

A Self-adaptive Duty Cycle Receiver Reservation MAC Protocol for Power Efficient Wireless Sensor Networks

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Abstract

Objectives: In Wireless Sensor Networks nodes are deployed into hazardous environments with limited battery source. The nodes must operate with utmost power efficiency to continue performing critical tasks. **Methods/Statistical Analysis:** In order to be power efficient, the underlying MAC protocol of the network has to be designed to expend minimal energy during the functioning of the nodes. Most of the MAC protocols achieve energy efficiency by controlling the duty cycle. Self-adaptive duty cycle along with receiver reservation provides a viable means to reduce energy expenditure of the nodes. **Findings:** In this paper, we propose a receiver reservation MAC protocol that utilizes self-adaptive duty cycling which bring better power efficiency in WSN. The sleep interval of the nodes is regulated based on the self-adaptive factor. This factor is determined based on the packets received at the node in current and previous transmission cycles. **Application/Improvements:** Receiver reservation helps the network to avoid collisions and back offs. The self-adaptive nature of the MAC protocol enables the nodes to tune their duty cycle based on the data transmitted in the network.

Keywords: Collisions and Back Offs, Energy Expenditure, Receiver Reservation, Self-adaptive Factor, Sleep Interval, Transmission Cycles

1. Introduction

A sensor network consists of multiple detection stations called sensor nodes, each of which is small, lightweight and portable. Every sensor node is packed with a transducer, microcomputer, transceiver and power source. The transducer generates electrical signals based on sensed physical effects and phenomena. The microcomputer processes and stores the sensor output. The transceiver receives commands from a central computer and transmits data to that computer. The power for each sensor node is derived from a battery. Thus a wireless sensor network is a group of specialized transducers with a communications infrastructure for monitoring and recording conditions at diverse locations. Commonly monitored parameters are temperature, humidity, pressure, wind direction and speed, illumination intensity, vibration intensity, sound

intensity, power-line voltage, chemical concentrations, pollutant levels and vital body functions. The primary issues in designing MAC¹ protocols for wireless sensor networks are how to efficiently use the limited amount of energy. To build up a system that will keep running for years, the concern for wireless sensor networks designers are to use robust hardware and software, but also lasting energy sources.

The following are the main functionalities of a MAC protocol:

- a) Reliability: successful transmission of acknowledgment messages and retransmission between devices when necessary.
- b) Framing: Framing is used to define encapsulation and de- encapsulation of frame format for communication between devices.

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- c) Error control: It's used for controlling the error present in the upper layers by using error correction and detection mechanisms
- d) Flow control: Flow control prevents frame loss, overloaded receiver buffers from starting to end.
- e) Medium access: The main function of MAC protocol is to transmit easily data corruption through collisions. The sensor nodes use medium access for communication at any time.

The reasons of power wastage in a MAC protocol for wireless sensor networks are the following:

- a) Idle Listening: Listening to receive possible traffic that is not transmitted.
- b) Overhearing: It occurs when nodes pickup packets which are destined to other nodes.
- c) Control Packet Overhead: To transmit and receive control packets power is used due to these less useful data packets can be transmitted.
- d) Collision²: When some time the packet gets corrupted during transmission these packets need to be discarded and resent, so it increases energy consumption

The four types of communication patterns in wireless sensor networks are:

- i) Convergecast: In convergecast the node is formed as cluster and transmitted to a cluster head
- ii) Multicast: In multicast data is transmitted to a particular group of sensor nodes.
- iii) Logical gossip: Sending and receiving of data between sensor nodes within a specific range.
- iv) Broadcast: In broadcast base station is used to send the data to all nodes of wireless sensor network.

The MAC protocols can be broadly divided into two categories for sensor networks. One is Schedule³ based MAC protocols and other one is Contention based MAC protocols. In the scheduled MAC protocol depends on the Time Division Multiple Access (TDMA). In every slot, one and only node is permitted to transmit. Nodes are composed into groups. A focal point of every cluster has the cluster head. It is in charge of all communication inside the cluster and also for between cluster communication. It additionally deals with channel time division and time synchronization of nodes. The Frequency (FDMA) or

Code (CDMA)⁴ division can be utilized in order to avoid interference at intercluster communication. There are no collisions in the schedule-based protocols, as stand out node at once is permitted to transmit. There is additionally no overhearing or idle-listening. At the point when a node's time slot expires, it about-faces to the sleep mode. The drawback of these protocols is absence of peer-to-peer connection. Therefore, nodes can just communicate with a cluster head⁴. These protocols are likewise ineffectively scalable and adaptable. At the point when a node joins or leaves a cluster, the cluster head makes a beeline for rethink the entire framework timetable and synchronize all nodes inside the cluster. There is additionally colossal weight on the cluster head which must be a unit practicing run of the mill node performance. As a result of clock drifts in the cluster of nodes, the time synchronization should likewise be absolutely kept.

Fundamental methodology of Contention based MAC protocols are Carrier Sense Multiple Access (CSMA) and Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA)⁵. To acquire wireless channel for sending information on system MAC Protocol battle with each other to get wireless channel. The channel is accessed randomly so there is no need of coordination. At the point when the possibility of collision declines in any system than it expands performance of network. Shot of collision is diminished if a station sense the medium before attempting to utilize it by this approach the likelihood of collision is decreased. In the event that the channel is free, send information on the channel yet in the event that channel is not free it will sit tight for irregular measure of time. The guideline of CSMA is "sense before transmit". CSMA/CA keeps away from the collision utilizing three methodologies: the interface space (IFS), the contention window and acknowledgement. Favorable position of these MAC protocol is to build scalability and flexibility. Under this classification these protocols T-MAC⁶, S-MAC⁷, U-MAC are characterized.

The medium access control protocols for the sensor networks can be classified broadly into following categories as shown in Figure 1.

Contention-based protocols: Sender-initiated protocols: Packet transmissions are initiated by the sender node. Single-channel sender-initiated protocols: A node that wins the contention to the channel can make use of the entire bandwidth. Multichannel sender-initiated protocols: The available bandwidth is divided into multiple

channels. Receiver-initiated protocols⁸. The receiver node initiates the contention resolution protocol.

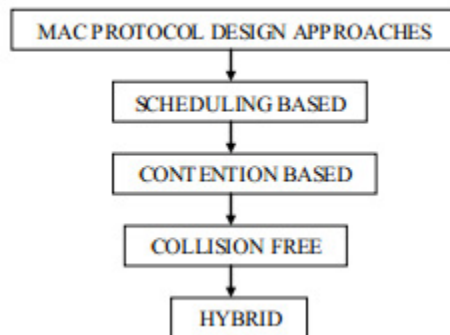


Figure 1. Classification of MAC protocol design approach.

Contention-based protocols with reservation mechanisms Synchronous protocols: All nodes need to be synchronized. Global time synchronization is difficult to achieve. Asynchronous protocols: These protocols use relative time information for effecting reservations.

Contention-based protocols with scheduling mechanisms Node scheduling is done in a manner so that all nodes are treated fairly and no node is starved of bandwidth. Scheduling-based schemes are also used for enforcing priorities among flows whose packets are queued at nodes.

S-MAC⁸ protocol is generally used for power consumption in wireless sensor networks. The basic design goal of S-MAC protocol is to minimize the power consumption, to support good scalability, and self-configurable. S-MAC reduces power from collision, overhearing, and control overhead. S-MAC is, composed of many small nodes assigned in an ad-hoc fashion. Communication between nodes done in a single base station. Nodes must be self-configure. S-MAC is dedicated to a single application. S-MAC reduces traffic and increase life time of the network. Applications will have long idle periods and can tolerate some latency.

In S-MAC communication between nodes occurs when protocol exchanges packets start with Carrier Sense (CS) to avoid collision. For unicast type packets uses Ready To Send and Clear To Send (RTS/CTS)⁹ packets. Data communication takes place on successful transmission of these packets. The nodes in these protocols have two states one is sleep state and other one is active/listen state. The nodes in S-MAC protocol will remain in listen state for 10 seconds for every 2 minutes. If no transmis-

sion or reception takes place between the nodes or if its neighbors are involved in communication it goes to sleep state. This sleep state in S-MAC reduces the overhearing and collision. After the completion of neighbor node transmission, the other nodes wake up for new transmission. By using RTS and CTS data transmission takes place and then node goes to sleep state and overcomes latency. This is known as adaptive listening and technique is called message passing.

When node goes to sleep mode it switches the radio off and sets timer to awake later. When timers expire, it wakes up. Selection of sleep and listen duration is based on application scenarios. All Neighboring nodes are synchronized together. Schedules are exchanged in nodes by broadcast. Multiple neighbors fight for the medium, once transmission starts and do not stop until it's completed.

2. Research Work

MAC¹⁰ is an existing protocol that is considered to be a promising approach at improving energy efficiency of nodes. In a typical MAC protocol, the participating nodes designated as senders and receivers remain active only for the necessary time for data transmissions and receptions. In other times, the nodes remain inactive or in sleep state. This wake up and sleep cycle is a very common attribute seen in most of the MAC protocols. EM-MAC different from rest of the MAC protocols in the way the nodes wake up and communicate each other to establish data transmission. A typical EM MAC contains its medium divided into multiple frequency channels. A node may wake up in any of the channels at any time. Each node uses the pseudo random sequence to catch the channel at the time of their wake up. The pseudo random sequence is unique at each node and its can be imitated by other nodes. This means when one node needs to send data to another, the sender node will be able to imitate and reproduce the pseudo random sequence of the to-be receiving node so as to determine when and where that receiving node will become active. Once determined, the sender node will also wake up at the same time and channel as the receiving node. The transmission begins with a Ready beacon from Receiver broadcasted to neighboring nodes. Sender nodes, if any nearby waiting to send data acknowledges the beacon from Receiver and then data is sent to receiver. If there are multiple senders trying to contact the receiver, only one sender succeeds in procuring the

receiver for transmission, while all other nodes back-off¹¹. The nodes that back-off attempt to contact the receiver in one of the forthcoming wake ups using exponential back-off algorithm. This back-off requires the node to attempt once again to communicate to receiver, though it is not guaranteed that by then the communication may succeed or the node may be subjected to back-off once again. This back-off causes significant energy drains in node in the attempt to communicate with receiver again and again till it succeeds.

RR-MAC (Receiver Reservation MAC protocol) inspired by this research work is equipped with strong features in it that brings out better results when compared to EM-MAC¹². RR-MAC targets at conserving the energy efficiency of nodes with inspiration from EM-MAC but in a way better than EM-MAC. In RR_MAC, as in EM-MAC, the nodes wake up in any frequency channel at any time which is determined by the pseudorandom sequence generated at each node. Every nodes pseudo random sequence can be imitated and reproduced at any other node to know the wake up time and channel of any other node. RR-MAC uses a versatile approach that completely eliminates back-offs thus saving energy life at nodes and it is implemented with pro-active intelligence that makes the nodes to operate on the edge when the network traffic is tough and demanding. On the other hand, it allows the nodes to relax and preserve their energy store when the network traffic is light and less demanding.

RR-MAC, as in EM MAC has its channel divided into several frequency channels. By means of a pseudo random sequence and the capability to imitate each other's pseudo random sequence, a node can determine another node's wake-up time and frequency channel. Sender nodes transmitting data to a receiver node find the wake up time and channel of the receiver. The senders register a request to transfer to the receiver. The requests are registered in a centralized registry. The requests are registered by Senders one after another, reserving the receiver for sending out transmission¹³ to the receiver one after another. When the receiver wakes up, the senders wake up in the order of the reservation made and complete the transmission and go back to sleep state, without having to wait to get hold of receiver, or having to undergo the trouble of competing for the receiver and face collisions in the attempt to compete.

As this approach of RR-MAC¹⁴ completely eliminates the need to compete and collide, there is significant reduction of back offs, which indicates there is no more

any necessity to re-attempt and get hold of receiver. Elimination of back-offs indirectly leads to conservation of the energy at the sender nodes. In a self-adaptive mode, RR MAC protocol adapts the duty cycle¹⁵ according to the traffic condition. When the packets inflow is high, it is inefficient for the senders and receivers to remain in sleep state for the same amount of time as they would do under less traffic. On the other hand, sensing the traffic and toggling between prescribed sleep times is also not a worthy idea for any kind of packets inflow. There needs to be an intelligent mechanism, where the sleep interval is continuously evolving and refining on par with the incoming traffic. RR-MAC precisely addresses this approach in a well-designed manner where the sleep interval is incremented or decremented exponentially with the increase or decrease in traffic. In a typical self-adaptive approach, the receiver upon completing the transmissions in the cycle goes to the sleep state. Before entering the sleep state, it computes the average data from senders in last 3 cycles and the time required transmitting that average data. This is done after every nth cycle periodically, where n is decided based on the network needs. For example, consider that the sum of all data sent by senders in last 3 cycles are 3000 packets. This computes to an average of 1000 packets per cycle. The time required for transmitting these 1000 packets is the projected transmission time for the receiver in coming cycles, which is denoted by T_{avg} . Preferred sleep time P_{sleep} for the network is set to one fourth of the projected transmission time, $P_{sleep} = 1/4 T_{avg}$. When the ratio of P_{sleep} / T_{sleep} increases by a factor of x, the actual sleep time T_{sleep} of the receiver is reduced by the same factor x.

$$\text{Self-adaptive factor } \alpha = P_{sleep} / T_{sleep}, \quad (1)$$

where, T_{sleep} is the current sleep time prevailing in network. P_{sleep} is the preferred sleep time. It is ideally set to be one fourth of T_{avg}

$$P_{sleep} = 1/4 * T_{avg}, T_{avg} \quad (2)$$

From the equation 2 the time required to transmit the average of all data transmitted in last n cycles.

The new sleep time for the receiver after self-adaptive correction is set as

$$T_{sleep} = T_{sleep} / \alpha, \quad (3)$$

where, T_{sleep} is the current sleep time, α is Self-adaptive factor of the network.

As seen above, when the Self-adaptive factor α increase, it indicates the traffic in the network increases.

It becomes demanding that the receiver kicks off from its sleep state sooner to wake up and cater to the transmissions. Thus, it is necessary to reduce the current sleep so as receiver remains in the sleep state for relatively lesser time and comes back again for transmissions.

1. Sender has data to transmit to a Receiver.
2. Sender A determines the wake up time T_r and wake up channel F_r of the receiver for the next wake up
3. Sender registers a RFT (Request For Transmission) in a centralized registry.
4. RFT registered for a duration of time from T_r till $T_r + T_{data1}$, where T_{data1} depends on the size of data in sender A
5. Another sender B also has data to transmit to the same receiver.
6. Sender B registers RFT for the receiver from $T_r + T_{data1}$ to $T_r + T_{data1} + T_{data2}$ where T_{data2} depends on the size of data in sender B
7. Other senders, if any, follow suit to register the RFTs
8. When receiver wakes up, senders transmit data in the order of their RFTs reserved.
9. Each sender is limited to a permitted transmission time λ . Any sender that cannot complete the entire data within time λ splits the remaining data δ .
10. Receiver switches to sleep state after all senders RFT are completed and transmission have ended.
11. Receiver self-adapts its sleep time based on the packet transmitted by senders during the current wake up and previous wake ups.
12. Receiver sleep time is adjusted by a factor α , proportionate to the data from senders' increase.

3. Experimental Results

RR-MAC is applied on a network comprising of various sources that intend to transmit data to a receiver. The important parameters of the network are given in Table 1. Mat lab is used for obtaining results. In a typical RR-MAC with 4 nodes transmitting to a Receiver, comparison is made between EM-Mac and RR-Mac performance.

Table 1. Network attributes

Attribute	Value
No. of Nodes	5
Transmission Speed	100 Kbps

EM-MAC¹⁶ which operates with a fixed sleep time was compared with Self-adaptive RR-MAC. As seen from the Figure 2, as the time progresses, RR-Mac is able to sense the packet¹⁷ arrival from senders and adjusts the sleep time. By doing so, the receiver is subjected to lesser sleep time and remains awake for a longer time. This allows the senders to complete the transmissions faster in RR-MAC as compared to EM-MAC and transmit more number of packets.

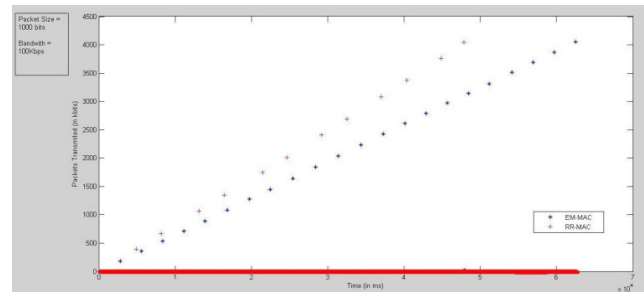


Figure 2. EM-MAC with sleep interval 1000ms vs Self-adaptive RR-MAC with four senders transmitting.

The sleep time of the EM-Mac is reduced by half to 500ms to see if this reduced sleep time will favor the EM-MAC for faster transmission than RR-MAC. But, as seen in Figure 3, EM-MAC is able to transmit more number of packets as compared to previous scenario with 1000ms. The number of packets transmitted by EM-MAC is nearly closer to RR-MAC after halving the sleep interval. Nevertheless, EM-MAC does not perform any better than RR-MAC.

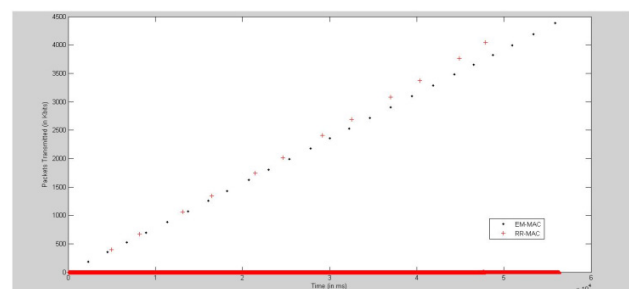


Figure 3. EM-MAC with sleep interval 1000ms vs Self-adaptive RR-MAC with four senders transmitting.

The senders in the network are then increased to six and the sleep¹⁸ time of EM MAC is maintained at 500ms, the performance of both the MAC protocols is observed. As, the nodes increases, EM MAC start to perform poorly when compared to EM MAC in 4 nodes as in previous

Figure 3. When compared to previous Figure 3, the Figure 4, shows EM-MAC is not as good as earlier, because the increase in the number of nodes causes more collisions and back-offs. This set back the performance of EM-MAC.

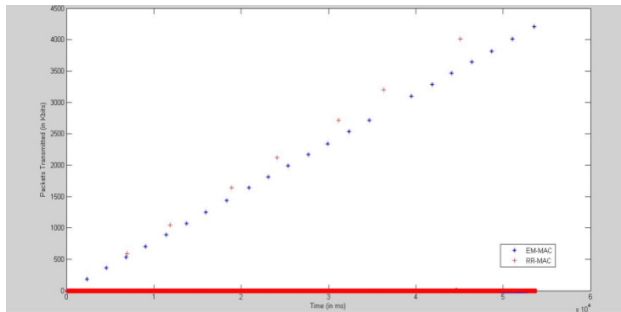


Figure 4. EM-MAC with sleep interval 500ms vs Self-adaptive RR-MAC with six senders transmitting.

In the Figure 5, RR-MAC is compared with EM_MAC with sleep time 500ms and again EM_MAC with sleep time 1000ms. EM_MAC with 500ms performs better and nearly well as RR_MAC. Whereas, EM_MAC¹⁹ with 1000ms lags far behind. On the other hand, RR-MAC can perform well because of its self-adaptive behavior.

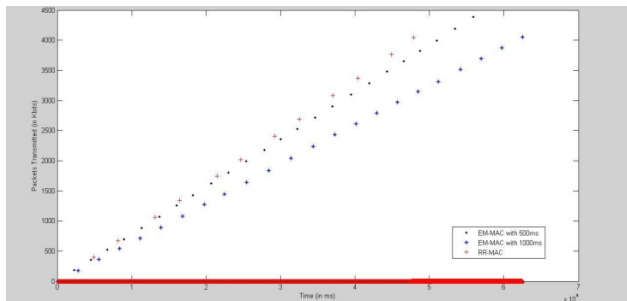


Figure 5. EM-MAC with sleep interval 500ms and 1000ms vs Self-adaptive RR-MAC with four senders transmitting.

4. Conclusion

RR-MAC protocol enables the senders to transmit data to receiver with reduced collisions. Reduced collisions indicate reduction in the back offs which gives considerable savings in energy for the senders. The self-adaptive nature of RR-MAC protocol leverages the Receiver to adjust the sleep interval based on the network needs. This makes the network perform very efficiently since the Receiver caters to the senders needs preemptively. In future work, the self-adaptive behavior will be refined further so that the

RR-MAC protocol can precisely tune its sleep intervals and wake up intervals. Further, a mechanism to predict the upcoming packets will be provided to complement the self-adaptive nature of RR-MAC protocol.

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