East West University

Department of Electronics and Communications Engineering

Course Code: ICE498

Course Title: Undergraduate Research Project

Title: "Study on MAC protocols for Wireless Sensor Network (WSN)"

A Research Project Submitted in Partial Fulfillment of the Requirements for the Bachelor of Science in ELECTRONICS & COMMUNICATIONS ENGINEERING

Supervisor

Dr. Mohammad Arifuzzaman

Assistant Professor

Submitted by:

Name: Nishi Sutradhar

ID: 2016-1-50-005

Summer 2020

APPROVAL

The Research Project titled “Study on MAC protocols for Wireless Sensor Network (WSN)” submitted by Nishi Sutradhar (ID:2016-1-50-005) to the Department of Electronics & Communications Engineering, East West University, Dhaka, Bangladesh has been accepted as satisfactory for the partial fulfillment of the requirements for the Bachelor of Science in ELECTRONICS & COMMUNICATIONS ENGINEERING and approved as to its style and contents.

Approved By

(Supervisor)

Dr. Mohammad Arifuzzaman

Assistant Professor,

Department of Electronics and Communications Engineering,

East West University.

DECLARATION

I hereby, declare that the work presented in this Research Project is the outcome of the investigation performed by me under the supervision of Dr. Mohammad Arifuzzaman, Assistant Professor, Department of Electronics & Communications Engineering, East West University, Dhaka, Bangladesh. I also declare that no part of this Research Project and thereof has been or is being submitted elsewhere for the award of any degree or diploma.

Countersigned	**Signature**
--------------------------------	**--------------------------------**
Dr. Mohammad Arifuzzaman	Nishi Sutradhar
(Supervisor)	ID:2016-1-50-005

Abstract

Wireless Sensor Network(WSN) is the collection of spatial self-explanatory devices or sensor nodes that's are tiny, cheap, low power and smart sensors which collect information's from the environment to attain particular application destinations and transfer it through the network to the base station or main location. For these nodes, energy is the most important factor in WSN. Sensor nodes have limited battery power. Short life time of these sensor nodes. For increasing the life time of these nodes have to replace or change the battery. Sensor nodes are dead when they are out of battery. The life time of this node can enhance and can also achieve desired energy efficiency by using a well-designed MAC (Medium Access Control) protocols. The challenge is to improve the system performance and to make network efficient. MAC layer protocols for battery-powered networks and energy harvesting- based networks are discussed and compared. In this survey paper, Various medium-access control (MAC) protocols with different objectives has been described for wireless sensor networks. Then, we describe several MAC protocols for sensor networks. In this article, we first outline the sensor network properties that are crucial for the design of MAC layer protocols. Then, we describe several MAC protocols proposed for sensor networks, emphasizing their strengths and weaknesses. Finally, we point out open research issues with regard to MAC layer design.

Index Page

List of Tables

1.Introduction:

Wireless sensor networks (WSNs) is a new branch of research due to its wide range of application. Wireless sensor nodes are special for tracking the objects or monitor environmental data or information and sending the collected information to the main station. It widely used in many fields such as precision agriculture, health care, environmental monitoring, security and surveillance, animal tracking, smart buildings intrusion detection, industrial automation etc. These application areas of wireless sensor network can be separated into three main categories: Observing space and monitoring intuitive between objects and space (observing natural threats like cataclysm and volcanic activities etc.) [1,2]. Wireless Sensor Networks (WSNs) have gotten to be a leading arrangement in numerous vital applications.

A huge number of wireless sensor nodes consists WSN that are generally small, and equipped with low-powered battery. Main focus of The construction of sensor node on conserving energy, reducing cost and complexity, increasing flexibility and providing robustness and fault tolerance. It is impractical to charge or replacement of the exhausted battery. Since prolonging lifetime is very important of the sensor nodes, fairness, latency, delivery ratio, and bandwidth, and energy efficiency becomes the most important attribute of design of communication protocol for sensor networks [3] . For WSN to supply high throughput in an energy-efficient way, reducing energy consumption and increasing network lifetime, which is achieved by optimally designed Medium Access Control (MAC) protocols. MAC protocols are one of the primary protocols in a network where the participating nodes share a common communication medium. Conventional MAC protocols are created to provide high throughput and QoS through better utilization of the medium. In order to increase network lifetime, energy must be utilized efficiently of the sensor network. As sensor nodes are bound in terms of power, handling capacity, and storage capabilities, modern communication protocols and administrations are required to fulfill all these necessities. The main purpose in WSN to solve the problem of energy-efficiency. A well-designed MAC protocol can increase the network lifetime and achieve the desired energy-efficiency.

In sensor nodes, there are a lot of sources of energy consumption such as computation storage and communication where communication consumes more energy than other processes. In communication process, the major sources of energy consumption are idle listening, collision, overhearing, over-emitting and control and control packets overheads.

The various sources of energy waste can be classified into the following:

- **Idle Listening:** Idle listening happens when a node listens to the channel holding up for activity. It is the main source of energy wastage in a sensor node, because of the low traffic loads situations found in WSNs. When a node has its radio transceivers turned on but it has no communication activities like transmission, reception etc., Idle listening occurs. Since idle listening consumes energy at almost the same rate as receptions, one of the vital design objectives of MAC protocol for sensor network is to play down the idle listening.
- **Collisions:** More than one nodes interfere with each other's transmission if the time is same, collision occurs. This results in wastage of sender's energy through transmitting and also of the receiver as it expands energy without any benefit, as senders may eventually retry transmission. The transmitting (source node) and the receiving (destination) nodes both are suffering from the expenditure of the useless transmit and receive costs respectively. To ignore collision is the one of the prime goal of the MAC protocol of WSNs. For some applications is no need to give much attention about collision in designing of the MAC protocol of WSNs.
- **Overhearing:** When a sensor node losts energy to receive a packet that is not destined for it due to the broadcast nature but for a different destination occurs Overhearing. Normally Data packets are tiny in size in WSNs. Hence overhearing is same as energy consumption during reception, minimizing overhearing is another design challenge for WSNs.
- **Overhead:** In WSNs, data packets are usually tiny in size. Sending and receiving control information also requires energy, causing an additional overhead. Sending, receiving and hearing certain control packets in WSN also consume more energy.
- **Hidden node problem**: In Figure 1, nodes A and C are within the range of node B, but they are not in the range of each other. If node A is communicating to node B, and node C wishes to communicate to node D, node C may sense the channel and finds it idle. Otherwise, it causes collision at node B.

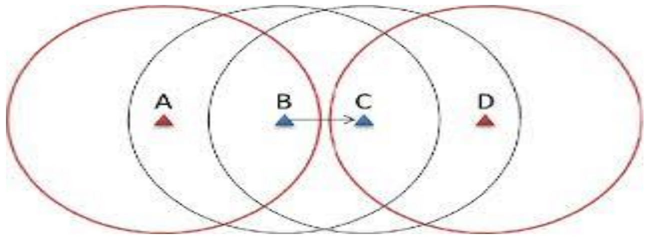


Figure:1

- **Traffic Fluctuation:** The fluctuations of the traffic load lead to wastage of energy in sensor nodes in WSN. So, the protocol must be deal with traffic.

1.1Properties of a Well-defined MAC Protocol

To design a good MAC protocol for the wireless sensor networks, the following attributes must be considered [56]. The first attribute is the energy efficiency. We have to define energy efficient protocols in order to prolong the network lifetime. Other important attributes are scalability and adaptability to changes. Changes in network size, node density and topology should be handled rapidly and effectively for a successful adaptation. Some of the reasons behind these network property changes are limited node lifetime, addition of new nodes to the network and varying interference which may alter the connectivity and hence the network topology. A good MAC protocol should gracefully accommodate such network changes. Other typical important attributes such as latency, throughput and bandwidth utilization may be secondary in sensor networks. Contrary to other wireless networks, fairness among sensor nodes is not usually a design goal, since all sensor nodes share a common task.

1.2 Performance Requirements for the MAC Layer

While designing MAC layer protocols, one needs to consider the following requirements [5]:

- **Throughput:** Protocol efficiency is measured by its throughput. In the case of a wireless link, it may be related to capacity.

- **Scalability:** Scalability refers to the protocol's adaptation to an increase in network size, traffic, overhead and load. One way to deal with this is to localize the interactions so that nodes need less global knowledge to operate.
- **Latency:** Latency can be referred as the time delay between message transmission and message arrival. Latency is an important constraint for time-critical applications, and needs to be minimized.
- **Number of hops:** It is the number of hops taken by packets to reach the sink. Operation of the MAC protocol varies between single-hop and multi-hop scenarios. In the case of multiple hops taken to reach the sink, data needs to be aggregated before sending it to the sink.

1.3 Design Constraints for the MAC protocol of Wireless Network:

Throughput, efficiency, stability fairness, low access delay and minimum transmission delay as well as the low overhead are the important performance necessities of MAC Protocol. The pre packet overhead, collisions of packets, exchange of extra control packets can be considered as the overhead in MAC protocol. Packet retransmission is needed as the allowance of more than one nodes to send the packet simultaneously causes the collision responsible for incorrect data packet receive. Time-bounded applications demands guarantee on data reception time. On the other hand, the replacement of important packets (lower bound of data rate and priority) with unimportant packets is necessary. The operation and performance of MAC protocols are effected by physical layers. Physical phenomena which is consist of the change of rate of fading, increased value of the path loss, attenuation and manmade noise [41] enhance the error rate and delay. All transceiver need minimum signal strength by which with the given transmit power the maximum range becomes limited to cover the maximum distance. Out of the limited communication zone, nodes face hidden terminal as well as exposed terminal problems [42]. Carrier Sense multiple Access (CSMA) protocols affected by the hidden terminal problem. In CSMA, a node after sensing the medium to avoid collision passes data if there is no traffic. If CSMA is not refined in a hidden terminal scenario, collision occurs. Likely, the exposed terminal scenario experience causes the needless waiting. Busy-Tone solution [42] and the RTS/CTS handshake used in the IEEE 802.11 WLAN standard [43] can reduce the problems. Wired media the transmitter can detect a collision at the receiving side rapidly and more effectively which is named as collision detection (CD). Collision detection (CD)concept is used in the CSMA/CD protocol. A wireless transceivers work on half-duplex mode. That's why collision detection protocols are not good choice for the wireless media [44]. WSN faces difficulty because of shearing its spectrum with other systems as there is no frequency band exclusively assigned. And as we know because of license free operations, many wireless systems use the ISM bands. ISM band 2.4 GHz for example. It can be noted that 2.4 GHz band is used by IEEE 802.11/IEEE802.11b WLANs [45,46], Bluetooth [46] and the IEEE 802.15.4 WPAN and others as well. Finally, the expected traffic load pattern is another key design issue of designing of MAC protocols. The traffic for the WSN can be periodic. WSN monitor a physical phenomenon for long period of time, a very low traffic and periodic traffic. Moreover, the deployment goal of the WSN can be to wait for the occurrence of an important event to report as much data as possible.

2. Low duty cycle and Wakeup Mac protocols

The thought behind the low duty cycle protocols is to reduce the time, and the proper condition of low duty cycle protocols is when a node is a sleep most of the time and wakes up only when needs to transmit or receive packets. Periodically a node wakes up at the time of transmission or receiving packets from other nodes. Consisting of a sleeping period and a listening period the whole cycle is denoted by a sleep/wake-up period. Duty cycle gives an indicator of how long a node spends in the listening period by measuring as the ratio of the listening period length to the wake-up period length. A balanced duty cycle size must be found in order to escape from higher latency and higher transient energy due to start-up costs. Various types of low duty cycle protocols are noted for WSNs that protocols are divided into two major classes: (1) **Synchronous** and (2) **Asynchronous** schemes.

synchronization and data exchanges in WSNs are relatable. In synchronous scheme, all the nodes in a group or cluster have the same wake-up phase. Each node sends frequent beacon frames to inform its neighbors about its wake-up cycle schedule and other information such as pending packets to be transmitted, etc.

2.1 Synchronous Low Duty Cycle MAC Protocols

Synchronized low duty cycle MAC protocols are typically prepared with predetermined periodic wake-up schedules for data exchanges that consist of a sleep period Tsleep and an active period, Tactive repeated at Twakeup_period intervals. Besides, synchronization is typically maintained only within a small group or cluster due to the difficulty of global synchronization in a large scale WSN deployment and also to ensure high scalability.

2.1.1 Power Aware Clustered TDMA (PACT): Power Aware Clustered Time Division Multiple Access protocol was proposed in 2001 for networks with a clustered multi-hop topology. PACT utilizes the concept of passive clustering where nodes are permitted to require turns as communication backbone.

2.1.2 Low-Energy Adaptive Clustering Hierarchy (LEACH): Low-Energy Adaptive Clustering Hierarchy or LEACH is a Time Division Multiple Access (TDMA-based) MAC protocol with clustering features. The LEACH protocol is arranged in rounds and each round is subdivided into a setup phase and a steady-state phase. The setup phase starts with the self-selection of nodes to become cluster heads. Here a network is formed as a star topology in two hierarchical levels and a cluster consists of one cluster head and a number of ordinary nodes. There is a single base station which communicates with all the cluster heads. Direct communication with high transmission power is needed for ensuring the cluster heads can reach the base station. The LEACH protocol applies two strategies to ensure energy efficient operation. The first strategy is to move the whole burden of energy consumption of a single cluster head by rotating the task of the cluster head to the other individuals within the cluster. The point of this strategy is to disseminate equitably the energy utilization between the individuals of the cluster. The second strategy is to switch the ordinary nodes in a cluster into the sleep mode at whenever point they enter inert TDMA slots.

LEACH reduces energy consumption, because cluster heads can be selected efficiently to increase network lifetime. LEACH protocol is demonstrated, where sensor nodes send data to cluster heads and cluster heads send aggregated data to the base station.

2.1.3 LEACH with Spare Management (LEACH-SM): It is a modification of the LEACH protocol. LEACH-SM has spare nodes which are normally in the sleep mode [65]. When the network is out of energy, spare nodes provide redundancy and increase network lifetime. LEACH-SM also has the capability to avoid deadlocks that may occur due to redundancy of nodes, and thus offers extended lifetime.

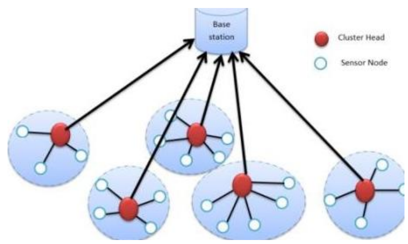


Figure2: LEACH MAC architecture.

2.1.4 Self-Organizing Slot Allocation (SRSA):

The Self-Organizing Slot Allocation protocol is a TDMA-based MAC and was proposed to move forward the LEACH MAC protocol in terms of energy efficiency and network scalability. The SRSA protocol has a similar network topology as LEACH like fig2. The strategy to extend energy efficiency is by utilizing different base stations instep of only one base station as within the LEACH architecture. To increase network scalability, SRSA provides local synchronization where each cluster maintains its own local TDMA MAC frame.

2.1.5 Traffic-Adaptive Medium Access (TRAMA): The Traffic-Adaptive Medium Access or TRAMA protocol is a TDMA-based MAC with a flat-based network topology. The basic operation of the TRAMA protocol is to create and hold a TDMA schedule for each node with its neighboring nodes inside the vary of two hops from every node. Basically, sensor nodes share a listing of node identifiers from a two hop nearby and then they change their schedules. The strategy to supply energy efficient operation is through implementing a duty cycle mechanism the place the node goes to sleep when it enters inert time slots. The adaptively of TRAMA protocol is good.

Advantages: Higher percentage of sleep time and less collision probability is achieved compared to CSMA based protocols. Since intended receivers are indicated with a bitmap, less communication is performed for multicast and broadcast type of communication patterns compared other 4protocols.

Disadvantages: Transmission slots are set to be seven times longer than the random access period [56]. However, all nodes are defined to be either in receive or transmit states during the random access period for schedule exchanges. This means that without considering the transmissions and receptions, the duty cycle is at least 12.5 %, which is a considerably high value. For a time, slot, every node calculates each of its two-hop neighbors' priorities on that slot. In addition, this calculation is repeated for each time slot, since the parameters of the calculation change with time.

2.1.6 SIFT: Sift [57] is a MAC protocol proposed for event-driven sensor network environments. The motivation behind Sift is that when an event is sensed, the first R of N potential reports is the most crucial part of messaging and has to be relayed with low latency. Here, uses a non-uniform probability distribution function of picking a slot within the slotted contention window. If no node starts to transmit in the first slot of the window, then each node increases its transmission probability exponentially for the next slot assuming that the number of competing nodes is small.

Sift is compared with 802.11 MAC protocol and it is showed that Sift decreases latency considerably when there are many nodes trying to send a report. Since Sift is a method for contention slot assignment algorithm, it is proposed to co-exist with other MAC protocols like S-MAC. Based on the same idea, CSMA/p* is proposed in where p* is a non-uniform probability distribution that optimally minimizes latency. However, sift has a distribution approximate to CSMA/p*. The adaptively of shift protocol is good.

Advantages: Very low latency is achieved with many traffic sources. Energy consumption is traded off for latency as indicated below. However, when the latency is an important parameter of the system, slightly increased energy consumption must be accepted. It could be tuned to incur less energy consumption. The high energy consumption is a result of the arguments indicated below.

Disadvantages: One of the main drawbacks is increased idle listening caused by listening to all slots before sending. The second drawback is increased overhearing. When there is an ongoing transmission, nodes must listen till the end in order to contend for the next transmission which causes overhearing. Besides, system-wide time synchronization is needed for slotted contention windows. That is why, the implementation complexity of Sift would be increased for the protocols not utilizing time synchronization.

2.1.7 DMAC: The DMAC protocol was proposed with the objective to provide energy efficient operation with low latency requirements. The network for DMAC is structured as a tree-based data gathering architecture where each node is equipped with a different duty cycle schedule according to the level of deepness in the tree structure. Thus nodes at the same depth in the tree have the same duty cycle schedule. Channel access is performed through CSMA and DMAC utilizes only one frequency channel for communication. The DMAC protocol is energy efficient for low load; however, it suffers higher latency when the load gets higher due to congestion at intermediate nodes. Converge cast is the mostly observed communication pattern within sensor networks. These unidirectional paths from possible sources to the sink could be represented as data gathering trees. The principal aim of DMAC [58] is to achieve very low latency, but still to be energy efficient. DMAC could be summarized as an improved Slotted Aloha algorithm where slots are assigned to the sets of nodes based on a data gathering tree. Hence, during the receive period of a node, all of its child nodes has transmit periods and contend for the medium. Low latency is achieved by assigning subsequent slots to the nodes that are successive in the data transmission path. The adaptively of DMAC protocol is weak.

Advantages: DMAC achieves very good latency compared to other sleep/listen period assignment methods. The latency of the network is crucial for certain scenarios, in which DMAC could be a strong candidate.

Disadvantages: Collision avoidance methods are not utilized, hence when a number of nodes that has the same schedule (same level in the tree) try to send to the same node, collisions will occur. This is a possible scenario in event-triggered sensor networks. Besides, the data transmission paths may not be known in advance, which precludes the formation of the data gathering tree.

2.2 Asynchronous Low Duty Cycle MAC Protocols

Asynchronous low duty cycle MAC protocols do no longer provide prior understanding about the global or neighborhood timing facts and schedules to the nodes in a network to aid with data communications. For identifying possible starting transmissions in the network asynchronous low duty cycle MAC gives a frequent channel sampling mechanism. At the receiver the frequent channel sampling is also denoted as a low power listening (LPL) mechanism. The transmission of a prologue packet is one of the examples of transmitter initiated approach in asynchronous WSNs. the most important asynchronous low duty cycle MAC protocols are:

2.2.1 RF Wake-up Protocol: RF wake-up scheme sampling protocols is the earliest proposed preamble sampling protocols. To check the channel activity this protocol samples the channel every 4 seconds. It waits for a small time for any incoming packets if it adds any activity. Because of the overhead of long preamble packet transmission, this protocol is not suitable for latency-critical networks. It is clear that from the observation that latency is traded off with energy efficiency. When the size of the preamble packet gets longer, thus putting a constraint on the maximum length of the sleep period then transmission power gets higher.

2.2.2 Wireless Sensor MAC (WiseMAC): The Wireless sensor mac or WiseMAC protocol was proposed to cut back the burden of long preamble packet transmission at the sender facet and to tackle the high collision chance in previous protocols. WiseMAC defines 2 kinds of nodes, the access point and ordinary sensor nodes. All ordinary sensor nodes should communicate solely with the access point that primarily forms a network with a star topology. WiseMAC utilizes the same channel get to strategy as the prior protocol where the ALOHA protocol is utilized some time recently a preamble packet is transmitted. By knowing the schedule, the access point of each sensor node learns the wake-up schedule, the access point can make the preamble transmission time shorter. WiseMAC provides more energy efficient operation than the previous protocols, but due to the fixed star topology operation, at the cost of low scalability.

Advantages: The simulation results show that WiseMAC performs better than one of the S-MAC variants [55]. Besides, its dynamic preamble length adjustment results in better performance under variable traffic conditions. In addition, clock drifts are handled in the protocol definition which mitigates the external time synchronization requirement.

Disadvantages: Main drawback of WiseMAC is that decentralized sleep-listen scheduling results in differen sleep and wake-up times for each neighbor of a node. This is especially an important problem for broadcast type of communication, since broadcasted packet will be buffered for neighbors in sleep mode and delivered many times as each neighbor wakes up. However, this redundant transmission will result in higher latency and power consumption.

2.2.3 Speck MAC (SpeckMAC): SpeckMAC was a variety of the B-MAC protocol with the concept of redundant transmission of short packets and an embedded destination address. The primary thought is targeted to reduce the transmission energy and the second idea provides a measure of reducing the significant overhearing problem in heavy traffic conditions. Basically there are 2 types: SpeckMAC-Back-off (SpeckMAC-B) and SpeckMAC-Data (SpeckMAC-D). SpeckMAC-B, sends a short wake-up frame preceded by carrier sensing with embedded target destination address and data transmission timing information. SpeckMAC-D sends the data packet many times which is preceded by carrier sensing until the receiver is hit by one of the data packet. The process of retransmission of data packets reduces the energy at the receiver but still affected by excess latency. When broadcast packets are transmitted, SpeckMAC-D is more energy efficient than SpeckMAC-B. SpeckMAC-B, on the other side, is more energy efficient when unicast packets are transmitted.

2.2.4 X-MAC: X-MAC protocol proposed the utilization of preamble packets with the destination address embedded in the packet. The X-MAC protocol provides more energy efficient and lower latency operation by decreasing the transmission energy and transmission period burdens, idle listening at the intended receiver and overhearing by the neighboring nodes. The noticeable thing is that the gaps between the series of preamble packets transmission can be mistakenly understood by the other contending nodes as an idle channel and they would begin to transmit their own preamble packets which can cause collision. One solution should make sure that the length of gaps must be upper bounded by the length of the listening interval.

Most of the protocols use a radio capable of receiving as well as transmitting wake-up messages, while few other protocols employ a very low power wakeup receiver that is able to only receive a wake-up message. All the protocols share a common feature of duty-cycling the wake-up radio of this category. Based on the duty cycle's policy, two subclasses can be distinguished, static vs. Traffic adaptive.

2. 3 Static Wake-up MAC Protocols

In static MAC protocols, the wake-up radio employment the same cycle during all the network's lifetime and does not follow the dynamic changes of the network. Adopting a steady duty cycle may facilitate the MAC protocol implementation and utilization due to its simplicity. However, this makes it inflexible and slows its responsiveness, which rises the end-to-end delay. STEM [4] is an example of a canonical multi-hop protocol in this category. Separate channels are used for the wake-up radio and the main radio, which prevents interference between data and wake-up messages. Depending on the wake-up message form, two variants are derived from this scheme, i) STEM-B and, ii) STEMT [5]. In STEM-B, when an initiator node wants to communicate with a target node, it starts transmitting beacon packets carrying the MAC addresses1 of both the transmitter and the receiver until a beacon packet meets an active period of the targeted radio and receives an acknowledgment from it. Then both the transmitter and the receiver power on their main radios to start data communication, while keeping the wake-up radios duty cycling periodically to check the presence of wake-up messages. If a collision occurs on the wake-up channel, nodes detecting it wake up their main radios without sending back any acknowledgment. As the initiator will not receive the ACK from the target node, it starts transmitting data in the next cycle. STEM-T has been driven as a simpler variant in collision handling, which simplifies the wake-up policy. Instead of sending a wake-up beacon with addresses, in STEM-T the wake-up message is a simple tone, but the same procedure is followed for data transmission when a collision happens.

2.3.1 DCMAC [6] is another static duty-cycled MAC protocol. It is based on periodic listening/sleeping mechanism combined with synchronization for the goal of saving energy in multi-hop based networks. This is because in the targeted hardware, the wake-up radio has the same capabilities as the main one. When there is data to be delivered, the node performs listening by activating its two radios. When the channels are found free, the nodes send a busy tone.

2.3.2 OPWUM is a similar scheme that has been presented in [7] but with a simpler and more efficient fashion. When a sender node that has not any information about its next hop neighbor, wants to transmit data, it should start by sending an RTS packet to wake up all its neighborhood. Each awaken node by this RTS sets a BE before responding by a CTS, depending on a given metric value.

2.3.3 Multi-Radio MAC (MR-MAC) protocol [8] combines the use of a p-persistent preamble sampling MAC approach with a dual-radio scheme for multi-hop networks. MR-MAC, allowing to keep the main radio in sleep mode all the time for more energy saving. The authors drive some equations to find the optimum duty cycle that leads to the minimum energy consumption, and the optimum transmit power of the two radios that allows to cover the same area with less energy dissipation. Using a slow data rate radio operating in a low frequency band for preamble exchange may achieve good energy efficiency, as it performs low power operations. However, the energy consumed by the preamble sampling mechanism is still not negligible, mainly when the sender is not aware of the receiver's wake-up schedule. MR-MAC also results in a high latency, as the sender waits until the receiver wakes up to start data transmission.

2.3.4 DCW-MAC [9] is another multi-hop scheme that duty cycles the wake-up radio statically. It is based on the idea of combining ultra-low power wake-up receiver with optimal duty cycling. The wake-up radio used in this protocol is only able to receive a wake-up beacon, while all the other tasks are delegated to the main radio. The latter is responsible for transmitting wake-up beacons when there are data packets to be communicated. Since the sender and the receiver are not synchronized, and the wake-up receiver follows a duty cycle scheme, the sender should transmit a precise number of wake-up beacons, to guarantee meeting the receiver. After each wake-up beacon, the sender turns on its main radio to check whether there is an acknowledgment destined to it. The acknowledgment (BACK) is sent by the main radio of the receiver, when its wake-up radio detects the 13 wake-up beacon. After acknowledgment reception, both of the sender and the receiver start data communication using their main radios. An acknowledgment (DACK) should be transmitted after data reception. Since the main radio is responsible for transmitting the wakeup message, frequent transitions between transmitting mode and receiving mode (waiting for an Ack) result in some energy dissipation.

2.4 Traffic Adaptive Wake-up MAC Protocols

2.4.1 Rate Estimation MAC (RATE-EST) [34] is a traffic adaptive multi-hop wake-up MAC protocol that tries to predict dynamically the next wake-up time based on the packet arrival rate. RATE-EST MAC to support the multi-hop environment with multiple flows.

2.4.2 STEM trades energy for latency. However, a mechanism has been introduced to control and delimit the delay, and to diminish the energy consumption resulted from awaking all the neighborhood for each data packet. Instead of immediate transmission of packets, a transmission queue is used. When the number of packets in the queue reaches a certain threshold, the node's wake-up radio starts transmitting simple tones. In case of no data packet is communicated within T_{thresh} sec, from the time of the triggered wakeup, the nodes should go back to sleep and wake up after $T - T_{thresh}$. The authors, according to the traffic state, tried to find dynamically the optimal value of T that minimizes the energy consumption, avoiding as well as possible pricey full wake-ups.

2.5 Advantages, Disadvantages, and Features

Duty cycled wake-up MAC protocols share the feature of using a wake-up radio that has similar performances as the main radio. This allows a large wake-up range at the same scale as that of data communication, and a more elaborated communication. It, however, comes at the cost of a higher energy consumption. To make the addition of a wake-up radio effective, the latter should consume less energy than the main one.

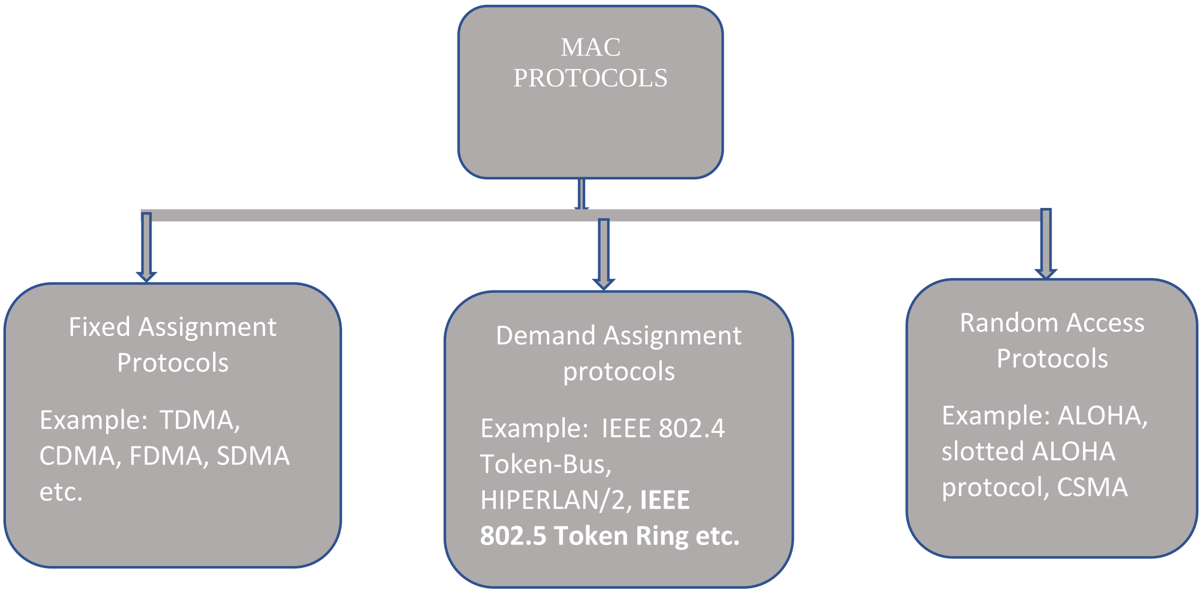
Table 2.5: Advantages, disadvantages and features of Static duty-cycled & Traffic adaptive duty cycled protocols duty cycled wake-up MAC

Subclasses	Features	Advantages	Disadvantages
Static duty-cycled protocols	Wake-up radio duty cycles statically	Simple to implement	Suffer from rigidity
Traffic adaptive duty cycled protocols	Wake-up radio duty cycles dynamically	Flexible to traffic conditions changes	Complicated implementation

Table 2.6 Comparison between static duty-cycled wake-up MAC protocols

Protocols	STEM-B	STEM-T	OPWUM	DCMAC	MR-MAC	DCW-MAC
Wake-up message nature	Addressed and acknowledged beacon	Simple tone	RTS packet	Busy tone with CTS from the best next hop	Addressed MFP	Addressed beacon with BACK
Wake-up message source	Wake-up radio	Wake-up radio	wake-up radio	Wake-up radio	Wake-up radio	Main radio
Energy dissipation factors	Transmitting several wake-up beacons to meet the receiver	Unnecessary wake-up of all the neighborhood	Calculation overhead	Unnecessary neighborhood wake-up, Listening with two radios, Next hop determination overhead	Neighborhood sleep schedule maintaining	Switching between Tx and Rx
Energy conservation mechanisms	Beacon strobing	Ack elimination	Receiver selection	Best next hop selection	Preamble strobing, Data piggybacking	Beacon strobing
Latency reasons	Waiting the wake-up time of the receiver	Longer wake-up tone		waiting the best next hop determination	Waiting the next hop wake-up time	Waiting the receiver wake-up time
Collision avoidance				CCA before transmission		

3. Classes of MAC protocols



Different types of MAC protocols for wireless networks are proposed for the few decades. The protocols are categorized into categories [11].

3.1 Fixed Assignment protocols:

In fixed assignment protocols the resources are distributed to the nodes for long time so there is no chance of collisions. If the topology is changed (due to the deployment of new nodes, due to mobility or changes in the load pattern) which causes scalability problems, some sort of signaling mechanisms are needed to reallocate the assignment of resources to nodes.

TDMA, FDMA, CDMA, and SDMA are examples of these protocols.

3.1.1 TDMA:

The Time Division Multiple Access (TDMA) divides the communication time into fixed length frames where each frame is subdivided into fixed number of time slots [10] to transmit data periodically. TDMA protocol depends on the synchronization between the nodes to prevent overlapping of signal. Each node transmits or receives in its allocated time slot only and keeps its radio off at other times. It conserves the energy wastage due to idle listening and collisions. For heavy traffic load TDMA protocol is mostly suitable. During light traffic load, non-source nodes also keep their radio on its allocated time slot and dissipate their remaining energy.

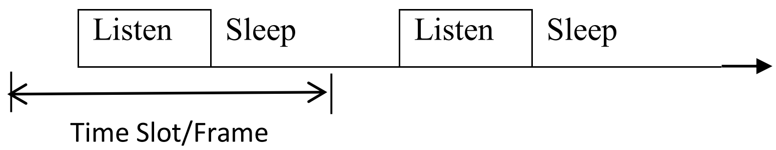


Figure: Periodic listen and sleep of a sensor node

Time division multiple access (TDMA) is also a well-known reservation based MAC protocol. They are more energy efficient since nodes in the network can be inactive until their allocated time slots. But the latency is directly proportional to the number of time slots and networks with large number of nodes like WSN requires a higher data rate and higher energy consumption to satisfy a deadline.

3.1.1.1 TDMA-BASED MAC LAYER PROTOCOLS are described below:

3.1.1.1.1 Energy Efficient TDMA (E-TDMA) Protocol)

Low-energy adaptive clustering hierarchy (LEACH) implements energy efficient (E-TDMA) MAC protocol [12] in its cluster. In LEACH cluster head is elected based on the remaining energy of cluster nodes. The cluster head divides the channel into equalized time slots and uniformly allocates these time slots to member nodes. The CH also transmits synchronization information to member nodes throughout the cluster. All sensor nodes transmit information directly to CH, which further routes their information to the base station. Leach is not adaptable to variable traffic loads as it uniformly schedules time slots across the nodes in the cluster.

3.1.1.1.2 Bit-Map-Assisted (BMA) MAC Protocol

BMA [13] is designed for event driven applications in which sensor nodes send data to cluster head only if specific events have occurred. During setup phase cluster formation takes place in which highest energy node is selected as cluster head. The steady state phase divides into contention period, data transmission period and idle period. The contention period is based on TDMA schedule in which each sensor node transmits control data into its assigned slot. After that, the cluster head announces the data transmission schedule to all sensor nodes and during the data transmission period each source node transmits data to the cluster head in its allocated data slots. Thus, BMA is an energy efficient protocol for low and medium traffic loads.

3.1.1.1.3 EA-TDMA Protocol

EA-TDMA [14] protocol is used to monitor lateral and vertical instability in railway wagons. Since BMA protocol is designed for low and medium traffic load applications, So for medium to high traffic load EA-TDMA is designed. EA-TDMA is an energy efficient protocol for railway applications. In EATDMA each sensor node transmits data to the cluster head in its scheduled slot and turn off its radio if it does not have data to send for energy conservation.

3.1.1.1.4 BMA-RR Protocol

Bit-Map-Assisted Round-Robin (BMA-RR) [15] MAC protocol is an adaptive TDMA based MAC protocol. The proposed protocol is designed to reduce energy consumption during less traffic load and to reduce latency and increase throughput during high traffic load. BMA-RR allocates vacant time slots to more demanding sensor nodes by using the Round Robin Technique in order to provide traffic additivity. The proposed round-robin algorithm for slot scheduling, minimize energy consumption and transmission latency and maximize the channel utilization. In BMA-RR, each node has different sleep and wake up schedules according to their traffic density. This protocol provides better performance than traditional TDMA based MAC protocol at variable traffic loads.

3.1.1.1.5 E-BMA Protocol

E-BMA [16] is a more energy efficient protocol as compared to BMA for low and medium traffic by reducing the idle time in contention period. Unlike BMA, in E-BMA source node uses piggybacking mechanism to make the reservation for data slots. The source node does not transmit data immediately after it becomes available, rather than it waits for the next frame to check whether it has successive packet to send. In E-BMA each non source node keeps its radio off during the contention period to reduce energy utilization as compare to BMA in which non source remains idle in contention period.

3.1.1.1.6 BS**-MAC Protocol**

Bitmap-assisted Shortest Job First based MAC (BS-MAC) [17] protocol is designed for hierarchical WSN. The main features of proposed protocol are that: a) It utilizes small size time slots which are allocated non uniformly to sensor nodes, according to their traffic load. b) It utilized Shortest Job First algorithm (SJF) for slot scheduling. c) It reduces the node address from 8 bytes to 1 byte which minimizes control overheads and increases energy efficiency.

3.1.1.1.7 BEST-MAC Protocol

Bitmap-assisted efficient and Scalable TDMA based MAC protocol (BEST-MAC) [18] is designed for smart cities applications where data traffic is variable and large delay is intolerant. The main features of proposed protocol are that: a) It utilizes small size time slots which are allocated non uniformly to sensor nodes, according to their traffic load. Traffic adaptability provides improved link utilization. b) It utilizes Knapsack Algorithm for slot scheduling. It reduces packet delay, increases link utilization and hence improves throughput. c) It introduces a Contention Access period to provide scalability to the network. d) It assigns a short address to each node to reduce the overheads.

3.1.1.1.8 Low Latency MAC (LL-MAC) [52]: Low latency MAC protocol is a TDMA based protocol which designed with low latency as the primary goal. The data interval is divided into X divisions which in turn is divided into Y time slot subdivisions. Each node communicates to its parent in the time slot subdivision within the assigned division corresponding to the hop number it is in and the parent aggregates the data until its turn to communicate.

Table 3.1.1: COMPARISON OF DFFERENT TDMA-BASED MAC PROTOCOLS

Protocols	**TDMA**	**ETDMA**	**EA-TDMA**	**BMA**	**BMA-RR**	**E-BMA**	**BSMAC**	**BESTMAC**
Energy consumption	High	Low	low	low	low	Very low	Medium	Medium
Transmission Latency	High	High	High	Medium	Less	High	Less	less
Traffic adaptability	No	No	No	Yes	Yes	Yes	Yes	yes
Scalability	No	No	No	No	No	No	No	yes
Fairness	low	low	low	Medium	low	Medium	High	High
Bandwidth utilization	low	low	low	Medium	High	Medium	High	High
Throughput	low	low	low	Medium	High	Medium	High	High
Communication Overheads	low	low	low	Medium	High	Medium	High	High

In Frequency Division Multiple Access (FDMA) the available frequency band is divided into a number of sub-channels where participating nodes are assigned to transmit signals. FDMA transceiver is more complex than a TDMA transceiver.

In Code Division Multiple Access (CDMA) scheme [19-20] the nodes spread their signals with code over a much larger bandwidth than needed. The receiver must know the code to decode the signal where noise may be created by parallel transmission.

Finally, since the Space Division Multiple Access (SDMA) uses the technique of the spatial separation between the nodes to separate their transmissions using array of antennas and refined signal processing techniques [21].

3.2 Demand Assignment Protocols

In these classes of protocols, the nodes used to have short time resources. The demand assignment protocol can be broadly classified into two; centralized protocol and distributed protocol. The examples of centralized protocols are HIPERLAN/2 protocol [22-24], MASCARA protocol [20], polling schemes [25-27]. In centralized scheme, the central nodes allocate resources by sending a confirmation massage with the description of bandwidth among the other nodes after accepting or rejecting their requests. Two mechanisms to manage the submission of requests are followed where the first option uses random access protocol on an exclusive signaling channel, and in second option, the central station polls the nodes defined within its region. Besides, the piggyback demand of the nodes on to data packets helps to avoid transmission of separate request packet. Here, the central nodes need to be switched on all the time to ensure proper resource allocation for other nodes which demands a lot of energy. An adequate number of energy-unconstrained nodes can support the central nodes i.e. IEEE 802.15.4 protocol [28]. The aim of IEEE 802.15.4 for low-cost, low-power and short-range wireless communications. Then released newer versions IEEE 802.15.4b, 802.15.4a, 802.15.4c and 802.15.4d subsequently.

- IEEE standard 802.15.4v-2017
- IEEE standard 802.15.4u-2016
- IEEE standard 802.15.4t-2017
- IEEE standard 802.15.4q-2016
- IEEE standard 802.15.4p-2014
- IEEE standard 802.15.4n-2016
- IEEE standard 802.15.4m-2014
- IEEE standard 802.15.4k-2013
- IEEE standard 802.15.4j-2013
- IEEE standard 802.15.4g-2012
- IEEE standard 802.15.4f-2012
- IEEE standard 802.15.4e-2012
- IEEE standard 802.15.4d-2009
- IEEE standard 802.15.4c-2009

- IEEE standard 802.15.4a-2007
- IEEE standard 802.15.4-2015
- IEEE standard 802.15.4-2011
- IEEE standard 802.15.4-2006
- IEEE standard 802.15.4-2003

IEEE standard 802.15.4v-2017 :

IEEE 802.15.4v-2017 - IEEE Standard for Low-Rate Wireless Networks.

Amendment 5: Enabling/Updating the Use of Regional Sub-GHz Bands. The smart utility network (SUN) physical layers (PHYs) in IEEE Std 802.15.4(TM)-2015 are changed by this correction to empower the utilize of the 870--876 MHz and 915--921 MHz groups in Europe, the 902--928 MHz band in Mexico, the 902--907.5 MHz and 915--928 MHz groups in Brazil, and the 915--928 MHz band in Australia and Modern Zealand. Extra Asian territorial recurrence groups are moreover indicated in this revision. Furthermore, the revision changes the channel parameters recorded for the SUN PHYs, the low energy critical infrastructure monitoring (LECIM) PHY, and the television white space (TVWS) PHY for the 470–510 MHz band in China and the 863--870 MHz band in Europe and adjusts these channel parameters with territorial prerequisites. The alteration incorporates channel get to and/or timing changes to the medium access control (MAC) vital for conformance to territorial prerequisites for these groups. [5]

IEEE standard 802.15.4u-2016: IEEE 802.15.4u-2016 - IEEE Standard for Low-Rate. The supported information charge need to be at least forty kb/s and the standard line-of-sight vary have to be on the order of 5 km using an Omni directional antenna. Included are any channel get entry to and/or timing modifications in the medium get right of entry to manage imperative to support this PHY layer. Wireless Networks. [3]

Amendment 3: Use of the 865 MHz to 867 MHz Band in India.

IEEE standard 802.15.4t-2017 : IEEE 802.15.4t-2017 - IEEE Standard for Low-Rate Wireless Networks.

Amendment 4: Higher Rate (2 Mb/s) Physical (PHY) Layer. This modification defines a physical layer for IEEE Std 802.15.4(TM)-2015, capable of aiding 2 Mb/s statistics rates, using the 2400-2483.5 MHz band, having backwards-compatibility to, and the equal occupied bandwidth as, the existing 2450 MHz O-QPSK bodily layer, and capable of easy implementation. Target vary ought to be at least 10 meters. This change defines changes to the medium access control (MAC) sublayer wished to guide this new physical layer [4].

IEEE standard 802.15.4q-2016: IEEE Standard for Low-Rate Wireless Networks.

Amendment 2: Ultra-Low Power Physical Layer. Two interchange physical layers (PHYs), Errand and RS-GFSK, are indicated in this revision in expansion to the PHYs of IEEE Std 802.15.4-2015. The correction moreover characterizes the medium get to control (MAC) adjustments required to back the usage of the Assignment and RS-GFSK PHYs. These interchange PHYs empower low-cost, ultra-low control utilization, as well as amplified battery life, in different recurrence groups and geological locales beneath numerous administrative spaces. [3]

IEEE 802.15.4p-2014: IEEE Standard for local and metropolitan area networks. Low-Rate Wireless Personal Area Networks (LR-WPANs).

Amendment 7: Physical Layer for Rail Communications and Control (RCC). This change to IEEE Std 802.15.4(TM)-2011 specifies a PHY to be used in instrumentation meant to deal with rail transportation business desires and to fulfill United States positive train management (PTC) regulative necessities and similar regulative necessities in alternative elements of the planet. additionally, the change describes solely those Mack changes required to support this PHY.

IEEE standard 802.15.4n-2016: IEEE Standard for Low-Rate Wireless Networks.

The Ministry of Industry and Information Technology (MIIT) of the People's Republic of China has approved the 174--216 MHz, 407--425 MHz, and 608--630 MHz bands for medical data transmission. China medical band (CMB) devices in operation inside these bands change to a group of rules per MIIT Doc 423-2005, that restricts use of the band to solely medical, among different necessities. A physical layer (PHY) for devices in operation on Chinese approved bands for medical signals is outlined during this change. [6]

Amendment 1: Physical Layer Utilizing China Medical Bands.

IEEE standard 802.15.4m-2014 : IEEE Standard for Local and metropolitan area networks. Low Rate Wireless Personal Area Networks (LR-WPANs) .

Amendment 6: TV White Space Between 54 MHz and 862 MHz Physical Layer. In this change to IEEE Std 802.15.4(TM)-2011, out of doors low-data-rate, wireless, tv white house (TVWS) network needs area unit addressed. Alternate physical layers (PHYs) area unit outlined still as solely the medium access control (MAC) modifications required to support their effectuation.

IEEE 802.15.4k-2013: IEEE Standard for Local and metropolitan area networks and Low-Rate Wireless Personal Area Networks (LR-WPANs). DSSS and FSK that support essential infrastructure observation applications square measure provided during this change to IEEE Std 802.15.4TM-2011. additionally, solely those raincoat modifications required to support the implementation of the 2 PHYs square measure delineated during this change.

Amendment 5: Physical Layer Specifications for Low Energy, Critical Infrastructure Monitoring Networks.

IEEE 802.15.4j-2013: IEEE Standard for Local and metropolitan area networks & Low-Rate Wireless Personal Area Networks (LR-WPANs).

Amendment 4: Alternative Physical Layer Extension to Support Medical Body Area Network (MBAN) Services Operating in the 2360 MHz – 2400 MHz Band. In this change to IEEE Std 802.15.4TM-2011, a physical layer for IEEE 802.15.4 within the 2360 megacycle per second to 2400 megacycle per second band that complies with Federal Communications Commission (FCC) MBAN rules is outlined. Modifications to the mackintosh required to support this new physical layer also are outlined during this change.

IEEE standard 802.15.4g-2012 : IEEE Standard for Local and metropolitan area networks. Low-Rate Wireless Personal Area Networks (LR-WPANs)

Amendment 3: Physical Layer (PHY) Specifications for Low-Data-Rate, Wireless, Smart Metering Utility Networks. In this amendment to IEEE Std 802.15.4-2011, outdoor low-data-rate, wireless, clever metering utility community requirements are addressed. Alternate PHYs are described as nicely as solely those MAC modifications needed to assist their implementation.

IEEE standard 802.15.4f-2012: IEEE Standard for Local and metropolitan area networks. Low-Rate Wireless Personal Area Networks (LR-WPANs).

Amendment 2: Active Radio Frequency Identification (RFID) System Physical Layer (PHY). This modification gives two PHYs (MSK and LRP UWB) that can be used in a huge vary of applications requiring various mixtures of low cost, low power consumption, multiyear battery life, reliable communications, precision location, and reader options. This PHY standard supports the performance and flexibility needed for future mass deployments of noticeably populated self-sufficient energetic RFID systems anywhere in the world.

IEEE 802.15.4e-2012: IEEE Standard for Local and metropolitan area networks. Low-Rate Wireless Personal Area Networks (LR-WPANs)

Amendment 1: MAC sublayer. IEEE Std 802.15.4-2011 is revised by this standard. The purposeful of this alteration is to upgrade and include usefulness to the IEEE 802.15.4 MAC to (distant better; a much better; a higher; a stronger; an improved">an) improved back the mechanical markets and (b) allow compatibility with alterations being proposed inside the Chinese WPAN.

IEEE 802.15.4-2015: IEEE Standard for Low-Rate Wireless Networks. The protocol and consistent interconnection for information communication gadgets utilizing low-data-rate, low-power, and low-complexity short-range radio recurrence (RF) transmissions in a wireless personal area network (WPAN) are characterized in this standard. An assortment of physical layers (PHYs) have been characterized that cover a wide assortment of recurrence groups. [7]

If not the rotation of the duties of the central station among all nodes occur i.e.: LEACH [40] protocol. There is a lot of distributed demand assignment protocols proposed. Like IEEE 802.4 Token-Bus [39] where after receiving token frame transmission of a node initiates where the token frame is designed to rotate among the nodes in within the network that are organized in a logical ring on top of a broadcast medium. Moreover, correcting failure like lost tokens is also need to be handled. Token passing protocols cannot be successfully used in the wireless media [40], because of the problem of maintaining of the logical ring where there is possibility of frequent channel errors [46]. In that case not only token circulation times are random but also this protocol has to maintain a logical ring if there is a case of frequent topology changes. In fact, it also includes considerable signaling traffic for the token frames and others required information with the unlimited activity of nodes to perform for the random token circulation times.

3.3 Random Access or Balance of requirements MAC Protocols for WSNs

In Random access protocols, there is no central control of the nodes and they operate in a distributed fashion. To save energy, the trade-off of design goals of WSNs is dissimilar from other wireless networks. The well-established MAC protocols ALOHA [8], CSMA (Carrier Sense Multiple Access), etc. do not have any option of dealing with the energy efficiency parameter. In Other sider energy efficiency, performance parameters like fairness, throughput, or delay requirements are less important consideration in designing the MAC protocol of the WSNs. In order to achieve the goal of energy efficiency, transmission delay is allowed in WSNs. For most of the application of WSNs Throughput is generally not an important issue. One of the basic and important mentionable random access protocols are ALOHA and slotted ALOHA protocol.

3.3.1 ALOHA:

ALOHA is a system for coordinating and arbitrating access to a shared communication channel. It was developed in the 1970s at the University of Hawaii. The original system used terrestrial radio broadcasting, but the system has been implemented in satellite communication systems. A shared communication system like ALOHA requires a method of handling collisions that occur when two or more systems attempt to transmit on the channel at the same time.

In the ALOHA system, a node transmits whenever data is available to send. In case of transmitting a new packet, the node is allowed to transmit the packet instantly. There is no provision of the consideration of the consultation with other nodes and thus the protocol is very susceptible for collisions at the receiver end. If another node transmits at the same time, a collision occurs, and the frames that were transmitted are lost. In order to clarify about the collision, the receiver sends an immediate feedback for a successful packet reception. If no acknowledgement is received the transmitter interprets it as a signal of a collision. After having decided that the sent packet suffered from the collision the transmitter retransmits it after a random time (back off time). After the back off time, it initiates its subsequent trial. In case of lighter traffic, the drawback of ALOHA protocol is transmission delays. And in case of higher traffic/loads, the protocol suffers from higher collisions and subsided throughput. This also results increased transmission delays. However, a node can listen to broadcasts on the medium, even its own, and determine whether the frames were transmitted.

In case of **slotted ALOHA**, the total communication time is divided into slots and a node is allowed to transmit a packet only at the starting point of a slot. A slot is large enough to accommodate a maximum-length packet. So, in slotted ALOHA only those nodes that start their packet transmission in the same slot can destroy other node’s transmission (packet). If any node failed to transmit at the beginning of a slot it must wait for the beginning of the next slot. This way the slotted ALOHA reduces the probability of collisions and achieves much improved throughput compared to basic/original ALOHA.

3.3.2 Carrier Sensed Multiple Access (CSMA): CSMA is a network access method used on shared network topologies such as Ethernet to control access to the network. In CSMA protocols, a transmitting node cares for the ongoing transmissions. If a node has a packet to transmit, it first listens the medium; which is termed as carrier sensing. If the node observes that the medium is idle, it starts transmission. Besides, if the medium is found busy, the node doesn’t start its transmission, rather it defers its transmission for an amount of time. The waiting time can be determined by several ways. Devices attached to the network cable listen (carrier sense) before transmitting. MA (Multiple Access) indicates that many devices can connect to and share the same network. All devices have equal access to use the network when it is clear.

Even though devices attempt to sense whether the network is in use, there is a good chance that two stations will attempt to access it at the same time. On large networks, the transmission time between one end of the cable and another is enough that one station may access the cable even though another has already just accessed it. There are two methods for avoiding these so-called collisions, listed here:

3.3.3 CSMA/CD (Carrier Sense Multiple Access/Collision Detection): CD (collision detection) defines what happens when two devices sense a clear channel, then attempt to transmit at the same time. A collision occurs, and both devices stop transmission, wait for a random amount of time, and then retransmit. This is the technique used to access the 802.3 Ethernet network channel.

This method handles collisions as they occur, but if the bus is constantly busy, collisions can occur so often that performance drops drastically. It is estimated that network traffic must be less than 40 percent of the bus capacity for the network to operate efficiently. If distances are long, time lags occur that may result in inappropriate carrier sensing, and hence collisions.

3.3.4 CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance) : In CA collision avoidance), collisions are avoided because each node signals its intent to transmit before actually doing so. This method is not popular because it requires excessive overhead that reduces performance.

There are some variants of CSMA protocols. For example, in case of non-persistent CSMA, the node draws a random time, at the end of this time interval the node again senses the medium. In case of p-persistent CSMA, a node initiates communication in each slot with the p probability. So with the $1 - p$ probability of the node postpones its transmission for the subsequent slot i.e., the node defers its transmission. If some other node starts to transmit in the meantime, the node defers again and repeats the whole procedure. If value of the probability, p is very small the probability of collisions also becomes very small or unlikely, but it results high access delays. As the value of p increases the collision also becomes more likely. In the back-off procedure performed Distributed Coordination Function (DCF) of IEEE 802.11 standard protocol, if a node wants to transmit a fresh packet, it takes a value randomly within the current contention window. After that the node starts a timer with this value which is decremented at the end of every slot. If other sensor node initiates its transmission by this time, the timer is suspended and resumed after the subsequent frame finishes. As soon as the value of the timer reaches to zero, the node starts transmission. Though the CSMA protocols are also suffer from the collisions, the throughput efficiency of CSMA protocols is better than ALOHA protocols. Because of the node interested to transmit packet always sense the medium before transmission and they care for the ongoing packets.

3.3.5 Ethernet:

3.3.5.1 IEEE 802.3 Local Area Network (LAN) Protocols: Ethernet protocols refer to the family of local-area network (LAN)covered by the IEEE 802.3. In the Ethernet standard, there are two modes of operation: half-duplex and full-duplex modes. In the half duplex mode, data are transmitted using the popular Carrier-Sense Multiple Access/Collision Detection (CSMA/CD) protocol on as hared medium. The main disadvantages of the half-duplex are the efficiency and distance limitation, in which the link distance is limited by the minimum MAC frame size. This restriction reduces the efficiency drastically for high-rate transmission. Therefore, the carrier extension technique is used to ensure the minimum frame size of 512 bytes in Gigabit Ethernet to achieve a reasonable link distance. Four data rates are currently defined for operation over optical fiber and twisted-pair cables:

10 Mbps - 10Base-T Ethernet (IEEE 802.3)
100 Mbps - Fast Ethernet (IEEE 802.3u)
1000 Mbps - Gigabit Ethernet (IEEE 802.3z)
10-Gigabit - 10 Gbps Ethernet (IEEE 802.3ae).

The **Ethernet System** consists of three basic elements:

(1) The physical medium used to carry Ethernet signals between computers,

(2) a set of medium access control rules embedded in each Ethernet interface that allow multiple computers to fairly arbitrate access to the shared Ethernet channel, and

(3) an Ethernet frame that consists of a standardized set of bits used to carry data over the system.

As with all IEEE 802 protocols, the ISO data link layer is divided into two IEEE 802 sub-layers, the Media Access Control (MAC) sub-layer and the MAC-client sub-layer. The IEEE 802.3 physical layer corresponds to the ISO physical layer.

Each Ethernet-equipped computer operates independently of all other stations on the network: there is no central controller. All stations attached to an Ethernet are connected to a shared signaling system, also called the medium. To send data a station first listens to the channel, and when the channel is idle the station transmits its data in the form of an Ethernet frame, or packet.

After each frame transmission, all stations on the network must contend equally for the next frame transmission opportunity. Access to the shared channel is determined by the medium access control (MAC) mechanism embedded in the Ethernet interface located in each station. The medium access control mechanism is based on a system called Carrier Sense Multiple Access with Collision Detection (CSMA/CD).

As each Ethernet frame is sent onto the shared signal channel, all Ethernet interfaces look at the destination address. If the destination address of the frame matches with the interface address, the frame will be read entirely and be delivered to the networking software running on that computer. All other network interfaces will stop reading the frame when they discover that the destination address does not match their own address.

3.3.5.2 IEEE 802.4 Token Bus : In token bus network station must have possession of a token before it can transmit on the network. The IEEE 802.4 Committee has defined token bus standards as broadband networks, as opposed to Ethernet's baseband transmission technique. The topology of the network can include groups of workstations connected by long trunk cables.

These workstations branch from hubs in a star configuration, so the network has both a bus and star topology. Token bus topology is well suited to groups of users that are separated by some distance. IEEE 802.4 token bus networks are constructed with 75-ohm coaxial cable using a bus topology. The broadband characteristics of the 802.4 standard support transmission over several different channels simultaneously.

The token and frames of data are passed from one station to another following the numeric sequence of the station addresses. Thus, the token follows a logical ring rather than a physical ring. The last station in numeric order passes the token back to the first station. The token does not follow the physical ordering of workstation attachment to the cable. Station 1 might be at one end of the cable and station 2 might be at the other, with station 3 in the middle.

While token bus is used in some manufacturing environments, Ethernet and token ring standards have become more prominent in the office environment.

3.3.5.3 IEEE 802.5 Token Ring: Token ring is the IEEE 802.5 standard for a token-passing ring network with a star-configured physical topology. Internally, signals travel around the network from one station to the next in a ring. Physically, each station connects to a central hub called a MAU (multi station access unit). The MAU contains a "collapsed ring," but the physical configuration is a star topology. When a station is attached, the ring is extended out to the station and then back to the MAU.

3.4 Contention Based MAC Protocols

3.4.1 S-MAC (Sensor MAC): The S-MAC [30] (Sensor MAC) protocol is a single-frequency contention-based protocol for sensor networks. The basic idea is locally managed synchronizations and periodic listen/sleep period schedules. In general, nodes are synchronized locally, to operate a periodic sleep-and-listen schedule. Each node belongs to a virtual cluster and each cluster has a common listen-and-sleep schedule. It has fixed duty cycle. S-MAC also includes the concept of message passing, in which long messages are divided into frames and sent in a burst. Every frame has two parts: an active part and a sleeping part. During the active part, it can communicate with its neighbors and send any messages queued during the sleeping part. With this technique, one may achieve energy savings by minimizing communication overhead at the expense of unfairness in medium access.

Advantages: The energy waste caused by idle listening is reduced by sleep schedules. In addition to its implementation simplicity, time synchronization overhead may be prevented with sleep schedule announcements.

Disadvantages: Broadcast data packets do not use RTS/CTS which increases collision probability. Adaptive listening incurs overhearing or idle listening if the packet is not destined to the listening node. Sleep and listen periods are predefined and constant, which decreases the efficiency of the algorithm under variable traffic load.

3.4.2 T-MAC (Timeout MAC) [31]: T-MAC is proposed to enhance the poor results of the S-MAC protocol under variable traffic loads. It is used for shortening the awake period when the channel is idle. It improves the design of S-MAC. In their synchronization phase the node is listening to the channel only a short time. If there no data is received during this window, then the node returns to sleep mode. So that duty cycling reduces energy and increased latency.

3.4.3 B-MAC [32]: **Berkeley MAC**(B-MAC) is the default MAC for Mica2. B-MAC defines the whole wake-up period of the LPL structure as a check interval. The check interval consists of two parts, the listen interval and the sleep interval, and provides a framework for analyzing the operations of B-MAC in a WSN. B-MAC allows an application to implement its own MAC through a well-defined interface. In B-MAC, a flexible interface is proposed to obtain low power operation and effective collision avoidance. To achieve low power operation, B-MAC introduces an adaptive preamble sampling scheme which can lessen the wakeup period of an idle sensor node resulting a minimized idle listening time which can save energy. In addition to the proposal of an analytical model of B-MAC, authors provided comparisons of its performance with respect to IEEE 802.11 based protocol and claimed that due to B-MAC's inherent flexibility, BMAC is capable of offering better packet delivery rates, throughput, latency, and energy consumption than S-MAC.

3.4.4 RC-MAC: A novel RC-MAC (receiver centric) protocol that seamlessly integrates duty cycling and receiver centric scheduling resulting high throughput without sacrificing the energy efficiency. RC-MAC takes advantage of the underlying data accumulating tree structure of WSNs and supported by current IEEE 802.15.4 RF transceivers to assist scheduling of medium access. The throughput is developed into phases with receiver centric medium access scheduling and distributed channel assignment. The performance of RC-MAC was evaluated through measurements of an implementation in Tiny OS on TelosB motes and extensive NS-2 simulation.

3.4.5 Wi-rArb MAC: A new MAC protocol named wireless arbitration (Wi-rArb) that allows each user to access channel based on versatile preference levels. The introduced MAC protocol supports multiple users and a specific arbitration frequency pre-assigned to each user that promote the order of channel access. Here, a user with higher priority will instantly gain channel access ensuring a deterministic behavior. They mathematically formulate the WirArb protocol for the proposed MAC using a discrete time markov chain model. The proposed protocol results in high performance to ensure deterministic real time communication as well as bandwidth efficiency.

3.4.6 Predictive Wake-up MAC (PW-MAC): In PW-MAC, the wake-up schedule of nodes can be randomized [59], [60]. To inform the intended transmitters, the node will send a signal upon waking up. A sender can predict the receiver's wake-up time and can wake-up simultaneously to save energy. To address timing challenges, PW-MAC has an on-demand prediction-based error correction mechanism. PW-MAC has a reduced duty cycle, as it has a random node wake-up schedule. It has improved performance compared to S-MAC and B- MAC, as collisions can be avoided. Latency is less than 5% of that typical of other MAC protocols. A node needs only 10 bytes of memory to store the prediction state of other nodes. Each node has to send a signal on waking-up, so the overhead of the protocol is increased, although it is low compared to other protocols. Also, hardware can induce errors in predicting wake-up times of the receiver.

3.4.7 Power Efficient and Delay Aware MAC (PEDAMAC): To minimize energy consumption due to overhearing, PEDAMAC transmits data at more than one power level. The access points (also called sinks) coordinate sensor nodes. Access points are assumed to have no power constraints, while sensor nodes have limited power. PEDAMAC assumes that each node can reach the sink in one hop. It has four phases: topology learning, topology collection, scheduling and adjustment. The protocol allows the nodes to operate at different power levels, as per the requirement of the task being processed by the node. It has three power levels: maximum power Pm, medium Px, and minimum Ps. Synchronization is done at Pm. The sink can broadcast topology-related information at Px. Data is transmitted at Ps. Low transmission power saves energy and it is used in delay-bound applications, but it has a few drawbacks, such as the fact that protocol assumes a one hop distance to the sink, which may not always be the case. Distinct power levels increase the protocol overhead. Also, data may be dropped before delivered, if transmission power is too low, i.e. the range of radio is decreased because of power limitation. PEDAMAC can be enhanced by increasing the number of media or channels to further reduce the delay [60]– [62]. Energy harvesting is considered as the only energy source by Eu et al. [15]. It is not easy to predict the wake-up schedule of nodes powered by energy harvesters. Authors exploited the uncertain nature of energy harvesting sources to increase the performance of MAC protocols. MAC protocols based on battery-powered WSNs have different goals, such as increased lifetime compared to energy harvesting based WSN (EH-WSN). So, there is a need to have protocols designed specifically for EH-WSN.

3.5 Energy Harvesting MAC protocols:

3.5.1 Probabilistic polling: In probabilistic polling, the sink sets contention probability Pc in each node through a polling packet [63]. Each node generates a random number ν, and when it is less than contention probability ($\nu < P_c$), the node is allowed to send. Otherwise, the node can go to the charging state. The sink keeps on changing contention probability depending on network response. If no sensor responds, the sink increases P_c. Also, when a node leaves the network, Pc is increased. In the case of collision and joining of new node, Pc is decreased by a larger amount. This approach is known as additive-increase and multiplicative-decrease. Contention probability Pc offers maximum throughput when it is equal to the inverse of the number of nodes receiving polling packets:

$$P_{opt} = 1/ N_r \text{ ……………(1)}$$

where P_{opt} is the optimal probability that maximizes throughput. N_r is the number of nodes receiving polling packets ($N_r \geq 1$). This protocol can adapt to varying energy harvesting rates to ensure high throughput and the sink can also adjust Pc in the case of a collision. Hence, the protocol increases scalability of the network. Since P_c keeps changing due to collisions or when a node joins or leaves a network, it takes quite some time for the network to stabilize. This leads to increased network latency. Also, bandwidth is wasted until the network stabilizes at an appropriate P_c. Another drawback is that the protocol assumes a single hop distance to the sink, limiting protocol scalability.

3.5.2 HEAP-EDF: Power generated by ambient energy harvesting sources (HEAP), may vary, i.e. solar energy has different rates in the morning and in the afternoon. To overcome this, Earliest Deadline First (HEAP-EDF) uses a predict and-update algorithm to reduce the temporal variations [66]. In HEAP-EDF, the sink polls the node with the minimum or the earliest wake-up time. The sensor will not poll the node whose energy has decreased below the transmission level because of previous polling. At the power balance ratio of 0.5, HEAP-EDF offers the best fairness. The power-balance ratio is given as:

$$\text{Ø} = \sum_{n=1}^{N} T_c / T_n \text{ ………………(2)}$$

In Eq. (2), Tc is the duration of polling cycle, Tn is energy harvesting delay for n-th node and N is the number of sensor nodes. Simulations in [66] show that channel utilization reduces as the link error probability increases. HEAP-EDF performs worse in the case of large networks. Also, the single-hop approach is assumed, which limits application of the protocol to small networks.

Table3.4: Performance evaluation of Contention Based MAC protocols

Protocol	S-MAC	T-MAC	B-MAC	PW-MAC	PEDAMAC	Probabilistic polling	HEAP-EDF
Throughput	Low	Low	High	High	Moderate	High	Moderate
Energy conservation	Low	High	Moderate	High	Moderate	N/A	N/A
Maximum % of energy saved vs. S-MAC	0	85	57	80	38	N/A	N/A
Latency	High	N/A	Moderate	Low	Low	Depends on energy harvesting rate	Depends on energy harvesting rate
Overhead	Low	Moderate	High	Moderate	High	Low	Moderate
Scalability	High	Low	Low	High	Low	High	Low

From Table we can shows the performance of MAC protocols reviewed. B-MAC has a high throughput owing to preamble sampling, but this increases the overhead too. Since probabilistic polling and HEAP-EDF are based on an ambient energy harvesting source, energy consumption is not a relevant factor to be compared. In this case of HEAP-EDF, overhead can be decreased if energy harvesting rates are correlated. Protocols with high overheads cannot be scaled to a large network due to the increase in the number of control packets. In PEDAMAC, as transmission power decreases, the range of radio also decreases, which affects the network scalability. Simulations are performed under different scenarios and with different considerations, so it is difficult to directly compare these protocols. Hence, the comparison values are presented as percentages of S-MAC serving as a benchmark. S-MAC consumes 2.8 mA/node and T-MAC consumes 0.4 mA/node. B-MAC saves 57% more energy than S-MAC for a throughput of 240 b/s, because synchronization overhead increases in S-MAC. PW-MAC protocol's duty cycle is only 11%, while duty-cycle of S-MAC is 50%. Decreased duty-cycle leads to decreased energy consumption. Also, owing to operation at distinct power levels, PEDAMAC saves 38% more energy than S-MAC.

3.6 Hybrid MAC Protocols

3.6.1 A-MAC (Asynchronous MAC): A-MAC [29] aims at providing collision-free, non-overhearing and less idle listening transmission services. Each node can adjust duration of the active period depending on traffic. According to the authors, this protocol is adaptive in terms of guard band assignment mechanism, and sleep or wakeup technique. It can be used for specific application like monitoring human body assuming the sensor nodes continuously scan body for updated information. Moreover, the synchronization scheme for collision avoidance has been precisely defined in the AMAC.

3.6.2 BAZ-MAC: Hybrid MAC protocol BAZ-MAC is proposed for Ad Hoc networks. The protocol uses a bandwidth aware slot allotment technique during the set-up phase; slots are assigned to the nodes according to their bandwidth requirements. In WiseMAC [36] a sender can minimize the length of the preamble by exploiting the knowledge of the sampling schedules of its neighbors during communication and thus reducing the preamble transmission overhead.

3.6.3 Hybrid MAC (H-MAC): In HMAC or Hybrid MAC [40], time is organized into frames. Each frame contains multiple short wakeup slots and multiple data slots. It employs two basic procedures: self-organization for wakeup slot assignment and data transmission H-MAC is a low power with minimal packet delay medium access control protocol for wireless sensor networks (WSNs). H-MAC achieves high energy efficiency under wide range of traffic load. It ensures high channel utilization during high traffic load without compromising energy efficiency. H-MAC does it by using the strength of CSMA and TDMA approach with intelligence. The novel idea behind the H-MAC is that, it uses both the broadcast scheduling and link scheduling. Depending on the network loads the H-MAC protocol dynamically switches from broadcast scheduling to link scheduling and vice-versa in order to achieve better efficiency.

3.6.4 HyMAC [39] is a hybrid TDMA/FDMA MAC protocol. The communication period comprises of a several fixed time slots. In each cycle, the beginning slots are scheduled slots and remaining slots are contention slots.

3.6.5 Intelligent Hybrid MAC (IH-MAC) [37]: IH-MAC is an improved version of H-MAC protocol providing low power with quality of service guaranteed medium access control protocol for wireless sensor networks (WSNs). Intelligent Hybrid MAC (IH-MAC) is a novel low power with quality of service guaranteed medium access control protocol for wireless sensor networks (WSNs). IH-MAC achieves high energy efficiency under wide range of traffic load, and ensures shorter latency to critical and delay-sensitive packets. IH-MAC protocol achieves high channel utilization during high traffic load without compromising energy efficiency, and does it by using the strength of CSMA and TDMA approach with intelligence. The novel idea behind the IH-MAC is that, it uses both the broadcast scheduling and link scheduling. Depending on the network loads, the IH-MAC protocol dynamically switches from broadcast scheduling to link scheduling and vice- versa in order to achieve better efficiency. The scheduling is done in IH-MAC with a novel decentralized approach where the nodes locally use the clock arithmetic to find the time slot, allocated for it. Furthermore, IH-MAC uses Request-To-Send (RTS), Clear–To-send (CTS) handshakes with methods for adapting the transmit power to the minimum level necessary to reach the intended neighbor. In this way, IH-MAC reduces energy consumption by suitably varying the transmit power. IH-MAC also uses the concept of parallel transmission which further reduces delay.

3.6.6 Z-MAC [33]: Z-MAC dynamically adjusts the behavior of MAC between CSMA and TDMA depending on the level of contention in the network. This protocol uses the knowledge of topology and loosely synchronized clocks as hints to improve MAC performance under high contention. Z-MAC uses DRAND [34], a distributed implementation of RAND [35] to assign slot to every node in the network. Z-MAC achieves high channel utilization and low latency if there is low traffic load hence lower chance of contention for channel. It has the capability to reduce collision with low cost. Besides, during high traffic, high channel utilization is possible by using Z-MAC. The worst case performance of Z-MAC is similar to CSMA.

3.6.7 Energy efficient and Quality of service aware MAC (EQ-MAC) [53]: EQ-MAC is a Hybrid MAC protocol. It differentiates the long and short messages and it uses the priority techniques for higher priority data. It uses schedule and non-schedule techniques for data transmission for greater performance.

3.6.8 SpeckMAC Hybrid: SpeckMAC-H protocol was proposed combining the preferences of each of the SpeackMAC variations. SpeckMAC-H embraces an versatile approach where the sender chooses which SpeckMAC variation to be utilized depending on the current traffic type. In this way, the energy consumption can be reduced significantly but the excess latency problem is still not addressed.

4. Another MAC Protocols for Wireless Sensor Networks are:

4.1 EP-MAC [38]: EP-MAC is a novel low power medium access control protocol for wireless sensor networks (WSNs). The proposed protocol achieves high energy efficiency and high packet delivery ratio under different traffic load. EP-MAC protocol is basically based on TDMA (Time Division Multiple Access) approach. The power of CSMA is used in order to offset the fundamental problems that the stand-alone TDMA method suffers from i.e., problem like lack of scalability, adaptability to varying situations etc. Novel idea behind the EP-MAC is that, it uses parallel transmission concept with the TDMA link Scheduling. EP-MAC uses transmission power adjustment method that uses the minimum level of power necessary to reach the intended neighbor within a specified BER target. This reduces energy consumption, as well as further enhances the scope of parallel transmission of the protocol. The simulation studies support the theoretical results, and validate the efficiency of the proposed EP-MAC protocol.

4.2 TEEM (Traffic Aware, Energy Efficient MAC): Traffic Aware, Energy Efficient MAC protocol is inspired by the S-MAC protocol. TEEM is also based on the concept of 'listen/sleep modes cycle'. However, unlike S-MAC where the duration of listen and sleep modes are fixed, TEEM protocol makes the durations adaptive by utilizing the 'traffic information' of each and every node, and hence achieves a significant decrease in power consumption as compared to S-MAC.

4.3 EM-MAC (Efficient Multichannel MAC) protocol: Efficient Multichannel MAC) protocol introduces different mechanisms for adaptive receiver-initiated multichannel rendezvous and for predictive wake-up scheduling. EM-MAC enhances channel utilization and transmission efficiency while resisting the wireless interference and jamming. EM-MAC achieves high energy efficiency by enabling the sender to predict the receiver's wake-up channel and wake-up time. EM-MAC outperformed other MAC protocols studied earlier. EM-MAC maintained the lowest sender and receiver duty cycles, the lowest packet delivery latency, and 100% packet delivery ratio across the experiments.

4.4 DE-MAC (Distributed Energy Aware MAC): Distributed Energy Aware MAC protocol exploits the inherent features of TDMA (Time Division Multiple Access) in order to avoid energy loss due to collision and control packet. DE-MAC uses the concept of periodic listen and sleep in order to avoid idle listening and overhearing. However, unlike many existing MAC-protocols, DE-MAC treats the critical nodes differently in a distributed manner. It is motivated by the idea that weaker node should be used less frequently in order to accomplish load balancing. DE-MAC performs local election procedure in order to choose the worst off nodes and makes them sleep more than the other neighboring nodes.

4.5 G-MAC (Gateway MAC): Gateway MAC protocol, which implements cluster-centric paradigm to distribute cluster energy resources and extend life time of the network. G-MAC's centralized cluster management function offers energy savings by leveraging the advantages of both contention-based and contention-free protocols. A centralized gateway node collects all transmission-related requirements during a contention-based period and then schedules their distributions during a contention-free period

4.6 LMAC (Lightweight Medium Access Protocol): Lightweight Medium Access Protocol is designed especially for WSN. The protocol uses TDMA for collision-free communication, the network is self-organizing in terms of synchronization and time slot assignment. The main goal of this protocol is to minimize overhead of the physical layer. For achieving this, the protocol reduces the number of overall transceiver state switches and hence the energy wastage is reduced occurring due to preamble transmissions. The protocol is able to extend the network lifetime as compared to EMACs and SMAC respectively.

4.7 Pattern MAC (PMAC): Pattern MAC [51] is CSMA based protocol. In PMAC the wakeup and sleep time of nodes are changed dynamically based on the its own traffic pattern and that of the neighbor's.

3.5 The properties of MAC protocols are summarized in the following Table:

Table 3.5: Comparison of Wireless Sensor Network MAC PROTOCOLS

Protocols	**S-MAC**	**T-MAC**	**Q-MAC**	**IH-MAC**	**EP-Mac**
Energy Efficiency	Low due to fixed duty cycle	High when there is a variation of network load/traffic and low when there is traffic with regular interval.	Low due to fixed duty cycle	High irrespective of network load	High when there is high traffic
Latency	Moderate	High latency because it trades off latency to gain energy efficiency	Moderate	Moderate	Low when there is high traffic
QoS support	No	No	Limited control and limited flexibility due to fixed scheduling	Limited control and limited flexibility due to dynamic scheduling	No
Control Packet Overhead	Moderate	Moderate	High	No	Moderate

Table 3.6: Various key attributes of each of the protocols discussed above along with its key merits and demerits

Protocol	S-MAC	T-MAC	B-MAC	WiseMAC	D-MAC	LL-MAC	TRAMA	W-MAC
Type	CSMA	CSMA	CSMA	np-CSMA	TDMA	TDMA	Hybrid	TDMA
Energy	Low	Low	Low	Low	Low	Low	Low	Low
Latency	High	High	Low	High	Low	Low	Low	Low
Through-put	High	Low	High	High	Low	Low	Low	Low
Merits	Reduced idle listening	Handles variable traffic load well	Good adaptability to changes	Performs better in variable traffic conditions	Low latency	Avoids hidden terminal problem.	Performs better in multicast /broadcast scenario	Tolerates traffic variation
Demerits	Predefined listen period results in over-hearing during variable traffic conditions	Early sleeping affects through put	Suffers from overhearing	Prone to hidden terminal problem	Increased chances for collision	High memory usage	High duty cycle value	Does not support concurrent transmission

Table: 3.7 Comparison of three Categories MAC Protocols for WSN

Approach	Contention Based	Scheduling Based	Hybrid Based
Protocols	S-MAC, T-MAC, ELMAC etc.	TDMA, CDMA, FDMA etc.	EQMAC, CTMAC, HYMAC, A-MAC, IHMAC, IEEE 802.15.4 and Z-MAC etc
Reliability Support	Good	Good	Good
Energy Efficiency	High	Low	High
Real Time Communication	Moderate	Low	Good

5. INTEGRATION OF MAC WITH OTHER LAYERS

Limited research has been carried out on integrating different network layers into one layer or to benefit from cross-layer interactions between routing and MAC layers for sensor networks. For instance, Safwat et al. proposed two routing algorithms that favor the information about successful/unsuccessful CTS or ACK reception [68]. looked at MAC/physical layer integration and Routing/MAC/physical layer integration [67]. They proposed a variable length TDMA scheme in which the slot length is assigned according to some criteria for optimum energy consumption in the network. Among these criteria, the most crucial ones are information about the traffic generated by each node and the distances between each node pair. Based on these values, they formulated a linear programming (LP) problem in which the decision variables are normalized time-slot lengths between nodes. They solve this LP problem using an LP solver that returns the optimum number of time slots for each node pair as well as the related routing decisions for the system. The proposed solution could be beneficial in scenarios where the required data would be prepared. However, it is generally difficult to have the node-distance information and the traffic generated by the nodes. Besides, the LP solver can only be run on a powerful node. The dynamic behavior of sensor networks will require online decisions which are very costly to calculate and hard to adapt to an existing system. Multi node Infrastructure Network Architecture (MINA) is another method for integrating MAC and routing protocols [68]. Ding et al. proposed a layered multi hop network architecture in which the network nodes with the same hope count to the base station are grouped into the same layer. Channel access is a TDMA-based MAC protocol combined with CDMA or

FDMA. The super-frame is composed of a control packet, a beacon frame, and a data transmission frame. The beacon and data frames are time slotted. In the clustered network architecture, all members of a cluster submit their transmission requests in beacon slots. Accordingly, the cluster-head announces the schedule of the data frame. The routing protocol is a simple multi hop protocol where each node has a forwarder node at one nearer layer to the base station. The forwarding node was chosen from candidates based on the residual energies. Ding et al. then formulated the channel allocation problem as an NP-complete problem and proposed a suboptimal solution. Moreover, the transmission range of the sensor nodes is a decision variable, since it affects the layering of the network (the hop-counts change). Simulations were run to find a good range of values for a specific scenario. The proposed system in [68] is a well-defined MAC/Routing system. However, the tuning of the range parameter is an important task that should be done at system initialization. In addition, all node-to-sink paths are defined at the startup and are defined to be static, since channel frequency assignments of nodes are done at the startup accordingly. This makes the system intolerant to failures. Geographic Random Forwarding (GeRaF) is actually proposed as a routing protocol, but the underlying MAC algorithm is also defined in the work, which is based on CSMA/CA. This work gives a complete (but not integrated) solution for a sensor network's communication layers. However, the sensor nodes and their neighbor's location information is needed for those protocols. Besides, the forwarding node is chosen among nodes that are awake at the time of the transmission request. That may result in routing with more power-consumption and an increase in latency.

6. OPEN ISSUES

Whereas TDMA based protocols has the most advantage of collision-free medium access, clock drift issue and diminished throughput at low traffic loads are open issues which are being tended to by analysts. In WSN, these TDMA protocols have the extra challenge of adjustment to topology changes caused by broken links due to battery exhaustion, inclusion of new nodes, sleep/wakeup schedules of relay nodes and clustering algorithms.

In accordance with common networking lore, CSMA methods have a lower delay and promising throughput potential at lower traffic loads, which generally happens to be the case in wireless sensor networks. However, additional collision avoidance or collision detection methods should be employed. While CSMA strategies offer lower delay and good throughput at lower traffic loads, additional collision avoidance or collision detection are required to handle the collision possibilities. CDMA based protocols offers collision-free medium, but they require high computational power which virtually rules them out of consideration for energy sensitive systems like WSN. There are open issues to prove that the collision-free medium offered by these protocols can be a tradeoff for energy consumption caused by high computational power. And comparison of CSMA, TDMA and other MAC protocols under a common framework is still an open research area.

FDMA is another scheme that offers a collision- free medium, but it requires additional circuitry to dynamically communicate with different radio channels. This increases the cost of the sensor nodes, which is contrary to the objective of sensor network systems.

CDMA also offers a collision-free medium, but its high computational requirement is a major obstacle for the less energy-consumption objective of sensor networks. In pursuit of low computational cost for wireless CDMA sensor networks, there has been limited effort to investigate source and modulation schemes, particularly signature waveforms, designing simple receiver models, and other signal synchronization problems. If it is shown that the high computational complexity of CDMA could be traded-off against its collision-avoidance feature, CDMA protocols could also be considered as candidate solutions for sensor networks. Lack of comparisons of TDMA, CSMA, or other medium- access protocols in a common framework is a crucial deficiency of the literature.

Also, rating these protocols based on not just the layer 2 performance but the overall system performance is still lacking or insufficient, which can provide a greater push for multi-layer protocols. With respect to specific protocols discussed in this paper, in S-MAC, adaptability to the changes in network topology requires more work. TMAC discusses virtual clustering but it is not clearly described. PMAC is not suitable for point to point converge gate and broadcast based network. In D-MAC the sensor nodes are fixed based on assumption and strength of sensor nodes are not considered. In X-MAC only few number of nodes can be used but latency can be measured with more data points, so the research can be carried out with more number of nodes. In W-MAC transmissions are not carried-out simultaneously, but if we reuse the same time slot again we can support concurrent transmissions.

7. Conclusion: This paper presents the study of various WSN specific MAC protocols based on various design factors that MAC protocols have been surveyed. MAC protocols have been reviewed for both type of nodes followed by their advantages and disadvantages. It must be highlighted that there is no one protocol accepted as a universal standard. The prime reason is that the choice of the MAC protocol in WSN will be application specific based on the requirement of the key attributes specific to that application. Another reason is that the lower layers lack standardization and similar conclusion can be drawn for upper layers as well. Hence, a cross-layer design approach is still feasible as attempted in few of the protocols discussed in this paper and it seems to be a promising research area which has to be studied more extensively. The cross-layer approach is a research area that needs to be studied and analyzed widely. Traffic modeling is another prospective area which can be analyzed and studied for improving performance or security of networks. Energy harvesting algorithms and models for WSNs also are subject to great advancements in the future. This paper also suggests that because of its low latency, PEDAMAC can be used for delay sensitive applications. Owing to the random wake-up schedule, PW-MAC offers high throughput. It sends one update in 1400 s, so overhead is moderate. Therefore, Comparison of MAC protocols are also describing in the following tables. Time sync needed Common pattern support Type Adaptively to changes S-MAC/T-MAC/DSMAC No All CSMA Good WiseMAC No All np-CSMA Good TRAMA Yes All TDMA/CSMA Good Sift No All CSMA/CA Good DMAC Yes Converge cast TDMA/Slotted Aloha Weak Variable loads in sensor networks are expected, since the nodes that are closer to the sink must relay more traffic and traffic may change over time. Although T-MAC gives better results under these variable loads, the synchronization of the listen periods within virtual clusters is broken.

Common wireless networking experience also suggests that link-level performance alone may provide misleading conclusions about the system performance. A similar conclusion can be drawn for the upper layers as well. Hence, the more layers contributing to the decision, the more efficient the system can be. For instance, the routing path could be chosen depending on the collision information from the medium access layer. Moreover, layering of the network protocols creates overheads for each layer, which causes more energy consumption for each packet. Therefore, integration of the layers is also a promising research area that needs to be studied more extensively.

References

[1] D. Christin, A. Reinhardt, P.S. Mogre, R. Steinmetz. ―Wireless sensor networks and the internet of things: selected challenges,‖ in Proc. the 8th GI/ITG KuVS Fachgespräch Drahtlose Sensornetze, 2009, pp. 31-34.

[2] D. Culler, D. Estrin, and M. Srivastava, ―Guest editors' introduction: Overview of sensor networks,‖ Computer vol. 37, no. 8, pp. 41-49, Aug. 2004.

[3] I. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "A survey on sensor networks,‖ IEEE Commun. Mag., pp.102-114, August, 2002.

[4] C. Schurgers, V. Tsiatsis, S. Ganeriwal, and M. Srivastava, "Topology management for sensor networks: Exploiting latency and density," in Proceedings of the 3rd ACM international symposium on Mobile ad hoc networking & computing. ACM, 2002, pp. 135–145.

[5] C. Schurgers, V. Tsiatsis, S. Ganeriwal, and M. Srivastava, "Optimizing sensor networks in the energy-latency-density design space," IEEE Transactions on Mobile Computing, vol. 1, no. 1, pp. 70–80, 2002.

[6] G. Zheng, J. Fu, S. Tang, Y. Li, and Z. Dong, "A dual channel-based energy efficient and low latency mac protocol for wsns," in 2nd International Conference on Networks Security Wireless Communications and Trusted Computing (NSWCTC), vol. 1, 2010, pp. 466–469.

[7] F. A. Aoudia, M. Gautier, and O. Berder, "Opwum: Opportunistic mac protocol leveraging wake-up receivers in wsns," Journal of sensors, vol. 2016, Article ID 6263719, 9 pages, 2016.

[8] J. Ansari, X. Zhang, and P. Mahonen, "Multi-radio medium access control protocol for wireless sensor networks," International Journal of Sensor Networks, vol. 8, no. 1, pp. 47–61, 2010.

[9] N. S. Mazloum and O. Edfors, "Dcw-mac: An energy efficient medium access scheme using duty-cycled low-power wake-up receivers," in IEEE Vehicular Technology Conference (VTC Fall), 2011, pp. 1–5.

[10] S. Glisic and B. Vucetic, "Spread Spectrum CDMA Systems for Wireless Communications", Artech House, Boston MA, 1997.

[11] I. Rubin, " Access Control Discipline for Multi-Access Communications Channels: Reservation and TDMA Scheme", IEEE Transactions on Information Theory, 25(5): 516-536, 1979

[12] Heinzelman, Wendi B., Anantha P. Chandrakasan, and Hari Balakrishnan, "An application-specific protocol architecture for wireless microsensor networks," IEEE Transactions on Wireless Communications, vol. 1, no. 4, pp. 660-670, 2002

[13] Li, Jing, and Georgios Y. Lazarou, "A bit-map-assisted energy-efficient MAC scheme for wireless sensor networks," in Proceedings of the 3rd international symposium on Information processing in sensor networks, pp. 55-60, 2004

[14] Shafiullah, G. M., Adam Thompson, Peter J. Wolfs, and Shawkat Ali, "Energy-efficient TDMA MAC protocol for wireless sensor networks applications," 11th International Conference on Computer and Information Technology (ICCIT), pp. 85-90, 2008.

[15] Hsu, T-H., and P-Y. Yen, "Adaptive time division multiple access-based medium access control protocol for energy conserving and data transmission in wireless sensor networks," Communications, IET, vol. 5, no. 18, pp. 2662-2672, 2011.

[16] Shafiullah, G. M., Salahuddin A. Azad, and A. B. M. Ali, "Energyefficient wireless MAC protocols for railway monitoring applications," IEEE Transactions on Intelligent Transportation Systems, vol. 14, no. 2, pp. 649-659, 2013.

[17] Alvi, Ahmad Naseem, Safdar Hussain Bouk, Syed Hassan Ahmed, Muhammad Azfar Yaqub, Nadeem Javaid, and Dongkyun Kim, "Enhanced TDMA based MAC protocol for adaptive data control in wireless sensor networks," Communications and Networks, vol. 17, no. 3, pp. 247-255, 2015.

[18] Alvi, Ahmad Naseem, Safdar Hussain Bouk, Syed Hassan Ahmed, Muhammad Azfar Yaqub, Mahasweta Sarkar, and Houbing Song, "BEST-MAC: Bitmap-Assisted Efficient and Scalable TDMA-Based WSN MAC Protocol for Smart Cities," IEEE Access, vol. 4, pp. 312- 322, 2016.

[19] N. Passas, S. Paskalis, D. Vali, and L. Merakos, "Quality-of-Service-Oriented Medium Access Control for Wireless ATM Networks", IEEE Communications Magazine, 35(11): 42–50, 1997.

[20] O. Sharon and E. Altman, "Efficient Polling MAC for Wireless LANs", IEEE/ACM Transactions on Networking, 9(4):439-451, 2001.

[21]]A. Doufexi, S. Armour, M. Butler, A. Nix, D. Bull, and J. McGeehan and P. Karlsson , "A comparison of the HIPERLAN /2 and IEEE 802.11a Wireless LAN Standards", IEEE Communications Magazine, 40 (5):172-80, 2002.

[22] Li, Hui, Goran Malmgren, and Mathias Pauli. "Performance comparison of the radio link protocols of IEEE802. 11 a and HIPERLAN/2." In Vehicular Technology Conference, 2000. IEEE-VTS Fall VTC 2000. 52nd, vol. 5, pp. 2185-2191. IEEE, 2000.

[23] P. Casari, M. Nati, C. Petrioli and M.Zorzi, “ALBA: an Adaptive Load-Balanced Algorithm for Geographic Forwarding in Wireless Sensor Networks,” in Proc. IEEE Military Communications Conference (MILCOM’06), Washington DC, October 2006.

[24] N. Passas, S. Paskalis, D. Vali, and L. Merakos, "Quality-of-Service-Oriented Medium Access Control for Wireless ATM Networks", IEEE Communications Magazine, 35(11): 42–50, 1997.

[25] H. Takagi, Analysis of Polling Systems. MIT Press, Cambridge, MA, 1986

[26] F.A. Tobagi and L. Kleinrock, "Packet Switching in Radio Channels: Part-III Polling and (Dynamic) Split Channel Reservation Multiple Access", IEEE Transactions on Communications: 24(8):832-845, 1976.

[27] LAN/MAN Standards Committee of the IEEE Computer Society. IEEE Standard for Information Technology-Telecommunication and information exchange between systems- Local and metropolitan area networks-specific requirements- part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low Rate Wireless Personal Area Networks(LR-WPANs) October 2003.

[28] W.B. Heinzelman, J. Kulik, and H. Balakrishnan. An Application-Specific Protocol Architecture for Wireless Microsensor Networks. IEEE Transactions on Wireless Networking, 1(4): 600-670, 2002.

[29] S. H. Lee, J. H. Park, L. Choi, "A-MAC : Traffic- Adaptive Sensor Network MAC protocol through Variable Duty-Cycle Operations ,‖ in Proc. ICC 2007, pp.3259-3264

[30] Lu, G.; Krishnamachari, B.; Raghavendra, C.S.; , "An adaptive energy-efficient and low-latency MAC for data gathering in wireless sensor networks," Parallel and Distributed Processing Symposium, 2004. Proceedings. 18th International, vol., no., pp. 224, 26-30 April 2004.

[31] Ji-Jun Zhao; Xiang Sun;, "MAC protocol based on T-MAC multihop reservation for short-latency wireless sensor network," Communication Technology, 2008. ICCT 2008. 11th IEEE International Conference on , vol., no., pp.114-117, 10-12 Nov. 2008.

[32] J. Polstre, J. Hill, and D. Culler, "Versatile low power media access for wire-less sensor networks,‖ in Proc. ACM SenSys, New York, 2004, pp.95-107.

[33] I. Rhee, A. Warrier, M. Aia, and J. Min, "Z-MAC: A hybrid MAC for wire-less sensor networks,‖ in Proc. SenSys'05, Nov 2-4, 2005.

[34] I. Rhee, W. J.Min, and L. Xu, "DRAND: Distributed randomized TDMA scheduling for wireless ad hoc networks,‖ in Proc. ACM MobiHoc, New York, 2006, pp.190-201.

[35] S. Ramanathan, "A unified framework and algorithm for (T/F/C) DMA chan-nel assignment in wireless networks,‖ in Proc. IEEE INFOCOM, 1997, pp.900-907.

[36] C. C. Enz., E. H. Amre, J. D. Decotignie, V. Peiris, "WiseNET: An ultra low-power wireless sensor network solution,‖ IEEE comput. Magazine, vol.37, no. 8, Aug 2004.

[37] M. Arifuzzaman, M. Matsumoto, and T. Sato. "An intelligent hybrid MAC with traffic-differentiation-based QoS for wireless sensor networks." IEEE Sensors Journal 13, no. 6, pp. 2391-2399, Jun. 2013.

[38] M. Arifuzzaman, and M. Matsumoto. "An Efficient Medium Access Control Protocol with Parallel Transmission for Wireless Sensor Networks." Journal of Sensor and Actuator Networks vol. 1. no. 2 pp.111-122, Aug. 2012.

[39] Mastooreh Salajegheh, Hamed Soroush, and Antonis Kalis “Hymac: Hybrid Tdma/Fdma Medium Access Control Protocol For Wireless Sensor Networks”, 2008 IEEE.

[40] Heping Wang; Xiaobo Zhang; Khokhar, A.; "WSN05-6: An EnergyEfficient Low-Latency MAC Protocol for Wireless Sensor Networks,"GLOBECOM '06. IEEE , vol., no., pp.1-5.

[41] C. D. Kidd, R. J. Orr, G. D. Abowrd, C. G. Atkeson, I. A. Essa, B. MacIntyre, E. Mynatt, T. E. Starner, and W. Newstetter. "The Aware Home: A Living Laboratory for Ubiquitous Computing Research", In Proc. of the 2nd International Workshop on Cooperative Buildings, Pittsburgh, PA, 1999.

[42] IEEE 802.11. IEEE Standard for Wireless LAN Medium Access Control (MAC) and Physical Layer Specifications, November 1997.

[43] P. Karn, "MACA — A New Channel Access Method for Packet Radio," in Proceedings of the ARRL/CRRL Amateur Radio 9th Computer Networking Conference, Ontario, Canada, September 1990, pp. 134-140.

[44] C. D. Kidd, R. J. Orr, G. D. Abowrd, C. G. Atkeson, I. A. Essa, B. MacIntyre, E. Mynatt, T. E. Starner, and W. Newstetter. "The Aware Home: A Living Laboratory for Ubiquitous Computing Research", In Proc. of the 2nd International Workshop on Cooperative Buildings, Pittsburgh, PA, 1999

[45] http://standards.ieee.org/about/get/802/802.11.html

[46] J.C. Haartsen. "The Bluetooth Radio System", IEEE Personal Communications, 7(1):28-36, 2000.

[47] https://arxiv.org/ftp/arxiv/papers/1406/1406.4701.pdf

[48] [file:///C:/Users/USER/Desktop/others%20protocols.pdf

[49] Islam, M. M., Akanda, M. R., Islam, M. E., & Arifuzzaman, M. (2016). Energy Efficient MAC Protocols for Wireless Sensor Networks: A Comprehensive Survey. International Journal ofComputer Science and Information Security, 14(10), 706.

[50] Yadav, R., Varma, S., & Malaviya, N. (2009). A survey of MAC protocols for wireless sensor networks. UbiCC journal, 4(3), 827-833.

[51] T. Zheng, S.Radhakrishnan and V.Sarangan, “PMAC: An adaptive energy-efficient MAC protocol for Wireless Sensor Networks”, Parallel and Distributed Processing Syeposiue, 2005. Proceedings. 19th IEEE International, pp4-8, April 2005.

[52] I. Marin, J. Arias, E. Arceredillo, A. Zuloaga, I. Losada and J. Mabe, “LL-MAC: A low latency MAC protocol for wireless self-organised networks”, Microprocessors Microsystees, voluee 32, pp 197-209, 2008.

[53] Ilker Deeirkol, Cee Ersoy and Fatih Alagöz, “Mac protocols for wireless sensor networks: A survey”,IEEE Coeeun. Mag. Vol. 06, pp. 115–121, April 2006.

[54] W. Ye, J. Heidemann, D. Estrin, “Medium Access Control With Coordinated Adaptive Sleeping for Wireless Sensor Networks”, IEEE/ACM Transactions on Networking, Volume: 12, Issue: 3, Pages:493 - 506, June 2004.

[55] C. C. Enz, A. El-Hoiydi, J-D. Decotignie, V. Peiris, “WiseNET: An Ultralow-Power Wireless Sensor Network Solution”, IEEE Computer, Volume: 37, Issue: 8, August 2004.

[56] V. Rajendran, K. Obraczka, J.J. Garcia-Luna-Aceves, “Energy-Efficient, Collision-Free Medium Access Control for Wireless Sensor Networks”, Proc. ACM SenSys 03, Pages:181 - 192, Los Angeles, California, 5-7 November 2003.

[57] K. Jamieson, H. Balakrishnan, and Y. C. Tay, “Sift: A MAC Protocol for Event-Driven Wireless Sensor Networks,” MIT Laboratory for Computer Science, Tech. Rep. 894, May 2003, http://www.lcs.mit.edu/publications/pubs/pdf/MIT-LCS-TR-894.pdf.

[58] G. Lu, B. Krishnamachari, C.S. Raghavendra, “An adaptive energy-efficient and low-latency MAC for data gathering in wireless sensor networks”, Proceedings of 18th International Parallel and Distributed Processing Symposium, Pages: 224, 26-30 April 2004.

[59] D. B. Johnson, “PW-MAC: An energy-efficient predictive-wakeup MAC protocol for wireless sensor networks”, in Proc. 30th IEEE Int. Conf. on Comp. Commun. IEEE Infocom 2011, Shanghai, China, 2011, pp. 1305–1313.

[60] J. Kabara and M. Calle, “MAC protocols used by wireless sensor networks and a general method of performance evaluation”, Int. J. of Distrib. Sensor Netw., vol. 8, no. 1, 2012 (doi: 10.1155/2012/834784)
[61] S. Coleri and P. Varaiya, “PEDAMACS: Power efficient and delay aware medium access protocol for sensor networks”, IEEE Trans. on Mob. Comput., vol. 5, no. 7, pp. 920–930, 2006.
[62] M. G. C. Torres, “Energy consumption in wireless sensor networks using GSP”, Master’s Thesis, University of Pittsburgh, 2006.
[63] Z. A. Eu, H. P. Tan, and W. K. G. Seah, “Design and performance analysis of MAC schemes for Wireless Sensor Networks Powered by Ambient Energy Harvesting”, Ad Hoc Netw., vol. 9, no. 3, pp. 300–323, 2011.
[64] Y. Jin and H. P. Tan, “Optimal performance trade-offs in MAC for wireless sensor networks powered by heterogeneous ambient energy harvesting”, in Proc. IEEE IFIP Networking Conf. IFIP Networking 2014, Trondheim, Norway, 2014 (doi: 10.1109/IFIPNetworking.2014.6857125)
[65] B. A. Bakr and L. T. Lilien, “Comparison by simulation of energy consumption and WSN lifetime for LEACH and LEACH-SM”, Procedia Comp. Sci., vol. 34, pp. 180–187, 2014.
[66] A. Safwat, H. Hassanein, and H. Mouftah, “ECPS and E2LA: New Paradigms for Energy Efficiency in Wireless Ad Hoc and Sensor Networks,” IEEE GLOBECOM ‘03, vol. 6, Dec. 2003, pp. 3547–52.
[67] S. Cui et al., “Joint Routing, MAC, and Link Layer Optimization in Sensor Networks with Energy Constraints,” IEEE ICC ‘05, Korea, May 2005.
[68] J. Ding et al., “A Multi-Layered Architecture and Protocols for Large-Scale Wireless Sensor Networks,” IEEE VTC 2003, vol. 3, Oct. 2003, pp. 1443–47.

TIn [69]-[70], detail elaboration of several MAC protocols for WSNs are compiled with few new proposals. In [71]-[76], novel idea about the energy efficient protocols and protocols with QoS are presented by the authors. In [77]-[82], authors mainly focus on the cross-layer protocol for WSNs.

[69] Arifuzzaman, M. (2015). Study of medium access control (MAC) layer energy efficient protocol for wireless ad-hoc and sensor networks (Doctoral dissertation, 早稲田大学).
[70] Islam, M. M., Akanda, M. R., Islam, M. E., & Arifuzzaman, M. (2016). Energy Efficient MAC Protocols for Wireless Sensor Networks: A Comprehensive Survey. International Journal of Computer Science and Information Security, 14(10), 706.
[71] Arifuzzaman, M., Matsumoto, M., & Sato, T. (2013). An intelligent hybrid MAC with traffic-differentiation-based QoS for wireless sensor networks. IEEE sensors journal, 13(6), 2391-2399.
[72] Arifuzzaman, M., Alam, M. S., & Matsumoto, M. (2011, December). A hybrid MAC with intelligent sleep scheduling for wireless sensor networks. In Proceedings of ITU Kaleidoscope 2011: The Fully Networked Human?-Innovations for Future Networks and Services (K-2011) (pp. 1-7). IEEE.
[73] Arifuzzaman, M., & Matsumoto, M. (2013). A hybrid MAC with dynamic sleep scheduling for wireless sensor networks. The Journal of the Institute of Image Electronics Engineers of Japan, 42(2), 197-205.

[74] Mohammad, A., Yu, K., & Takuro, S. (2014). An Optimum Relay Sensor Placement Technique to Enhance the Connectivity of Wireless Sensor Network. International Journal of Engineering and Advanced Technology (IJEAT), 4.

[75] Arifuzzaman, M., & Matsumoto, M. (2012). An efficient medium access control protocol with parallel transmission for wireless sensor networks. Journal of Sensor and Actuator Networks, 1(2), 111-122.

[76] Hasan, M. M., & Arifuzzaman, M. (2019, July). AVAQ-EDCA: Additional Video Access Queue Based EDCA Technique for Dense IEEE 802.11 AX Networks. In 2019 International Conference on Computer, Communication, Chemical, Materials and Electronic Engineering (IC4ME2) (pp. 1-4). IEEE.

[77] Haqbeen, J. A., Ito, T., Arifuzzaman, M., & Otsuka, T. (2018, June). Traffic Adaptive Hybrid MAC with QoS Driven Energy Efficiency for WSNs Through Joint Dynamic Scheduling Mode. In 2018 IEEE/ACIS 17th International Conference on Computer and Information Science (ICIS) (pp. 3-9). IEEE.

[78] Haqbeen, J. A., Ito, T., Arifuzzaman, M., & Otsuka, T. (2017, November). Joint routing, MAC and physical layer protocol for wireless sensor networks. In TENCON 2017-2017 IEEE Region 10 Conference (pp. 935-940). IEEE.

[79] Haqbeen, J. A., Ito, T., Arifuzzaman, M., & Otsuka, T. (2017). Design of joint cooperative routing, MAC and physical layer with QoS-aware traffic-based scheduling for wireless sensor networks. International Journal of Networked and Distributed Computing, 5(3), 164-175.

[80] Haqbeen, J. A., Ito, T., Arifuzzaman, M., & Otsuka, T. (2017). An Intelligent cross-layer QoS-aware protocol with traffic-differentiation-based for energy efficient communication in WSNs. International journal of networked and distributed computing, 5(2), 80-92.

[81] Arifuzzaman, M., Dobre, O. A., Ahmed, M. H., & Ngatched, T. M. (2016, December). Joint routing and mac layer qos-aware protocol for wireless sensor networks. In 2016 IEEE Global Communications Conference (GLOBECOM) (pp. 1-6). IEEE.

[82] Haqbeen, J. A., Ito, T., Arifuzzaman, M., & Otsuka, T. (2016, November). Intelligent Cross-Layer Protocol with traffic-differentiation-based QoS for wireless sensor networks. In 2016 IEEE Region 10 Conference (TENCON) (pp. 1088-1092). IEEE.