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MAC protocols dedicated to WSN and IoT

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Sommaire

1) Introduction

[1] Wireless Sensor Networks (WSNs) are networks of sensors that can be spatially dispersed. Those are dedicated sensors that monitor and record data about the environment and forward these data to a central station. The topology of a WSN can be a simple star network but also an advanced multi-hop wireless mesh network and the propagation can either be by routing or flooding. A WSN is made of nodes, from a few to hundreds or thousands, and each node is connected to other sensors. A node is composed of several parts: a radio transceiver (with an internal or external antenna), a microcontroller, an electronic circuit, and an energy source, usually a battery.

As a result, the key problem of WSN is the energy consumption and the autonomy. The Medium Access Control (MAC) layer has a major role in minimizing this energy consumption. It is in the link layer that larger gains can be made. Indeed, it is where the MAC protocol manages the use of the radio transceiver unit, one of the most power consuming components. The installation of reliable an efficient communication link between WSN nodes is managed by the MAC layer. Furthermore, the MAC layer is responsible for energy waste. More precisely, it is responsible for scheduling, channel access policies, error control and buffer management.

2) Critical issues of WSN

As we have seen in the previous chapter, the main critical issues are the energy wastes. [10] This energy waste is mainly caused by five mechanisms:

- **Overhearing**, when a node receives a packet belonging to another node.
- **Collision**, when two nodes emit and try to access the medium at the same time, there can be interferences between the transmitted data. When a collision occurs, the resulting packets need to be rejected and retransmitted. This can lead to an energy waste, can also compromise the data reception, and can increase the latency in the network.
- **Overhead**, when there is a high ratio control/data in a packet. For example, the control packets, such as RTS, CTC and ACK, do not contain any application data. The energy needed for transmitting or receiving these packets can be considered as overhead.
- **Idle listening**, when a node keeps listening to the medium because it does not know when it will receive data, the radio uses energy. So, if it listens when there is no transmission, it consumes energy. This is the major source of energy waste.
- **Over emitting**, when a node emits data to a sleeping or non-listening node.
- **Control packets**, such as RTS, CTC and ACK.

To limit these mechanisms as much as possible, different types of MAC protocol have been developed and implemented towards an energy efficient WSN. The aim of this report is to explain, categorize and compare these different protocols.

3) Classification of MAC protocols

There are three main categories of MAC protocols for WSNs. According to how the MAC layer manages the communication time of a node on the channel, we divide the protocols into these three groups:

- Contention-based protocol,
- Scheduled-based protocol,
- Hybrid protocol.

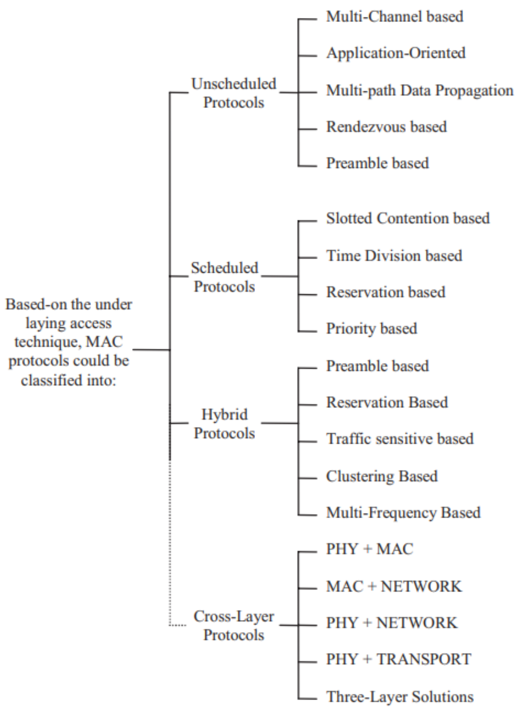

Figure 1 : Classification of wireless sensor networks MAC protocols [10]

4) Contention-based protocols

The main advantage of contention-based protocol is allowing users to communicate on the same channel without pre coordination. The most used operation procedure of contention-based protocol is the "listen before talk" one. It usually uses Carrier-Sense Multiple Access (CSMA). The nodes compete to access the channel. This means that a node checks the absence of other traffic before transmitting on a shared medium. It is adapted for large scales. However, it offers less performance for high load traffic and usually forwards small data packets.

[5] The CSMA has different access methods:

- Collision Detection (CD), if the emitting station detects collisions in the transmitted packets, it stops the transmission and waits for a random period to resend the same data packet. It is notably used by the Ethernet network.
- Collision Avoidance (CA), it tries to avoid collision by prior negotiation. If the medium is occupied, the transmitting station waits until it is inactive for a certain period to emit. The emitting station uses a Request To Send (RTS) to notify the receiver who responds with a Clear To Send (CTS). The emitting station can then forward data and the receiving station sends an Acknowledged (ACK) at the end of the reception. It is used by WiFi (IEEE 802.11) and other wireless networks.

We can also divide the contention-based protocols into two sub-categories:

- Synchronous,
- Asynchronous.

a. Synchronous

In synchronous protocols, the sensor nodes periodically wake up and exchange traffic in common active periods. Synchronizing with neighboring nodes to wake up at the same time can ensure energy efficient communication between WSN nodes. However, it leads to additional synchronization overhead.

i. S-MAC

[1] The Sensor-MAC (S-MAC) protocol is one of the first protocol proposed for WSNs and is based on the synchronization of the listening and sleeping periods. It is classified as a CSMA/CA-based protocol. It is a modification of the IEEE 802.11 protocol mentioned earlier. The periodic sleep-listen schedules are locally managed by synchronization. The nodes in the same neighborhood share a common sleeping schedule. If they are from different virtual clusters, they stay awake for a period equal to the listening period of the two clusters.

The working principle is the following:

1. During the listening session, the sensor nodes exchange control packets with each other.
2. During the sleeping session, the nodes turn their radio off to save energy.
3. The first part of the listening session is the synchronization thanks to the SYNC packets.
4. When a node wants to transmit data, it sends an RTS packet and waits for the neighbor node to answer.
5. If it is ready to receive the data, it responds with a CTS packet.
6. The data transmission can then start immediately.
7. The nodes not exchanging enter sleeping mode to save energy.

The scheme of the S-MAC is shown in the figure below:

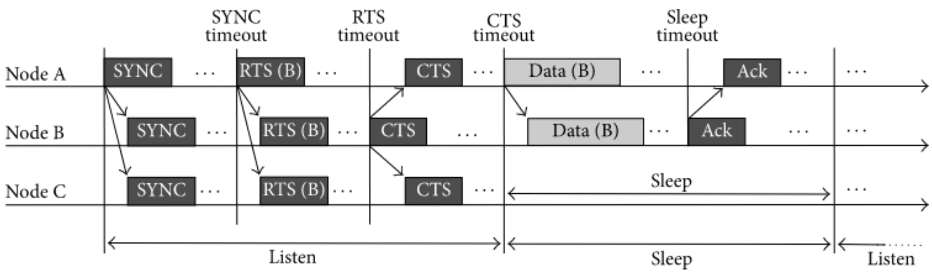

Figure 2: Basic S-MAC scheme [9]

One advantages of this protocol is the use of the sleeping mode. Indeed, it allows a reduction in energy consumption. This protocol also adapts easily to topology change. Moreover, there is no need for a central entity since nodes manage their synchronization with their SYNC tables. However, nodes have to detect neighboring nodes who may have different schedules by listening for a period. This results in packet overhead and is the disadvantage of this protocol.

The Dynamic S-MAC (DS-MAC) protocol is an extension of the S-MAC protocol. It allows the nodes to add supplementary periods of activity.

ii. T-MAC

The Timeout MAC (T-MAC) protocol works the same way as the S-MAC, but it implements an adjustment mechanism for the traffic to reduce the rigidity of the S-MAC protocol. In fact, the nodes can increase their active period.

b. Asynchronous

The asynchronous protocol does not use overhead for synchronization unlike synchronous protocols. It improves the energy efficiency. Each node can individually set its own wake up and sleep schedule. To achieve low power communication, this protocol uses a preamble. To indicate incoming data transmission, an emitting node precedes its data with a preamble long enough to be detected by all potential receivers.

Asynchronous schemes include B-MAC, WiseMAC and X-MAC but we will solely focus on B-MAC and X-MAC in the following section.

i. B-MAC

[1] The Berkeley MAC (B-MAC) is a widely used for the WSNs. It uses Low-Power Listening (LPL) to reduce power consumption caused by idle listening. When nodes wake up after a sleeping period, they check the medium from preambles. If none is detected, the node goes back to sleep. If it does, the nodes will stay awake and receive the data packet coming after the preamble. An emitting node must send a preamble for at least one sleeping session for all other nodes to detect it. To avoid collision, the preamble is the size of the entire sleeping period to make sure that the nodes listen. The preamble does not contain information about the receiving node: it is broadcasted. An ACK can be added optionally. After the data packet exchange, the nodes enter sleeping mode [2].

The main advantage of this protocol is the fact that it does not need to use RTS and CTS control frames by default, since the node schedules are not synchronized. Its drawbacks are overhearing because nodes that are not concerned with the data still receive it. Another drawback is excess latency at each hop because the receiver must wait until the end of the preamble transmission to start receiving data. Accumulated latency influences the overall network performance.

The B-MAC scheme is represented in the figure below:

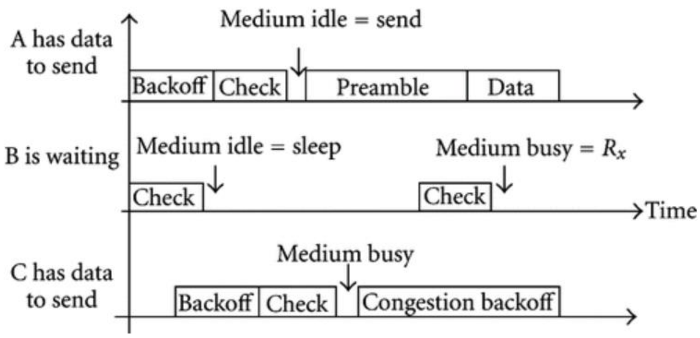

Figure 3: basic B-MAC communication scheme [1]

ii. X-MAC

X-MAC is a development on B-MAC and aims to improve on some of B-MAC's shortcomings. In B-MAC, the entire preamble is transmitted, regardless of whether the destination node awoke at the beginning of the preamble or the end. Furthermore, with B-MAC, all nodes receive both the preamble and the data packet. X-MAC employs a strobed preamble, i.e. sending the same length preamble as B-MAC, but as shorter bursts, with pauses in between. The pauses are long enough that the destination node can send an acknowledgment if it is already awake. When the sender receives the acknowledgment, it stops sending preambles and sends the data packet. This mechanism can save time because potentially, the sender doesn't have to send the whole length preamble. Also, the preamble contains the address of the destination node. Nodes can wake up, receive the preamble, and go back to sleep if the packet is not addressed to them. These features improve B-MAC's power efficiency by decreasing nodes' time spent in idle listening.

5) Scheduled based protocols

Scheduled based MAC protocols reduce energy consumption by coordinating sensor nodes with a common schedule. Most of these protocols use some form of Time Division Multiple Access (TDMA) since other forms of multiple access, such as FDMA or CDMA, would increase the cost and power requirement of the sensor nodes. TDMA protocols assign different time slots to nodes. Nodes can transmit data only in their time slot, thus eliminating contention. This mechanism limits or eliminates collisions, idle listening,and overhearing. Nodes not participating in message communication may enter in a sleep mode until they have work to perform or need to receive a message. Examples of this kind of MAC protocols include LMAC, TRAMA, etc.

TDMA based protocols have limited scalability and adaptability to the changes on number of nodes (no node mobility). In general, TDMA based protocols can provide good efficiency but they are not flexible to change in node density or mobility and lack peer to peer communication because nodes are normally restricted to communicate with the cluster head within a cluster.

a. L-MAC

[2] The Lightweight MAC protocol is a TDMA-based MAC protocol. It uses data transfer timeframes, which are divided into time slots. The number of time slots in a timeframe is configurable according to the number of nodes in the network. Each node has its own time slot to transmit. This feature saves power, as there are no collisions or retransmissions. The control message contains the destination of the data, the length of the data unit, and information about which time slots are occupied. If there is no transmission, the time slot is assumed to be empty,

and the nodes go back to sleep. If there is a transmission, after receiving the control message, nodes that are not the intended receiver go back to sleep. The recipient node and the sender node go back to sleep after receiving/sending the transmission. Only one message can be sent in each time slot. In the first five timeframes, the network is set up and no data packets are sent. The network is set up by nodes claiming a time slot. They send a control message in the time slot they want to reserve. If there are no collisions, nodes note that the time slot is claimed. If there are multiple nodes trying to claim the same time slot, and there is a collision, they randomly choose another unclaimed time slot.

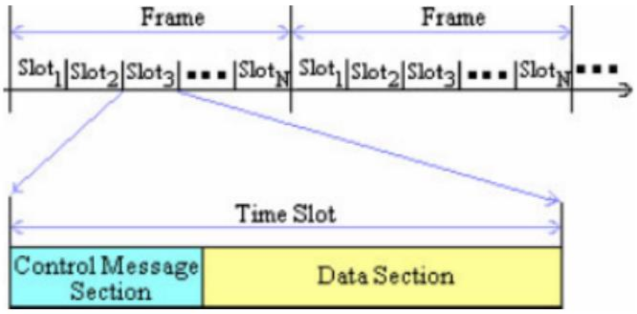

Figure 4: L-MAC frame [10]

b. TRAMA

[10] The Traffic Adaptive Medium Access Control (TRAMA) protocol relies on global synchronization. This protocol is a TDMA based protocol which reduces energy by ensuring a collision-less transmission and more usage of node's low power sleep mode. This protocol consists of three components that assign time slots:

1) Neighbor Protocol (NP), collecting information about neighboring nodes.
2) Schedule Exchange Protocol (SEP), exchanging information about two-hop neighbors and their schedule.
3) Adaptive Election Algorithm (AEA), deciding the transmitting and receiving nodes for the next round during the current time slot by using neighborhood and schedule information. All other nodes are in sleeping mode during this time.

The time slots in this protocol are organized and shown in the following figure. It divides these slots which are collision-free and usable for data transmission.

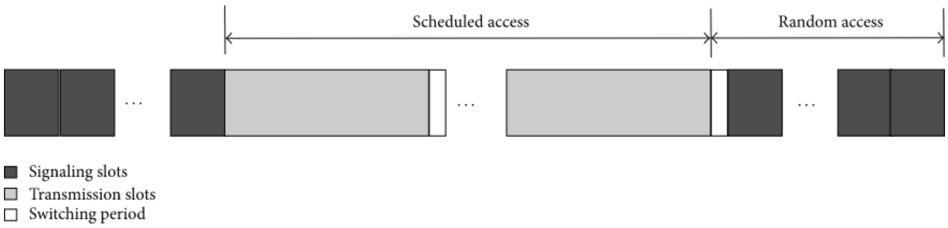

Figure 5: time slot organization in TRAMA [9]

To avoid collisions and the hidden node problem, every node has a knowledge of its two-hop neighbor. Using the NP, a node spreads out its one-hop neighbor information to its direct neighbors. This enables a node to know about its neighbor's neighbor (the two-hop neighbor). The nodes transmit the NP during random access periods to permit node additions and deletions. If a node does not hear from its neighbor for a certain period, it times out this neighbor and shares this information with other neighbors. This makes the network more dynamic.

6) Hybrid based protocols

[5] Hybrid MAC protocols combine the strengths of scheduled and unscheduled MAC protocols while balancing their weakness to design an efficient MAC protocol. The hybrid protocols use the concepts of both type of protocols at the same time. For example, they use the SCP protocol which is a mix between the following characteristics:

- The preamble of B-MAC
- The synchronization of S-MAC

Indeed, the nodes have synchronized listening periods but also uses short preambles.

a. H-MAC

[11] The Hybrid MAC (H-MAC) protocol is based on the IEEE 802.11's Power Saving Mechanism (PSM). It uses multiple slots dynamically to improve performance. Existing MAC protocols for WSNs reduce energy consumptions by introducing variation in an active/sleep mechanism. But they may not provide energy efficiency in varying traffic conditions as well as they did not address Quality of Service (QoS). H-MAC maintains energy efficiency as well as QoS issues like latency, throughput, and channel utilization.

In H-MAC, time is divided into large frames. Every frame has two parts: an active part (on time) and a sleeping part. Active part is like Announcement Traffic Indication Message (ATIM) window in PSM mode. Sleeping part is further divided into N slots where each slot is a bit bigger than the data frame. The following figure shows the comparison between S-MAC and H-MAC time frames.

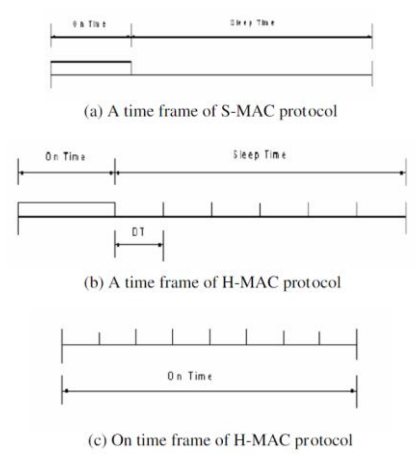

Figure 6: time frame of S-MAC and H-MAC protocols [11]

The nodes who want to transmit packets negotiate slots with the destination nodes during active time. They then transmit/receive the data packets in pre-negotiated slots during sleep time. If the nodes do not have to transmit or receive any data packets, they go to sleep during the sleep-time slots. The next figure illustrates the working of H-MAC.

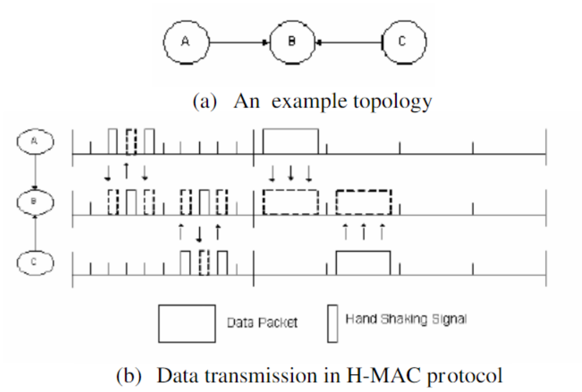

Figure 7: working of H-MAC protocol [11]

If node A has buffered packets destined for node B, it will notify node B by sending ATIM packet including its preferable slot(s) list. Node B, after receiving the packet, select slot(s) based on A's list and its own list but the receiver's list has higher priority. After that, node B includes the information in the ATIM-ACK packet. When node A receives it, it sees if it can also select the slot(s) specified. The ATIM-RES is a new type of packet used in H-MAC which notifies the neighboring nodes which slot(s) node A is going to use. So, they can use this information to update their list. Similarly, the ATIM-ACK packet notifies the nodes in the vicinity of node B. After the ATIM (On Time) time, node A and node B will transfer the data packet(s) in the selected slot(s).

b. Z-MAC

[12] The Zebra-MAC (Z-MAC) protocol is a hybrid MAC protocol based on B-MAC. It begins with a set-up phase so it will act like a TDMA based protocol. Time slots are assigned by a scheduling algorithm called DRAND. Time slots are owned, and all the other nodes are named "non-owner". DRAND will guarantee that two nodes within a two-hop neighborhood cannot be assigned the same time slot. But, unlike TDMA, a time slot can be used by several nodes and that is when the CDMA mechanism is useful.

Using a mix of CSMA and TDMA, the Z-MAC protocol is protected against timing failure, time-varying channel conditions, slot assignment failures and topology changes. Nonetheless, the initialization includes the construction of the network topology, distribution of time slots, exchanging of local time frame and network-wide synchronization. Thus, it causes a high load on the network and overhead. But it is considered that the initial overhead is amortized over a long period of network operation. Another flaw is the topology since it is supposed to be static until the next set-up phase. This means that if a node is leaving or entering the network, the change in the network will not be detected unless there is another set-up.

7) Comparison

Here, we will try to compare the protocols explained in this report.

Protocol name	Channel access type	Clock sync	Energy consumption	Mobility	Drawbacks
S-MAC	CSMA	Yes	Reception: 0,65 μJ/bit Transmission: 1,24 μJ/bit Idle: 0,65 μJ/bit Sleep: 7,4.10^-4 μJ/bit	No (MS-MAC)	Overhearing, idle listening, latency
B-MAC	CSMA	No		No	Overhearing, collision
L-MAC	TDMA	Yes	Reception: 14.4 mW0 Transmission: Energy consumption Tx 21 mW Energy consumption Energy consumption Sleep 15 μW	No	Overhearing, idle listening
TRAMA	TDMA	Yes		No	
Z-MAC	CSMA/ TDMA	Yes		No	Overhead

S-MAC being one of the first MAC protocols implemented, it has the most energy waste. To calculate the energy consumption, we considered the OOK data rate of 30 kbps according to the RFM TR 1001 datasheet. Since the S-MAC is a very known protocol, it is the most documented and its energy consumption has been measured, whereas the other protocols lack information on that matter.

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