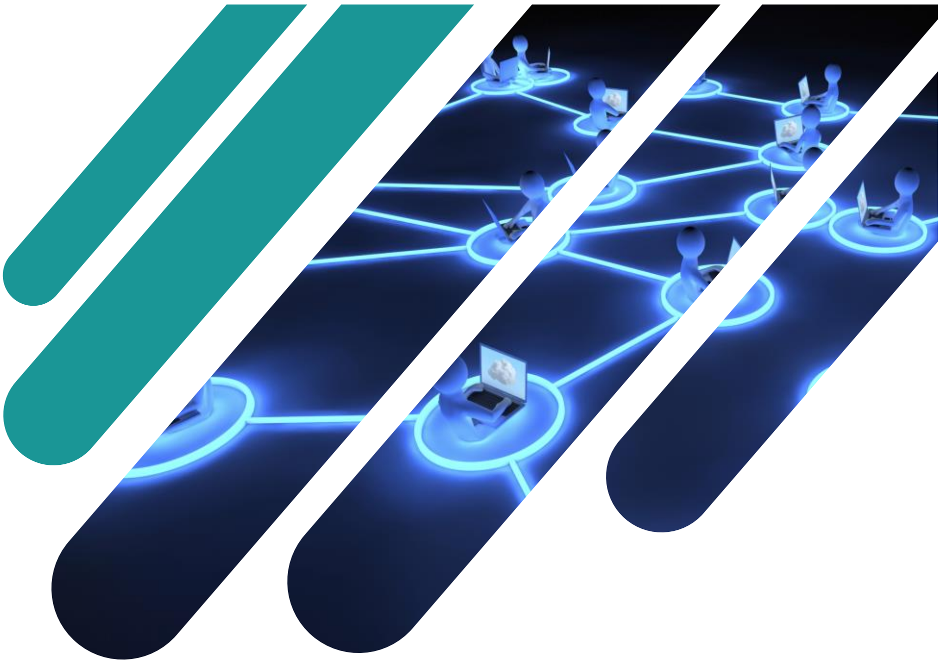

MAC Layer for Wireless Sensors Network

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SUMMARY

INTRODUCTION

After having studied different technologies for wireless networks (Zigbee, BLE, NB-IoT, LoRa and Sigfox), we want to know more about the **MAC layer** in those technologies. For this, in this report, I will explain what MAC Layer is, and compare the different protocols for this layer and the differences between them (security, data rate).

It is important to understand that MAC Layer is a part of the **OSI Model**. The OSI model allows to characterize the **communication functions** over a network. With the model, vendors and developers can create communication products and software programs that can interoperate and easy to understand with a clear framework.

OSI Model describes **7 layers** divided in Media and Host Layers.

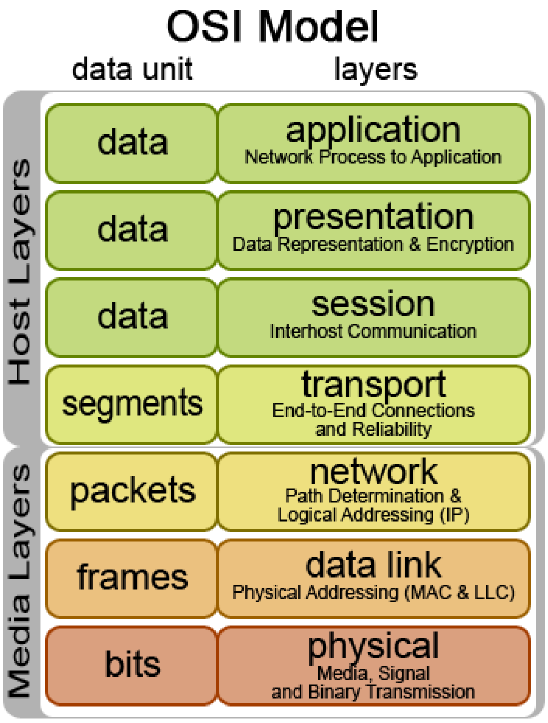


Figure 1: OSI Model

We can see that **MAC** layer is one sublayer of the **Data Link Layer**. This layer is the protocol layer that transfers data between network nodes. It provides the functional and procedural protocol to transfer data between network entities. The second sublayer of Data Link layer is the Logical Link Control (**LLC**), upper than the MAC layer, which provides addressing and control of the data exchanged between the originator and recipient.

I. MAC LAYER: DEFINITION

The Media Access Control (MAC) layer is responsible for regulating access to the medium and for moving data packets across a shared channel.

This sublayer uses MAC protocols to:
- Decide **when a node accesses** the medium
- Resolve any potential **conflicts** between nodes
- Correct **communication errors** occurring at the physical layer
- Perform other activities such **as framing, addressing, and flow control**

The MAC address, also called physical address, is a unique identifier assigned to network interfaces for communications on the physical network segment.

The characteristics we must study for MAC layer are:
- Energy Efficiency
- Scalability
- Adaptability
- Low Latency and predictability
- Reliability
- Security

Here is a classification of the different protocols:

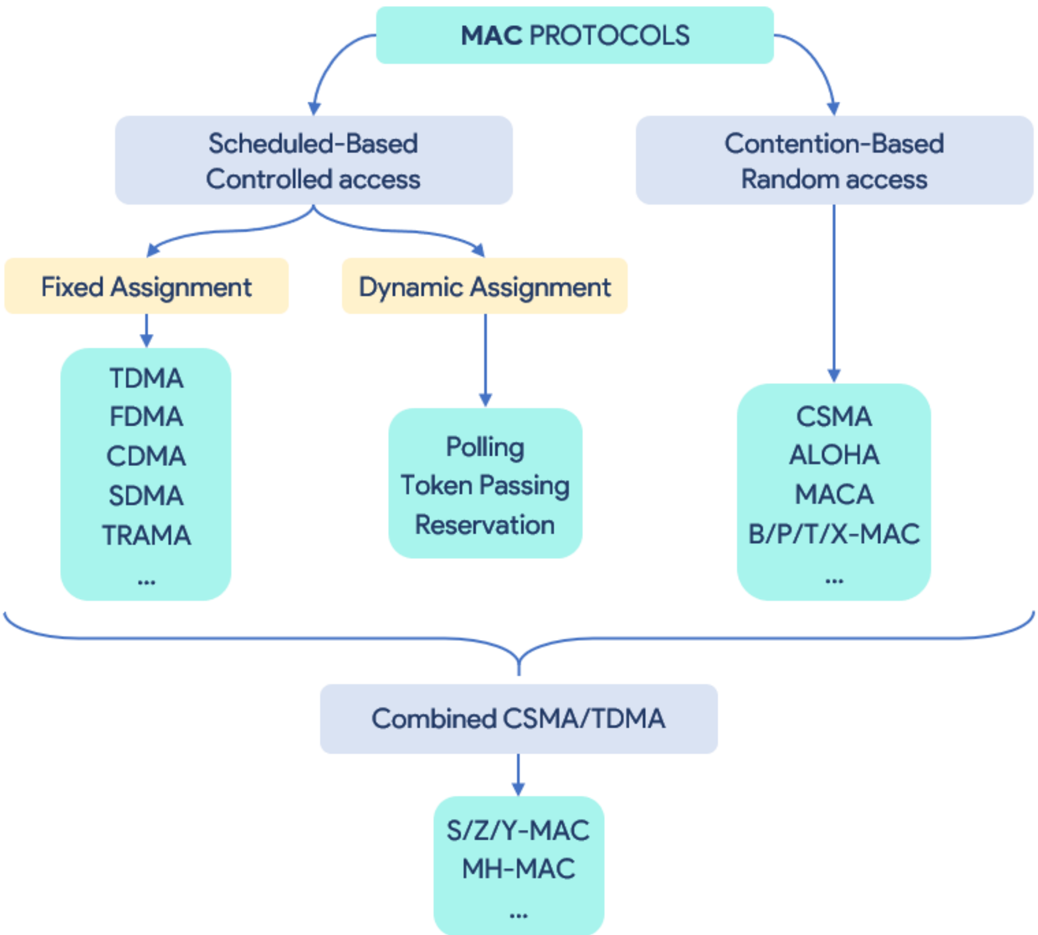


Figure 2: MAC protocols

II. PROTOCOLS FOR MAC LAYER

There are two types of Multiple Access Protocols for MAC layer: **Random Access protocols** and **Controlled Access Protocols**. Here is a list of the different protocols.

A. Random Access Protocols

In the **contention-based MAC protocols**, nodes may initiate transmissions at the same time, it requires mechanisms to reduce the number of collisions and to recover from collisions:

- Random back off and carrier-sensing
- No time synchronization, and robust to network changes
- High idle listening and overhearing overheads
- Duty cycling

1. CSMA CD/CA

The CSMA (Carrier-Sense Multiple Access° is the main protocol of contention-based protocols. It is built on listening before transmitting:

- if the channel is detected **idle**: it **transmits** the entire packet
- if the channel is detected **busy**: it **defers** transmission

There are two types of CSMA:

- **Persistent CSMA: retry immediately** with probability p when the channel becomes idle (may cause instability)
- **Non-persistent CSMA: retry after random interval**

About collisions, we can also define two different types of CSMA: with collision detection or collision avoidance:

CSMA with Collision Detection (CSMA/CD) the sender first determines whether the medium is idle or busy:

- if it is busy: the sender does not transmit packets
- if it is idle: the sender can initiate data transmission

CSMA with Collision Avoidance (CSMA/CA): requires that the sender is aware of collisions. The nodes determine if the medium is free, but do not immediately access the channel when it is found idle. In case there are multiple nodes attempting to access the medium, the one with the shorter back-off period will win.

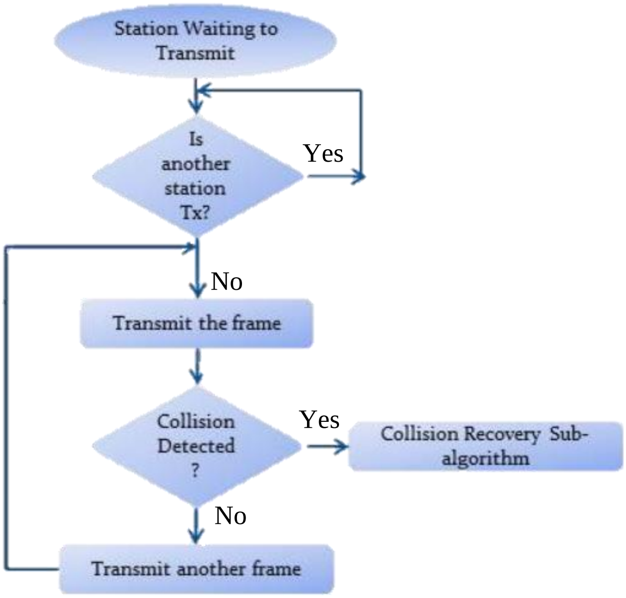


Figure 3: CSMA/CD

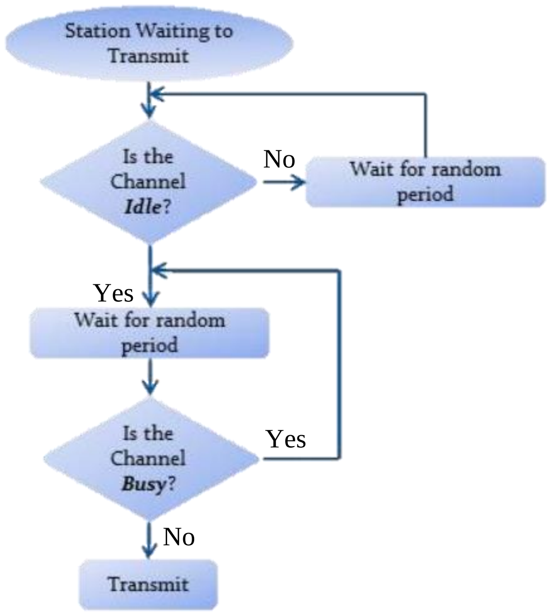


Figure 4: CSMA/CA

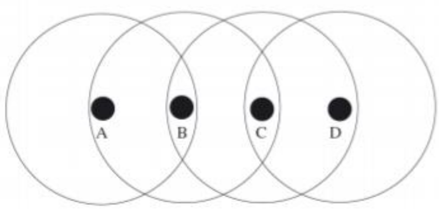
2. ALOHA

ALOHA uses acknowledgments to confirm the success of a broadcast data transmission, that allows nodes to access the medium immediately.

Slotted-ALOHA requires that a station begin its transmission only at predefined points in time (the beginning of a time slot). This protocol increases the efficiency of ALOHA and introduces the need for synchronization among nodes.

3. MACA and MACAW

The contention-based solutions (CSMA and ALOHA) encounter the **hidden/exposed terminal problems**.



Hidden-terminal problem:

- Senders A and C can reach B, but cannot overhear each other’s signals
- A and C can transmit data to B at the same time, causing a collision at B, without being able to directly detect this collision

Exposed-terminal problem

- C wants to transmit data to D, but decides to wait because it overhears an ongoing transmission from B to A
- B's transmission could not interfere with data reception at C

To solve these problems, **MACA** (Multiple Access with Collision Avoidance) is a new protocol with dynamic reservation mechanism.

The sender indicates its desire to send with ready-to-send (RTS) packet, the receiver responds with a clear-to-send (CTS) packet. If the sender does not receive CTS, it will retry later.

Nodes overhearing RTS or CTS know that reservation is done and must wait (based on the size of data transmission). That solves the hidden terminal problem and reduces the number of collisions

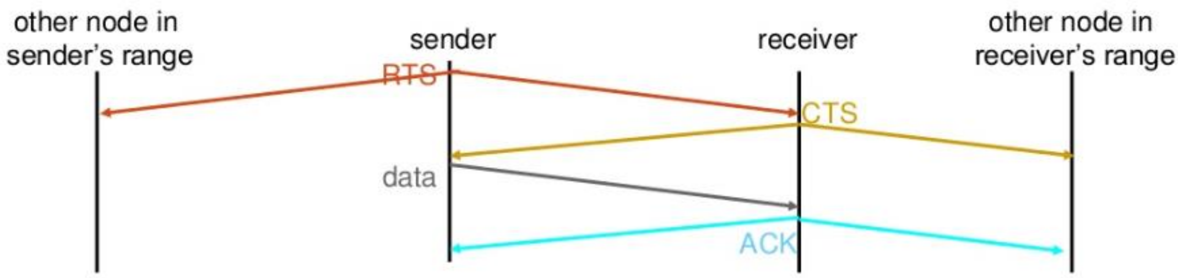


Figure 5: MACA Protocol

Another version of MACA for Wireless LANs is **MACAW**. The receiver responds with acknowledgment (ACK) after data reception and the other receiver nodes learn that the channel is available. But the nodes hear RTS and not CTS, then they do not know if the transmission will occur, so MACAW uses data sending (DS) packet, sent by sender after receiving CTS to inform other nodes of successful transmission.

4. IEEE 802.11

The IEEE 802.11 standard id based on CSMA/CA. The Wi-Fi uses this standard and combines concepts found in **CSMA/CA and MACAW**, but also offers features to preserve energy.

There are two modes of operation in the standard protocol:

- **Point Coordination Function (PCF)** mode: the communication between devices goes through a central entity called an **access point** (AP) or base station (BS). It is the managed mode.
- **Distributed Coordination Function (DCF)** mode: devices communicate directly with each other, it is the **ad-hoc** mode.

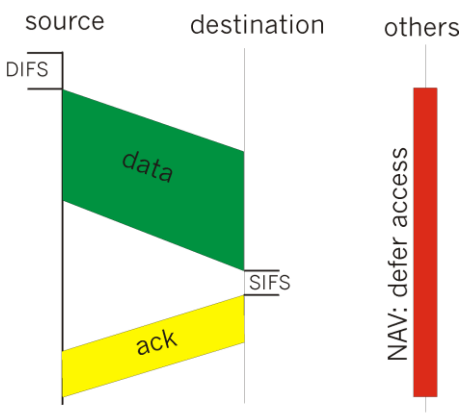


Figure 6: IEEE 802.11 Protocol

Before a node transmits, it first detects the medium activity and defers transmission if it is busy (DIFS). After a successful transmission, the receiver device responds with an acknowledgment after waiting for a time period called the short interframe space (SIFS).

5. Other

- **B-MAC (Berkeley MAC)** with effective collision avoidance, low power operation and tolerant to changes on the network. It uses a Clear Channel Assessment (CCA), Low Power Listening (LPL) using preamble sampling. However, hidden terminal problem and multi-packet mechanisms are not solved.

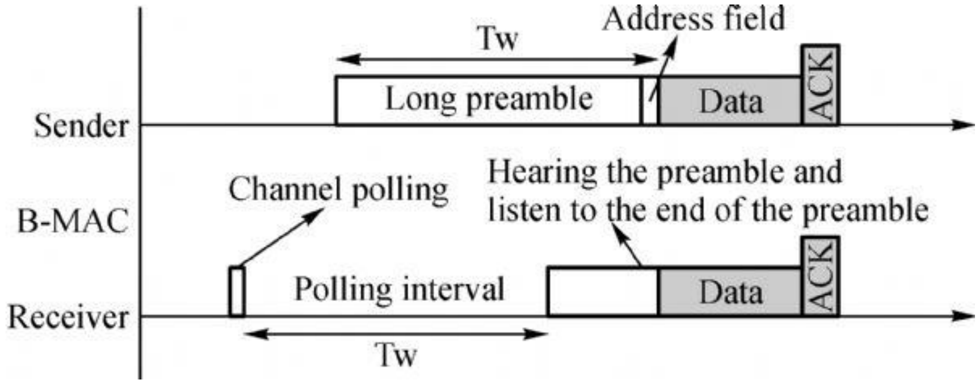


Figure 7: B-MAC Protocol

B. Controlled Access Protocols

In the **Scheduled based MAC protocols,** nodes within interference range transmit during different times, so there are no collisions. It requires a time synchronization, low throughput and high latency and low idle listening. It wakes up and listens only during its neighbour transmission (great for energy).

1. Fixed assignment: TDMA, FDMA, CSMA, ...

In these protocols, collisions can be avoided by ensuring that each node can use its allocated resources exclusively.

- **TDMA** (Time Division Multiple Access)

There are multiple devices using the same frequency band. The access to channel is made in "rounds": every station can talk at each round (periodic time windows or frames).

Each station gets a fixed length slot (with a length equals to packet Tx time) in each round and the unused slots go idle.

For example, a 6-station LAN, 1 3 & 4 have packets and slots 2 5 & 6 idle, here is the frame schema:

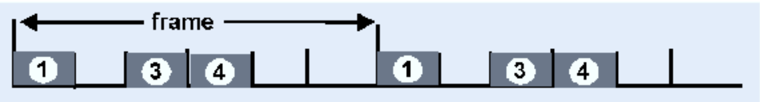


Figure 8: TDMA slots

- **FDMA** (Frequency Division Multiple Access)

For this protocol the frequency band is divided into several smaller frequency band and the data transfer between a pair of nodes uses only one frequency band. All other nodes use a different frequency band.

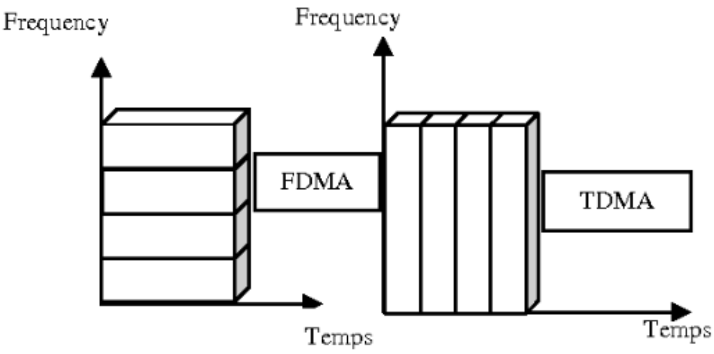


Figure 9: TDMA vs FDMA

- **CDMA** (Code Division Multiple Access)

It supports simultaneous accesses of the medium by using different codes. If codes are orthogonal, it is possible for multiple communications to share the same frequency band.

Forward error correction (FEC) at the receiver is used to recover from interferences among these simultaneous communications.

Fixed assignment strategies are inefficient: it is impossible to reallocate slots belonging to one device to other devices if not needed in every frame, then generating schedules for an entire network can be a hard task. These schedules may require modifications every time the network topology or traffic characteristics in the network changes.

- **SDMA** (Space Division Multiple Access)

This protocol allows the reception of more than one packet from spatially separated transmitters. This technology provides collision-free access to the medium based on the location of a node.

A typical application is to find the optimal base station to a mobile phone user. The MAC algorithm could decide which base station in best, taking into account which frequencies (FDM), time slots (TDM) or code (CDM) are still available.

- **TRAMA** (Traffic-Adaptive Medium Access)

It is an example of contention-free MAC protocol with the goal to increase network throughput and energy efficiency (compared to TDMA). It uses a **distributed election scheme** to determine when nodes are allowed to transmit based on information about the traffic at each node. It avoids assigning slots to nodes with no traffic to send and allows nodes to determine when they can become idle and do not have to listen the channel.

In TRAMA, there is a time-slotted channel where time is divided between periodic random-access intervals (signaling slots) and scheduled-access intervals (transmission slots).

2. Dynamic assignment

These assignment protocols allow nodes to access the medium on demand.

- **Polling-based protocols:** a controller device issues small polling frames, asking each station if it has data to send. If there is no data to send, the controller polls the next station.
- **Token passing**: stations pass a polling request to each other using a special frame called a token. A station is allowed to transmit data only when it holds the token.
- **Reservation-based protocols:** static time slots are used to reserve future access to the medium. A node can indicate its desire to transmit data by using a reservation bit in a fixed location. These protocols are complex but ensure that other potentially conflicting nodes take note of such a reservation to avoid collisions.

C. Combined Protocols

It is about **combining CSMA and TDMA** (contention and scheduled based protocols), for example with:

- S-MAC: for the benefit of energy efficiency
- Z-MAC: for the benefit of throughput

1. Z-MAC

Zebra-MAC is a hybrid contention resolution using TDMA when scheduling the transmissions of the nodes but differing from TDMA by allowing non-owners of slots to steal the slot from owners if they are not transmitting.

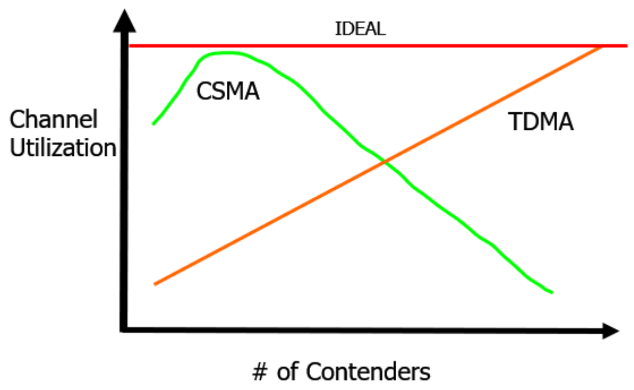


Figure 10: Channel utilization in CSMA and TDMA

The goal is to find the best channel utilization by combining CSMA and TDMA. On the following graph we can see that for a high number of contenders, the best channel utilization is for TDMA but for a low number it is for CSMA.

Z-MAC has a setup phase in which the flowing operations are run in sequence:

1. Neighbors discovery
2. Time slot assignment
3. Local frame exchange
4. Time synchronization

The owner of a time-slot always has priority over the non-owners while accessing the medium, but unlike TDMA, non-owners can steal the time-slot when the owners do not have data to send. This enables Z-MAC to switch between CSMA and TDMA depending on the level of contention.
To conclude, under low contention, Z-MAC acts like CSMA (high channel utilization and low latency), while under high contention, Z-MAC acts like TDMA (high channel utilization, fairness and low contention overhead).

Limitation of Z-MAC: longer delay, do not solve hidden terminal problem.

2. S-MAC

Sensor-MAC combines key advantages of scheduled and unscheduled protocols, it adds lite-802.11 with scheduling.

The goal is to try to reduce wastage of energy from at least 3 sources of energy inefficiency:

- nodes periodically sleep to reduce energy consumption (turn off the radio when sleeping and reduce duty cycle to 10% (120ms on VS 1.2s off)
- resolve contention by using RTS and CTS
- avoid overhearing

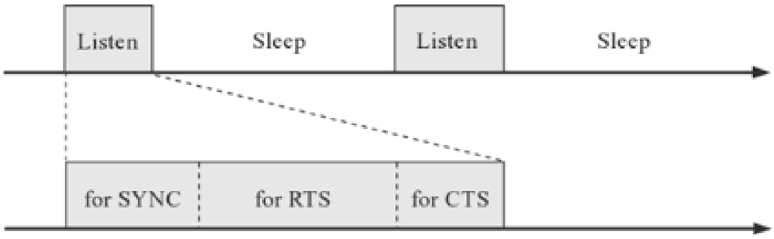


Figure 11: S-MAC Protocol

S-MAC sets the radio to sleep during transmissions of other nodes: all immediate neighbors of sender and receiver should sleep and the duration field in each packet informs other nodes the sleep interval.

It also deals with global synchronization: schedules can differ but preferring that neighbors nodes have the same schedule (border nodes may have to maintain more than one schedule).

It is a well-designed, complete protocol that correct deficiencies of 802.11.

3. MH-MAC

It is the **Mobility Adaptive Hybrid MAC** using a scheduled-based approach for static nodes and a contention-based approach for mobile nodes.

MH-MAC allows mobile nodes entering a neighborhood to use a contention-based approach to avoid the delays to be inserted into the schedule. Each node uses a mobility estimation algorithm to determine its mobility.

4. Others

- There are other hybrids like the **IEEE 802.15.4** for low-power devices in the 868 MHz, 915 MHz and 2.45 GHz frequency bands. Zigbee is incorporating IEEE 802.15.4.

This MAC protocol has two modes:

- Nonbeacon mode using CSMA/CA
- Beacon mode using two periods

The master sends beacon frames including duty cycle duration. A contention access period (CAP) following, allow devices to send frames using CSMA/CA. After this period, the collision free period (CFP) begins, and guarantees time slots for low latency required devices.

- **Y-MAC** is an energy-efficient multi-channel MAC protocol for dense WSNs that uses a hybrid access method. It assigns time slots to receivers instead of senders (closer to TDMA protocol).

III. COMPARATIVE TABLE

The main comparison has to be done between TDMA and CSMA (scheduled and contention based protocols):

Parameter	TDMA	CSMA
Energy for sync.	Bad	Good
Throughput	Good for multiple sources	Good for single source
Complexity	Bad	Good
Fairness	Good	Bad
Scalability	Bad	Good
Latency	High or low	High or low
Node failures + new node	Bad	Good
Energy for collision avoidance	Good	Bad
Channel utilization	High for high contention	High for low contention

CONCLUSION

To conclude, ccommercial MAC (802, Bluetooth) are suitable for wireless LAN with much more powerful devices. Energy is secondary concern compared with throughput. Asynchronous MAC (B/X-MAC) is flexible and works well in low traffic scenario and Hybrid synchronous MAC (S/Z-MAC) can achieve better performance in high traffic scenario.

The **choice of a medium access protocol** has a substantial impact on the performance and energy-efficiency of a network.

MAC protocols should be designed to accommodate changes in network topology and traffic characteristics. Latency, throughput, and fairness among competing nodes determined or affected by the characteristics of the MAC layer

Protocols based on scheduled transmission are collision-free, may require well synchronized nodes throughout the network and are difficult to adapt to changing topologies.

Protocols that let nodes compete to access to the medium are more flexible (easily accommodate changing network topologies), require less overhead, but are not collision-free and must possess features that allow them to recover from collisions.

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