Energy Efficient MAC Protocols For Wireless Sensor Networks: A Survey

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Abstract - Wireless sensor networks (WSN) have been used in many important fields such as target detection and tracking, environmental monitoring, industrial process monitoring and tactical systems. As nodes in wireless sensor networks typically operate unattended with a limited power source, energy efficient operations of the nodes are very important. Although energy conservation in communication can be performed at different layers of the TCP/IP protocol suite, energy conservation at MAC layer is found to be the most effective one due to its ability to control the radio directly. Therefore, to ensure a long-lived network of wireless communicating sensors, we are in need of a MAC protocol that is able to improve energy efficiency by maximizing sleep duration, minimizing idle listening and overhearing, and eliminating hidden terminal problem or collision of packets. In this paper, we investigated the available energy-efficient MAC protocols for wireless sensor networks and provide a fair comparison based on certain metrics.

Index Terms Energy Model in WSN, MAC protocols, Sensor Nodes,

1 Introduction

Wireless sensor networking is an emerging technology that has potential usage in diverse applications like environment monitoring, military, scientific research, and medical condition monitoring. Wireless Sensor Network (WSN) consist of one or more battery-operated sensor devices with an embedded processor, small memory and a low power radio. Nodes in a wireless sensor network work in conjunction to achieve a common design goal. Low power capacities of sensor nodes result in limited coverage and communication range for sensor nodes compared to other mobile devices. However, to cover large target area successfully, sensor networks are composed of large number of nodes which are geographically dispersed over the entire coverage area. The most preferred choice to increase the endurance of a node may be to recharge or replace the depleted power source but often this might not be a viable choice depending on deployed number of nodes and scenario limitations. Thus, often other alternates are sought to enhance the life span of a sensor node.

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Generally in a sensor node the three main activities involved in energy consumption are sensor sensing, computation and radio operations. Out of these three factors, energy loss due to radio operation is the most high [1]. Not only transmitting costs energy, receiving and merely scanning the wireless channel for communication, can also use up to half as much power. As the MAC protocols are directly involved in controlling the operations of radio they are a major research area of focus in maximizing the availability of a WSN.

In this paper we investigate the main causes of energy wasted in the MAC layer of WSNs and their existing solutions. We compare those existing methods and give some indications about methods to achieving improvement over them.

This paper is organized in eight sections. The first two are introductory sections on WSNs and MAC protocols respectively. The third section presents the general energy model for MAC layer in WSN. The fourth section classifies design approaches generally followed in MAC protocol whereas the fifth section discusses pros and cons of various existing MAC protocol designs. The sixth section gives a summary of the comparison in the format of a chart. The seventh and eighth paragraphs discuss the future research trends and concluding paragraphs.

2 MAC Protocol in WSN

In a wireless network, controlling when to send a packet and when to listen for a packet are the two most important operations to be performed by the medium access layer [2]. In general, idle waiting wastes huge amounts of energy during communication. Medium Access Control (MAC) protocol deals with when and how to access the transmission medium by a node, and how to transfer the data safely when there is more than one node accessing a single wireless channel simultaneously. One fundamental task of the MAC protocol

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is to avoid collisions so that two interfering nodes do not transmit
at the same time.

MAC layer is a part of DLC (data link layer) which is divided into MAC and LLC (Logical link layer) sub layers [3]. The main tasks of LLC are Error Control and Flow Control. MAC layer resolves contentions in a multi-access wireless environment. Problems in medium access are influenced by a number of attributes and trade-offs like - Collision Avoidance, Energy Efficiency, Scalability,Adaptivity, Channel Utilization, Latency, Throughput and Fairness. While traditional MAC protocols are designed to maximize packet throughput, minimize latency and provide fairness, protocol design for wireless sensor networks focuses on minimizing energy consumption. The application determines the requirements for the minimum required throughput and maximum affordable latency.

3 ENERGY MODEL IN MAC LAYER OF WSN [2]

The energy model of a sensor in a WSN is a node attribute which represents the level of energy in a mobile host. The best energy model is that which keeps record of the radio state along with the battery condition. Radio in a sensor node uses most of the energy and managing it effectively can increase the life of a node considerably. In fact, not only transmitting costs energy, receiving or merely scanning can use up to half as much power, depending on the type of radio.

3.1 Factors Composing the Energy Model

Energy is consumed for every packet being transmitted and received, idle and sleep states and for transitions. These types of energy consumption may be categorized as:

- rxPower: power consumption in state (watt)
- txPower: power consumption in sleep state (watt)
- idlePower: power consumption in idle state (watt)

Parameters newly added in the Energy Model are:-

- Sleep Power: power consumption in sleep state (watt)
- Transition Power: power consumption in transition from sleep to active state (watt)
- Transition Time: time (second) used in state transition from sleep to active state

3.2 Energy Waste in MAC protocol

The major sources of energy waste in a MAC protocol for wireless sensor networks are the following:

Collision: When a transmitted packet is corrupted it has to be discarded, and the follow-on retransmissions increase energy consumption.

Control Packet Overhead: Sending and receiving control packets consume energy too, and lesser number of useful data packets can thus be transmitted.

Idle Listening: Listening to receive possible traffic that is not sent can consume extra energy.

Overhearing: Meaning that a node picks up packets that are destined to other nodes which can unnecessarily consume
energy.

4 MAC PROTOCOL DESIGN APPROACHES [2]

Based on the way how medium is accessed, MAC protocols are basically divided into two types. These are synchronous (or slotted) and asynchronous (or random access) MAC Protocols. The figure below gives the basic chart classifying the protocols discussed in this paper.

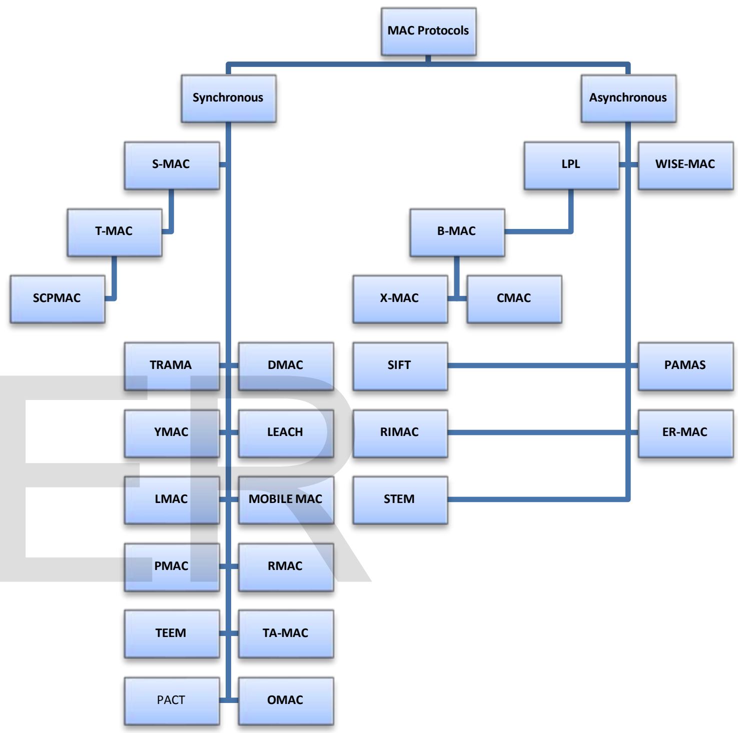

Fig. 1. Classification of MAC protocols.

4.1 Synchronous MAC Protocols

Synchronous MAC Protocols are also called Schedule-Based or Slotted MAC Protocols. Unnecessary power consumption takes place on synchronization message exchanges. Schedule based medium access protocols in general require a mechanism to establish a non-conflicting schedule regulating which participant may use which resource at which time. Schedule can be fixed or computed on demand. Time synchronization is needed and time is divided into slots
so that the time schedule can be fixed or computed on demand.

A traditional wakeup scheduling approach like SMAC [4] uses fixed duty cycle (Duty Cycle is defined as Listen Interval divided by Frame Length). SMAC [4] and TMAC [5] use coordinated scheduling to reduce energy consumption, but require periodic synchronization, whereas CMAC [6] avoids synchronization overhead while

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supporting low latency. CMAC uses unsynchronized sleep scheduling and allows operation at very low duty cycles. TMAC has advantage of dynamically ending active part, it uses adaptive duty cycle. This reduces energy wasted on idle listening [2].

4.2 Asynchronous MAC Protocols

Asynchronous MAC Protocols are also called as Contention-based or Random Access MAC Protocols. Here randomization is used to gain access to the communication media. Nodes do not synchronize time slots but contend for access to the radio channel. To reduce idle listening, protocols in this class shift the costs from the receiver to the sender by extending the MAC header (i.e., the preamble). Asynchronous MAC protocols allow nodes to check the channel periodically and otherwise sleep most of the time.

5 AVAILABLE WSN MAC PROTOCOLS - THEIR PROS AND CONS

In this section, we present different proposed MAC layer protocols for WSNs. We shall focus our attention to their energy saving methods and not present their other important design achievements.

5.1 SENSOR MAC (S-MAC) [4]

It is a low power RTS-CTS based synchronous MAC protocol that makes use of loose synchronization between nodes to allow for duty cycling in sensor networks. In S-MAC, active period is of fixed length. Energy savings in S-MAC depends on duty cycle timing and uses three techniques to achieve low power duty cycle i.e. periodic sleep, virtual clustering, and adaptive listening. A group of nodes or a virtual cluster in a network can locally manage synchronizations and periodic sleep-listen schedules as shown in Fig. 2. Neighboring cells form virtual clusters to set up a common sleep schedule. However, if two neighboring nodes reside in two different virtual clusters, they can then wake up at listen intervals of both clusters causing delay. Collision avoidance is achieved by carrier sense and RTS/CTS packet exchanges as in IEEE 802.11 standards. This scheme is generally preferred for unicast communication. Periodic sleep may result in high latency especially for multi-hop routing algorithms, since all immediate nodes have their own sleep schedules.

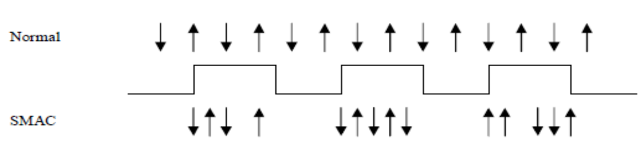

Fig. 2. Periodic listens and sleeps in sensor in SMAC

Advantages of Sensor MAC protocol

- Energy waste caused by idle listening is reduced by sleep schedules.
- Beside implementation simplicity, global time synchronization overhead may be prevented with sleep schedule announcements.

Disadvantages of Sensor MAC Protocol:

- S-MAC follows the fixed duty cycle principle thus if no traffic flow actually occurs, nodes stay awake needlessly long
- If message rate is less then energy is still wasted in idle-listening.
- Sleep and listen periods are predefined and fixed which lowers the efficiency of the algorithm under variable traffic load.
- Having long listening interval can be an expensive energy drain - Everyone stays awake unless somebody transmits.
- Time sync process is an overhead when network is idle.
- RTS/CTS and ACK overhead when sending data.

5.2 Timeout MAC (TMAC) [5]

This mode was an improvement on the SMAC to avoid nodes staying needlessly awake for fixed periods when there is no traffic. The solution presented was to have the nodes prematurely go back to sleep mode when no traffic has happened for a certain amount of time known as the "timeout" period TA. A node keeps listening and transmitting as long as it is in an active period else it sleeps. In TMAC, nodes transmit messages in bursts of variable length and sleep between the bursts. It uses RTS-CTS-ACK scheme and synchronization is done similar to S-MAC. TMAC also improves on S-MAC by shortening the awake period when it is in IDLE through adaptive duty cycle. Active time is dynamically adjusted by timeout on hearing nothing during time period (TA). Fig.4 shows adaptive duty cycling in Timeout MAC.

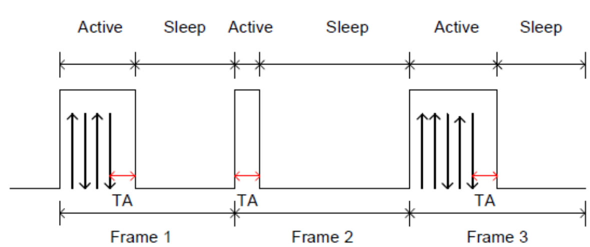

Fig. 3. Adaptive duty cycling in TMAC

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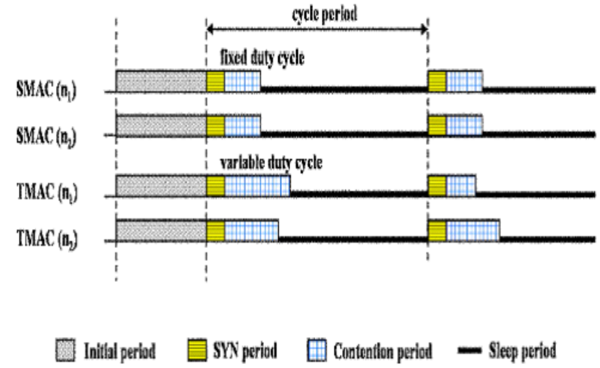

Fig. 4. Comparison of duty cycle in SMAC and TMAC.

Advantages of TMAC:

The major advantage of TMAC is that it gives better result under variable load.

Disadvantages of TMAC:

- TMAC suffers from an early sleeping problem, a node goes to sleep when a neighbor still has messages for it due to the asymmetric communication as virtual clusters have different listen and sleep periods. To overcome this problem somewhat, FRTS (Future-Request-To-Send) pulse can be sent quickly by a transmitting node after it overhears CTS signal.
- Both, S-MAC and TMAC use periodic synchronization messages to schedule duty cycling and packet transmissions. Such message exchanges consume significant energy even when no traffic is present.

5.3 LOW POWER LISTENING (LPL) [8]

In the protocols like S-MAC and TMAC periodic sleeping is supported by some means to synchronize wake up of nodes to ensure that both sender and receivers have time to communicate effectively. In Low Power Listening (LPL) protocol it does not try to explicitly synchronize the nodes but allows the receiver to sleep most of the time and periodically sample the channel and detect the long preambles transmitted by nodes ready to send message. Thus the trick is to ensure that the preambles are long enough to ensure that receiver stays awake to catch the actual packets (Refer to Fig 5).

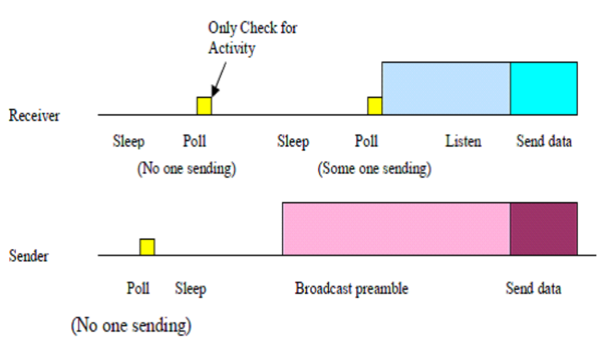

Fig. 5. Preamble sampling in Low Power Listening

Advantages of LPL:

- Low power consumption for low traffic.
- Does not incur overhead due to synchronization.

Disadvantages of LPL:

- The latency accumulated along multi-hop routes could be overwhelming due to the use of long preambles on e each hop.
- A lot of energy can be wasted in transmitting the preamble bits which carry no valuable messages for the network. Thus the preamble length is to be chosen conservatively otherwise it can result in waste of scant node energy.
- Neighbor nodes other than the intended receiver will also be kept awake by the long preamble until the data packet transmission finishes and the intended receiver is resolved. This results in further loss of energy.
- Increased latency at each hop - the target node has to wait for the full preamble before exchanging the data.

5.4 BERKELEY MAC (B-MAC) [9]

B-MAC is a carrier sense media access (CSMA) protocol for wireless sensor networks that combines CSMA and Low Power Listening technique to save energy. B-MAC uses unsynchronized duty cycling and long preambles to wake up receivers. In B-MAC a filter mechanism is presented that increases the reliability of channel assessment. This mechanism provides a flexible interface that allows the nodes to change operating variables in the protocol, such as delay and back off values. B-MAC employs an adaptive preamble sampling scheme to reduce duty cycle and the idle listening time as shown in fig. 6. B-MAC uses the clear channel assessment (CCA) techniques to decide whether there is a packet arriving when a node wakes up. Timeout puts node back to sleep if no packet arrived. B-MAC uses CCA and packet bakeoffs for channel arbitration and link layer acknowledgments for reliability. B-MAC does not have synchronization, RTS or CTS.

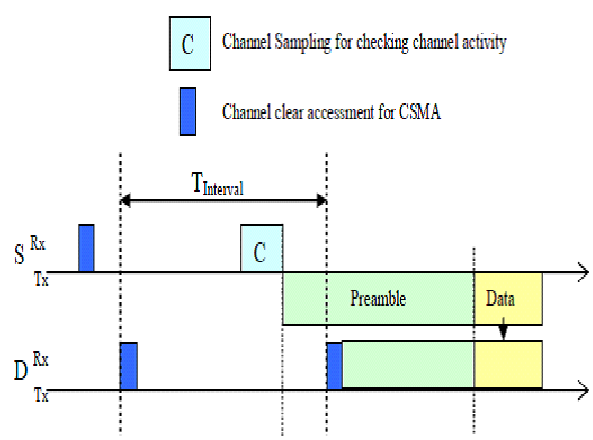

Fig.

Preamble sampling in B-MAC

Advantages of B-MAC:

- Idle Listening is reduced to a minimum and thus B-MAC has a better overall performance than S-MAC
- Low overhead when network is idle, and simple to implement

Disadvantages of BMAC:

- BMAC still suffers from overhearing problem like SMAC and TMAC.
- Long preamble is still required which is an energy drain.
- B-MAC has lower duty cycle leading to higher average latency, higher cost to send and higher cost to overhear thus resulting in more contention.

5.5 WISE MAC [10]

In Wise MAC is also an asynchronous MAC protocol whereby a sender starts the preamble before the receiver is expected to wake up rather than selecting a random time. The preamble precedes each data packet for alerting the receiving node. All nodes in a network sample the medium with a common period, but their relative schedule offsets are independent. If a node finds the medium busy after it wakes up and samples the medium, it continues to listen until it receives a data packet or the medium becomes idle again. The size of the preamble is initially set to be equal to the sampling period. Fig.7 shows preamble minimization in Wise MAC. The nodes learn and refresh their neighbor's sleep schedule during every data exchange as part of the acknowledgment message. Every node keeps a table of the sleep schedules of its neighbors and decides its own schedule accordingly. To decrease the possibility of collisions caused by the specific start time of a wake-up preamble, a random wake-up preamble can be adopted for improvement on the basic protocol. The clockdrifts between the source and the destination also affects the wake-up preamble length.

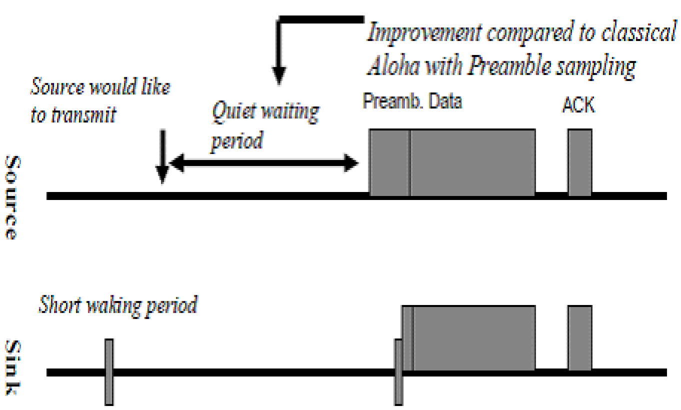

Fig. 7. Wise MAC preamble minimization

Advantages of Wise MAC:

- It performs better than S-MAC under varying traffic loads.
- Clock drifts are handled in the protocol definition, which mitigates the external time synchronization requirement.

Disadvantages of Wise MAC:

- Decentralized sleep-listen scheduling in Wise MAC results in different sleep and wake-up times for each neighbor of a node causing wastage of energy for synchronizing.
- In broadcast-type communication packets are buffered for neighbors in sleep mode and delivered many times as each neighbor wakes up resulting in latency and undue power consumption.
- Due to hidden terminal problem collision occurs at start of node transmission. The hidden terminal problem is also similar to Spatial TDMA CSMA case as Wise MAC is based on non-persistent CSMA. This problem results in collisions when one node 'A' starts to transmit preamble to a node 'B' that is already receiving transmission from a node 'C' that is outside the range of node 'A'.

5.6 XMAC [11]

XMAC is an improvement on the earlier asynchronous protocols. XMAC protocol further minimizes the problems of low power listening, overhearing, and excessive preamble by using strobe preamble which allows interruption and enables a node to wake up faster. XMAC also uses short preamble embedded with address information of the target thereby also retaining the benefits of low power listening i.e. low power consumption, simplicity and decoupling of transmitter and receiver sleep schedules. Fig. 8 shows a comparison between low power listening and XMAC.

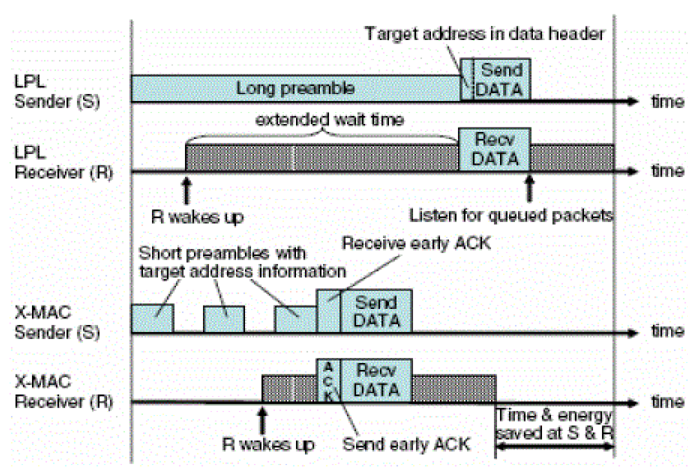

Fig. 8. Asynchronous duty cycling in XMAC

Advantages of XMAC:

- XMAC protocol is energy-efficient and has low latency (due to reduced preamble length)
- XMAC does not require synchronization and hence has low overhead making it less complex.

Disadvantages of XMAC:

- The process of "avoiding overhearing" by embedding the target receiver node ID makes multicasting/broadcasting difficult.
- The protocol is unable to schedule sufficiently small node listening periods.

5.7 CONVERGENT MAC (CMAC) [12]

CMAC is a novel MAC layer protocol, which improves the latency and energy efficiency by utilizing aggressive RTS, any cast and convergent packet forwarding mechanisms. It uses "aggressive RTS" equipped with double channel check for channel assessment as shown in fig. 9. CMAC uses unsynchronized sleep scheduling (or duty cycling) when there is no packet to transmit. CMAC avoids synchronization overhead while supporting low latency. By using zero communication when there is no traffic, CMAC allows operation at very low duty cycles. When carrying traffic, CMAC first uses anycast for packet forwarding to wake up forwarding nodes or to quickly discover forwarder and then converges from route- suboptimal anycast with unsynchronized duty cycling to route-optimal unicast with synchronized scheduling. Anycast is used for flow initialization and for flow stabilization it uses convergent Packet Forwarding.

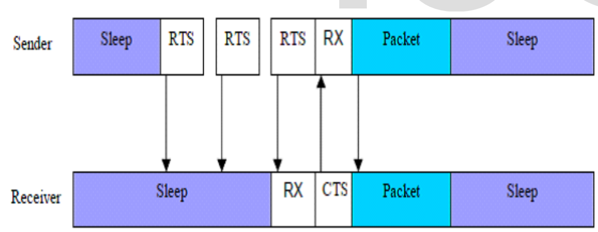

Fig. 9. Aggressive RTS in Convergent MAC

CMAC checks the channel twice to avoid missing activities. The time between the two checks should be larger than inter-RTS separation and smaller than RTS duration as shown in fig. 10. Receiver only needs to check if the channel is busy after waking up. Time between the two checks should be larger than inter-RTS separation and should be smaller than RTS duration

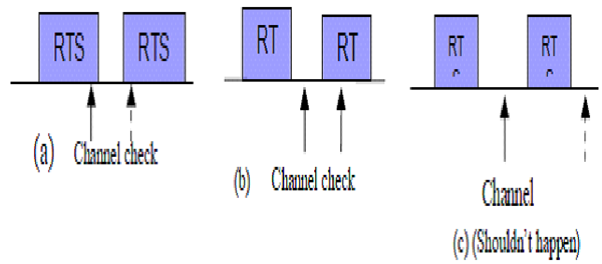

Fig. 10. Double channel checking in Convergent MAC

Advantages of CMAC Protocol:

- CMAC supports high throughput, low latency and consumes less energy than the protocols discussed earlier.
- CMAC's performance difference from the other discussed approaches increases with speed of the moving event.

5.7 SCHEDULED CHANNEL POLLING MAC (SCP-MAC) [13]

SCP-MAC is a very energy efficient scheduling MAC protocol. It minimizes the preamble by combining preamble sampling and scheduling techniques and thus finds optimal parameters under periodic traffic. SCP-MAC however does not prevent energy loss due to overhearing and, in addition, results in increased contention and delay due to its synchronization procedure. SCP-MAC adapts to variable traffic well. Basic idea of SCP-MAC is based on SMAC and TMAC. It synchronizes all nodes in a virtual cluster like SMAC. It also synchronizes their channel polling time. It increases duty cycle for heavy traffic. It can also detect bursty traffic, and dynamically adds additional, high-frequency polling slots to nodes on the required paths.

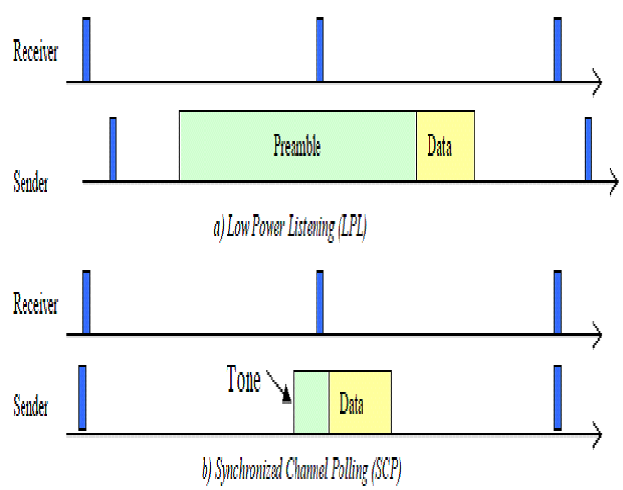

Fig. 11. Preamble sampling with scheduled channel polling in SCPMAC

Advantages of SCP-MAC:

- SCP-MAC supports broadcast very well because of the clustering
- SCP-MAC synchronizes all nodes in a cluster
- SCP adapts well to variable traffic
- SCP achieves duty cycles of < 0.1%
- SCP results in optimal performance under periodic traffic

Disadvantages of SCP-MAC:

- Long preamble costs more on faster radios
- Since all nodes in a neighborhood wake up at the same time, nodes cannot avoid overhearing the packets from, and for, each of their neighbors.
- SCP-MAC results in increased contention. At each synchronized wake-up time, every sender in a neighborhood has to contend to acquire the channel. This high contention increases packet loss and degrades the energy efficiency and throughput due to the resulting collisions.
- SCP-MAC incurs relatively large delays in multi-hop scenarios.

5.8 TRAMA [14]

TRAMA is a TDMA-based algorithm and proposes to increase the utilization of classical TDMA in an energy-efficient manner. A distributed election algorithm is used to select one transmitter within two-hop neighborhood in each time slot. This kind of election eliminates the hidden terminal problem and hence, ensures all nodes in the one-hop neighborhood of the transmitter will receive data without any collision.

Time is divided into random-access and scheduled-access (transmission) periods. Random-access period is used to establish two-hop topology information where channel access is contention-based. A basic assumption is that, by the information passed by the application layer, MAC layer can calculate the transmission needed known as the "SCHEDULE_INTERVAL". Then at time t, the node calculates the number of slots for which it will have the highest priority among two-hop neighbors within the period [t,t+SCHEDULE_INTERVAL]. The node announces the slots it will use as well as the intended receivers for these slots with a schedule packet. Additionally, the node announces the slots for which it has the highest priority but will not be used. The schedule packet indicates the intended receivers using a bitmap whose length is equal to the number of its neighbors. Bits correspond to one-hop neighbors ordered by their identities. Since the receivers of those messages have the exact list and identities of the one-hop neighbors, they find out the intended receiver. When the vacant slots are announced, potential senders are evaluated for re-use of those slots. Priority of a node on a slot is calculated with a hash function of node's and slot's identities.

Advantages of TRAMA:

- Since intended receivers are indicated with a bitmap, less communication is performed for multicast and broadcast type of communication patterns compared other protocols using CSMA.
- During the random-access intervals, nodes are awake to either transmit or receive topology information, that is, the length of the random-access interval (relative to the scheduled-access interval) affects the overall duty cycle and achieves energy savings for a node.

Disadvantages of TRAMA:

- Transmission slots are set to be seven times longer than the random access period [5] but 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 also repeated for each time slot, as the parameters of the calculation change with time.

5.9 SIFT [16]

SIFT 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. 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.

Advantages of SIFT:

- In [16], 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 data.

Disadvantages of SIFT:

- Increased idle listening time caused by listening to all nodes before sending.
- Increased overhearing which is brought about when there is an ongoing transmission and nodes must listen till the end of transmission to contend for the next transmission opportunity.
- System-wide time synchronization is needed for slot contention windows resulting in implementation complexity when timed synchronization is not used.

5.10 DMAC [18]

The Data-Gathering MAC (DMAC) protocol exploits the fact that many wireless sensor networks rely on converge cast communication pattern, that is data from sensor nodes are collected at a central node (the "sink") in a data-gathering tree. The goal of DMAC is to deliver data along the data gathering tree with low latency and high energy efficiency.

In DMAC, the duty cycles of nodes along the multi-hop path to the sink are "staggered", and nodes wake up sequentially like a chain reaction (refer to figure 12). Nodes switch between sending, receiving, and sleep states. During the sending state, a node sends a packet to the next hop node on the route and awaits an acknowledgment (ACK). At the same time, the next hop node is in the receiving state, immediately followed by a sending state (unless the node is the destination of the packet) to forward the packet to the next hop. Between these intervals of receiving and sending of packets, a node enters the sleep state, where it can power down its radio to conserve energy.

The sending and receiving intervals are kept large enough for exactly one packet. Since there are no queuing delays, a node at depth *d* in the tree can then deliver a packet to the sink within the interval. While limiting a node's activity to brief intervals for sending and receiving reduces the contention, collisions can still occur. Particularly, nodes with the same depth in the tree will have synchronized schedules. In DMAC, if a sender does not receive an ACK, it queues the packet until the next sending interval. After three failed retransmissions, the packet will be dropped. To reduce collisions, nodes do not transmit immediately at the beginning of the sending slot, but instead have a bakeoff period plus a random time within a contention window.

When a node has multiple packets to send during a sending slot, it can increase its own duty cycle and request other nodes along the route to the sink to do the same. This is implemented through a slot-by-slot renewal mechanism using a "more data" flag in the MAC header. A receiver checks for this flag and, if set, it returns an acknowledgment that has also the more data flag set. It then stays awake to receive and forward one additional packet.

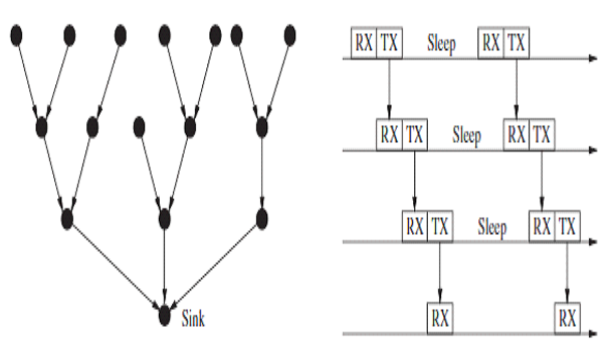

Fig. 12 . Data-gathering tree & converge cast communication in DMAC

Advantages of DMAC:

- DMAC achieves very good latency compared to other sleep/listen period assignment methods. The latency of the network is crucial for certain scenarios like military and disaster management etc. in which DMAC could be a strong candidate.

Disadvantages of DMAC:

- Collision avoidance methods are not utilized, hence when a number of nodes that have the same schedule (same level in the tree) try to send to the same node, collisions will occur. This is a general case for any event-triggered sensor network.
- The data transmission paths may not be known in advance, which precludes the formation of data gathering tree before time.

5.11 Y-MAC [19]

Y-MAC is a TDMA-based MAC protocol that relies on multiple channels. Y-MAC divides time into frames and slots, where each frame contains a broadcast period and a unicast period. Every node must wake up at the beginning of a broadcast period and nodes contend to access the medium during this period. If there are no incoming broadcast messages, each node turns off its radio awaiting for its first assigned slot in the unicast period. Each slot in the unicast period is assigned to only one node for receiving data. This receiver-driven model can be more energy-efficient under light traffic conditions and for sensor nodes in which radio receiving mode is costlier, because each node samples the medium only in its own receive time slots.

Medium access in Y-MAC is based on synchronous low power listening. Contention between multiple senders is resolved in the contention window, which is at the beginning of each slot. A node wishing to send data sets a random wait time (back off value) within the contention window. After this wait time, the node wakes up and senses the medium for activity for a specific amount of time. If the medium is free, the node sends a preamble until the end of the contention window to suppress competing transmissions. The receiver wakes up at the end of the contention window to wait for packets in its assigned slot. If it receives no signal from any of its neighboring nodes, it turns off the radio and returns to the sleep mode.

During the unicast period, messages are initially exchanged on the base channel. At the beginning of its receive slot, a receiver switches its frequency to the base channel. The node that wins the access to the medium also uses the base channel to transmit its packet. The receiver acknowledges this packet if the acknowledgment request flag was set in the packet. Similarly, in the broadcast period, every node tunes to the base channel and potential senders take part in the contention process described above.

Every node polls the medium only during broadcast time slots and its own unicast receive time slots, making this approach energy-efficient. However, under heavy traffic conditions, many unicast messages may have to wait in the message queue or are dropped due to the limited bandwidth reserved for the receiving node. As a consequence, Y-MAC uses a channel-hopping mechanism to reduce packet delivery latency as shown in figure 13 for four channels. After receiving a packet during its time slot on the base channel, the receiving node hops to the next channel and sends a notification that it can receive packets on the second channel. Contention for the medium in the second channel is resolved as before. At the end of this slot, the receiving node can decide to hop again to another channel until reaching the last channel or until no more data is being received. The actual hopping sequence among the available channels is determined by the hopping sequence generation algorithm, which should guarantee that there is only one receiver among one-hop neighbors on any particular channel.

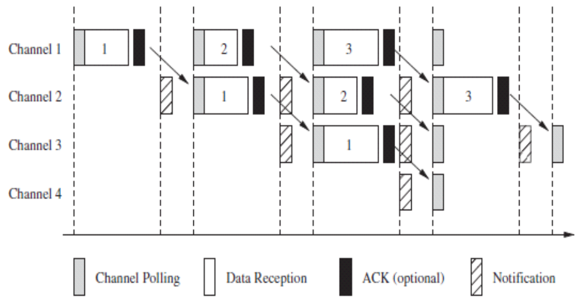

Fig. 13. Example of channel hopping in Y-MAC (using four channels)

Advantages of Y-MAC

- Y-MAC uses slot assignments such as TDMA, but communication is receiver-driven to ensure low-energy consumption.
- Multiple channels are used to increase the achievable throughput and reduce delivery latency.

Disadvantages of Y-MAC

- Y-MAC approach suffers from the same flexibility and scalability issues as TDMA (i.e., fixed slot allocations).
- Requires sensor nodes with multiple radio channels.

5.12 LEACH [20]

Low Energy Adaptive Clustering Hierarchy or LEACH is a protocol for micro sensor networks that combines the energy efficient cluster-based routing and media access ideas with application specific data aggregation methods to conserve energy. LEACH utilizes following techniques to distribute energy loads evenly in the network [6]:

- Randomized, adaptive, self configuring cluster formation.
- Localized control of data transfers.
- Low energy medium access control.
- Application specific data processing, such as data aggregation or compression.

Nodes organize themselves into a cluster with one node selected as a cluster head using cluster head selection algorithms. Cluster head receives all the information from all the nodes present in its cluster, aggregates the data by removing redundancy and transfers the actual necessary 'effective' data it to base station (BS). Cluster heads are randomly rotated to avoid drain of energy of one sensor.

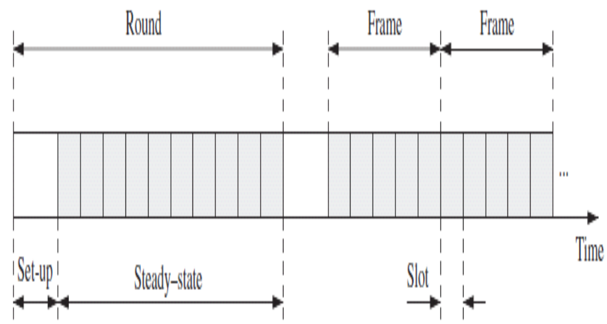

Fig. 14. Operation and communication structure of LEACH

Advantages of LEACH

- Interference among clusters is minimized by using Direct Sequence Spread Spectrum Technique (DSSS) such that each cluster has a unique spreading sequence.
- The intra cluster communication is contention free and interference among nodes are avoided.

Disadvantages of LEACH

- LEACH assumes that all nodes are able to reach the base station, which affects the scalability of this protocol.
- Since LEACH rotates the cluster head responsibility among sensors to evenly distribute the energy load thus the protocol requires that each cluster head should know or estimate the total energy state of the network.

5.13 Lightweight Medium Access Control (LMAC) [21]

The Lightweight Medium Access Control (LMAC) protocol is based on TDMA that is communication time is again divided into frames and slots, where each slot is owned by exactly one node. However, instead of relying on a central manager to assign slots to nodes, nodes execute a distributed algorithm to allocate slots. Each node uses its slot to transmit a message consisting of two parts: a control message and a data unit.

The fixed-size control message carries information of the identity of the time slot controller, the distance (in hops) of the node to the gateway (base station), the address of the intended receiver, and the length of the data unit. Upon receiving a control message, a node determines if it is the intended receiver and then decides whether to stay awake or to turn off its radio until the next slot. The occupied slots field of the control message is a bitmask of slots, where an unoccupied slot is represented by 0 and an occupied slot is represented by 1. By combining control messages from all neighbors, a node is able to determine unoccupied slots. The process of claiming slots starts at the gateway device, which determines its own slots. After one frame, all direct neighbors of the gateway know the gateway's slots and choose their own slots. This process continues throughout the network and during each frame, a new set of nodes with a higher hop distance from the gateway determine their slots. Each node must select slots that are not in use within a two-hop neighborhood. Slots are selected randomly; therefore, it is possible for multiple nodes to select the same slot. This will result in a collision of control messages during a slot, which can be observed by the competing nodes, which in turn can result in a restart of the selection process in worst case scenario. We discuss the advantages and disadvantages of LMAC below with its variant Mobile LMAC.

5.14 Mobile LMAC [21]

The Mobile LMAC protocol uses a distributed slot allocation mechanism. When a node X leaves the radio range of node Y, both nodes will realize that they no longer receive control messages from each other and will remove each other from their neighbor lists. Now assume that node X moves into the radio range of node Z and that another node in Z's range, node W, uses the same slot as X. In this case, the control messages from X and W will collide at Z. Node Z will no longer receive any correct control messages during this slot and will therefore mark this slot a unused. Nodes X and W will receive Z's control message, indicating that their slot is unused, meaning that there must have been a collision. As a consequence, they give up their current slot and restart the slot selection mechanism.

Advantages LMAC and Mobile LMAC

- Both LMAC and MLMAC have the same advantages as TDMA (collision-free communication, energy efficiency), but additionally they are able to establish transmission schedules in a distributed fashion.
- Mobile LMAC is able to adapt to changes in the network.

Disadvantages of LMAC and Mobile LMAC

- In both the protocols, the slot size is fixed and slot allocations are also fixed (except when a node has to restart the slot selection mechanism), which can lead to bandwidth inefficiency.
- The slot allocations in Mobile LMAC are computed therefore,this protocol is not suitable for mobile sensors networks in which nodes frequently join and leave.

5.15 POWER AWARE MULTI-ACCESS with SIGNALING (PAMAS) [22]

The focus of the Power Aware Multi-Access with Signaling (PAMAS) protocol is to avoid unnecessary energy expenditure caused by overhearing. For example, in figure 15, node B's transmission to node A is overheard by node C since it is an immediate neighbor of node B. Therefore, node C consumes energy for receiving a frame intended for another node. Further, since C is in B's interference range, C cannot receive a frame from another node during B's transmission. Therefore, to conserve energy, C can turn its radio into a low-power sleep mode for the duration of B's transmission. This is particularly useful in dense networks where a node can be in the interference range of many other nodes.

PAMAS uses two separate channels, one for data frames and one for control frames, to prevent collisions among data transmissions. The control messages exchanged in PAMAS are ready-to-send (RTS) and clear-to-send (CTS) messages. This separate signaling channel allows nodes to determine when and how long to power down their wireless transceivers. In addition to RTS/CTS, devices transmit busy tones on the control channel to ensure that devices that did not overhear either RTS or CTS will not access the data channel for transmissions.

To initiate a data transfer, a PAMAS device sends an RTS message over the control channel to the receiver. If the receiver does not detect activity on the data channel and has not overheard other recent RTS or CTS messages, it will respond with a CTS message. If the source does not receive CTS within a specific timeout interval, it will attempt to transmit again after a backoff time (determined by an exponential backoff algorithm). Otherwise, it begins data transmission and the receiver node issues a busy tone over the control channel (whose length is greater than twice the length of CTS). The receiver device also issues a busy tone over the control channel whenever it receives an RTS message or detects noise on the control channel while it receives a frame. This is done to corrupt possible CTS message replies to the detected RTS, thereby blocking any data transmission of the receiver's neighbors.

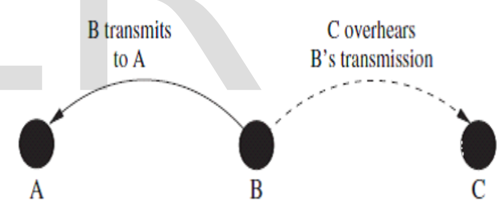

Fig.15**.** Power consumption caused by unnecessary overhearing

Advantages of PAMAS

- Energy is conserved by the nodes that are not communicating with any other nodes by turning off their radios to a low power sleep mode.
- PAMAS is particularly useful in dense networks where a node can be in the interference range of many other nodes.

Disadvantages of PAMAS

- PAMAS relies on the presence of two radios, which in itself can greatly increase the energy consumption and implementation cost.

5.16 PATTERN-MAC [23]

The Pattern MAC (PMAC) protocol is another example of a TDMA style protocol that uses frames and slots, but it adapts its sleep schedules on the basis of its own traffic and the traffic patterns of its neighbors. Compared to SMAC and

TMAC, PMAC further reduces energy costs of idle listening by allowing devices to turn off their radios for long durations during periods of inactivity. Nodes use patterns to describe their tentative sleep and awake times, where a pattern is a string of bits, each bit representing a time slot and indicating whether a node plans to sleep (bit is 0) or be awake (bit is 1). While patterns are only tentative, schedules represent the actual sequence of sleep and awake times. The format of a pattern is always 0m1, where m = 0, 1, . . . , N − 1 and N time slots are considered to be a period. For example, a pattern of 001 and N = 6 indicate a node's plan to be awake during the third and sixth slot of the period (i.e., the pattern is repeated whenever its length is less than N). The value of m (i.e., the number of leading zeros) is an indicator of traffic load around the node - that is, a small value indicates heavy traffic and a large value indicates light traffic. At network activation, every node's pattern during the first period is 1, that is, m=0, and every node assumes a heavy traffic load and that it should be awake at all times. If a node does not have any data to send during the first slot, then it uses this as an indicator that the traffic around it is potentially light and it updates its own pattern to 01. The node continues to double the sleep interval (doubling the number of zeros) every time it has no data to send, allowing it to sleep longer. This process (which mimics the slow-start behavior of TCP) is continued until a predefined threshold is reached, after which the number of zeros is increased linearly. That is, if there is no data for node i to send, the following sequence of patterns will be generated: 1, 01, 021, 04 1, . . . , 0δ 1, 0δ 01, 0δ 02 1, 0δ 031, . . . , 0N −11. Whenever a node has data to send, the pattern is immediately reset to 1, allowing the node to wake up quickly to handle the traffic load.

While a pattern is only a tentative sleep plan, patterns are used to derive actual sleep schedules. A node broadcasts its own pattern at the end of a period, during a time interval called the Pattern Exchange Time Frame (PETF). The PETF is divided into a sequence of brief slots, where the number of slots is set to the maximum number of neighbors a node could have. These slots are accessed using CSMA and collisions can occur. If a node does not receive a pattern update from one of its neighbors (most likely due to a collision), the node simply assumes that the neighbor's pattern remains unchanged. Once a node has received the patterns from its neighbors, it determines its own schedule, where each slot can be used for one of three possible operations. A node wakes up and transmits a message to a neighbor if the neighbor has advertised a 1 for that slot. If a node has advertised a 1, but has no data to send, the slot is used to listen. If none of these two conditions holds, the node sleeps.

Advantages of PMAC

- PMAC provides a simple mechanism to build schedules that adapt to the amount of traffic in a neighborhood. When traffic loads are light, a node is able to spend considerable amountsof time in the sleep mode, thereby preserving energy.
- PMAC achieves higher throughput under heavy loads.

Disadvantages of PMAC

- Collisions during the PETF may prevent nodes from receiving pattern updates from all neighbors, while other nodes may have received these updates. This leads to inconsistent schedules among nodes in a neighborhood, which can cause further collisions, wasted transmissions, and unnecessary idle listening.

5.17 ROUTING-ENHANCED MAC [24]

The Routing-Enhanced MAC (RMAC) protocol another example of a protocol that exploits duty cycles to preserve energy. Compared to SMAC, it attempts to improve upon end-to-end latency and contention avoidance. The key idea behind RMAC is to align the sleep/wake periods of nodes along the path of sensor data such that a packet can be forwarded to the destination within a single operational cycle. It achieves this by sending a control frame along the route to inform nodes of the upcoming packet, allowing them to learn when to be awake to receive and forward this packet.

RMAC partitions an operational cycle into three components: the SYNC period, the DATA period, and the SLEEP period (figure 17). During the SYNC phase, nodes synchronize their clocks to ensure that they maintain sufficient precision. The DATA period is used to announce and initiate the packet transmission process along the packet's route to the destination. The DATA period is contention-based and the sender waits for a randomly chosen period of time plus an additional DIFS period, during which it senses the medium. If no activity is detected, the sender transmits a Pioneer Control Frame (PION), containing the addresses of the sender, destination, and next hop; the duration of the transmission,

and the number of hops the PION has travelled so far (which is set to zero at the sender). The next hop along the route (node A in figure 15 looks up the next hop for this route (from the network layer) and forwards the PION to the next hop after waiting for a SIFS period. This process continues until the PION reaches the destination.

Actual data transmission takes place during the SLEEP period of the protocol. In figure 15, node A stays awake to receive the data packet from the sender and after successful transmission, A returns an acknowledgment (ACK). Similar to the PION schedule during the DATA period, all data and

ACK packets are separated by a SIFS period. After receiving the ACK from node A, the sender has completed its part and can return its radio to the sleep mode. Node A relays the received packet to the next hop, node B, and also returns its radio to sleep mode once B has acknowledged the data packet. This process continues until the data packet has been received and acknowledged by the destination.

In this example, the sender and node A stay awake after the DATA period to immediately begin the transmission of the data packet over the first hop. All other nodes along the route can turn off their radios after the DATA period has completed to further preserve energy. Each node wakes up at the right time to receive the data packet from the upstream node. This time to wake up can be computed by node i as:

Twakeup(i) = (i − 1) × (size(DATA) + size(ACK) + 2 × SIFS)

Where size (DATA) and size (ACK) are the times required to send a single data and ACK frame, respectively.

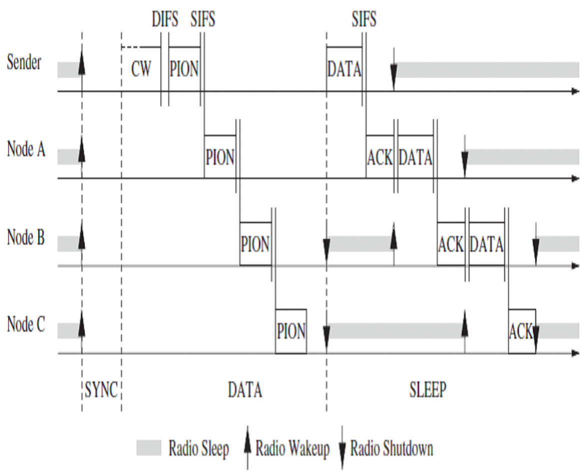

Fig. 16. Duty cycle and communication pattern in RMAC

Advantages of RMAC

- RMAC addresses the large latencies often experienced in MAC protocols that use duty cycles in the design process to minimize energy consumption.
- It is able to perform end to end packet delivery within a single operational cycle.
- It also alleviates contention by separating medium contention and data transfer into two separate periods.

Disadvantages of RMAC

- Collision can occur even on data packets during sleep periods. A source always commences transmission at the beginning of the SLEEP period. Therefore, it is possible that data packets coming from two different sources may still collide.

5.18 RECIEVER-INITIATED MAC [25]

Another contention-based solution is the Receiver-Initiated MAC (RI-MAC) protocol, where a transmission is always initiated by the receiver of the data. Each node wakes up periodically to check whether there is an incoming data packet. That is, immediately after turning on its radio, a node checks if the medium is idle and, if so, broadcasts a beacon message, announcing that it is awake and ready to receive data. A node with pending data to transmit stays awake and listens for a beacon from its intended receiver. Once this beacon has been received, the sender immediately transmit the data, which will be acknowledged by the receiver with another beacon (see left graph in figure 17). That is, the beacon serves two purposes: it invites new data transmissions and it acknowledges previous transmissions. If there is no incoming data packet for a certain amount of time after the beacon broadcast, the node goes back to sleep after waiting a certain time.

If there are multiple contending senders, a receiver uses its beacon frames to coordinate transmissions. A field in the beacon, called the backoff window size (BW), specifies the window over which to select a backoff value. If the beacon does not contain a BW (the first beacon sent out after waking up does not contain a BW), senders immediately commence transmission. Otherwise, each sender randomly selects a backoff value within BW and the receiver increases the BW value in the next beacon when it detects a collision. The right graph in figure 18 shows an example with two senders immediately transmitting data packets after receiving the receiver's beacon. The receiver notices the collision and sends another beacon, this time containing a BW.

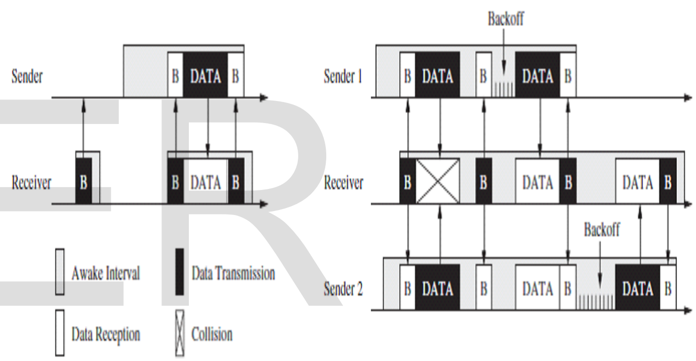

Fig. 17. Data transmission from a single header (left) and two contending senders (right)

Advantages of Receiver Initiated-MAC(R-MAC)

- In RI-MAC, the receiver is in control of when to receive data and it is responsible for detecting collisions and recovering lost data.
- Since transmissions are triggered by beacons, the receiver will have very little overhead due to overhearing.
-

Disadvantages of Receiver Initiated-MAC(R-MAC)

- Senders must wait for the receiver's beacon before they can transmit, potentially leading to large overhearing costs.
- When packets collide, the senders will retry until the receiver gives up, potentially leading to more collisions in the network and to increased data delivery latencies.

5.19 ENERGY & RATE MAC PROTOCOL [26]

ER-MAC (Energy and Rate), the distributed energy aware MAC protocol is based on TDMA. ER-MAC uses the concept of periodic listen and sleep. A sensor node switches off its radio and goes into a sleep mode only when it is in its own time slot and does not have anything to transmit. It has to keep the radio awake in the slots assigned to its neighbors in order to receive packets from them even if the node with current slot has nothing to transmit.

The protocol has two types of packets, data packets and control packets. Initially each node is assigned two TDMA slots for transmission according to an pre-defined algorithm. Each node knows the transmission slots of its neighbors. Nodes periodically exchange information about their energy levels and criticality and determine whether to use one or two slots for transmission. Initially, the Radio-power-mode of all nodes is set to TRUE to allow nodes to transmit in two slots. Each sensor node can be in any of the following two phases:

Normal operation phase: The nodes operate normally, routing data packets to the sink/base-station. In normal operation mode, the activity of each node in a time slot is, if it owns the current slot then it sends its available data. In case it has nothing to transmit, the radio is put to sleep. If it does not own the current slot, it checks its slot table to see whether this is the second slot of the current winner. If so, the slot is idle and it puts its listening radio to sleep

Voting phase: Critical nodes enter the voting phase to do a local election and readjust their slots. The voting phase is triggered by criticality of a node. A node becomes critical if its energy falls below a threshold factor of the previous winner's (then) energy value. The critical node then triggers a local voting phase. A node in the voting phase is a winner if criticality values of all its neighbors are greater than its own. Otherwise it declares itself a loser. The voting phase is integrated with the normal TDMA phase and control packets are sent along with normal data packets when necessary. The sequence of steps followed by sensor node triggering the voting phase is as follows:

Note that multiple nodes can become critical and initiate the voting phase at the same time, i.e., during the same TDMA cycle. At the end of one TDMA cycle, starting from the slot of the first node initiating the voting phase (node i), all critical nodes have complete neighbor energy and flow information and can determine the winner. To save slots, node can declare the identity of the winner during its transmission slot.

Advantages of Energy & Rate MAC (ER-MAC)

- Packet loss due to collisions is absent because two nodes do not transmit in the same slot. Although packet loss may occur due to other reasons like interference, loss of signal strength, etc.
- No contention mechanism is required for a node to start sensing its packets since the slots are pre-assigned to each node.
- No extra control overhead.

Disadvantages of Energy & Rate MAC (ER-MAC)

- The sensor node has to keep the radio awake in the slots assigned to its neighbors in order to receive packets from them even if the node with current slot has nothing to transmit.
- Nodes periodically exchange information about their energy levels and criticality and determine whether to use one or two slots for transmission which may lead to network congestion and energy wastage.

5.20 TRAFFIC AWARE ENERGY EFFICIENT MAC PROTOCOL (TEEM) [27]

Changsu Suh, et. al. focused on the contention-based MAC protocol and present a novel scheme, named as TEEM (Traffic aware, Energy Efficient MAC) protocol based on SMAC synchronous protocol. In order to minimize energy consumption, the proposed TEEM makes two important modifications over the SMAC protocol: firstly by having all nodes turn off their radios much earlier when no data packet transfer is expected to occur in the networks, and secondly by eliminating communication of a separate RTS control packet even when data traffic is likely to occur. Remember that in SMAC, the likelihood of data communication is never considered - thus, every node is required to be in active during the whole listen period. The goal is to avoid such a fully active listen interval by utilizing traffic information of each node.

SMAC had a long listen interval, divided into three parts for SYNC, RTS, and CTS packets, respectively. TEEM has a much smaller listen interval of 83 ms, which is divided into only two parts: the first part of the listen interval is for sending SYNC packets when a node has any data messages queued for transfer (hence, we call it "SYNCdata" period), and the second part is also for sending SYNC packets but when a node has no data packets to transmit in its buffer (we name it as "SYNC no data" period). That is, in TEEM; each node tries to differentiate its time for broadcasting a SYNC packet. This differentiation is based on whether a node has data traffic or not. Basically, when a node does not have any outgoing data traffic, it will delay a time for sending its own SYNC into the second part of our listen interval, i.e., the SYNC no data period. It is important to note that there will be no SYNC packets going on at the SYNCdata period when no one has outgoing messages currently queued in their buffers. In this case, all nodes will be allowed to sleep right after receiving a SYNC packet at the SYNC no data period until the next listen schedule, resulting in much longer sleeping time.

The proposed TEEM can further reduce the listen interval of some other nodes that are not involved in data communication, even in the case when there exists node X that has data traffic and thus needs to send its SYNC packet in the first part of the listen interval, i.e., the SYNCdata period. Such a reduction of the listening time can be achieved by allowing node X to piggybacking a RTS onto its SYNC packet. It is possible to combine these two control packets in the protocol since, if node X is assumed to win the channel contention for sending its SYNC packet in the SYNCdata period, node X should also be assumed to send out its data messages. This combined control packet between SYNC and RTS is called a SYNC RTS packet. Figure 2 represents a SYNC RTS packet structure. It looks quite similar to a SYNC packet, just borrowing two additional fields for the address of the receiver and NAV duration from a RTS.

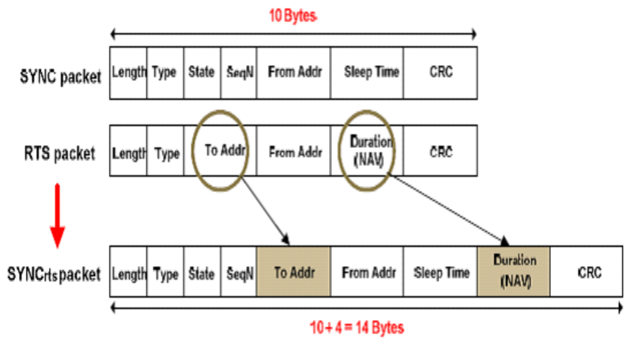

Fig 18. SYNC RTS packet type: A combination of SYNC and RTS

When nodes receive SYNC RTS packet by the end of SYNCdata time interval, they will come to know not only synchronization information, but also information about who is the receiver for data packets. Therefore, while the destined receiver is required to reply a CTS packet back to the sender, any other nodes are free to go to sleep without necessarily staying awake in the SYNC no data period - thus, they are needed to be in active only for the first, very short duration of listen interval. In this sense, the duration of listen and sleep modes in TEEM scheme is not fixed but adaptive. See figure 19 as an example.

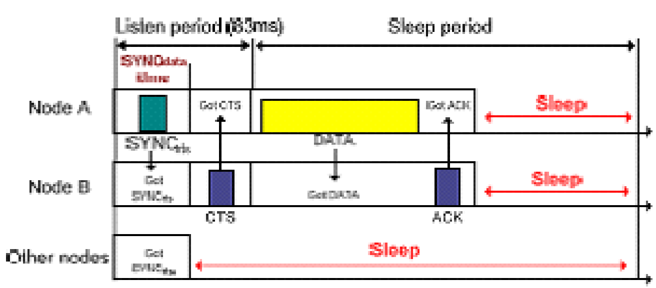

Fig. 19

(a) When node A has data for node B

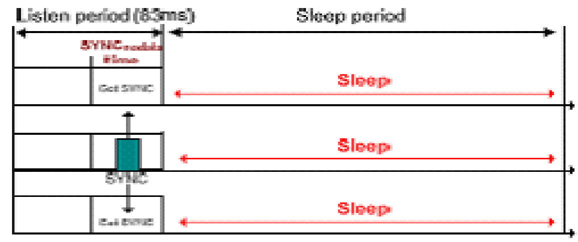

Fig. 19 (b) When no nodes have data traffic

Advantages of TEEM

- The protocol achieves energy efficient consumption by utilizing 'traffic information' of each node, achieving a significant decrease in power consumption. Thus, the listen time of nodes can be reduced by putting them into sleep state earlier when they expect no data traffic to occur.
- Eliminating communication of a separate RTS control packet even when data traffic is likely to occur.

Disadvantages of TEEM

- It still lacks on latency efficiency as it is subjected to energy efficient operation.

5.21 TASK AWARE MAC (TA-MAC) PROTOCOL [28]

The TA-MAC protocol consists of two procedures: task monitoring and collaborative adjusting. A sensor node first monitors its task activity that the node is involved and estimates the transmission attempt rate. The transmission attempt rate represents the frequency that the sensor node tries to access the channel per unit time. Since the optimal channel access probability is also dependent on the network load, the sensor node adjusts its channel access probability through the collaboration with neighboring nodes. Figure 19 shows an illustrative example for task monitoring.

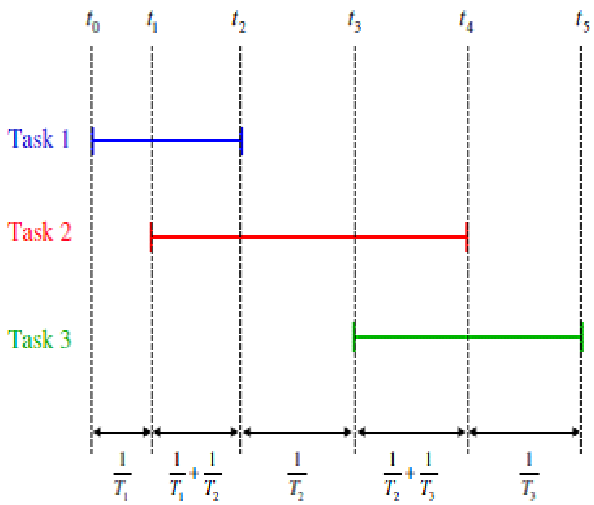

Fig. 20. An example of Task Monitoring

Advantages of TA-MAC

- As a kind of cross layering approach, TA-MAC protocol determines the channel access probability depending on a node's and its neighbor nodes' traffic loads through the interaction with the data dissemination protocol.
- TA-MAC protocol can reduce energy consumption and improve the throughput by eliminating unnecessary collisions.
- The TA-MAC protocol is feasible because it can be integrated with an energy efficient MAC protocol (e.g., SMAC). - This is because the TA-MAC protocol focuses on the determination of channel access probability that is orthogonal to the previous MAC protocols for WSNs.

Disadvantages of TA-MAC

- The sensor collects neighbor nodes' task activities and determines its channel access probability using the collected information, may disrupt the nodes' own activity if the neighboring traffic is corrupt or large enough to cause computational overhead.

5.22 Sparse Topology and Energy Management (STEM) PROTOCOL [29, 30]

STEM is an event triggered protocol used for applications where nodes spend most of the time in waiting for an event. If any event occurs then it forwards the data to the desired nodes. In a wireless sensor network a node spends huge part of energy sensing an event and forwarding it into the network refers as transferring state. STEM reduces the energy used in monitoring state and reduces the latency between monitoring and transferring states. To trace an event and forward it to the sink node, all nodes must be synchronized.

If a node is away from sink and it sensed an event which is not sensed by the node near to sink. It cannot forward the information to sink because the next node is in sleep state. To handle this kind of situation, STEM lets the nodes turn on their radio periodically and listen if any node wants to communicate with them.

Advantages of STEM

- The STEM protocol is efficient for event-triggered application where the rate of event occurring is not high.
- In STEM, a node sends a beacon before sending the data packet. The wake-up radio works on low duty cycle and if there is any data to process by the data radio, it awakes the data radio.

Disadvantages of STEM

- The STEM technique can increase the delay when there is heavy communication among nodes.
- STEM does not focus on quality of service because it tries to improve the energy consumption of a node by using two radios as radios are the major source of energy consumption.

5.23 POWER AWARE CLUSTER TDMA (PACT) PROTOCOL [31]

In wireless sensor network applications like surveillance, a large number of nodes are placed to detect an event where the typical communication between the nodes is multi-hop. PACT is a TDMA-based protocol used for large multi-hop wireless sensor networks. PACT uses adaptive duty cycle with respect to traffic. It turns the radio off if there is no traffic in the network. It uses the passive clustering to save the energy in which small number of nodes participated in the communication and are called cluster heads or gateways. These nodes are elected with respect to their energy level and it eliminates the need to send a separate packet defining the energy level. PACT considers both the space and time domain to minimize the energy consumption and communication cost. In the space domain, PACT uses the passive clustering structure to minimize the communication cost, while it saves the energy by allowing the nodes to use only active slots and sleep during in inactive slots.

In [34], the authors describe the Low Energy State (LES) of cluster heads and gateway nodes. When the energy level of cluster heads and gateways become less than the threshold level, they change their state to LES. A node in the LES state will not act as a cluster head or gateway until it is recharged, but it can participate as a cluster member. Each node exchanges the information of cluster heads ID using a control packet and this information limits the number of gateways between the cluster heads. If there are multiple gateways, the node with the highest number of IDs will be selected as a gateway and the rest of the gateways will preserve their energy for future use.

There are two common slot-assignment schemes used i.e. node activation and link activation. In the node-activation scheme, each node uses a single time slot to transmit the information to a number of nodes. While in the link-activation scheme, a node can transmit a packet to its neighbor only. In link activation, a node sends a separate broadcast message to its neighbors. Node activation is suitable for those applications where the network is large and with a low traffic load.

Each frame in PACT protocol consists of control slots and data slots. Each node uses a control slot to inform other nodes about its data slots. During each control slot all nodes will turn on their radio. Control slots remove the transmission conflict among nodes because every node can know about transmission or data slots of its neighboring nodes through the control information. The member nodes will give priority to the cluster heads and gateways in slot selection while in each control packet, the node will specify the destination address so that the destination node can turn on its radio and other nodes can turn off their radio during inactive slots.

Advantages of PACT Protocol

- The PACT protocol provides collision-free communication as each node has pre-assigned time slots for communication.
- It uses the passive clustering technique to make nodes energy efficient by only allowing gateways and cluster head nodes to participate in data forwarding.

Disadvantages of PACT Protocol

- Each node has to listen to the mini slots or control packets from other nodes in order to get the control information. This may lead to some energy consumption.

5.24 DW-MAC DEMAND-WAKE-UP MAC (DW-MAC) PROTOCOL [35]

Yanjun Sun et al, produced DW-MAC (Demand-Wakeup) [35]. DW-MAC is a synchronized duty cycle MAC protocol, where each cycle is divided into three periods: Sync, Data, and Sleep. DW-MAC assumes that a separate protocol is used to synchronize the clocks in sensor nodes during the Sync period
with required precision. The basic concept of DW-MAC is to wake up nodes on demand during the Sleep period of a cycle in order to transmit or receive a packet. This demand wakeup adaptively increases effective channel capacity during a cycle as traffic load increases, allowing DW-MAC to achieve low delivery latency under a wide range of traffic loads including both unicast and broadcast traffic.

Advantages of DW-MAC Protocol

- DW-MAC is better suited to varying traffic loads due to its adaptive channel capacity change during operational cycle. This allows DW MAC to achieve low delivery latency under dynamic traffic loads.
- The scheduling algorithm in DW-MAC integrates scheduling and access control to maintain a proportional one-to-one mapping function between a Data period and the subsequent Sleep period, which minimizes scheduling overhead while ensuring that data transmissions do not collide at their intended receivers.

Disadvantages of DW-MAC Protocol

- The protocol works on demand, this approach increases delay between the requirement and actual delivery of data.

5.25 AN ORGANIZED ENERGY AWARE MAC (O-MAC) PROTOCOL [36]

O-MAC design proposed by Farid Nait-Abdesselam et. al. is mainly based on two main ideas to increase energy efficiency. First, it adopts a locally scheduled algorithm on a CSMA protocol which will prevent possible collisions among the neighboring contending nodes. Second, it allows the nodes in the vicinity of a transmission and that are not concerned by the data being sent the possibility to sleep during the duration of one transmission and to inform their neighbors of their ultimate entry into sleep mode to prevent them from sending data wastefully during the sleep period.

Advantages of O-MAC Protocol

- O-MAC introduces two new control frames OTS and NTS to help nodes confirm the channel reservation to all the nodes that may go to the sleep due to RTS or CTS collisions.
- O-MAC allows isolated nodes in the vicinity of one transmission to turn off their radios.

Disadvantages of O-MAC Protocol

- The performance of O-MAC decreases with the increase in node density, due to overheads introduced by new O-MAC overhead packets.
- The size of both NTS and OTS packets increases with increase in neighbors, resulting in large overheads.

6 A COMPARISON OF EXISTING MAC PROTOCOLS

Table 1 compares the different MAC protocols discussed in the preceding section. Here, we have shown their comparison by taking parameter scheme used, energy saving, advantages, disadvantages.

Table-1: Comparative study of MAC protocols.

Name of Protocol	Scheme Used	Need Sch.	Energy Saving	Latency	Contention basedor free	QoS	Sync
SMAC[4]	Fixed duty cycle,virtual cluster,CSMA	Yes	Power savings over standard CSMA/CA MAC	Increaes due to fixed duty cycle	Contention free	Low due to fixed duty cycle	Yes
TMAC[5]	Adaptive duty cycle,over hearing	Yes	Uses 20% of energy used in S-MAC	Increases when traffic load is high	Contention free	Decreases in heavy traffic	Yes
LPL[8]	Fixed preamble sampling	No	Perform better than S-MAC	Increased latency at each hop	Contention based	Low due to increased latency at each hop	No
B-MAC[9]	LPL,channel assesment,software interface	No	Better power savings,latency,and throughput than S-MAC	High average latency	Contention based	Low overhead when network is idle	No
Wise-MAC[10]	Minimized preamble sampling	No	Better than S-MAC and low power listening	Increases latency with each hop	Contention based	Performs better than SMAC in high traffic loads	No
X-MAC[11]	Short preamble sampling with target address information	No	Better than S-MAC,B-MAC,WMAC	Low latency	Contention based	Better due to low overhead as synchronization is required	No
CMAC [12]	Aggressive ACK,Anycast,convergent packet forwarding	No	Consumes less energy than many existing solutions	Low latency	Contention based	It supports high throughput	No
SCPMAC [13]	Minimized preamble sampling,schedule, multihop stream	Yes	Low energy consumption than BMAC and TMAC	Low latency	Contention free	The high contention increases packet loss	Yes
TRAMA [14]	Uses distributed election scheme,assumes atime slotted channel	Yes	TRAMA is more energy efficient than SMAC	Low latency	Contention free	Throughput is high due to distributed election scheme	Yes
SIFT[16]	Uses a non uniform probabaility distribution function	No	It could be tuned to less energy consumption	Low traffic is achieved with many traffic sources resulting in low latency	Contention based	QoS decreases due to overhearing	No

Name of Protocol	Scheme Used	Need Sch.	Energy Saving	Latency	Contention basedor free	QoS	Sync
DMAC [18]	Data gathering tree and convergent communication	Yes	High energy efficiency	It achieves better latency as compared to other sleep/listen period assignment methods	Contention based	Since many nodes share the same medium, collisions will occur and DMAC only employs limited collision methods	Yes
YMAC [19]	Divides time into frames and slots, medium access is based	Yes	Energy consumption is low due to reciever driven communication	Reduced delivery latency	Contention free	High achievable throughput due to usage of multiple channels	Yes
LEACH [20]	Clustering algorithm,two phases of operation:setup and steady state phases	Yes	Reduces energy consumption by using techniques like min. transmit energy,avoid idle listening of cluster members.	It assumes that all nodes are able to reach the base station which affects the latency of the protocol	Contention free	High due to clustering	Yes
LMAC & Mobile MAC [21]	Based on TDMA	Yes	Both these protocols has the advantage of energy effeciency like TDMA	In Mobile LMAC latency is high because slots computed only once	Contention free	Bandwidth ineffeciency due to fixed slot sizes but collision free communication	Yes
PAMAS [22]	Uses two separate channels,one each for data frames and control frames	No	Due to the usage of two radios energy consumption is high	Latency problem is less as there is no overhearing	Contention based	Achieves higher throughput under heavy loads	Yes
PMAC [23]	A TDMA style protocol that uses framed slots	Yes	It achieves more power savings under light loads	Collisions during PETF may prevent nodes from receiving pattern updates from all neighbors while other nodes may have received thses updates	Contention based	Achieves higher throughput under heavy loads	Yes

Name of Protocol	Scheme Used	Need Sch.	Energy Saving	Latency	Contention basedor free	QoS	Sync
RMAC [24]	Sends a Control frame along the route to infrom nodes of the incoming packets	Yes	It is able to perform end to end data delievery within a single operational cycle.Thus saving energy considerably	Addresses the large latencies often experienced in MAC protocols using duty cycles	Contention based	Collision can still occur on data packets during sleep periods	Yes
RIMAC [25]	Transmission is initiated by the reciever,reciever uses its beacon frames to coordinate transmitter	No	Saves considerable amount of energy as transmissions are triggered by beacons	Increased data delievery latencies	Contention based	When packets collide the sender will retry until the reciever gives up,thus leading to more collisions in the network	Yes
ER-MAC [26]	Uses the concept of periodic listen and sleep	No	Nodes periodically exchange information about their energy levels, which may lead to energy wastage	Low latency as each node has its own dedicated slot	Contention free	Packet loss due to collision is absent because two nodes do not transmit in the same slot	No
TEEM [27]	Turn off all radios much before when no data packet is expected to transfer,eliminatati ng communication of separate RTS control packet even when data packet is likely to occur	Yes	Achieves energy efficient consumption by utilizing "transfer information" of each node	Increases in multihop network	Contention based	Better in lower network load	Yes
TA-MAC [28]	Protocol consists of two procedures:task monitoring and collaborative adjusting	Yes	TA-MAC protocol can reduce energy consumption as it first monitors the task activity	Latency is low as collisions are minimum	Contention based	It improves the throughput by eliminating unneccasry collisions	Yes
STEM [29,30]	An event triggered protocol	No	It reduces energy in monitoring state	It reduces latency between monitoring and transfering states	Contention based	It does not focus on QoS	Yes

Name of Protocol	Scheme Used	Need Sch.	Energy Saving	Latency	Contention basedor free	QoS	Sync
PACT [31]	Uses adaptive duty cycle with respect to traffic,uses passive clustering	Yes	Moderate in large networks	Reduced by passive clustering	Contention free	Increased through passive clustering	Yes
OMAC [36]	Adopts locally scheduled algorithm on CSMA protocol	Yes	Decreased energy consumption as nodes are not concerned with neighboring data transmission	Low latency	Contention based	Performance decreases with increase in node density due to overhead introduced by new overhead packets	Yes

7 FUTURE RESEARCH DIRECTIONS

In the recent years a large number of medium access control (MAC) protocols for the wireless sensor network have been developed. Most of the work on the MAC protocols focuses primarily on the energy efficiency in the sensor network [37]. However, still a lot of work has to done in the other areas at the MAC layer such as:

- Network Security: Sensor network security at MAC layer to protect against eavesdropping and malicious behavior has to be studied further. Karlof et al. in TinySec [38] have proposed secure MAC protocol based on use of a shared key but still more advanced schemes needs to be developed.
- Nodes Mobility: The nodes in the wireless sensor network were originally assumed to be static. Recently, there has been increasing interest in medical care and disaster response applications where the mobile sensors can be attached to the patient, doctor or first responder. The mobility at the MAC layer has been considered in MMAC [39], however there is still a lot of scope for future research in this area.
- Evaluation on Sensor Platforms: Most of the protocols for the wireless sensor network have been evaluated through the simulations. However, the performance of the MAC protocol needs to be evaluated on the actual sensor system. The research should focus on experimenting on the real sensor platforms.
- Real Time Systems: Energy efficiency is the main design objective of the sensor network but the reliable delivery of data in real-time is essential for certain time critical applications. This is also a promising area for Further research.

8 CONCLUSION

Designing a MAC protocol which can improve energy-efficiency to extend network lifetime in wireless sensor networks is a challenging problem. This daunting task is mainly due to stringent resource constraints both in sensor nodes and in wireless media. Several energy-efficient medium access control protocols, both contention-based and reservation-based, for the wireless sensor network that have been proposed by the researchers are presented in this paper. The design of an optimized MAC protocol for energy efficiency also depends on the actual application. However, no specific MAC protocol so far has been accepted as a standard. Another reason is the lack of standardization at lower layers (physical layer) and the sensor hardware. Therefore, it will be difficult to have one standard MAC protocol which will work for all possible WSN applications and there is still a lot of work to be done in working out a MAC protocol which will adapt its research area which needs to be studied more extensively behavior based on its application.

REFERENCES

[1] DemirkoL C Ersoy, and F. Alagoz. MAC Protocols, for Wireless Senior Networks: Survey, IEEE Communication Magazine, Vol. 44, Issue 4, pp. 115-121. April 2006.

[2] Roy and N.Sarma, Energy Savings in MAC layer of Wireless Sensor Networks: A Survey, National workshop in design and analysis of Algorithm, Tezpur University, India, 2010.

[3] LAN-MAN Standards Committee of the IEEE Computer Society. Wireless LAN medium access control (MAC) and physical layer (PHY) specification. IEEE. New York, NY, USA, IEEE Std 802.11-1997 edition" 1997.

[4] Wei Ye. John Heidemaoo. and Deborah Estrin An energy-efficient MAC protocol for wireless sensor networks. In Proceedings of the IEEE Infocom. pages 1567- 1576. New York. NY, June 2002.

[5] Tijs van Dani and Koeu Langendoen. An adaptive energy-efficient MAC protocol for wireless sensor networks. In Proceedings of the First ACM SenSys Conference, pages 171-180. Los Angeles. California, USA. November 2003. ACM.

[6] A.El-Hoiydi. Aloha with preamble sampling for sporadic traffic in ad hoc wireless sensor networks. In Proceedings of IEEE International Conference on Communications. Apr. 2002.

[7] Zlmvei Zhao. Xinming Zhang. Peng Sun. Pengxi Lin. "A Transmission Power Control MAC" Protocol for Wireless Sensor Networks". Pi-acceding? of Sixth ImernanonaJ Conference on Networking 2007.

[8] A. El-Hoiydi. Aloha with preamble sampling for sporadic traffic in ad hoc wireless sensor networks. In Proceedings of IEEE International Conference on Communications. Apr. 2002.

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

[10] El-Hoiydi and J. Decotigaie. Low power downlink MAC protocols for infrastructure wireless sensor networks. ACM Mobile Networks and Applications. 10(5):675HS90, 2005.

[11] M. Bxiettner. G. V. Yee. E. Anderson, and R. Han. X-MAC: A short preamble MAC protocol for duty-cycled wireless sensor networks. In Proc. Sensys'06
. 2006.

[12] Sha Liu. Kai-Wei Fan and Prasun Sinha . "An Energy Efficient MAC Layer
Protocol Using Convergent Packet Forwarding for Wireless Sensor Networks". IEEE SECON, 2007.

[13] Wei Ye. Fabio Silva. John Heideniann. "Ultra-Low Duty Cycle MAC with scheduled Channel Polling". ACM SenSys 2006, November, 2006

[14] V.Rajendra, K Obrazcka, JJ 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

[15] L.Bao and J.J. Garcia-Luna-Aceves, "A New Approach to Channel Access Scheduling for Ad Hoc Networks", Seventh annual International Conference on Mobile Computing and Networking,pp.210-221,2001.

[16] K, Jamie'soa, H. Balafcrishnan, aad Y. C. Tay, "Sift: A MAC Protocol for Event-Driven Wireless Sensor Networks," MIT Laboratory for Computer Science, Tech. Rep. S947 May 2003.

[17] Y.C. Jay. K.Jamieson. "Collision minimizing CSMA and Its Applications to Wireless Sensor Networks". IEEE Journal on Selected Areas in Communications, Volume: 22. Issue: 6. Pages: 1048 - 1057. Aug. 2004.

[18] Kim Y. Shin, H., and Cha,H.(2008) YMAC: An energy efficient multi-channel MAC protocol for dense wireless sensor networks, Proc. of the International
Conference on Information Processing in Sensor Networks(IPSN).

[19] Lu.C,. Krishnamachari B. and Raghavendra. C.S.(2004) An adaptive energy efficient and low latency MAC for data gathering in wireless sensor networks. Proc. of the 18th International Parallel and Distributed Processing Symposium.

[20] Heinzelman, W.B., Chandrakasan, A.P., and Balakrishan,H.(2002)An application specific protocol architecture for wireless micro sensor networks. IEEE Transactions on Wireless Communications.

[21] Van Hoesel, L., and Havinga, P. (2004) A lightweight medium access protocol (LMAC) for wireless sensor networks: Reducing preamble transmissions and transceiver state switches. Proc. of the 1st International Conference on Networked Sensing Systems (INSS).

[22] Singh, S., and Raghavendra, C. (1998) PAMAS: Power aware multi-access protocol with signaling for ad hoc networks. SIGCOMM Computer Communications Review 28 (3), 5 - 26.

[23] Zheng, T., Radhakrishnan, S., and Sarangan, V. (2005) PMAC: An adaptive energy-efficient MAC protocol for wireless sensor networks. Proc. of the 19th IEEE International Parallel and Distributed Processing Symposium (IPDPS)

[24] Du, S., Kumar, A., David, S., and Johnson, B. (2007) RMAC: A routing-enhanced duty-cycle MAC protocol for wireless sensor networks. Proc. of the 26th IEEE International Conference on Computer Communications (INFOCOM).

[25] Sun, Y., Gurewitz, O., and Johnson, D.B. (2008b) RIMAC: A receiver initiated asynchronous duty cycle MAC protocol for dynamic traffic loads in wireless sensor networks. Proc. of the 6th ACM Conference on Embedded Networked Sensor Systems (SenSys).

[26] Rajgopal Kannan. Ram Kalidini, S. S. lyengar "Energy and rate based MAC protocol for Wireless Sensor Networks" SIGMOD Record. Vol.32. No. 4. December 2003.

[27] Changsu Suh, Young-Bae Ko, "A Traffic Aware Energy Efficient MAC protocol for Wireless Sensor Networks". IEEE 2005.

[28] Saogheon Pack. Jaeyouag Choi, Taekyoung Kwon and Yanghee Choi, "TA-MAC: Task Aware MAC Protocol for Wireless Sensor Networks". Vehicular Technology Conference, 2006. VTC 20CW-Spring. IEEE 63rd.

[29] Curt Schurgers. Vlasios Tsiatsis. Saurabh Ganeriwal. and Mani
Srivastava. "Optimizing Sensor Networks in the Energy-Latency-Density Design Space", IEEE Transactions on Mobile Computing, Vol. 1 No.l, January 2002.

[30] Benjie Chen, Kyle Jamieson. Hari Balakrishnan. and Robert Morris." Span: An Energy-Efficient Coordination Algorithm for Topology Maintenance in Ad Hoc Wireless Networks". ACM Wireless Networks Journal, Volume S, Number 5, September:, 2002.

[31] Guangyu Pei and Charles Chien. "Low Power TDMA. in Large Wireless Sensor Networks'". IEEE 2001.

[32] Xiaoyan Hong. Mario Gerla. Yunjung Yi. Kaixm Xu. and TaekJin Kwon. "Scalable Ad Hoc Routing in Large. Dense Wireless Networks Using Clustering and Landmarks." in Proc of IEEE International Conference on Communications (ICC 2002), April 2002,

[33] Jing Li, "A Bit-Map-Assisted Energy-Efficient MAC Scheme for Wireless Sensor Networks". Mississippi State, Mississippi May, 2004.

[34] Michael Ignatius Brownfield, "Energy-efficient Wireless Sensor Network MAC Protocol". Blacksburg, Virginia Polytechnic Institute and State University, 2006, 219 pages; AAT 3207957