

A Survey on Energy Efficient Contention based and Hybrid MAC Protocols for Wireless Sensor Networks

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Abstract

Backgrounds/Objectives: The objective is to determine an energy efficient, MAC protocol for wireless sensor networks.

Method/Statistical Analysis: All the sensor nodes communicate through a Medium Access Protocol (MAC). Energy is wasted while communicating data among sensor nodes. Since wireless sensors nodes are unwired they do not have any means of external power supply and it is only battery operated. Hence designing energy efficient MAC Protocol to expand battery span is very important. A thorough survey on various contention based and hybrid protocols has been done in this paper. **Findings:** Hybrid MAC Protocol implements the combined advantages of CSMA and TDMA. A clear comparison of some of the best Hybrid MAC protocols and contention based protocols has been explained in this paper.

Applications: Based on the performance of various MAC protocols, it is found that contention based MAC protocols can be implemented for low traffic level networks, hybrid MAC protocols can be implemented for high traffic level networks including industrial critical processes.

Keywords: Energy Efficiency, Latency, Packet Delivery, Throughput

1. Introduction

Wireless Sensor Networks is employed in various applications, almost in every field, and increasingly used in industrial automation. A typical sensor mote has three main operating units, a sensing unit, an embedded processor and a transceiver as shown in Figure 1. These sensor motes have batteries which have life span of about merely a year. A typical AA battery stores about 2.2-2.5 Ah at 1.5V. So, various MAC Protocols have been proposed to use the available energy of a sensor node in an efficient manner.

MAC layer is a sub layer in the Data Link layer of the OSI model which is responsible for framing, error control and addressing of data. The earlier proposed MAC protocols were classified as contention based and schedule based protocols. Both the protocols found various

advantages and disadvantages at different contention levels.

1.1 Requirements of a Good MAC Protocol

- **Traffic Load:** It depends on the reporting speed of the sensor nodes. The MAC Protocol is expected to offer reliable delivery when the traffic load increases¹.
- **Energy Efficiency:** Battery powered sensor nodes becomes extremely complicated when it comes to recharging. Sometimes it is better to replace the sensor node rather than recharging them. So MAC protocols must be designed to be energy efficient¹.
- **Latency:** The third is latency. Latency requirement depends on the field of application. The detected

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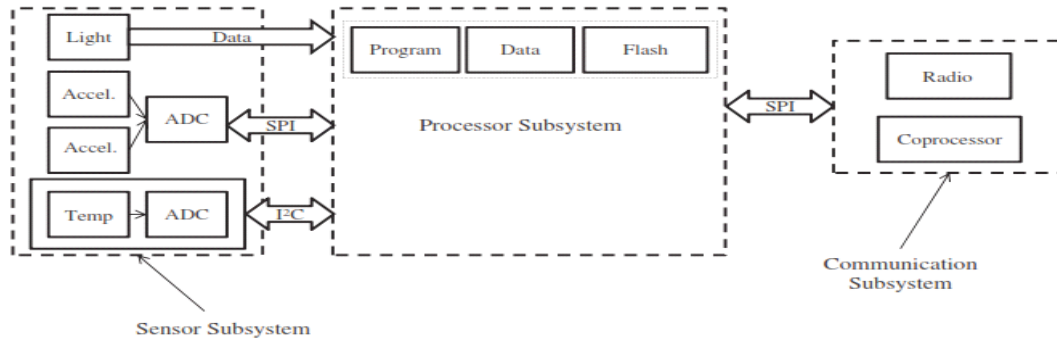


Figure 1. Sensor Node Architecture.

events must be reported to the other nodes in real time in the sensor network as soon as possible.

- **Throughput:**

$$U = \frac{\text{Throughput}}{\text{Maximum data transmit rate}}$$

It is the data transferred in unit time. For different applications the throughput requirement varies. A few sensor network applications require every available data to be processed without missing any of it. In such sensor applications it is better that sink node receives more amount of data. A best MAC protocol is described by better utilization. Utilization is the probability of which exactly one packet is present in one time slot in every successive time slots (i.e) no time slot is left unused. This is given by,

- **Fairness:** In several sensor network applications, it is compulsory to confirm that the sink node receives information from all sensor nodes efficiently. It is simply, the range of utilization of a particular channel. By minimizing the energy wastage, fairness can be increased. The fairness index is calculated as,

$$F = \frac{(\sum X_i)^2}{N \sum X_i^2}$$

Where X is the throughput is achieved by node i and N is the total number of nodes in a network.

- **Fault Tolerance:** The sensor nodes are either deployed as fixed nodes or mobile nodes. In either of the cases topology varies due to dead nodes or adding of new nodes. The network must adapt to varying topology without affecting the throughput.

1.2 Factors Causing Energy Degradation

The battery of a sensing node is finite. Hence considering the energy consumption during data communication is very important.

- **Sensing:** Sensing of various field parameters like temperature, humidity, flow, pressure etc. in various applications require energy from the battery.
- **Collision:** Sometimes a packet might get corrupted or interrupted during transmission, so these packets need to be discarded and resent, this leads to increased energy consumption².
- **Control Packet Overhead:** Energy is required for sending and receiving control packets due to this, less useful data packets can be transmitted causing overhead of data in nodes.
- **Overhearing:** The next one is overhearing which means that a node picks up packets that are destined to other nodes².
- **Idle listening:** This is a situation where nodes wait for a longer time to receive packet from other nodes. Many protocols have proved that idle listening consumes about 50-100% of the energy required to that of receiving³.

2. Contention based MAC Protocols

2.1 S-MAC

The goal of the sensor MAC (S-MAC) protocol is to reduce unwanted energy consumption, while providing good scalability and collision avoidance. S-MAC imple-

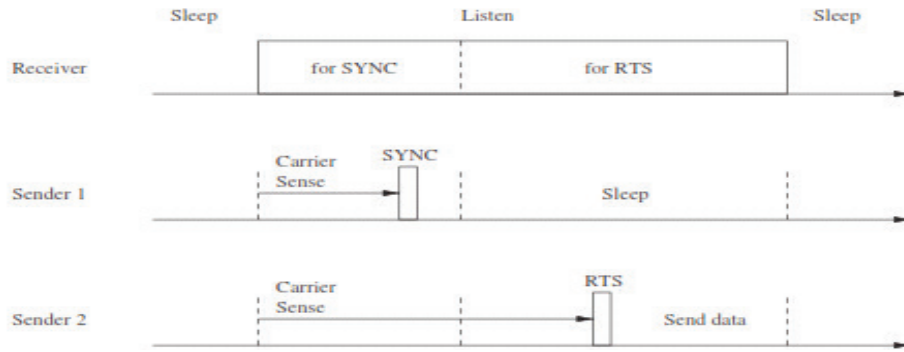


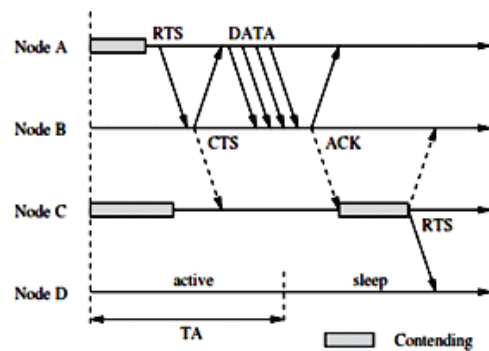
Figure 2. Data exchange in a Sensor MAC.

ments a duty-cycle approach, that is, nodes periodically transits between a listen state and a sleep state. Each node chooses its own schedule and nodes synchronize their schedules such that they listen or sleep at the same time^{4,5}. In this case, nodes using the same schedule are considered to belong to the same virtual cluster, but no real clustering takes place and all nodes are free to communicate with nodes outside their clusters. Contention for the medium involves the RTS/CTS scheme. The Figure 2 given below provides a clear idea of the working of S-MAC.

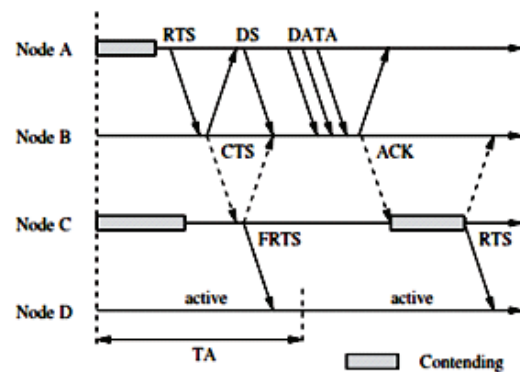
In summary, S-MAC is a contention-based protocol that utilizes the sleep mode of wireless radios to save energy for throughput and latency. When compared with IEEE 802.11 MAC, it is seen that S-MAC out performs IEEE 802.11 at light traffic case, whereas during high traffic SMAC consumes more energy than IEEE 802.11 because of synchronization overhead of sending and receiving SYNC packets and also for allowing more latency⁶. Collision avoidance is based on RTS/CTS and NAV, which is not used by broadcast packets, thereby increasing the collision probability. Finally duty cycle parameters (sleep and listen periods) are decided beforehand and may be inefficient for the actual traffic characteristics in the network.

2.2 T-MAC

The listening period of S-MAC is of fixed duration, that is, if there is only little traffic, this will result in wasting useful energy. On the other hand, if traffic is heavy, the fixed duration is just not enough. Therefore, the Timeout MAC (T-MAC) protocol is a variation of S-MAC that uses an active period that adapts to traffic density⁷. Nodes wake up during the beginning of a slot to listen very briefly for activity and returns to the low power sleep mode when



(a) The early sleeping problem in T-MAC



(b) The future-request-to-send technique in T-MAC

Figure 3. (a) Data exchange in T-MAC, (b) Data exchange in T-MAC.

no communication has been observed to minimize idle listening

When a node either transmits or receives or even if it overhears a message, it stays awake for a brief period of time after completion of the message transfer to check

if more traffic can be possible. The brief timeout period allows a node to return to the sleep mode as quickly as possible. To reduce potential collisions, each node waits for a certain period of time within a fixed contention period before the medium is accessed. The minimum time a node remains active to listen for activity is expressed as TA and it has to be long enough to hear a potential CTS from one of its neighbors.

Assume that node a sends message only to node B, node B sends to node C and consider the above given Figure 3. If node C wants to send a message to node D, it has to contend for the medium and may lose to either node B or to node A. While node C stays awake after overhearing node B's CTS message and its intended receiver (node D) is not aware of C's intention to transmit data and therefore returns to the sleep mode after TA is over. This sort of a problem is referred to as the early sleeping problem, and one possible solution to this problem is the Future-Request-To-Send (FRTS) technique, a node with pending data can inform its intended receiver by transmitting a future-request-to-send (FRTS) packet as soon as possible after overhearing a CTS message. Figure 3. Shown above explains the early sleeping problem and FRTS. Node D, upon receiving the FRTS message, knows that node C will try to send data to it and will therefore remain active. In T-calculated MAC, nodes send messages as bursts of variable length and sleep between such burst periods in order to conserve energy.

TA was taken as $TA=1.5x(C+R+T)$ to overcome early sleeping problem, where C is the level of contention level, R is the length of an RTS packet and T is the turn around time(short time between the end of the RTS packet and the beginning of CTS packet).The FRTS mechanism increases throughput by 75%⁷.

Both S-MAC and T-MAC concentrate message exchanges to small length of time, which results in inefficiencies under high traffic loads. In T-MAC, nodes that are not required to exchange data also stay awake and waste energy. Finally, intended receivers stay awake using messages that indicate future transmissions, which can significantly increase the idle listening times and therefore energy consumption of nodes. S-MAC can transmit only one packet in a frame, causing high latency.

2.3 B-MAC

B-MAC is a carrier sense multiple access with collision avoidance MAC protocol for WSN. In order to achieve low power consumption an adaptive preamble sampling

scheme to reduce duty cycle and idle listening is implemented. Aspects such as enabling and disabling the use of Clear Channel Assessment (CCA) or acknowledgments, setting preamble lengthened listening intervals are carried out⁸. It uses the asynchronous duty cycle mechanism and sends a long continuous preamble for communication. It performs CCA (Clear Channel Assessment) before communication. B-MAC outperforms S-MAC in energy efficiency but does not produce fairness of packet delivery. As the number of nodes increases channel contention and capture effect causes B-MAC's performance to outperform S-MAC's performance.

3. Hybrid MAC Protocols

Hybrid MAC Protocol is a combination of both contention based and schedule based approach of MAC protocols. TDMA (Time Division Multiple Access) is a schedule based MAC protocol which has been reviewed to be best during high traffic condition avoiding much of colliding problems whereas it suffers certain disadvantages as it needs global synchronization, does not easily adapt to changes in network topology and it is difficult to ascertain interference among neighborhood nodes (interference irregularity). CSMA (Carrier Sensing Multiple Access) is a contention based MAC Protocol which provided fine results during less traffic levels whereas experienced hidden terminal problems and hence chance of packet collision is more. Below we have listed a set of various Hybrid MAC Protocols and its performance.

3.1 ADV-MAC

Even Hybrid MAC protocols where we combine TDMA/CSMA approach, also suffers energy inefficiency due to idle listening. ADV-MAC uses the concept of advertising for data contention and hence tries to minimize the energy lost in idle listening without compromising for throughput and latency. It also provides synchronization during transmission.

ADV-MAC has four periods. A fixed sync period and an Adv period then a variable data and sleep period⁹ which is explained clearly in the Figure 4 given above. The analytical model of ADV-MAC was analyzed and it is found that it overcame the performance of earlier proposed ADV-MAC¹⁰. Even though it produced better performance than S-MAC and T-MAC, the arbitrary value of ADV period as proposed in⁵ failed to meet optimization.

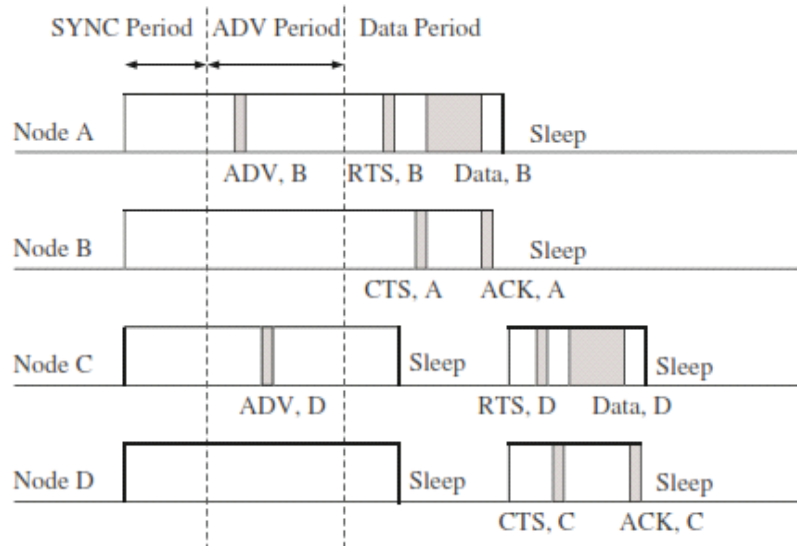


Figure 4. ADV-MAC.

The analytical model outperformed older ADV-MAC and resulted in 31-51% less power consumption. Better PDR performance was obtained. During the ADV period, the node transmits ADV packet which intimates the receiver about the data transmission and during the DATA period only the intended receivers will be awake to accept the data and the rest of the nodes are in the low power sleep mode. As we increase ADV period, every node gets an equal chance to transmit data thus avoiding idle listening period. Packet Delivery Ratio was found to increase to almost 100% as during small duration of ADV period, only few nodes were able to transmit ADV packets.

ADV-MAC had two major draw backs.

- Since every node were assigned slots in the ADV period, time remaining in the data period of the frame is not enough to accommodate all the nodes that successfully transmitted ADV packets.
- Since no ACK is sent for ADV packets, in case of any collision the transmitting node and receiver node is not intimated, hence transmitting node is awake and receiver is in sleep mode, hence data is sent only in the next frame.

3.2 X-MAC

This is an asynchronous MAC protocol for short duty-cycled wireless sensor network. XMAC posses short

Preamble packets instead of extended preambles as in B-MAC and piggybacks the receiver address¹¹. Former reduces latency and energy consumption. Since a receiver is capable of knowing that if the packet is destined to itself before actually receiving, it can either switch off the radio or send an ACK to the sender. In advance in the latter case the sender stops sending the preamble and focuses in sending the data. To study the performance of X-MAC's throughput at various network conditions, a Markov model was designed in¹¹. X-MAC avoids synchronization overhead and hence is proved to be energy efficient. A combination of X-MAC/CA focuses in maximizing randomized transmission in overcrowded networks and to avoid collisions. It is reviewed through simulations that nearly 30% improvement in throughput was achieved when compared to the earlier proposed X-MAC¹².

3.3 Y-MAC

This is a CSMA/TDMA based light-weight channel hopping mechanism focusing mainly on low power listening approach. Y-MAC avoids redundant channel allocation by not assigning fixed channels to the nodes. When a traffic burst occurs, a receiver and the capable senders hop to one of the other available channels, according to a predefined hopping sequence. Because these packets are carried over additional channels, each node has maximum possibility to receive at least one message on the base channel.

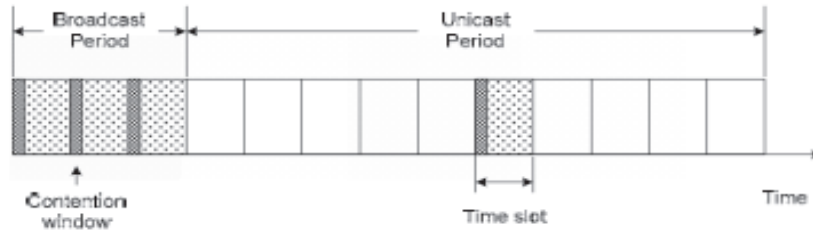


Figure 5. Frame structure of Y-MAC.

One disadvantage of this protocol is that if two nodes positioned within a one hop distance are being located on different channels, then they still have to communicate via a bridge node. This accounts to increase in packet latency and additional energy consumption by bridge nodes¹³. In most of the commercial radio transceivers available for WSNs, energy consumption while receiving is even greater than while transmitting due to the de-spreading and error correction techniques. To avoid this problem, Y-MAC was proposed. Determining the number of time slots is important because there is a relationship between the number of time slots and the delivery latency in proceeding this protocol. The Frame structure of Y-MAC is shown in Figure 5. The more time slots, the more nodes can be allocated exclusive time slots to, but delivery latency increases due to the very long length of the frame period. An other approach is to increase the number of possible time slots using multiple channels.

The sensor nodes synchronize their forth coming timer events by exchanging the time remaining in the current frame period and not just agree on a common clock (i.e) the time remaining to the start of the next frame period, and the sequence number originated from the sink node. This scheme is implanted to control time synchronization over head. If a node has not received any control messages during a predefined time, it is considered to be detached from the network and hence goes to sleep mode.

This scheme is energy efficient under light traffic levels, since every node contends the medium only during the broadcast time slots and the unicast receive time slot. Under heavy traffic conditions, many unicast messages may have to wait for a certain time in the message queue. To overcome this problem, we propose a light-weight channel hopping mechanism that exploits multiple channels to reduce the packet delivery latency. The Figure 6.given below explains this technique.

In Y-MAC protocol, the average duty cycle remaining is reduced because the overhearing problem is reduced by allocating receive time slots to the nodes.

The latency of LPL is significantly higher than the other protocols, because a sender has to send a preamble much longer than the sleep interval to wake up a receiver. In Y-MAC and Crankshaft the delivery latency is higher than the average delivery latency of half of the frame length. Y-MAC achieves good reception rate even under high traffic levels, while the other single channel MAC protocols suffer due to limited reception bandwidth.

3.4 Z-MAC

Zebra MAC focuses on combining the advantages of CSMA/TDMA approaches. It adapts easily to the level of contention in the network. CSMA suffers hidden terminal problem within one hop neighbors whereas Z-MAC applies CSMA for two hop neighbors overcoming the hidden terminal problem using RTS/CTS. This technique reduced overhead by about 40% - 75% of channel capacity¹⁴.

It implements a channel reuse scheduling algorithm using Distributed RAND, which allocates slots for all the nodes in the network. A single slot can be owned by many nodes but only the owner can transmit at first the next priority is given to non owners. This is clearly explained in Figure 7 shown above. It uses a ping message and DRAND technique¹⁵ to discover its one hop and two hop neighbors. Even if the topology changes, a local slot assignment is carried out without disturbing the main slot. It allows more than one node to own a time slot.

Since this protocol involves one hop and two hop neighbors, it does not need global time synchronization thus local synchronization (i.e) information about the neighbor nodes is enough. This local synchronization is

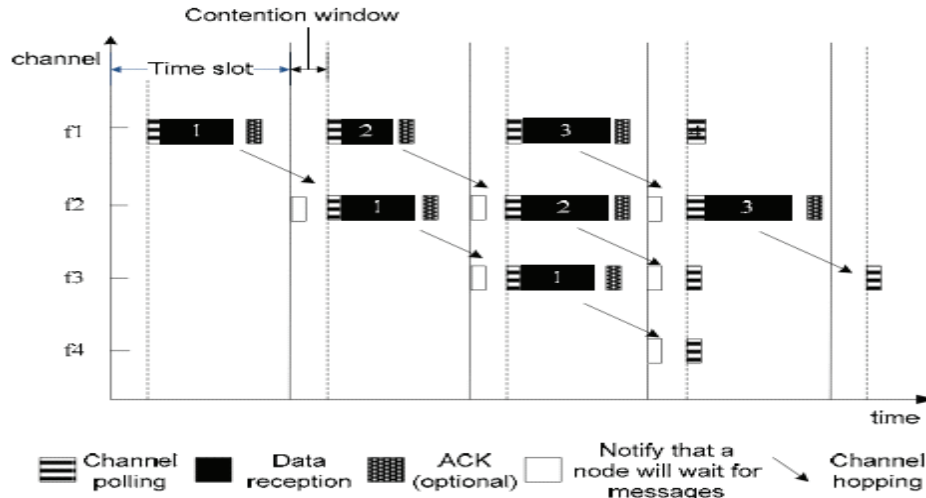


Figure 6. Multi hop mechanism in Y-MAC.

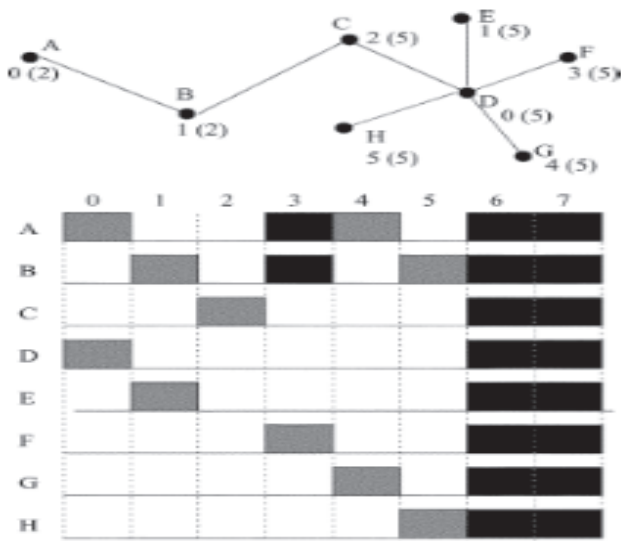


Figure 7. DRAND technique in Z-MAC.

carried on by adjusting its frequency based on current data rate and response budget.

Z-MAC has two phases a set up phase and a Z-MAC phase. It follows the sequence, RTS, CTS, DATA, ACK. During the set up phase it runs the following steps of discovering the neighbors, assigning slots, local frame exchange and global time synchronization. During the Z-MAC phase, nodes forward the frame size, slot number to two hop neighbor and maintain synchronization. Each node has its own local time frame.

Z-MAC works under two modes namely a Low Contention Level (LCL) which implements CSMA approach to access the channel and a High Contention Level (LCL) which uses TDMA approach. These two modes are implemented using back off's algorithm and CCA (Clear Channel Assessment) interfaces of a B-MAC, a default MAC for MICA-2 Mote.

Z-MAC shows 40% higher fairness index and latency it was reviewed to be same as that of B-MAC. It finds better efficiency during high contention level, providing better channel utilization at variable loads. A major drawback is it does not compromise for energy inefficiency during low contention levels.

3.5 ER-MAC

ER-MAC (Emergency-MAC) is a special type of Hybrid protocol that gives priority to emergency packets giving up latency and delivery ratio of low priority ones during emergency period. ER-MAC is better than Z-MAC, Funneling MAC and Burst MAC since these do not support packet prioritization¹⁶. ER-MAC uses two queues, high priority packet queue and low priority packet queue. Low priority data is sent only if the higher priority queue is empty. Under normal mode of ER-MAC, if there is no data available to transmit, then the nodes go to low power sleep mode.

During the initial startup phase, the sink node initiates tree construction using simple flooding mechanism. The whole ER-MAC design process involves hop tree configuration. At the end of start phase each node

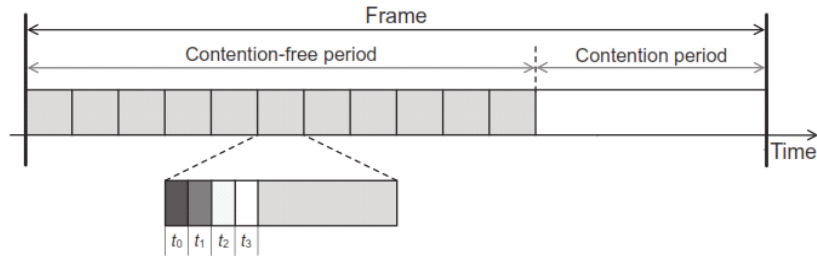


Figure 8. Time frame of ER-MAC.

knows the number of hops to reach the sink, its parent, its child (ren) and the one hop neighborhood list. Total frame length is divided into slots and each slot is assigned more than one node within two hop neighborhood (i.e.) nodes apart from two hop neighborhood can also own the same slot which is similar to that of previously mentioned Z-MAC. During normal conditions it operates by CSMA/CA ER-MAC was found to give better results regarding energy efficiency when compared with Z-MAC, this is because in Z-MAC, nodes have to contend for the channel but in case of ER-MAC as soon as emergency is detected, it immediately transmits data.

At the time of emergency, it switches on to emergency mode, emergency flag is set in both the packets and all nodes are scheduled to wake up allowing contention in TDMA slots. ER-MAC consists of contention free slots and contention period. In contention free slots, there are sub slots which appear only during emergency mode as shown in the Figure 8 detected packet is transferred immediately enhancing better delivery ratio and latency. A major drawback of ER-MAC is that it consumes more energy during normal mode than compared to the emergency mode.

3.6 EE-Hybrid MAC

It is an energy efficient and low latency MAC protocol, which uses interrupt method to assign priority for certain wireless sensor nodes assumed to be present in critical loops of industrial process control domain.

The network nodes begin by first identifying the one hop neighbors from its location by broadcasting ping messages. The nodes then start sensing their respective parameter's, and transfer data's to the sink using CSMA mechanism. When the node in the high priority region is to be transferred, that particular node id information is

available, using that information, the neighboring nodes stop their transmission and change over to TDMA giving the first slot to the node that is in high priority region. If two nodes are present in the same high priority region, then slots are assigned to the nodes one after the other. The node id information is available in the packets and then this information is passed along with the other packets, which enables them to transfer data from one node to the other faster¹⁷. The nodes farthest away from the sink have least memory buffer level, moving towards the sink the nodes buffer level will increase. In the existing models it has been observed that the actual equation being used is $Q_{threshold}$ is a part of the Q_{total} where $Q_{threshold}$ is the level to which the memory in the node can store information Q_{total} is the total memory available in the node.

$$Q_{threshold} = \lceil (\lambda - \alpha) 10 \rceil \quad \alpha < \lambda$$

$$Q_{threshold} = \lceil (\alpha) 10 \rceil \quad \alpha = \lambda$$

The first equation is considered for nodes that are except for the last node in the network towards the sink.

And the second equation is used for the node that was left in the first. Thus energy is saved by the varying buffer level. In the above two equations, α is the current node in the gird, while λ is the total number of nodes in the sensor network. It was found to provide good results for Packet Delivery Ratio, Average end to end delay, and Residual Energy which are better than S-MAC and H-MAC.

4. Comparison of the Performance of Various MAC Protocols

A clear comparison regarding energy efficiency, throughput, latency, fairness and the targeted applications of the

Table 1. Comparison of MAC protocol

CONTENTION BASED MAC PROTOCOLS					
	ENERGY EFFICIENCY	THROUGHPUT	LATENCY	FAIRNESS	TARGETED APPLICATION
S-MAC	Good	Less	High	Good	Small scale WSN's
T-MAC	Good	Less	High	Good	Small scale WSN's
B-MAC	Better	Medium	Low	Better	Applications that focuses only energy efficiency
HYBRID MAC PROTOCOLS					
ADV-MAC	Best	Best	Low	Best	Can be implemented for even large networks involving high traffic
X-MAC	Best	Medium	Low	Best	Applicable for high traffic networks
Y-MAC	Best	Best	Low	Best	Applicable for all contention levels
Z-MAC	Better	Best during high contention	Low	Best	Can be implemented for high traffic networks
ER-MAC	Better	Best	Low during emergency period	Best	Affordable for disaster management
EE-MAC	Best	Best	Low	Best	Industrial applications targeting critical process

various MAC Protocols mentioned in this paper is given in the Table 1. Provided above

5. Conclusion

After a thorough study on the above mentioned MAC Protocols, it is seen that if it supports best energy efficiency, it gives up efficient throughput and vice versa. Hybrid Protocols were able to achieve both the above mentioned performance parameters among which, ADV-MAC produces better efficiency, throughput and also fairness at all traffic levels and so can be assumed to be best during all contention levels. A clear performance comparison of the MAC Protocols is tabulated in Table1. Contention based MAC Protocols concentrate message exchanges to small periods of time, which results in inefficiencies under high traffic loads. Hence these contention based protocols can be implemented during low contention period. Z-MAC can be applicable during high traffic periods without giving up fairness and latency. ER-MAC can be applied for disaster managing applications since this protocol prioritizes emergency packets. EE-MAC is suggested for industrial applications involving time critical process.

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