Locally Synchronized MAC Protocols in Wireless Sensor Networks: A Survey

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ABSTRACT
Wireless Sensor Networks (WSNs) consist of large number of sensor nodes. These nodes are distributed in a particular area for the purpose of collecting data/queries etc. WSNs have played an important role in applications such as industrial automation, smart buildings and intrusion detection so on. On the basis of energy efficiency, overhead and data delivery performance, WSN MAC is divided into four categories: locally synchronized, non- synchronized, globally synchronized and multichannel. This paper surveys the latest progresses in locally synchronized MAC protocols.

Keywords
Energy Efficiency, MAC protocols, Latency, Throughput, Wireless Sensor Networks.

1. INTRODUCTION
Wireless Sensor Networks (WSNs) [1][2] consist of large number of sensor nodes. A WSN typically has little or no infrastructure and classified into two categories: structured and unstructured. In a structured WSN, all or some of the sensor nodes are deployed in a preplanned manner. Management and network maintenance cost is low in structured network. An unstructured WSN has dense collection of sensor nodes in which nodes may be deployed in an ad hoc manner into the field. The network is left unattended after deploying the nodes to perform monitoring and reporting functions. Network maintenance such as managing connectivity and detecting failures is difficult in an unstructured WSN, since there are so many nodes. Energy efficiency is one of the major criteria in unstructured WSN. Radio is the major power consuming component of a sensor node which is controlled by the MAC protocol. The lifetime of a sensor network increases by using an energy efficient MAC protocol [3][4]. An efficient MAC protocol can reduce collisions and improve throughput to great extent.

We divide WSN MAC [2] protocols into four branches: non-synchronized, locally synchronized, globally synchronized and multichannel. Duty cycle is the mechanism on which non-synchronized and locally synchronized protocols are based. Here each node alternates between active and sleep states and only active nodes can communicate with each other. In locally synchronized MAC protocols, neighboring nodes are synchronized to wake up at the same time. To efficiently establish communication between two nodes that have different active/sleep schedules is the basic mechanism used in non-synchronized MAC protocols. In globally synchronized mechanism time slots are allocated in a way that no two nodes within the two-hop communication neighborhood are assigned to the same slot. Here the focus is to improve channel utilization under low contention. To further boost network capacity multichannel technique is employed. Distributed channel assignment and efficient cross channel communication are two major challenging issues in multichannel MAC protocols.

2. LOCALLY SYNCHRONIZED MAC PROTOCOLS
2.1 Sensor MAC
In SMAC (Sensor-MAC) [7][9], there are periodic sleep and listen schedules of nodes. Each cluster has an independent schedule composed of three periods: SYNC, DATA, and SLEEP. Clocks are synchronized by nodes within the same cluster in SYNC period. Nodes contend for exchange of Request-to-Send (RTS) and Clear-to-Send (CTS) frames in the DATA period when they have packets to send. Nodes that are not involved in the communication go back to sleep at the start of the START period. Other nodes return to sleep after they finish transmission of data packets and acknowledgment (ACK) frame. The main problem of S-MAC is that in each cycle packet can be forwarded by one hop only. To increase the number of hops, SMAC with adaptive listening [2][8][10] is introduced which increases the hops to two instead of one. As shown in Fig 1, nodes can only hear their immediate neighbors (e.g., node B can only hear node A and node C). Because node C can overhear the CTS sent by node B, it goes back to sleep at the beginning of the SLEEP period but wakes up at the end of the current transmission. Node B can therefore immediately forward the data packet to node C instead of waiting for the next cycle

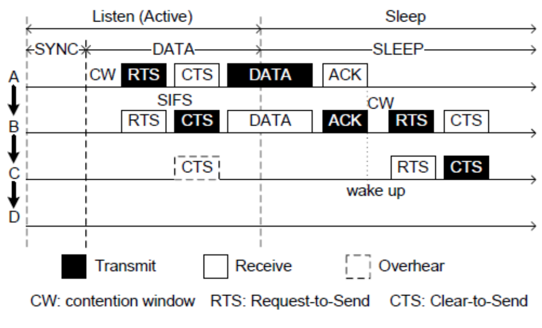

Figure 1: The adaptive listening in S-MAC

2.2 Timeout MAC
S-MAC has static sleep schedules which lead to sleep delay. So to improve the efficiency, TMAC (Timeout-MAC) [2][11] is introduced in which length of the active period is not fixed. Here nodes stay awake for a certain amount of time until no activation event has occurred. Future Request-to-Send (FRTS) packet is used in T-MAC, in which nodes notify the target receiver that it cannot access the medium at the current time. As shown in Fig 2, when node C loses contention and overhears a CTS packet, it sends a FRTS packet to its target receiver D. The FRTS packet contains the length of the

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current data transmission from node A to B, So that D which is target receiver can learn its wake-up time. Downstream nodes cannot overhear the FRTS and thus will not wake up. Iteratively this mechanism cannot be performed and a packet can only be forwarded by at most 3 hops per cycle. Node A must transmit a Data-Send (DS) packet of the same size of FRTS to prevent any neighboring node from taking the channel when it postpones its data transmission for the FRTS. The main advantage of using TMAC is that it handles variable load due to dynamic sleeping schedule but also has a disadvantage of early sleeping problem

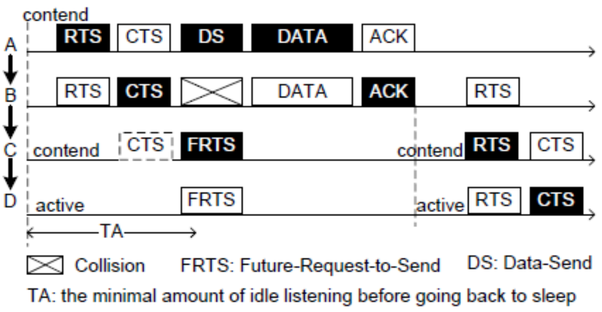

Figure 2: FRTS mechanism in S-MAC

2.3 Routing Enhanced MAC

RMAC (Routing Enhanced MAC) [2][12] uses multi hop forwarding in single operational cycle by shifting the data transmission to the sleep period. In RMAC cycle can be divided in to three stages: SYNC, DATA, and SLEEP. Separate protocol is used in SYN period to synchronize the clock of all the nodes which are in the same cluster. To initiate the communication with the downstream nodes that are multiple hops away, a control frame is send during DATA period. RMAC uses control frames, named PIONs (Pioneer frames) instead of using a pair of RTS (Request to send) and CTS (Clear to send) frames between two nodes. A PION is used as RTS frame as well as CTS frame. A single PION is used to confirm receipt traffic from upstream and downstream nodes. This dual function makes the multi hop relaying of PIONs very efficient as shown in Fig 3, and is able to forward data packets multiple hops within an single operational cycle.

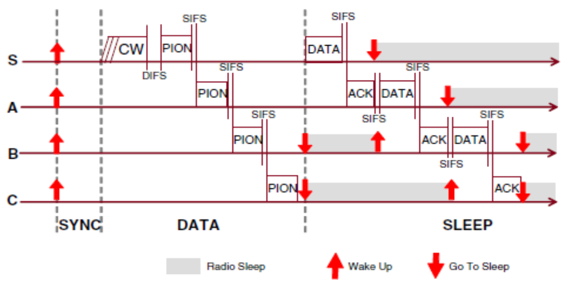

Figure 3: R-MAC overview

2.4 Demand Wakeup MAC

In DW-MAC (Demand Wakeup-MAC) [2][3], one-to-one mapping function between the DATA period and the SLEEP period is done to ensure collision free transmission in SLEEP period. Nodes are wake up on demand during the sleep period of a cycle in order to transmit or receive a packet. Effective channel capacity is increased during a cycle as traffic load increases. This allows DW-MAC to achieve low delivery latency under a wide range of traffic loads which includes both broadcast and unicast traffic. As shown in Fig 4, node B calculates its wake up time t_1^s as:

$$t_3^d/t_{data}=t_3^s/t_{sleep} \qquad (1)$$

Equation (1) implies that if node A can receive a confirmation SCH from node B, the time length of t_3^s is assured to be collision-free because node B can receive a SCH correctly during t_3^d. Based on the ratio between T_{SLEEP} and T_{DATA} they are one to one scaled. The data transmission which is reserved will never collide at a target receiver in the SLEEP period. If the SCH sent to node B is collided, node B will not respond a confirmation SCH and thus node A and B will not reserve a time for data transmission during t_d^3. However, if the confirmation SCH is collided at node A, node A will not wake up to send during t_s^3 sender cannot distinguish the collision of a request SCH and the collision of a confirmation SCH. It can only assume that reservation failed. Due to the false alarm all downstream nodes will wake up unnecessarily to receive the expected data packet that will not arrive. Low latency, high power efficiency and high packet delivery are the main factors that contribute in the success of DW-MAC.

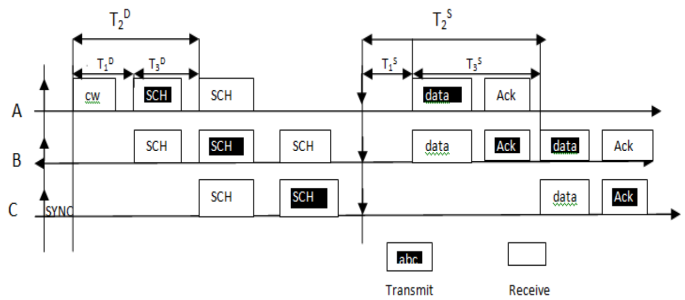

Figure 4: Multihop forwarding in DW-MAC

2.5 Dynamic MAC

Applications where data are delivered from multiple sources to a sink, D-MAC (Dynamic MAC) [2][14] is used. Staggering of active/ sleep schedule of nodes is done based on data gathering tree. Staggering is done so that packets can flow continuously toward the sink. In Fig 5, each node skews its wake-up time d_μ ahead of the sink's schedule in accordance with its depth d on the data gathering tree. Here µ represents the length of the time that is needed for one packet transmission and reception. Low delay is observed because of ordered offsets of schedules. Also sequential transmission is attained due to ordered offset of schedules. Nodes contend for sending to their receivers which have same depth and same offset. Neighboring nodes of the same level lose their chance of transmission when one node wins channel access, A data prediction mechanism and a More-to-Send (MTS) are introduced in order to increase the number of active slots. In Fig 5, if node B wins channel access opportunity to send to C, node C needs to add another RECV slot 3µ later than the current RECV slot to check whether node A has data to send to it. The length of 3µ is selected to ensure that the previous packet has to be forwarded 3 hops away. In addition, node D also needs to send a MTS packet to node E to make node E wake up periodically. This ensures that when node D wins channel access, node E is ready to receive. But overhead is increased along with the traffic load because nodes on routing paths have to wake up repeatedly for contention of sending and receiving and this is the limitation of D-MAC.

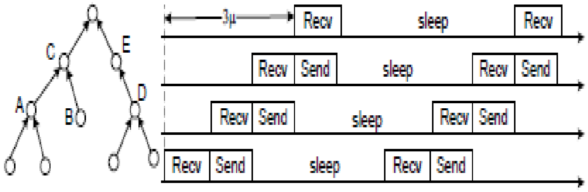

Figure 5: D-MAC in a data gathering tree

2.6 Query Based MAC

To provide minimum end-to-end latency with energy efficient data transmission Q-MAC (Query Based-MAC) [2][15] is used. Static sleep schedule is followed in Q-MAC when there is no query and dynamic sleep schedule is followed in Q-MAC when a query is transmitted. Each node acquires readings from sensors based on the type of query and the data flow can be either from single destination or from multiple destinations after a query has been disseminated. It is assumed that region A is one hop away from the sink. As shown in Fig 6, the two hop neighbors (region B), three hop neighbors (region C), four hop neighbors (region D) are made active for a particular period based on the query type. The active time period of the nodes at different regions are synchronized such that the next hop node is made active before the current node's active period is over.

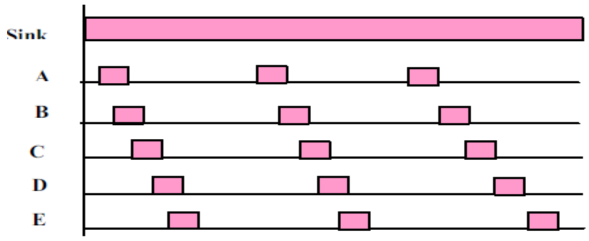

Figure 6: Static sleep schedule for radios of nodes

There are two cases in Dynamic Sleep Schedule for Single Destination. In first case the exact hop length to the destination is unknown to the sink, but it may know the appropriate region (e.g. temperature of a node in particular direction). The sink can send the query to the cluster head and the cluster head (knowing the location) can send it to the destination shown in Fig 7(a). In second case, if the destination is known (i.e. how many hops away from a node), the schedule can be changed dynamically based on the arrival time of the data as shown in Fig 7(b). The intermediate nodes calculate the time at which they have to forward the data using the following details: the time at which the query packet is forwarded, the distance of the destination node and time taken to transmit one hop data packets. Main advantage of using Q-MAC is that it provides minimum end-to-end latency in query based sensor networks with low energy consumption. Disadvantage is that it leads to long idle listening if the route is known.

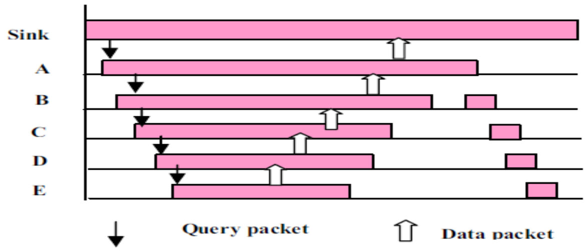

Figure 7(a): Dynamic sleep schedule if destination node's location is not known

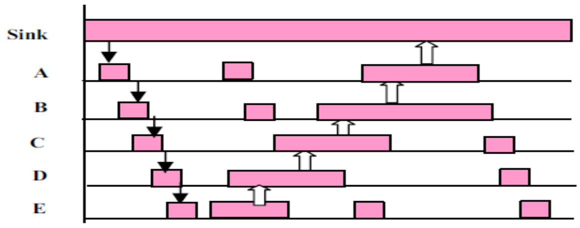

Figure 7(b): Dynamic Sleep schedule if destination is known

2.7 Scheduled Channel Polling

When channel polling is done periodically and nodes are put on periodic sleep state and there is no traffic, SCP-MAC (Scheduled Channel polling) [2][16] is used. The polling time of all neighboring nodes are synchronized. Channel polling and scheduling both are used in SCP-MAC [9]. In Fig 8, the wakeup and data transmission scheme for SCP-MAC is shown. A node has to wait until the receiver's time to poll the channel, if that node is having a packet to send. A short wakeup tone is used to activate the receiver. Before sending the tone, carrier-sense is performed within the first contention window (denoted as CW1 in the figure). Slot is selected randomly in a fixed-length contention window to reduce chances of collision. A wake up tone is sent if channel is idle. Otherwise, it will perform regular channel polling and goes back to sleep. It enters the second contention window CW2 after a sender wakes up a receiver, as shown in Fig 8. When the node detects idle channel in the second contention phase, it starts sending packets immediately. The main advantage of using SCP-MAC is that it combines the strength of channel polling and scheduling such as low energy consumption and disadvantage is that contention is more severe compared with schedule learning in asynchronous MAC protocols

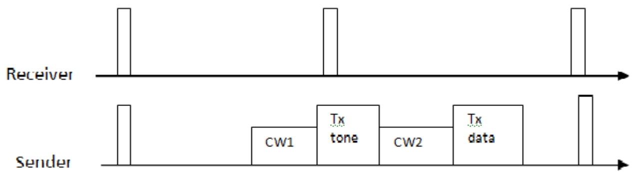

Figure 8: Data transmission with synchronized channel polling

3. COMPARATIVE ANALYSIS

Table1 shows the comparison of locally synchronized MAC protocols on the basis of energy efficiency, delay and their limitations. S-MAC and S-MAC with adaptive listening are less energy efficient and suffer from end-to-end delay. T-MAC and R-MAC protocols have comparatively less delay but suffer from early sleeping problem and hidden terminal collision respectively. DW-MAC, D-MAC, Q-MAC, SCP-MAC protocols have least data latency and higher energy efficiency as compare to above protocols.

Table 1: Comparison of Locally synchronized MAC protocols (Technical parameters)

Protocol	**Proposed year**	**Energy Efficient**	**Delay**	**Limitations**
Sensor MAC	2002	No	High	End to end delay and only one hop communication
Sensor-MAC Adaptive listening	2004	No	High	Overhearing, idle listening and more battery usage
Timeout-MAC	2003	Yes	Medium	Early sleeping problem
Routing Enhanced-MAC	2007	Yes	Medium	Hidden terminal causes collision and PION increases complexity
Demand Wakeup-MAC	2008	Yes	Less	Collision of SCH-frames- no reservation for data transmission
Dynamic –MAC	2004	Yes	Less	Overhead is increased along with the traffic load
Query based- MAC	2006	No	Less	long idle listening if the route is known. Energy efficiency is questionable.
Scheduled Channel Polling	2006	Yes	Less	Contention is more severe

4. CONCLUSION

Based on the survey of locally synchronized MAC protocols it has been observed that S-MAC protocol is based on only one hop communication, so adaptive listening is introduced in S-MAC. FRTS mechanism is introduced in T-MAC which leads to early sleeping problem. Shifting of data transmission to sleep state is introduced in R-MAC but leads to collision because of hidden terminals. DW-MAC ensures collision free data transmission in the sleep period but still collision of SCH frame is there which leads to latency. DMAC (Staggered schedule) was introduced for specific applications in which delivered data from multiple sources to sink. For minimum end-to-end latency with energy efficient data transmission Q-MAC was introduced. The strengths of channel polling and scheduling are combined in SCP-MAC for low energy consumption.

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