5ISS - Wireless sensor networks

MAC protocols dedicated to WSN / IoT

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1 Introduction

The wireless sensor networks (WSNs) are used in a wide range of applications to capture, gather and analyze data from their environment. The wireless sensor network architecture typically consists of a large number of small battery-powered sensor nodes displayed over an area of interest and forming a multi-hop communication network. In a wireless sensor network sensors nodes are a low cost, resource constrained devices.

Due to their location and possibly difficulty of access, energy efficiency is an important requirement in a medium access control (MAC) protocol for most wireless sensor networks. As seen in our first research work about Bluetooth low energy (BLE), many reasons lead to energy waste and WSN life reduction, such as:

- Idle listening: a node doesn't know when will be receiving a frame so it must always be ready to receive. This energy is wasted if there isn't any transmission on the channel.
- Collisions: they concern the MAC contention protocols. A collision can occur when a node receives two signals or more simultaneously from different sources that transmit at the same time. When a collision occurs, the energy provided for frame transmission and reception is lost.
- Overhearing: occurs when a node receives packets that are not destined to him or redundant broadcast.
- Overmitting: occurs when a sensor node sends data to a recipient who is not ready to receive them. Indeed, the sent messages are considered useless and consume an additional energy.
- Packets size: The size of the messages has an effect on the energy consumption of the emitting and receiving nodes.

This paper provides an overview of the different MAC protocols dedicated to wireless sensor networks (WSN) and Internet of Things (IoT). The common point of those protocols is to reduce sources of energy waste, but they also differ in many ways.

2 Presentation of the MAC layer

The MAC layer serves as an interface between the software part controlling the link of a node and the physical (hardware) layer. Above it, the Logical Link Control layer ensures that the frames are well-encapsulated, synchronized and without error. LLC and MAC layers together form the Data Link Layer, responsible for sending and receiving data from a node to another one. It is the second layer of the OSI model (Open System Interconnection model), as seen on Figure 1, that standardizes the way a system communicates. Each layer offers services to the layer above, each layer has services offered by the layer below.

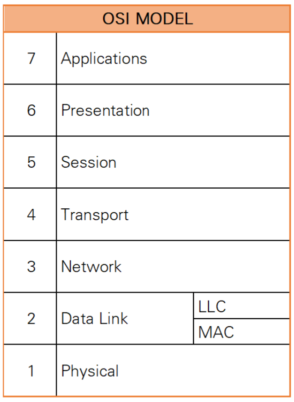

Figure 1: OSI model

The role of the MAC sub-layer is mainly to :

- Recognize the beginning and the end of the frames in the bit stream received from the physical layer;
- Delimit the frames sent by inserting information (such as extra bits) in or between them, so that the recipient can determine the beginning and end of the frame;
- Detect transmission errors, for example by using a checksum inserted by the sender and verified by the receiver;
- Insert the source and destination MAC addresses in each transmitted frame;
- Filter the received frames, keeping only those intended for it, by checking their destination MAC address;
- Control access to the physical media when it is shared.

Also, features of good MAC protocols [1] should be:

- Energy efficiency: The sensor nodes are battery charged and it has to be recharged frequently. Sometimes it‘s better to replace the sensor nodes rather than recharging.
- Latency: It refers to the time delay between time when data is sent by the sender and the time when data is received by the receiver. It depends on the application the detected quarts must be reported, so that the designed table is achieved.
- Throughput: It refers to the amount of data successfully transferred from a sender to the receiver in the given time similar to destiny. Its requirement depends on required application.
- Fairness: When bandwidth is limited, it is required to ensure that the sink nodes receive information from all sensor node fairly.

3 Classic channel access methods

A channel access method or multiple access method allows more than two terminals connected to the same transmission medium to transmit over it and to share its capacity. [5] There are various way of accessing the communication medium, and the goal is to allow several entities to use a single communication medium at the same time.

Channel access schemes generally fall into the following categories:

- FDMA – Frequency Time Division Access : most standard analog system, based on the frequency-division multiplexing (FDM) scheme, which provides different frequency bands to different data streams. In the FDMA case, the frequency bands are allocated to different nodes or devices.

- TDMA – Time Division Multiplex Access (GSM TDMA with 8 slots) : based on the time-division multiplexing (TDM) scheme. TDMA provides different time slots to different transmitters in a cyclically repetitive frame structure.

- CDMA – Code Divison Multiple Access (UMTS) : based on spread spectrum, meaning that a wider radio channel bandwidth is used than the data rate of individual bit streams requires, and several message signals are transferred simultaneously over the same carrier frequency, utilizing different spreading codes. Per the Shannon–Hartley theorem, the wide bandwidth makes it possible to send with a signal-to-noise ratio of much less than 1 (less than 0 dB), meaning that the transmission power can be reduced to a level below the level of the noise and co-channel interference from other message signals sharing the same frequency range.

- CSMA/CA – Carrier Sense Multiple Access with Collision Avoidance : : Listen to the channel and wait for it to be idle before using it. Statistical time division multiplexing multiple access is typically also based on time-domain multiplexing, but not in a cyclically repetitive frame structure. Due to its random character, it can be categorized as statistical multiplexing methods and capable of dynamic bandwidth allocation. This requires a media access control (MAC) protocol, i.e. a principle for the nodes to take turns on the channel and to avoid collisions. It is used in wireless networks (Wi-Fi).

- CSMA/CD – Carrier Sense Multiple Access with Collision Detection : same as CSMA/CA, but a “master” informs the transmitter that the channel is idle. It is used in Ethernet bus networks and hub networks.

4 MAC protocols for WSN/IoT and their specifications

According to channel access policies, most of the existing protocols fall in two categories: contention-based and schedule-based protocols. ([3]) Contention-based protocols are also divided in two categories, depending if they are synchronous or asynchronous. Recently, the use of hybrid protocols has also been considered.

4.1 Contention-based MAC protocols

Contention-based MAC protocols are mainly based on CSMA or CSMA/CA. The main idea is listening before transmitting. The purpose of listening is to detect if the medium is busy, also known as carrier sense. The typical contention-based MAC protocols are S-MAC, T-MAC, D-MAC, DS-MAC and B-MAC.[3]

4.1.1 Synchronous

- S-MAC - Sensor-MAC: As a slotted energy-efficient MAC protocol, S-MAC is a low-power RTS-CTS protocol for WSNs. It includes four major components: periodic listening and sleeping, collision avoidance, overhearing avoidance, and message passing. After the sleep period, the nodes wake-up and listen whether communication is addressed to them, or they initiate communication themselves. This implies that sleep and listen periods should be *synchronized* between nodes. The advantage of S-MAC is the reduction of energy waste caused by idle listening thanks to sleep schedules. But S-MAC doesn't meet simple implementation, scalability, and tolerance to changing network conditions.

- T-MAC - Time out MAC: the S-MAC protocol does not work well when the traffic load fluctuates. To overcome this problem, the T-MAC protocol introduces the timeout value to finish the active period of a node. If a node does not hear anything within the period corresponding to the time-out value, it allows the node to go into sleep state. But T-MAC suffers from the same complexity and scaling problems of S-MAC.

- DS-MAC - Dynamic Sensor MAC: DS-MAC provides simple solution to static duty cycle. All nodes start with same duty cycle. If one-hop latency is observed higher by receiver, it doubles its duty cycle. Nodes share their one-hop latency values with neighbors during SYNC period. The transmitter also doubles its duty cycle if the destination Reported higher one-hop latency. This change will not affect the schedule of other neighbors.

- D-MAC: The D-MAC could be summarized as an improved Slotted Aloha algorithm in which slots are assigned to the sets of nodes based on a data gathering tree. During the receive period of a node, all of its child nodes have transmit periods and contend for the medium. It can achieve very good latency compared to other sleep/listen period. However, collision avoidance methods are not utilized in D-MAC. Hence, when a number of nodes that have the same schedule try to send to the same node, collisions will occur.

Timeout MAC (T-MAC) and Dynamic Sensor MAC (DS-MAC) aim at optimizing S-MAC duty cycle and/or latency by adapting it according to the traffic load.

4.1.2 Asynchronous

- B-MAC - Berkeley Media Access Control [4]: B-MAC provides a flexible interface to obtain ultra low power operation, effective collision avoidance, and high channel utilization. To achieve low power operation, B-MAC employs an adaptive preamble sampling scheme to reduce duty cycle and minimize idle listening. B-MAC is designed for low traffic, low power communication, and is one of the most widely used protocols.

- Wise-MAC: 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. To reduce the power consumption incurred by the predetermined fixed-length preamble, WiseMAC offers a method to dynamically determine the length of the preamble which uses the knowledge of the sleep schedules of the transmitter node's direct neighbors. Based on neighbors' sleep schedule table, WiseMAC schedules transmissions so that the destination node's sampling time corresponds to the middle of the sender's preamble. *Advantages*: WiseMAC dynamic preamble length adjustment results in better performance under variable traffic conditions. In addition, clock drifts are handled in the protocol definition which mitigates the external time synchronization requirement. *Disadvantages*: Main drawback of WiseMAC is that decentralized sleep-listen scheduling results in different sleep and wake-up times for each neighbor of a node. This is especially an important problem for broadcast type of communication, since broadcasted packet will be buffered for neighbors in sleep mode and delivered many times as each neighbor wakes up. However, this redundant transmission will result in higher latency and power consumption.

4.2 Schedule-based protocols

Although random access achieves good flexibility and low latency for applications with low traffic loads, deterministic scheduling is actually the most effective way of eliminating the sources of energy waste. With perfect scheduling, only one transmitter-receiver pair would be active during each transmission period, therefore, reducing collision and eliminating idle-listening and overhearing.

- TRAMA - Traffic-Adaptive MAC Protocol [2]: TDMA-based algorithm proposed to increase the utilization of classical TDMA in an energy efficient manner. For each time slot a distributed election algorithm is used to select one transmitter within two-hop neighborhood. 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. *Advantages*: Higher percentage of sleep time and less collision probability is achieved compared to CSMA based protocols. Since intended receivers are indicated with a bitmap, less communication is performed for multicast and broadcast type of communication patterns. *Disadvantages*: Transmission slots are set to be seven times longer than the random access period. However, all nodes are defined to be either in receive or transmit states during the random access period for schedule exchanges.

- L-MAC - Lightweight MAC: takes into account the physical layer properties. The intentions of the protocol is to minimize the number of transceiver switches, to make the sleep interval for sensor nodes adaptive to the amount of data traffic. During its time slot, a node will always transmit a message which consists of two parts: control message and a data unit. The control message has a fixed size and is used for several purposes. It carries the ID of the time slot controller, it indicates the distance of the node to the gateway in hops for simple routing to a gateway in the network, it addresses the intended receiver and reports the length of the data unit. The control data will also be used to maintain synchronization between the nodes and therefore the nodes also transmit the sequence number of their time slot in the frame.

4.3 Hybrid protocols

Recently there are others research that there have been some hybrid proposals which combine the advantages of contention-based MAC with that of TDMA-based MAC.

- Z-MAC - Zebra Media Access Control [6]: Z-MAC combines the two approaches Carrier Sense Multiple Access (CSMA) and Time Division Multiple Access (TDMA) so that the network behaves at low data load as in CSMA and high network traffic as in TDMA. The protocol begins with a set-up phase, including the following four steps: construction of the network topology, distribution of time slots, exchanging of local time frame and network-wide synchronization. This initialization causes a high load on the network, which is made up for from the perspective of the developer with long service life and efficient data transfer. After activation, each sensor node transmits every second ping for 30 seconds. Pings are in the network technology brief messages that are sent back immediately from sender to receiver, usually to check connection and line quality. With Z-MAC, the ping contains information on the sending node itself and all the information that has been collected through the direct neighbors of the node. By pinging the environment experienced by a sensor node, the nodes it directly contacts (one-hop neighborhood) and what it can contact indirectly with an intermediate station (two-hop neighborhood) are known. Concerning timeslots distribution, the neighborhood lists are given in an algorithm for allocation of time slot according to TDMA.

5 Protocol comparison

There is a wide variety of MAC protocols based on different channel access methods, which provide different advantages depending on the use-case. Protocols can be separated into large families to classify them, according to the channel access method for example. Figure 2 represents a kind of MAC classification I could make according to my research work.

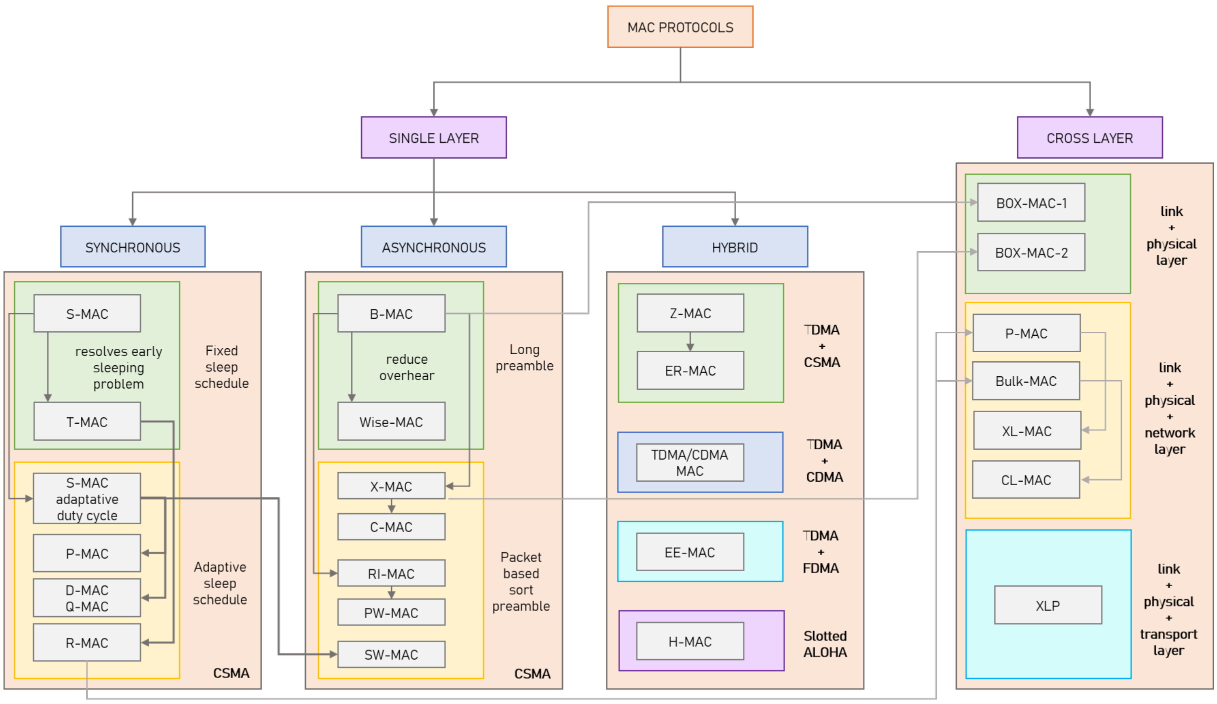

Figure 2: Example of MAC classification

The different MAC protocols are brought to evolve in order to become more efficient and therefore it is important to choose the protocol according to the appropriate use-case. Each protocol has its own strengths and weaknesses, and the main characteristics for each are summed up in Figure 3.

Protocols	Channel Access Method	Main Objectives	Traffic Adaptability	Topology Adaptability	Fairness
Contention-based					
S-MAC	CSMA	↓ energy	Medium	Medium	No
T-MAC	CSMA	↓ energy	Medium	Good	No
B-MAC	CSMA	↓ energy	Medium	Medium	Medium
WiseMac	CSMA	↓ energy	Medium	Good	No
TA-MAC	CSMA	↓ delivery, ↓ latency	Medium	Medium	No
X-MAC	CSMA	↓ energy, ↓ latency	Medium	Medium	Medium
MaxMAC	CSMA	↓ energy, ↑ delivery, ↓ latency	Good	Medium	No
Schedule-based					
TRAMA	TDMA	↓ energy	Medium	Good	Yes
Hybrid					
Z-MAC	TDMA/CSMA	↑ thoroughput	Good	Good	Yes

Figure 3: Main characteristics of MAC protocols

6 Conclusion

This paper gives an overview of the major families of existing MAC protocols, specifying their advantages, disadvantages and differences in the context of minimizing energy utilization in wireless sensor communications.

The contention-based protocols are more used in multi-hops networks because of their simplicity and of their capacity to operate in a decentralized context. Schedule-based protocols are categorized into centralized and distributed. Schedule-based protocols mostly rely on TDMA, viewed as a natural choice for sensor networks because it allows to conserve energy and collisions are avoided. However, deterministic TDMA scheduling requires a large overhead in order to maintain accurate synchronization between sensors and to exchange local information, such as the network topology and the communication pattern. Also, the latency increases linearly with the total number of sensors sharing the channel since TDMA assigns a separate timeslot to each transmitting sensor.

There are some hybrid proposals as Z-MAC, which combine the advantages of contention-based MAC with that of TDMA-based MAC. However hybrid MAC protocols are usually complex in transition mechanisms between contention-based and TDMA-based, and also more complex in implementation than their counterparts.

Finally, this survey of WSN MAC protocols and their concepts shows that despite many proposals, no perfect protocol has ever been proposed. However, adaptive and cross layer designs solutions can lead to achieve both high performance and low energy consumption at the same time. The design of optimal WSN MAC protocol with optimal parameters must take as input the application specifications (network topology and packet generation rate), the application requirements for energy consumption, delay and reliability, and the constraints from the physical layer (energy consumption and data rate).

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