

Manarat International University Studies, 2 (1): 141-151, December 2011
ISSN 1815-6754
© Manarat International University, 2011

Review of Energy-Efficient MAC Protocols for Wireless Sensor Networks

*Muhammad Sajjad Hussain**

ABSTRACT

This paper compares the performance and technology of several energy-adaptive MAC protocols of wireless sensor networks. It investigates S-MAC[1], T-MAC[3], B-MAC[5] and X-MAC[7]. In general, it is evident from the analysis that the performances of the newer MAC protocols are much better than those of earlier ones. Wireless Sensor Networks (WSNs) use battery-operated computing and sensing devices. A network of these devices will collaborate for a common application such as environmental monitoring. Energy conservation and self-configuration are primary goals of wireless sensor networks, while per-node fairness and latency are less important.

Keywords: *Energy, Efficient, MAC, Protocols, Wireless, Network.*

1. INTRODUCTION

Wireless sensor networking is an emerging technology that has a wide range of potential applications including environment monitoring, smart spaces, medical systems and robotic exploration. Such a network normally consists of a large number of distributed nodes that organize themselves into a multi-hop wireless network. Each node has one or more sensors, embedded processors and low-power radios, and is normally battery operated. Typically, these nodes coordinate to perform a common task.

Nodes in a wireless sensor network do not exist in isolation; rather they are embedded in the environment, causing network links to be unpredictable. As the surrounding environment changes, nodes must adjust their operation to maintain connectivity. For example, RF performance may be hindered by a sudden rainstorm or the opening and closing of doors in a building.

While traditional MAC protocols are designed to maximize packet throughput, minimize latency and provide fairness, protocol design for wireless sensor networks

* Assistant Professor, Department of CSE, Manarat International University, Gulshan, Dhaka, Bangladesh.

focuses on minimizing energy consumption. The goals of a Medium Access Control (MAC) protocol for wireless sensor network applications can be summarized as follows[5]:

- Low Power Operation
- Effective Collision Avoidance
- Simple Implementation, Small Code and RAM Size
- Efficient Channel Utilization at Low and High Data Rates
- Reconfigurable by Network Protocols
- Tolerant to Changing RF/Networking Conditions
- Scalable to Large Numbers of Nodes

1.1 Berkeley Motes

MICA2DOT mote has the following properties:

Size: 4cm x 4cm

CPU: 4 MHz, 8bit

512 Bytes RAM, 8KB ROM

Radio: 900 MHz, 19.2 Kbps, ½ duplex

Serial communication

Range: 10-100 ft.

Sensors: Acceleration, temperature, magnetic field, pressure, humidity, light, and RF signal strength

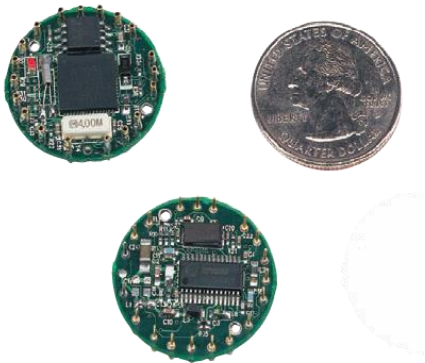


Figure 1 : MICA2DOT

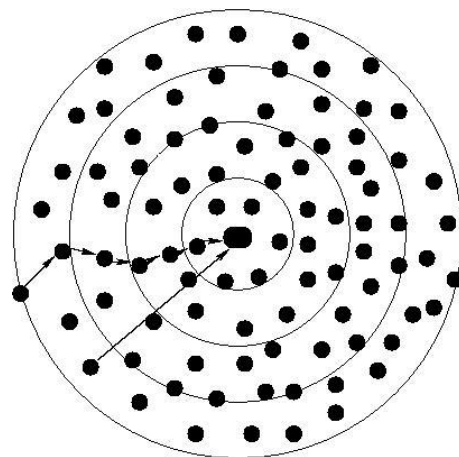


Figure 2:A Sensor Network (base-station at the center)

1.2 Salient features of a wireless sensor network

- A sensor network has an objective or a task
- Nodes collaborate to achieve the objective
- Many-to-one data flow

- Very high number of nodes, so each node may not have an id
- Energy-efficiency is extremely important
- Mainly use broadcast communications

1.3 Synchronous and Asynchronous Protocols

Standard MAC protocols developed for duty-cycled WSNs can be roughly categorized into synchronous and asynchronous approaches, along with hybrid combinations. These approaches are motivated by the desire to reduce idle listening, which is the time that the node is awake listening to the medium even though no packets are being transmitted to that node. Idle listening has been found in 802.11 protocols to consume substantial energy, and therefore must be avoided in WSNs. Synchronous protocols, such as S-MAC and T-MAC, negotiate a schedule that specifies when nodes are awake and asleep within a frame. Specifying the time when nodes must be awake in order to communicate reduces the time and energy wasted in idle listening. Asynchronous protocols such as B-MAC, WISEMAC and X-MAC, rely on Low Power Listening (LPL), also called preamble sampling, to link together a sender with data to a receiver who is duty cycling. Idle listening is reduced in asynchronous protocols by shifting the burden of synchronization to the sender[7]. When a sender has data, the sender transmits a preamble that is at least as long as the sleep period of the receiver. The receiver will wake up, detect the preamble, and stay awake to receive the data. This allows low power communication without the need of explicit synchronization between the nodes. The receiver only wakes for a short time to sample the medium, thereby limiting idle listening. Hybrid protocols also exist that combines a synchronized protocol like T-MAC with asynchronous low power listening. Z-MAC (Zebra-MAC) [8] is a hybrid MAC protocol, which combines a synchronized protocol with asynchronous low power listening.

A key advantage of asynchronous low power listening protocols is that the sender and receiver can be completely decoupled in their duty cycles. The simplicity of this design removes the need for, and the overhead introduced by, synchronized wake/sleep schedules. Studies of lower power listening have demonstrated its energy-saving capabilities. While the low power listening approach is simple, asynchronous, and energy-efficient, the long preamble in low power listening exhibits several disadvantages: it is suboptimal in terms of energy consumption at both the sender and receiver; it is subject to overhearing that causes excess energy consumption at non-target receivers; and it introduces excess latency at each hop. First, the receiver typically has to wait the full period until the preamble is finished before the data/ack exchange can begin, even if the receiver has woken up at the start of the preamble. This wastes energy at both the receiver and transmitter. Second, the low power listening approach suffers from the overhearing problem, where receivers who are not the target of the sender also wake up during the long preamble and have to stay awake until the end of the preamble to find out if the packet is destined for them. This wastes energy at all non-target receivers within

transmission range of the sender. Third, because the target receiver has to wait for the full preamble before receiving the data packet, the per-hop latency is lower bounded by the preamble length. Over a multi-hop path, this latency can accumulate to become quite substantial.

2.MAC Protocols of Wireless Sensor Network

Sensor network application scenarios and network traffic characteristics differ significantly from conventional computer networks. Typically data is sent periodically in short packets. There are a number of approaches to duty-cycling MAC protocols seen in the literature. Among these approaches this paper is going to discuss S-MAC (Sensor-MAC), T-MAC(Timeout-MAC), B-MAC (Berkeley-MAC), and X-MAC.

2.1 S-MAC

S-MAC [1] is a low power RTS-CTS based MAC protocol that makes use of loose synchronization between nodes to allow for duty cycling in sensor networks. The basic idea of this single-frequency contention-based protocol is that time is divided into fairly large frames. Every frame has two parts: an active part and a sleeping part. During the sleeping part, a node turns off its radio to preserve energy. During the active part, it can communicate with its neighbors and send any messages queued during the sleeping part, as shown in Figure 3 and 4. Since all messages are packed into the active part, instead of being 'spread out' over the whole frame, the time between messages, and therefore the energy wasted on idle listening, is reduced. Each active period is of fixed size, 115 ms, with a variable sleep period. The length of the sleep period dictates the duty cycle of S-MAC. At the beginning of each active period, nodes exchange synchronization information but that is not very critical. A clock drift of 500 μ s will not be a problem. Following the SYNC period, data may be transferred for the remainder of the active period using RTS-CTS.

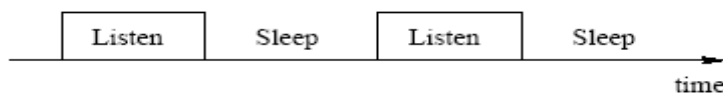


Figure 3: Periodic listen and sleep.

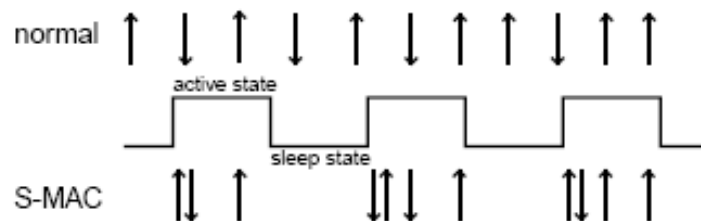


Figure 4: The S-MAC duty cycle; the arrows indicate transmitted and received messages; note that messages come closer together.

The protocol uses three techniques to achieve low power duty cycling: periodic sleep, virtual clustering, and adaptive listening. The nodes in the network periodically wake up, receive and transmit data, and return to sleep. At the beginning of the awake up period, a node exchanges synchronization and schedule information with its neighbors to assure that the node and its neighbors wake up concurrently. This schedule is only adhered to locally, resulting in a virtual cluster, which mitigates the need for system wide synchronization. Nodes that lie on the border of two virtual clusters adhere to the schedules of both clusters, which maintains connectivity across the network. After the synchronization information is exchanged, the nodes transmit packets using RTS-CTS until the end of the awake period and the nodes then enter sleep mode. In a follow up paper [2], the authors introduce adaptive listening to reduce latency. With this, when a node hears an RTS or CTS from its neighbor, it will wake up briefly at the end of the transmission. If the node is the next hop on the data path, waking up at the end of the transmission will reduce latency as the packet can be forwarded immediately without having to wait until the next scheduled awake period.

Drawbacks of S-MAC: Although S-MAC achieves low power operation, it does not meet the requirement of simple implementation, scalability, and tolerance to changing network conditions. As the size of the network increases, S-MAC must maintain an increasing number of neighbors' schedules or incur additional overhead through repeated rounds of resynchronization. This low power operation is achieved at the cost of reduced throughput, increased latency and overhead associated with synchronization.

2.2 T-MAC

T-MAC [3] improves on the design of S-MAC by shortening the awake period if the channel is idle. In S-MAC, the nodes will remain awake through the entire awake period even if they are neither sending nor receiving data. T-MAC improves S-MAC by listening to the channel for only a short time after the synchronization phase of the active period; there is a short window to send or receive RTS and CTS packets. If no activity occurs in that period, the node returns to sleep. If data is received, the node remains awake until no further data is received or the awake period ends. The authors show that, for variable workloads, T-MAC uses one fifth of the energy used by S-MAC. While this adaptive duty cycling reduces energy usage for variable workloads, these gains come at the cost of reduced throughput and increased latency. In homogeneous workloads, T-MAC and S-MAC perform equally well.

A comparison of duty cycling MAC protocols for WSNs is performed in [4]. Specifically, S-MAC and T-MAC are compared to standard CSMA/CA. S-MAC and T-MAC are also modified to use low power listening during the awake period, which further decreases the energy consumption of the protocols. While they show that T-MAC in combination with low power listening provides very low power communication, the

protocol still suffers from reduced throughput, high latency and overhead associated with synchronization. Drawbacks of the protocol are reduced throughput, increased latency and overhead associated with synchronization.

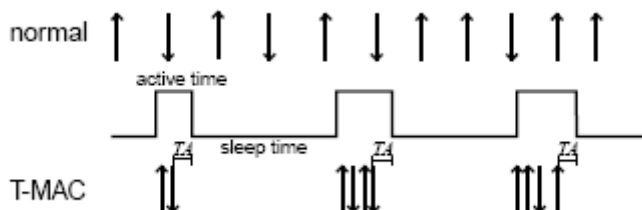


Figure 5: The basic T-MAC protocol scheme, with adaptive active times.

Basic Protocol: Figure 5 shows the basic scheme of the T-MAC protocol. A node will keep listening and potentially transmitting, as long as it is in an active period. An active period ends when no activation event has occurred for a time T_A . A node will sleep if it is not in an active period. Consequently, T_A determines the minimal amount of idle listening per frame.

The described timeout scheme moves all communication to a burst at the beginning of the frame. Since messages between active times must be buffered, the buffer capacity determines an upper bound on the maximum frame time.

Fixed Contention Interval: RTS transmission in T-MAC starts by waiting and listening for a random time within a fixed contention interval. This interval is tuned for maximum load. The contention time is always used, even if no collision has occurred yet.

RTS Retries: A node should retry by re-sending the RTS if it receives no answer. If there is still no reply after two retries, it should give up and go to sleep.

Determining T_A : A node should not go to sleep while its neighbors are still communicating, since it may be the receiver of a subsequent message. Receiving the start of the RTS or CTS packet from a neighbor is enough to trigger a renewed interval T_A . Since a node may not hear, because it is not in range, the RTS that starts a communication with its neighbor, the interval T_A must be long enough to receive at least the start of the CTS packet (Figure 6). This observation gives the length of the interval T_A : $T_A > C + R + T$ where C is the length of the contention interval, R is the length of an RTS packet, and T is the turn-around time (the short time between the end of the RTS packet and the beginning of the CTS packet). A larger T_A increases the energy used.

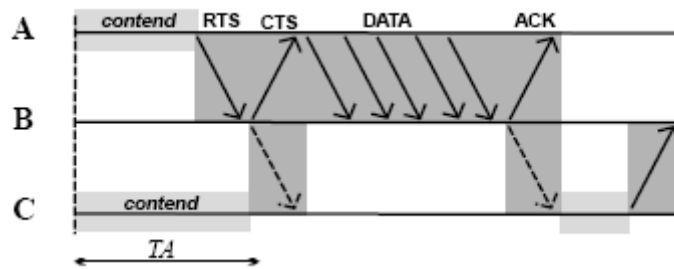


Figure 6: A basic data exchange. Node C overhears the CTS from node B and will not disturb the communication between A and B. T_A must be long enough for C to hear the start of the CTS.

Early Sleeping Problem: This problem is overcome by Future-Request-to-Send (FRTS) and Full-Buffer-Priority in T-MAC protocol.

2.3 B-MAC

B-MAC [5], developed at the University of California at Berkeley, is a CSMA-based technique that utilizes low power listening and an extended preamble to achieve low power communication. B-MAC duty cycles the radio through periodic channel sampling that are called Low Power Listening (LPL). Nodes have an awake and a sleep period, and each node can have an independent schedule. If a node wishes to transmit, it precedes the data packet with a preamble that is slightly longer than the sleep period of the receiver. During the awake period, a node samples the medium and if a preamble is detected it remains awake to receive the data. With the extended preamble, a sender is assured that at some point during the preamble the receiver will wake up, detect the preamble, and remain awake in order to receive the data. After reception the node returns to sleep. If no packet is received (a false positive), a timeout forces the node back to sleep. B-MAC also provides an interface by which the application can adjust the sleep schedule to adapt to changing traffic loads. The method of adaptation is left to the application developer. The authors show that B-MAC surpasses S-MAC and T-MAC protocols in terms of throughput, latency, and for most cases energy consumption. B-MAC is used as the default MAC for Mica2/TinyOS since version 1.1.3 and thus is becoming the standard MAC protocol for sensor network[6].

B-MAC also adopts Clear Channel Sensing (CCA) technique (Figure 7) to improve channel utilization. For effective collision avoidance, a MAC protocol must be able to accurately determine if the channel is clear, referred to as Clear Channel Assessment (CCA). Since the ambient noise changes depending on the environment, B-MAC employs software automatic gain control for estimating the noise floor. Signal strength samples are taken at times when the channel is assumed to be free—such as immediately after transmitting a packet or when the data path of the radio stack is not receiving valid data. Samples are then entered into a FIFO queue. The median of the queue is added to an

exponentially weighted moving average with decay α . The median is used as a simple low pass filter to add robustness to the noise floor estimate.

B-MAC provide ultra low power operation, effective collision avoidance, and high channel utilization. B-MAC supports on-the-fly reconfiguration and provides bi-directional interfaces for system services to optimize performance, whether it be for throughput, latency, or power conservation.

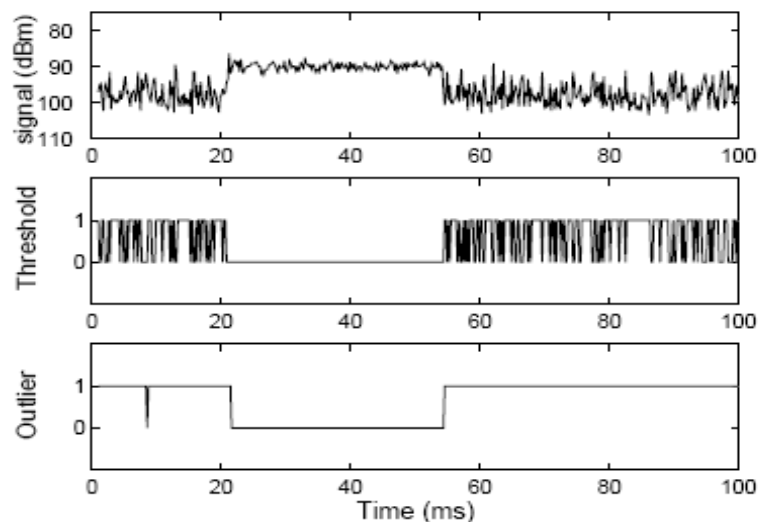


Figure 7: Clear Channel Assessment (CCA) effectiveness for a typical wireless channel.

The graph shown in Figure-7 is a trace of the received signal strength indicator (RSSI) from a CC1000 transceiver. A packet arrives between 22 and 54ms. The middle graph shows the output of a thresholding CCA algorithm. 1 indicates the channel is clear, 0 indicates it is busy. The bottom graph shows the output of an outlier detection algorithm.

Drawbacks of B-MAC: Overhearing issue is not solved. A long preamble increases the power consumption of all nodes in the sender's transmission coverage. The duty cycle and thus the preamble length are tunable, but the sender and the receiver should be tuned together. This requires a loose synchronization that is not easily achieved in a wireless sensor network.

2.4 X-MAC

X-MAC [7] is a low power, short preamble MAC protocol for duty-cycled wireless sensor networks. A key advantage of asynchronous low power listening protocol B-MAC is that the sender and receiver can be completely decoupled in their duty cycles. The **simplicity** of this design removes the need for, and the overhead introduced by, synchronized wake/sleep schedules. Studies of lower power listening have demonstrated its energy-saving capabilities [4, 5].

While the low power listening approach is simple, asynchronous, and energy-efficient, the long preamble in low power listening exhibits several disadvantages: it is suboptimal in terms of energy consumption at both the sender and receiver; it is subject to overhearing that causes excess energy consumption at non-target receivers; and it introduces excess latency at each hop. First, the receiver typically has to wait the full period until the preamble is finished before the data/ack exchange can begin, even if the receiver has woken up at the start of the preamble. This wastes energy at both the receiver and transmitter. Second, the low power listening approach suffers from the overhearing problem, where receivers who are not the target of the sender also wake up during the long preamble and have to stay awake until the end of the preamble to find out if the packet is destined for them. This wastes energy at all non-target receivers within transmission range of the sender. Third, because the target receiver has to wait for the full preamble before receiving the data packet, the per-hop latency is lower bounded by the preamble length. Over a multi-hop path, this latency can accumulate to become quite substantial.

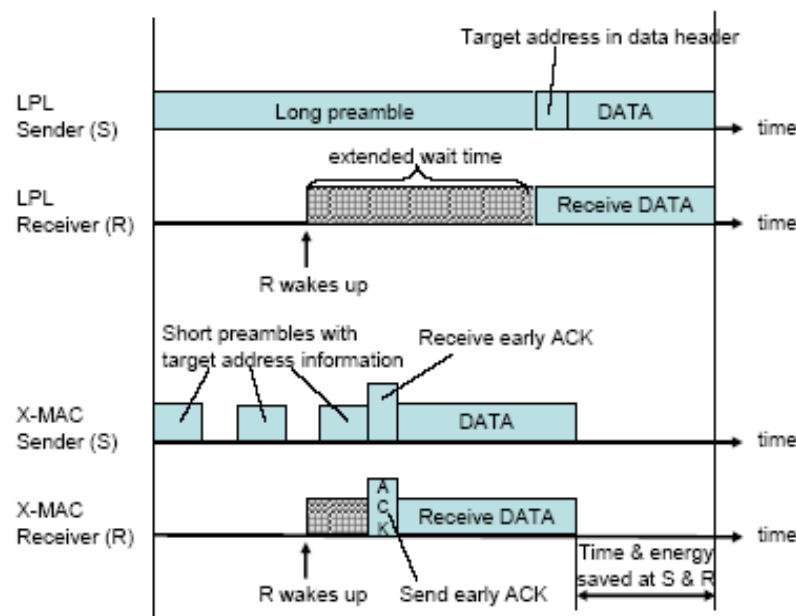


Figure 8: Comparison of the timelines between LPL's (B-MAC's) extended preamble and X-MAC's short preamble approach.

X-MAC employs a short preamble (Figure 8) to reduce energy consumption and to reduce latency. Address information of the target is embedded in the preamble so that non-target receivers can quickly go back to sleep. This solves the overhearing problem. Moreover, X-MAC use a *strobed preamble* to allow the target receiver to interrupt the long preamble as soon as it wakes up and determines that it is the target receiver. This short strobed preamble approach reduces the time and energy wasted waiting for the entire preamble to complete. XMAC results in significant savings in terms of both energy

and per-hop latency. Finally, X-MAC includes an automated algorithm for adapting the duty cycle of the nodes to best accommodate the traffic load in the network. Additional savings in energy and latency is achieved by this adaptation.

3. COMPARISON

Comparisons of various energy-efficient MAC protocols are shown below:

	Synchronous/ Asynchronous	Preamble	Energy Efficiency
S-MAC	Synchronous Protocol	No Preamble Used	Energy Efficient
T-MAC	Synchronous Protocol	No Preamble Used	More Energy Efficient than S-MAC
B-MAC	Asynchronous Protocol	Long Preamble Used	More Energy Efficient than T-MAC
X-MAC	Asynchronous Protocol	Short Strobed Preamble Used	More Energy Efficient than B-MAC

Table 1

CONCLUSION

This paper presents the evolution of the energy adaptive MAC protocols of wireless sensor networks. The paper compares the technology and performance of several synchronous and asynchronous MAC protocols of wireless sensor networks which include S-MAC, T-MAC, B-MAC, and X-MAC. The trend shows that the newer MAC protocols are gradually becoming more energy efficient.

REFERENCES

G. Halkes, T. V. Dam, and K. Langendoen. “Comparing energy-saving mac protocols for wireless sensor networks”. *ACM Mobile Networks and Applications*, 10(5):783–791,2005.

<http://webs.cs.berkeley.edu/tos/>.

I. Rhee, A. Warriier, M. Aia, J. Min. “Z-MAC: a hybrid MAC for wireless sensor networks”, 2005 ACM, SenSys '05, Nov 2005, San Diego, California, USA

J. Polastre, J. Hill, and D. Culler. “Versatile low power media access for wireless sensor networks”. In *The Second ACM Conference on Embedded Networked Sensor Systems (SenSys)*, pages 95–107, November 2004.

- M. Buettner, G. Yee, E. Anderson, R. Han. X-MAC: “A Short Preamble MAC Protocol for Duty-Cycled Wireless Sensor Networks”, Technical Report CU-CS-1008-06, , Department of Computer Science, University of Colorado, Boulder, USA, May 2006
- T. Van Dam and K. Langendoen. “An adaptive energy-efficient mac protocol for wireless sensor networks”. In Proceedings of the First ACM Conference on Embedded Networked Sensor Systems, Nov. 2003.
- W. Ye, J. Heidemann, and D. Estrin. “Medium access control with coordinated, adaptive sleeping for wireless sensor networks”. ACM Transactions on Networking, 12(3):493–506, June 2004.
- W. Ye, J. Heidemann, and D. Estrin.”An energy-efficient mac protocol for wireless sensor networks”. In 21st International Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM’02), New York, NY, USA 2002.