A Survey of Medium Access Control Protocols in Wireless Sensor Network

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ABSTRACT
With the recent technological advances of wireless sensor network (WSN) and the nature of wireless sensor networks which is the power constraint, researchers face new challenges related to the design of algorithms and protocols. This work tries to survey the research that has been conducted on a number of levels to design and assess the deployment of wireless sensor networks. It highlights the current state of the Medium Access Control (MAC) protocol in WSN with a view to advance the research in the field.

General Terms
Wireless Sensor Network (WSN)

Keywords: MAC, Network lifetime, TDMA and CSMA, Sensor

1. INTRODUCTION
Wireless sensor network (WSN) is a collection of very small, self-contained, micro-electro-mechanical devices as shown in figure 1. These tiny devices have sensors, computational processing ability (CPU), wireless receiver and transmitter technology and a power supply unit (batteries).

The sensing device measure ambient conditions related to the environment surrounding the sensor and transforms them into an electrical signals [1]. Processing such signals reveal some properties about objects location and/or events happening that vicinity of the sensor. A large number of these sensors can be networked in many applications. A Wireless Sensor Network (WSN) contain hundreds or thousands of these sensor nodes. These sensors have the ability to communicate either among each other or directly to an external base-station (BS) [2].

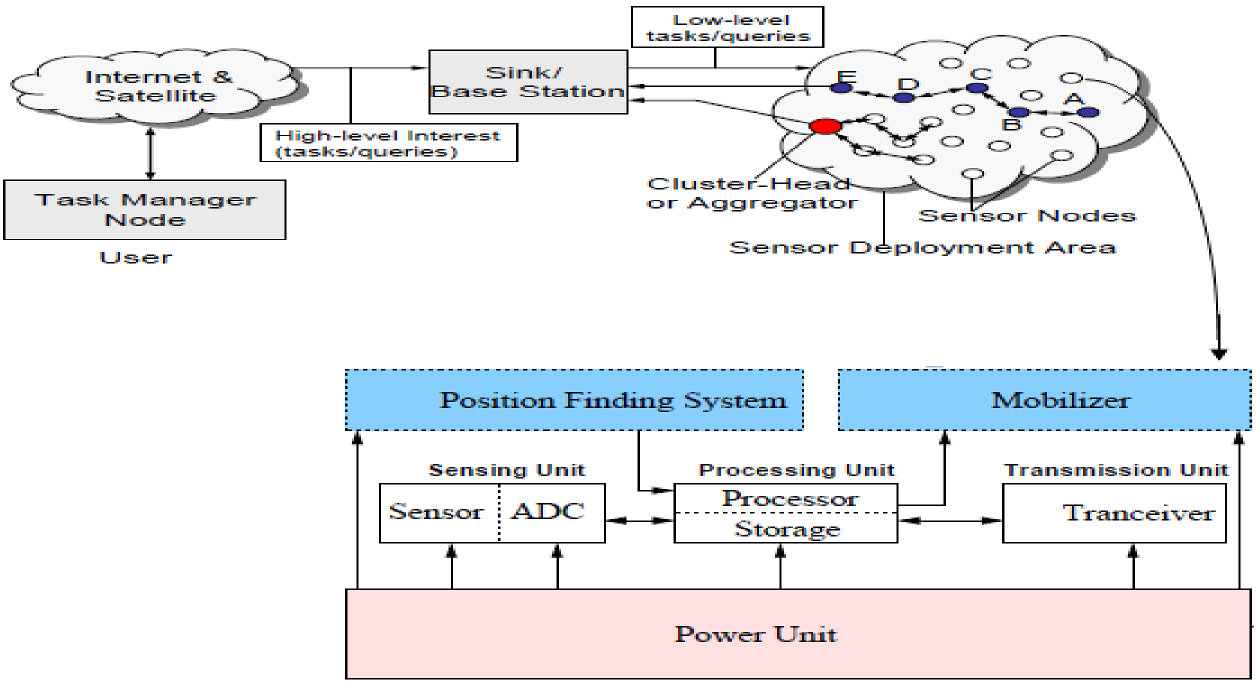

Fig. 1: Wireless Sensor Network Architecture [1],[30]-[31]

A main design criterion in WSN is to extend the lifetime of the network. This should be done without negatively affecting the reliability and efficiency of communications from sensor nodes to other nodes as well as data sinks or base station since the largest design constraint is the energy budget of a sensor node together with the requirement of long network runtime [29]. In order to achieve this aim, it is very important to optimize every facet of the communication protocols in WSN since it is the largest source of energy drain in this network [1].

Medium Access Control (MAC) is a part of the Data link layer in the OSI layer model and is central to the proper functioning of any communication system. The main task of

MAC is to coordinate access to and transmission over a medium common to several nodes. With wireless as the medium of communication in WSN, it is complicated. This means that in wireless channel an ongoing transmission interferes with any other transmission within the same communication range. Interference may lead to packet losses and thus the need for suitable retransmission mechanisms. Hence an appropriate MAC rules have to be put in place in order to minimize interference and packet collisions. Traditionally this can be achieved by optimizing the channel access, packet transmission and retransmission methods; packet frame lengths (trading throughput with the probability of collision over the packet transmission duration); modulation and coding schemes (trading throughput with the reliability to achieve error free reception and hence avoiding re-transmission); transmission powers (trading communication with interference range); etc. [2], [3].

MAC in sensor networks is very different from the traditional networks because of its constraints on computational ability, storage and energy resources thus the techniques discussed above are not suitable for WSNs. Therefore media access control should be energy efficient and should also allocate bandwidth fairly to the infrastructure of all nodes in the network. The followings attributes should be considered when designing a good MAC protocol for the wireless sensor networks [2]:

1. Energy Efficiency: The sensor nodes are battery powered and it is often very difficult or at times impossible to change or recharge batteries for these sensor nodes. In some cases, it is beneficial to replace the sensor node rather than recharging them.
2. Latency: This basically depends on the application. In the sensor network applications, the detected events must be reported to the sink node in real time so that the appropriate action could be taken immediately.
3. Throughput: This varies with different applications. Some of the sensor network application requires to sample the information with fine temporal resolution. In such sensor applications it is better that sink node receives more data.
4. Fairness: In many sensor network applications when bandwidth is limited, it is necessary to ensure that the sink node receives information from all sensor nodes fairly.
5. Scalability: A WSN may consist of hundreds of nodes in a single network. MAC protocol in WSNs have to be designed to be able to work with these large numbers of nodes and also utilize the high density of nodes. The density of a WSN can be anything from a few nodes to a few hundred nodes per square meter.
6. Reliability: Reliability is one of the most important factors. A sensor node can fail due to several reasons such as environmental interference, physical damage, depleted energy source and etc. The failure of a single node should not affect the overall network performance. Reliability of MAC protocol in a WSN is the ability of the protocol to sustain its functionality regardless of the failure of nodes.

This paper surveys various MAC protocol designed by researchers for WSN. The rest of the paper is organized as follows: The second section gives an overview of the Medium Access Control (MAC) layer in WSNs including recent research conducted by researchers as well as open research issues. Section three concludes the work showing further areas that needs to be developed.

1. MAC PROTOCOLS FOR WSN

The medium access control protocols for the wireless sensor networks can be classified broadly into two categories namely: schedule based and contention based.

1.1 Schedule Based Protocol

Schedule based: This protocol can avoid collisions, overhearing and idle listening by scheduling transmit and listen periods but have strict time synchronization requirements. Sensor nodes are allocated time slots using Time Division Multiplex Access (TDMA) or Frequency Division Multiplex Access (FDMA) in combination with TDMA. In each time slot a node has access to the shared medium and can transmit without collision. As can be seen in Figure 2, the TDMA, nodes are allocated different times such that at time t2, node N3 has access to the medium. Receiver nodes are synchronized with their sender nodes to wake up at the same time [2]. This protocol enhances energy efficiency by avoiding collision and overhearing. However a lot of overhead is incurred in synchronization, which together with clock drift is an issue with this protocol [3] [4]. Also, it is prone to idle listening under low traffic which wastes energy.

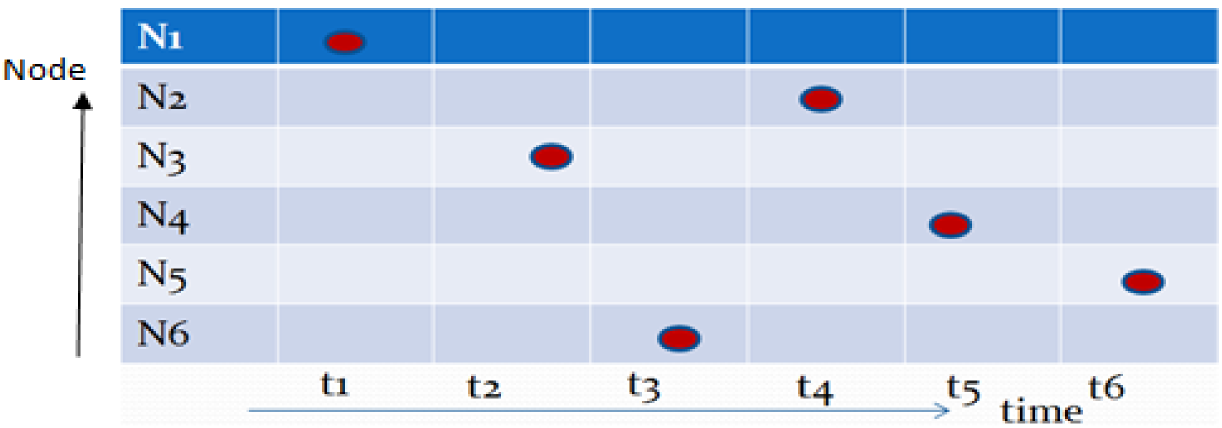

Fig. 2: Scheduled access protocol

In TDMA, a specific node, the base station, has the responsibility to coordinate the nodes of the network. The time on the channel is divided into time slots, which are generally of fixed size. The node of the network, as shown in figure 3, is allocated a certain number of slots where it can transmit. Slots are usually organized in a frame, which is repeated on a regular basis. The base station specify in the beacon, the organization of the frame. Each node just needs to follow blindly the instruction of the base station. Very often, the frame is organized as downlink (base station to node) and uplink (node to base station) slots, and all the communications goes through the base station. A service slot allows a node to request the allocation of a connection, by sending a connection request message in it.

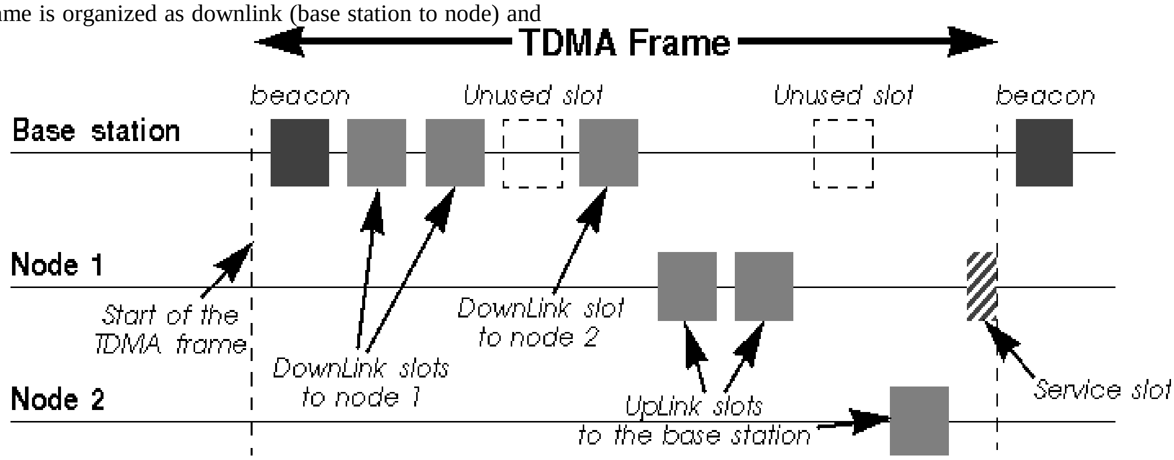

Fig. 3: TDMA channel access mechanism

Advantages of TDMA include low latency and guarantee of bandwidth, which is not the case of CSMA/CA. TDMA is not well suited for data networking applications, because it is very strict and inflexible. TDMA is connection oriented thus, it to suffer the overhead cost. The followings are types of TDMA protocol which are classified based on reliability, latency, scalability and fairness.

1.1.1 Latency MAC

Latency MAC (LMAC) protocol [5], was introduced to reduce idle listening through increasing data arrival prediction accuracy, by increasing sleep cycle which keeps nodes in low power sleep state for longer periods. But this leads to low throughput, high latency and low channel utilization. For light traffic networks, LMAC offers good energy savings with long sleep cycles. If data arrival rate is predictable, and transmissions occur at a fixed rate.

1.1.2 Application-driven, energy-efficient communication

Application-driven, energy-efficient communication in wireless sensor networks [6] offer an improvement by using time schedule to turn on the radios. For an event occurring every 10s, the radios are scheduled to come on every 10s, stay on for the duration of the communication and then go back to sleep. This approach avoids idle listening by ensuring that nodes remain in power saving sleep mode, when no transmission is required, which saves energy. However, energy is wasted if there are no transmissions in any interval. This principle is not so efficient since it leads to unnecessary delay in latency or loss of packets due to randomness of data arrival rate.

1.1.3 An energy efficient and delay sensitive centralized MAC protocol

This protocol [7] incorporated adaptive TDMA in [6] in order to enhance the energy efficiency. Nodes with no packets to transmit go back to sleep without waiting for its entire slot duration to elapse. Another variant of this protocol was proposed in [8] in which an adaptive sleep/wake schedule was employed in place of a fixed sleep/wake schedule. As the node traffic changes, the schedule adaptively changes according to the traffic. Nodes with light traffic sleep more while nodes with heavy traffic have low duty cycle. If a node has more packets than can be transmitted in one duty cycle, the duty cycle will be extended to accommodate the entire packets, and reversed when packets are less. The latency, throughput and channel utilization, were improved using this method, although it incur overhead. This protocol is also adapts to network changes thus it is scalable.

1.1.4 Adaptive time division multiple access-based medium access control protocol

This protocol is dynamic and uses TDMA-based protocol [9]. Nodes that have nothing to send or receive during their active cycle go back to sleep immediately to save energy as in [7]. This is an improvement on protocols like low-energy adaptive clustering hierarchy (LEACH) that remains active during the listen frame even though there are no data to transmit. For nodes with more packets than can be sent within the scheduled duty cycle, cluster heads, dynamically assign different time slots to these nodes in accordance with their needs [8]. Thus protocols are being designed to be more application sensitive and responsive without compromising energy efficient. Energy depletion of the cluster head because of heavy traffic is mitigated by round-robin-based algorithm used for efficient rotation of cluster headship. Energy is saved for nodes with low data traffic while enhancing channel utilization and for heavy traffic nodes; latency is reduced while there is increase in throughput. This protocol is also scalable since it adapts to network changes.

1.1.5 Self-Reorganizing Slot Allocation Protocol

Self-Reorganizing Slot Allocation Protocol [12] or simply Slot Allocation Protocol (SAP), which is also a scheduled based protocol. They are used to avoid partial collision which is as a result of packets colliding with a part of another packet. Partial collision has the same effect as full collision as all the packets are lost. However, with Slot Allocation protocol, frames are divided into slots with duration longer than that required for a packet transmission. Stations are allowed to transmit only at the start of each slot hence collisions can only occur at the beginning of slot. In [12] the TDMA MAC frame is kept by each cluster independent of other clusters. Inter cluster collision is avoided by carrier sensing. Whenever the medium is sensed busy, a *carrier sense-collision* is declared which informs the cluster head that there is an overlapping slot. This and hidden terminal issue were resolved by cluster heads reorganizing slot allocations after each TDMA frame whenever any of these occurs. This approach increases overhead and there is also the probability that two cluster heads will embark on reorganization and end up with overlapping slots all the time since slots are assigned independently. Frame scaling includes empty slots and increases frame duration while time slots are allocated to nodes irrespective of whether they have data to send or not. These reduce spectrum efficiency and increase latency. Most TDMA protocols assume that event detection is deterministic but in reality this is not so hence the need for an adaptive protocol that will take into consideration the non-deterministic nature of events. Dynamic Slot Assignment protocol was proposed in [13] and [14], to minimize the effect of nodes occupying the channel when they have no data to transmit. Cluster heads allocate time slots dynamically only to nodes with packets to transmit to cover transmission of all the packets. This saves idle energy and improves bandwidth employment. Nevertheless, if network traffic is heavy, the number of slot requests may exceed the available slots leading to loss of packets.

Generally Scheduled based protocols conserve nodes energy by avoiding collision since all the nodes are allocated timeslots during which they can transmit. For events that occur at a regular intervals, [6] saves energy by ensuring that node's wake up coincides with event occurrence. But it is not scalable and idle listening addressed in [9] still occurs. Adaptive and dynamic protocols were presented [7] [8] [9]. These adaptively turn ON or off nodes according to the network traffic load demands. This technique saves energy that could have been wasted in idle listening for fixed duty cycles and enhances channel utilization.

1.2 Contention based Protocol

Contention based protocols relax time synchronization requirements and can easily adjust to the topology changes as some new nodes may join and others may die few years after deployment. These protocols are based on Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) technique and have higher costs for message collisions, overhearing and idle listening.

CSMA/CA, a channel access mechanism, is derived from CSMA/CD (Collision Detection), which is the base of Ethernet. The main difference is the collision avoidance: on a wire, the transceiver has the ability to listen while transmitting and so to detect collisions (with a wire all transmissions have approximately the same strength). But, even if a radio node could listen on the channel while transmitting, the strength of its own transmissions would mask all other signals on the air. So, the protocol can't directly detect collisions like with Ethernet and only tries to avoid them.

The basic principles of CSMA/CA are listen before talk and contention. This is an asynchronous message passing mechanism (connectionless), delivering a best effort service, but no bandwidth and latency guarantee. The *protocol* specifies how the node uses the medium: when to listen, when to transmit. The protocol, as shown in figure 4, starts by listening on the channel, and if it is found to be idle, it sends the first packet in the transmit queue. If it is busy, the node waits the end of the current transmission and then starts the contention. When its contention timer expires, if the channel is still idle, the node sends the packet. The node having chosen the shortest contention delay wins and transmits its packet. The other nodes just wait for the next contention. Because the contention is a random number and done for every packets, each node is given an equal chance to access the channel.

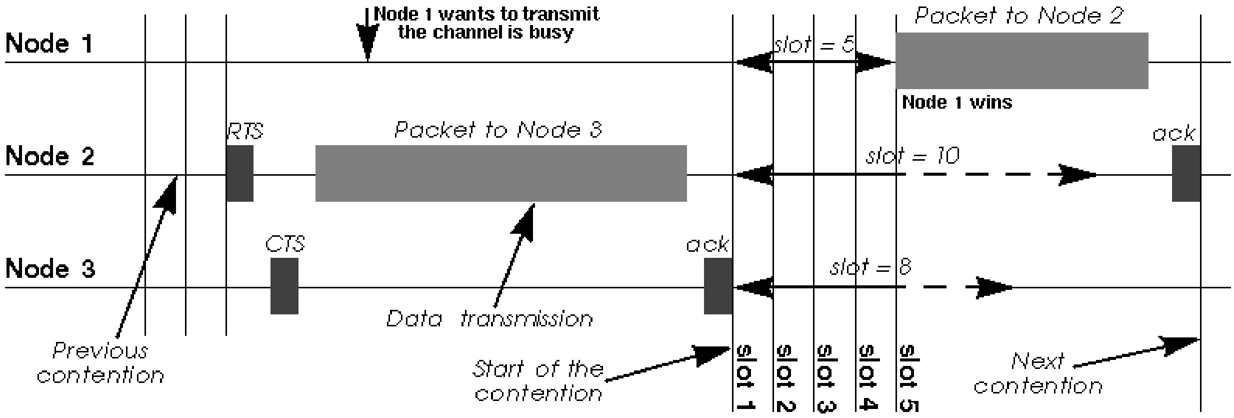

Fig. 4: CSMA/CA channel Access Mechanisms

Contention based Protocol are less compounded than the Schedule based protocols and also they can be completely distributed thus endangering more scalability [17]. CSMA/CA is used by the nodes to access the medium with no master-slave relationships but all nodes compete to gain access to the channel. Less processing and smaller memory are required in contention based because of no need to schedule all the nodes thereby reducing control overhead which is the main source of energy drain in Schedule based protocol. Invariably, the rate of collision is higher and actually the main concern in contention based protocols. CSMA/CA, though has good scalability, consumes more power and offers low bandwidth utilization during heavy traffic. Also contention based uses preamble sampling or low power listening which occupies the channel for longer time than data packets while hidden stations' preambles keep colliding. The probability of collision remains constant with fixed contention windows. This means that all the sensors will compete during each successive contention window after a collision. Collision entails loss of packets and retransmission which waste energy.

1.2.1 A New Contention Access Method for Collision Avoidance

A technique was proposed in [15] to enhance the contention window. The probability of collision was reduced by halving contending probability which is the likelihood that a sensor will wake-up and contend to access the medium. Hence for any collision, the number of sensors that will be contending in the subsequent contention period will be reduced by half, thus generating a probability sequence $\frac{1}{2}, \frac{1}{4}, \frac{1}{8}, \ldots$ and simple probability computation reduces overhead. Figure 5 shows that collisions increase as the number of nodes increase.

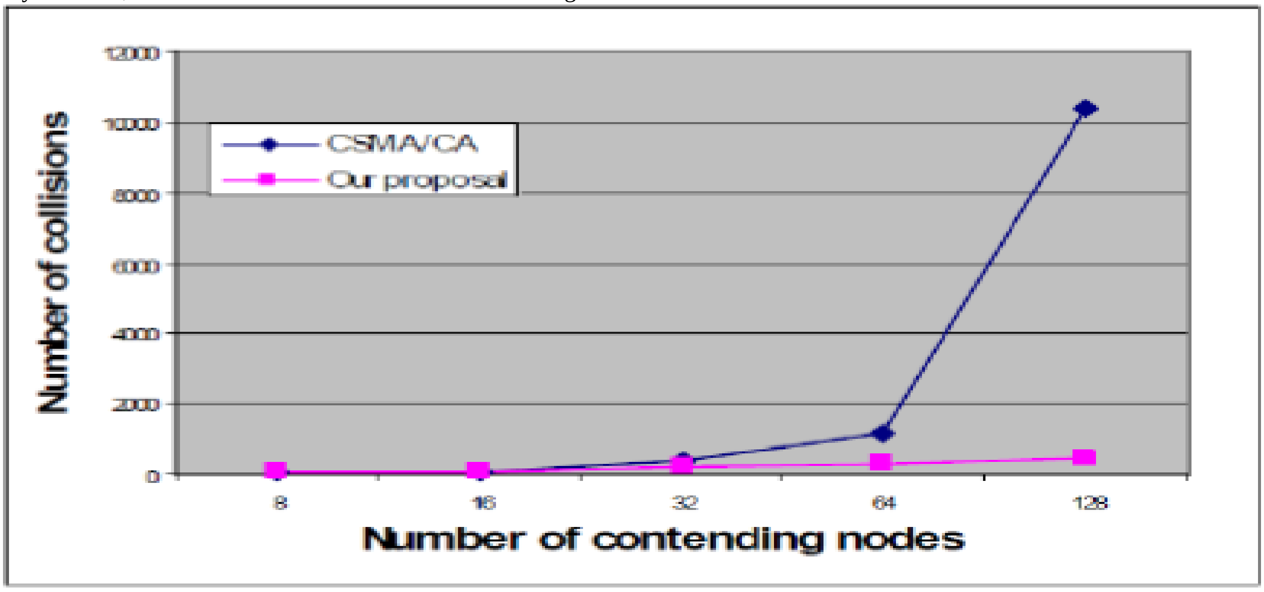

Fig. 5: CSMA\CA vs protocol presented in [15]

The protocol proposed in [15] is more energy efficient as it reduces the number of collisions considerably. Less collision preserves energy since there will be less retransmissions. Nonetheless, collisions still occur and many nodes waste energy being awake and contending for channel access. Also in large networks, contending windows will be quite large, wasting energy, increasing latency and lowering bandwidth utilization.

1.2.2 Nano-MAC and its variance

Nano-MAC [16] is a non-persistence CSMA/CA energy saving scheme []. Contending nodes do not need to continuously listen to the medium, but sleep randomly in the contention window only sensing after back off. Energy wasted by idle listening is conserved since nodes listen randomly to the medium. However energy is wasted in carrier sensing and in collision of control packets. More energy is saved by similar protocol, High Efficient Sensor MAC proposed by [18]. It minimizes idle listening by allowing longer sleep periods. Nevertheless idle listening is not completely eliminated since nodes stay awake in case there are packets to transmit. All the nodes hear any on-going transmission and these constitute sources of energy inefficiency. Collision which still occur after the back-off time was not addressed by [16] and [18]. This was addressed by the algorithm proposed in [19]. In this algorithm, a node randomly selects back-off period, and notifies others which then select their corresponding back-off time avoiding overlapping. Collision is thus eliminated thereby saving energy but overhead increases which consume more energy.

1.2.3 Adaptive Energy Efficient MAC (AEE-MAC) Protocol

The energy conservation of ML-MAC was improved on by Adaptive Energy Efficient MAC (AEE-MAC) Protocol [20]. The proposed protocol reduces overhearing by causing nodes having no packets to send to go to sleep upon receipt of Clear-To-Send (CTS) destined for other nodes. There are three optimization stages in this protocol. The first tries to reduce idle listening of standard S-MAC protocol by incorporating the duration of the communication in the control packets. When anode overhears the CTS, it knows the duration of the communication and goes to sleep until the end of the communication. The second optimization considers the actual traffic load of the network and if there are no nodes with packets to send during the active cycle, the nodes will go back to sleep immediately. The last optimization inserts RTS in ACK packets, reducing overhead and collision while engendering good channel utilization. But if there are no packet bursts at the beginning of cycle and no multi-hop communications, the protocol will not be effective in saving energy.

1.3 Hybrid based Protocols

In low traffic, TDMA of Schedule based protocol offers low channel utilization, while in heavy traffic, CSMA of Contention based protocol is beset with collisions. Since no MAC protocol addressed all the sources of energy inefficiencies, hybrid protocols were developed to combine the advantages of the CSMA, TDMA and other energy efficient MAC protocols to maximize energy efficiency, improve latency and spectrum utilization.

1.3.1 Zebra-MAC

Zebra-MAC (Z-MAC) [21] was developed to mitigate the short comings of the CSMA and TDMA based protocols while harnessing their advantages. Nodes perform carrier sensing prior to accessing the medium but priority is always given to nodes that own the slot. Each node is assigned a time slot but if it does not have any data to send other nodes will contend for the channel after a predefined set time. Only the slot owner and its one-hop neighbors can contend for the medium in high contention level (HCL). But all nodes can contend in the low contention level (LCL). Explicit congestion notification (ECN) messages are broadcast by a node, upon sensing heavy traffic on the network, to its two-hop neighborhood to avoid hidden terminal problem. The protocol dynamically uses CSMA and TDMA in light and heavy traffics respectively. Since CSMA is more energy efficient in low traffic by avoiding idle listening, the protocol saves energy. The use of TDMA in heavy traffic reduces collision hence energy is preserved, thus engendering high channel utilization. Idle listening, waiting for set time to elapse and clear channel assessment (CCA) all contribute to energy depletion and low throughput. Synchronizations of nodes within two hops and switching between TDMA and CSMA have overhead cost also.

1.3.2 Centralized Hybrid MAC Protocol

Centralized Hybrid MAC Protocol [22] is a centralized hybrid scheme that uses both the principle of modified slotted contention-based and contention free protocols to preserve energy. It improved on the energy consumption of Bit-Map-Assisted Energy-Efficient MAC (BMA-MAC) protocol [23] by reducing control overhead. The cluster heads broadcast a schedule for all nodes with data to send while nodes without data go to sleep [13] and [14]. Synchronization and defining of the super frame structure were done with beacons to reduce overhead and save energy. No node is required to know its ordering number or to synchronize with its one-hop or two-hop neighbours like in Z-MAC [21]. Compliance period and reservation were intruded to reduce overhearing and collision thereby conserving energy, while dynamic slot allocation improves channel efficiency. However, the protocol dealt only with intra-cluster collisions, a protocol that dealt with both intra-cluster [22] and inter-cluster collision was proffered in [24]. Schedule based TDMA, which reduces energy waste due to collision was used for intra-cluster medium access. Contention based CSMA was used for inter-cluster spectrum access among cluster heads thus reducing energy inefficiency of control overhead. However in order to be responsive to network demands, adaptive sleep/active cycle was employed. Nodes on active mode if they have no packets to send or receive go back to sleep immediately, whereas those with more packets have their active cycle increased. Multi-hop communication, which improves energy efficiency, was used in [24] for transmission from cluster heads to the sink. But cluster heads are permanently on active mode and this will lead to energy wastage. Since TDMA is used in intra-cluster communications, during low traffic, there will be low channel utilization. On the other hand, during heavy inter cluster communications, collisions will increase.

1.3.3 Emergency Response MAC (ER-MAC) hybrid protocol

Emergency Response (ER-MAC) hybrid protocol [25] works on a similar principle as Z-MAC, but saves more energy by avoiding contention by a node that owns a slot. Also it improves on Hybrid MAC Protocol [24] by eliminating permanently on cluster heads thus saving more energy. It is a multi-hop tree protocol that can be applied in events like patient monitoring, wild fire and intruder detections. In these applications, there may be no activity for a long time and suddenly, there might be an event sensed by different nodes that might require immediate reporting, thus bursts of packets. Packets are queued and prioritized in the protocol, and high priority packets are transmitted before low priority packets. Though slot owner with high priority packet are exempted from contention, maintaining an update of the time remaining before a packet deadline expires implies lots of overhead control cost. The use of fixed frame in this protocol means that, it is not adaptive to the dynamics of network load traffic variations.

1.3.4 Queue-length aware MAC Protocol

Queue-length aware MAC (Queue-MAC) [26] is a multi-hop beacon enabled hybrid MAC protocol that addressed the issue of fixed cycle of in ER-MAC [25]. It incorporates a dynamic duty cycled TDMA while the CSMA duty cycle remains fixed. This allows frames to be dynamically adjusted to make room for the transmission of more packets within a frame. Similarly, CSMA and TDMA are used interchangeably according the volume of traffic. Accordingly, making the protocol suitable for applications with fluctuating traffic and saving energy that would have been wasted for idle listening and collisions. Nonetheless, beacon, ACK packets and updating of the queue length indicator table will lead to increase in overhead energy cost.

1.3.5 Energy Efficient Hybrid MAC (EE-MAC)

EE-MAC is an improved hybrid MAC protocol designed for wireless sensor networks. It combines the strengths of TDMA and FDMA techniques and also introduces an adaptive priority scheme for channel access [28]. The performance of EE-MAC is independent of underlying synchronization protocol and is well in WSN platforms in which-out-of-band hardware synchronization is used. EE-MAC operates in two phases: a setup phase and a transmission phase. During the setup phase the following operations take place: Neighbor discovery, TDMA slot assignment, FDMA slot assignment, Local framing, and Global synchronization.

These operations run only during the setup phase and if there is any change in the topology. Neighbor discovery operation is run in order to find out one-hop and two-hop neighbors in the network. The time slot is allocated for each node such that there is no duplication of time slot within two-hop distance. After the slot assignment phase, periodically the slots are reused by nodes in a predetermined period called local frame. If the local frame is computed, then global synchronization is done.

During the transmission phase, the period is divided into a number of frames. Each frame is divided into fixed time slots. Slot duration is the maximum time required to transmit a maximum sized packet. Each slot is divided into scheduled subs lots and contention sub slots. Each cycle starts with scheduled slots followed by contention slots. The base station will take the responsibility of assigning time and frequency to each node by using a specific algorithm. The performance of the protocol was based energy efficiency, delay, and packet delivery ratio. The use of HELLO packets and updating of list of neighbor will lead to an increase in overhead energy cost and complexity of the protocol

3. CONCLUSION

The design of an energy efficient MAC protocol is an important issue. Each categories of MAC protocols addressed in this paper have it strength and weakness.

While scheduled based MAC protocol need to keep strict clock synchronization among nodes, which introduces large latency and control packets, contention based MAC protocol waste energy by idle listening and large control packet overhead. The introduction of hybrid MAC protocol tries to address the weakness in existing MAC protocol as well as improving the energy efficiency. However hybrid MAC protocols are usually complex in transition mechanisms between contention-based and scheduled-based, in addition, these protocols are usually complex in implementation. Energy efficiency in MAC for WSN is still a critical issue and need more studies. There is also the need to develop MAC protocols that are more scalable and adaptable to changes in network size, node density and topology in WSN. The development of Hybrid MAC protocol which is energy efficient and also focuses on scalability, reliability and less complex is of great importance.

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