed to minimize the inter-block interference by considering the inter-block distance and sensor node transmission range.

The paper is organized as follows. Section II gives a brief literature survey on MAC protocol designs for wireless sensor networks. Section III introduces details of L-MAC protocol design. The simulation results of L-MAC and comparison to existing MACs will be given in section IV. The conclusion is drawn in section V.

II. RELATED WORK

MAC protocol design receives a lot of attentions in sensor network research community. Various MAC protocols [1]-[11] were proposed in recent years.

S-MAC [1] introduces periodic listening and sleep mechanism to save the energy of sensor node. The listen time of sensor node is reduced by going into periodic sleep mode. During sleep, the node turns off its radio, and sets a timer to awake itself later. In order to reduce control overhead, neighbor nodes synchronize to each other so that they have the same duty cycle after synchronization. The disadvantage is that the latency is increased due to the periodic sleep of each node. Moreover, the delay can accumulate on each hop. The topologies of the experiments are five nodes forming two-hop networks and ten nodes forming a straight line.

T-MAC [2] is an adaptive energy-efficient MAC protocol for wireless sensor networks. It manages to save more energy by assigning the duty cycle of each node adaptively, other than fixed duty cycle in S-MAC. The novel idea of the T-MAC protocol is to reduce idle listening by transmitting all messages in bursts of variable length, and sleeping between bursts. The length is determined dynamically and the active time is ended when hearing for nothing for a given time. The topology of the experiments is 100 nodes forming a grid topology.

B-MAC [9] is a CSMA protocol for wireless sensor networks. It provides a flexible bidirectional interface to obtain ultra low power operation, effective collision avoidance, and high channel utilization. To achieve low power operation, B-MAC employs an adaptive preamble
sampling scheme to reduce duty cycle and minimize idle listening. B-MAC also supports on-the-fly reconfiguration and provides bidirectional interfaces for system services to optimize performance. The major features of B-MAC include using clear channel assessment (CCA) and packet backoff for channel arbitration, link layer acknowledgments for reliability, and low power listening (LPL) for low power communication. B-MAC achieves over 4.5 times the throughput of the standard S-MAC unicast protocol because B-MAC has lower per-packet processing and effective CCA.

Z-MAC [10] is a hybrid MAC protocol for wireless sensor networks that combines the strengths of TDMA and CSMA while offsetting their weaknesses. Z-MAC achieves high channel utilization and low-latency under low contention under CSMA and achieves high channel utilization under high contention and reduces collision among two-hop neighbors at a low cost under TDMA. Z-MAC has high cost in setup phase. During setup phase, the node would discover neighbors, obtain time slot and exchange local frame. The two-hop neighbor list is used as input to a time slot assignment algorithm. Z-MAC assigns time slots to every node in the network and ensures a broadcast schedule where no two nodes within a two-hop communication neighborhood are assigned to the same slot. The distributed time slot algorithm is called DRAND, which is based on RAND algorithm in [12]. Currently the time slot assignment algorithm only supports the static topology. The issues incurred by dynamic topology is left untouched. In one-hop Mica2 benchmark, the throughput of Z-MAC is larger than B-MAC when the contention gets intensive because Z-MAC runs on TDMA when high contention. In one-hop ns2 benchmark, the throughput of Z-MAC is larger than B-MAC when the contention gets intensive.

The packet delivery latency due to periodic sleep schedule is addressed in [11]. It is desirable to maintain the energy efficiency from duty cycling and reduce the sleep latency in the same time. The paper designs algorithm to assign time slots to minimize the maximum delay between sensor nodes that can communicate in an arbitrary pattern.

### III. L-MAC Protocol Design

As we mention in previous section, the MAC protocol design in wireless sensor network should be given special consideration on the energy efficiency. To best understand how we design our L-MAC protocol, we describe first three main energy wastes in MAC layer. Avoiding these energy wastes in protocol should be always kept in mind when we design MAC protocols for wireless sensor network.
• **Collision**: Collision is a major resource of energy waste. Collision directly leads to packet loss and retransmission, which obviously wastes energy. The ability to avoid collision almost determines the performance of MAC, especially the energy efficiency.

• **Overhearing**: The signal transmitted by the source can usually cover a region consisting of several nodes. If it is not broadcast, then some nodes may hear the signal that are not for him. The results is that these nodes will waste energy in receiving and decoding the packets though they are useless.

• **Idle Listening**: It has been identified in previous literature, the sensor spends almost the same power in idle as it does in receiving or transmitting modes.

In L-MAC, we implements several techniques to solve the three energy waste problems described above. To avoid the collision, we divide the whole network into small blocks in geography, assign time slot to them to avoid collision in block-to-block communication. To avoid the overhearing problem, nodes go to sleep mode once it hears some on-going communications between other nodes. To avoid idle listening, we let sensor nodes go to sleep when they are not transmitting or receiving packets. In the following, we describe L-MAC protocol in four parts.

A. **Network Division**

In L-MAC, the network is divided into small blocks each of which contains several sensors. The size and the shape of the block are application specific. In this work, we assume the network is divided into square blocks with the side length equal to the one-hop transmission range of the sensor as shown in Fig. [1](#).

Network division is performed at the design phase of the sensor network application. Since it is application specific, it remains unchanged unless the requirement of application changes. It will not affected by new node deployment or node failure, and it will not change even when nodes move around.

Obviously, any pair of one-hop communicating nodes can either be within the same block or within two different blocks. Accordingly, we define the following two concepts: inter-block communication and intra-block communication.

• **Inter-block communication** - if the node and its one-hop communicating neighbor are within different blocks. Obviously, in our network division, they must be within adjacent blocks, for an example, node $A$ and $B$ in Fig. [1](#).
• **Intra-block communication** - if the node and its one-hop communicating neighbor are within the same blocks, for an example, node $C$ and $D$ in Fig. 1.

Note that increasing or decreasing the size of block will affect the number of inter-block and intra-block communications.

### B. Slot Schedule Setup

In this section, we will show how we introduce the TDMA mechanism into the L-MAC protocol. We describe two important concepts and then discuss the algorithm for time slot assignment in L-MAC.

1) **Inter-/Intra- Block Slot**: L-MAC introduces TDMA mechanism into the protocol. Each block will be assigned two time slots, one for inter-block communication and the other for intra-block communication. We call the time slot *inter-block slot* if it is assigned to the block for its inter-block communication, and *intra-block slot* if it is assigned to the block for its intra-block communication. We restrict that any inter-block communication should be completed in inter-block slot, and any intra-block communication should be completed in intra-block slot. Note that, none of inter-block slot and intra-block slot are overlapped.

We give an example here to clarify how the above mechanism works. Let us revisit Fig. 1 and consider a block A. If two nodes in block A want to conduct a direct transmission, they

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1Direct transmission means they are within one-hop distance from each other
have to wait until the intra-block slot of A. If node e in block A and node f in block B want to conduct a direct transmission, node e has to postpone the transmission until the beginning of inter-block slot of B if node e is the sender and vice versa.

2) Time Slot Reuse: A very important reason that we divide the network into blocks geographically is that blocks far away from each other can share the same time slot (inter-block slot or intra-block slot or both) without interfering each other. For an example, in our configuration of network as shown in Fig. 1, block A and block C can share the same inter-block slot and intra-block slot without interfering each other as any node in block A is at least two-hop distance from any node in block C and vice versa.

Although there may be different criteria to design the algorithm that assign inter-block slot and intra-block slot to each block in the network, it is straightforward that one reasonable criterion is to design an algorithm that needs the least total number of time slots for the whole network as this reduce the delay of transmission. We will not focus on any specific algorithm to achieve this goal in order to leave our protocol more flexibility. However, we show an example of time slot assignment that is implemented in our work to reveal the basic idea.

3) Inter-block Slot Assignment: We depict 16 blocks in Fig. 1 separately in Fig. 2. If we assign time slot 1 to block A as inter-block slot, then to eliminate the interference, we have to assign different slots to A’s surrounding 8 blocks. As shown in Fig. 2 a total of 9 time slots are used for the inter-block slot assignment of these 9 blocks. Since in our configuration, the side length of each block is equal to the one-hop transmission range, we can reuse these 9 time slots in the blocks that are at least two-hop away, as illustrated in Fig. 2. Then the whole network will just need 9 time slot inter-block slot assignment.

|   |   |   |   |
|---|---|---|---|
| 2 | 3 | 4 | 2 |
| 9 | 1 | 5 | 9 |
| 8 | 7 | 6 | 8 |
| 2 | 3 | 4 | 2 |

Fig. 2. Example of inter-block slot assignment. The number in the block is the inter-block slot assigned to this block.
4) **Intra-block Slot Assignment:** In intra-block slot, node can only communicate with nodes in the same block. Therefore, the intra-block communication will not result in the interference to any other communication that is at least one-hop away. For our simple configuration of network division, a intra-block slot assignment can be given as in Fig. 3.

![Fig. 3. Example of intra-block slot assignment. The number in the block is the intra-block slot assigned to this block.](image)

As we can see in Fig. 3, the node in any block is at least one-hop away from the node in the closest block which share the same intra-block slot. The only possible collision occurs, for an example, when node \( a \) and \( b \) are both in activity. And with reuse of intra-block slot, we use only 6 time slot for the intra-block slot assignment of the whole network.

It should be noted that though we use time slots 1-9 for inter-block slot and time slots 10-14 for intra-block slot in the above example, we have no restriction on the assignment of inter- or intra-block slot. The only restriction that should be kept in mind is that any time slot assignment should avoid the interference resulted from the reuse of time slot. Actually, another assignment algorithm developed from the above example only needs just 9 time slots to complete the inter/intra-block slot assignment for the whole network.

C. **Inter-block Communication**

In this section, we describe how L-MAC protocol achieves energy efficiency in inter-block communication.

1) **First-In First-Receive (FIFR) Rule:** At the beginning of the inter-block slot of block \( A \), all nodes in will wake up and waiting for the incoming packet. To avoid collision, we do not allow two nodes to receive packets at the same inter-block slot if the packets come from different senders. Thus, to decide which node should keep awake, we design the First-In First-Receive (FIFR) Rule as below.
First-In First-Receive (FIFR) Rule: The node hearing the packet destined for itself at the earliest time will keep alive to receive the packet. It will response to that incoming packet so that every other node within the same block will be informed and they will go to sleep mode.

It is possible that there is no incoming packets for a block in the whole inter-block slot. Considering this situation, we set a threshold of $\theta$ where $0 < \theta < 1$ that when there is still no incoming packets after $\theta$ of one inter-block slot elapses, all nodes in the block will go to sleep.

D. Intra-block Communication

Since the number of nodes in one block is not large as we divide the network, we simply use CSMA/CA mechanism for the intra-block communications. All nodes will wake up in intra-block slot. They will possibly transmit packets to each other or exchange neighborhood information.

IV. Simulation Results

To evaluate the performance of L-MAC, we implement L-MAC and run Z-MAC, and S-MAC in NS-2 ([13]) respectively. We randomly distribute nodes in 800 $\times$ 800 m$^2$ area. We assume that the nodes know their own positions and we set the transmission range of 250m. The side length of each block is set to 200m. The packet size is 512 bytes unless otherwise specified. The simulation runs for 500 seconds. The metrics we used to compare different MAC schemes are: (1) energy consumption. We divide sensor node operation as four modes: sleep, active (idle), transmit, and receive. We calculate energy consumption in each mode and add them together. (2) end-end delay.

V. Conclusion and Future Works

In this paper, we presented a new energy and delay efficient MAC protocol, which features a simple, flexible implementation and robust to network changes and node failure. The beauty of L-MAC comes from its novel scheme and optimal time slot assignment algorithm. In L-MAC, time slots are assigned to each block and each block operates within two time slots: inter slot and intra slot. With optimal time slot assignment algorithm, L-MAC can achieves impressive energy and delay efficiency. L-MAC also successfully solve the issue of node movement and node failure. Simulation results demonstrate that L-MAC has a better energy efficiency than SMAC and L-MAC (with medium to high traffic), and that L-MAC always presents better delay properties. Future work may include parameter analysis and be extended to implement L-MAC
on sensor motes. We expect to compare and test our L-MAC protocol in a more comprehensive and realistic way.

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