MAC Protocols dedicated to Wireless Sensor Network

MAC Layer

MAC layer goal : Rules for medium access
Main responsibility for energy consumption = it has to manage it properly to consume less possible. To do that, the MAC protocol needs to :

- optimize the loss of packets (packet collisions)
- optimize the hearing and sleep time
- optimize the delay to transmit
- reduce the overhearing (reception of packets not destined to this device)

Channel type presentation

CSMA - Carrier Sense Multiple Access

CSMA is popular because it is simple, flexible and durable. It’s based on probabilistic technique where each node listens (carrier sense) before it sends and if nobody transmits the node will try to transmit a packet. Multiple access means multiple sensors can access the medium at same time = collisions. It doesn't require clock synchronization and global topology knowledge. Nodes can join the network dynamically without having to do extra operations and can receive packets from different out-of-coverage area nodes. But it leads to packet collisions. Packet collisions can occur (hidden terminal problem), leading to energy loss in sensor applications. It can be alleviated by using a RTS/CTS (Request to send, clear to send, which is a handshake) operation. But it’s not perfect as RTS/CTS leads to additional loss (wasting time and frequency resources), data packets being small.

Note : CSMA/CA, mainly used in WSN stands for Carrier Sense Multiple Access with Collisions Avoidance.

TDMA - Time division multiple access

Deterministic protocol, with a schedule plan which associates a time slot for each sensor node to avoid collisions and reduce the effect of overhearing and idle listening problems. It requires management authority like a dedicated access point which manages the schedule. Fix the hidden terminal problem because it programs the transmission time of neighbor nodes at different times. Effective timing program in order to avoid packet collision and an efficient timing program is very difficult with a high degree of compatibility and reuse of the channel. TDMA requires strict clock synchronization, a necessary feature for most sensor applications that leads to a high energy load. It is quite costly for TDMA to control dynamic topology changes. And in this type of network, it happens all the time (change due to reason such as the conditions of the physical environment, battery cuts, or corruption of the node). TDMA allows low channel use during low latency and leads to a higher latency when compared to CSMA because a node in TDMA can only transmit in its own time zone.

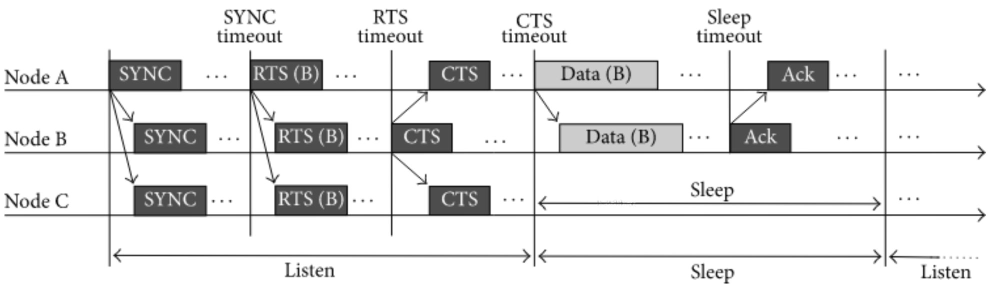
TDMA	CSMA
Strict Synchronization	Synchronization is flexible
Controlled Access	Random Access
High Channel Utilization under high contentions	High Channel Utilization under low contentions
Need Central Control	Completely decentralized

Described Protocols

Channel Type	CSMA - Synchronous	CSMA - Asynchronous	TDMA	Hybrid
Protocol	S-MAC T-MAC P-MAC DSMAC	B-MAC X-MAC WiseMAC	TRAMA	Z-MAC

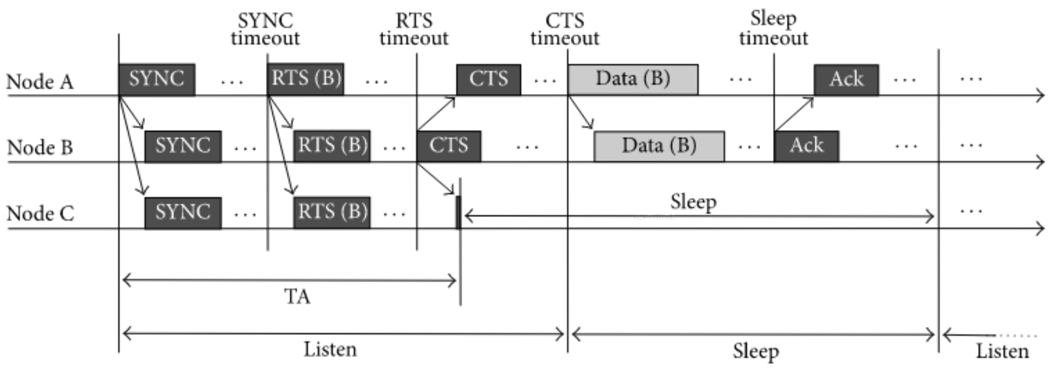
S-MAC

The innovations compared to classic CSMA/CA in this protocol are periodical listening, reducing collision, preventing unintentional receiving, and message transition.
Nodes generally sleep instead of continuously listening to the medium. Listening and sleeping times are stable and periodic, each node knows the schedules of 1-hop neighbors. There should be a strict synchronization so that the nodes can move together due to stable listening/sleeping timing, it does not synchronize and thus latency increases.
It supports message transition so that large-sized packets can be sent more efficiently.



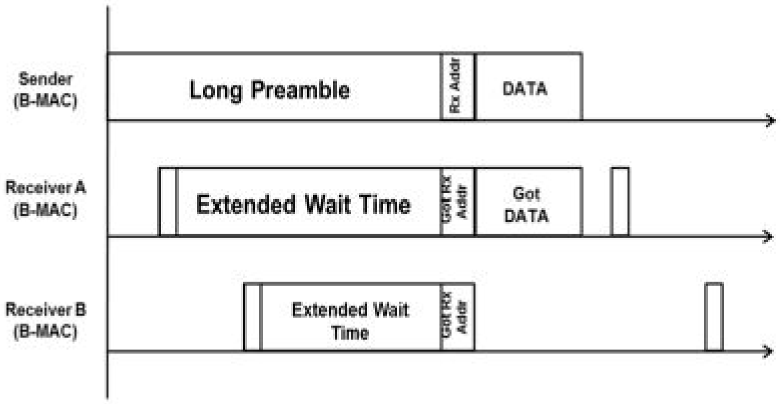
T-MAC

Although stable sleeping listening periods in S-MAC increase energy efficiency, they also lead to high latency and low-efficiency. TMAC is proposed to improve weak results of S-MAC during variable traffic densities. If any communication does not occur during a certain period of listening time in T-MAC (timeout, TA), sleeping mode occurs.
T-MAC consumes less energy than S-MAC, but causes more latency.



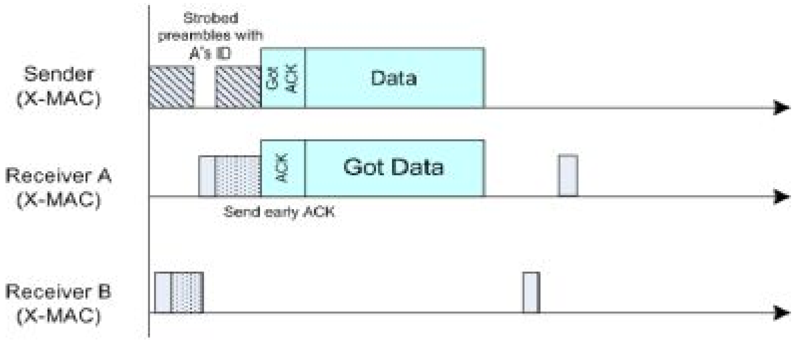
B-MAC

B-MAC uses periodic sleep/wakeup cycles.
Fairness not guaranteed.
The sleep periods of the nodes can differ from each other. B-MAC is asynchronous.
When there is data to send a node switches the radio mode and starts to send an announcement,preamble (it has to be long enough for everyone to hear it, same as interval between 2 wake-ups of receivers.).
Afterwards, the sender transmits the target address and starts sending data.
Asynchronous networks don't need complicated and expensive synchronization methods. There is no data fragmentation used in B-MAC (complicated to coordinates, so B-MAC expects short messages.).
B-MAC is using LPL (Low power listening) to check if another node is sending a preamble.



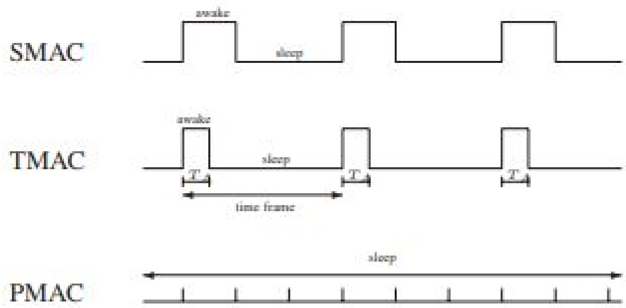
X-MAC

Similar to B-MAC.
Improvement of B-MAC by sending better announcements/preamble (with target address).
Reduced overhearing.
Nodes not addressed as targets can go to sleep after reception of a short message (announcement).
Addition of short pauses between preamble messages. The receiver has not to wait for the full period and send ACK to inform the sending peer it is ready (no preamble time).



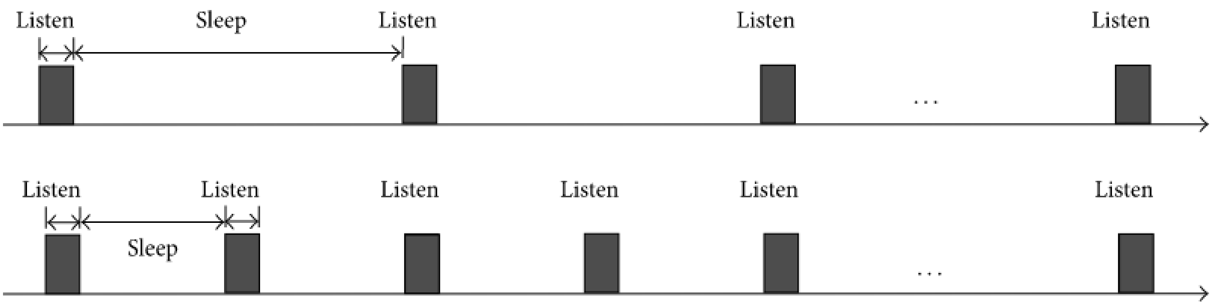
P-MAC

Most of the MAC protocols like S-MAC sleep periodically to save energy. Duty cycle is constant in these protocols. Instead of stable sleeping and listening periods, sleeping-listening periods in PMAC are determined in a different way. Timing is determined by the traffic of the node and its neighbors (image shows the idle listening period when there is no traffic).



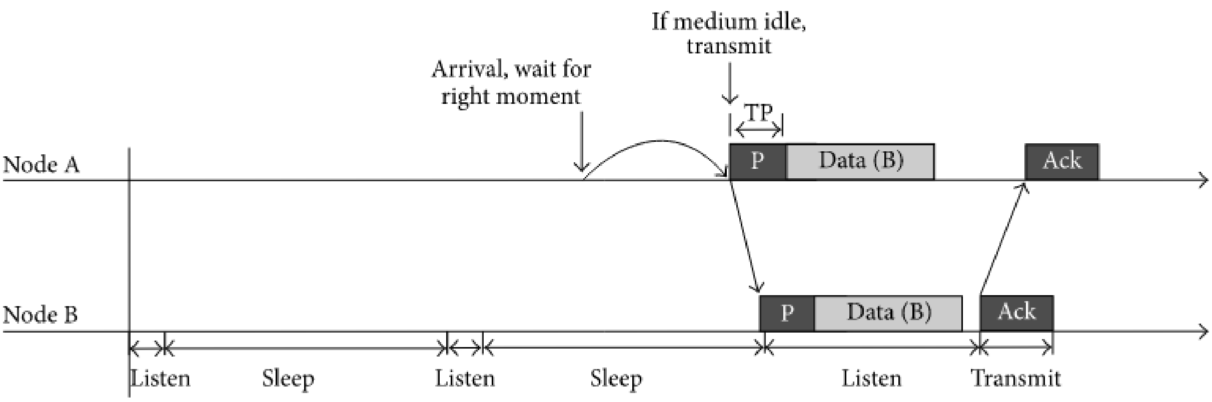
DSMAC

DSMAC has added a dynamic time zone feature to the S-MAC protocol. Its goal is to reduce latency for delay-sensitive applications. All the nodes share one hop latency in SYNC period (the elapsed time between the meeting packet in the queue and sending it) and also start in the same time zone.



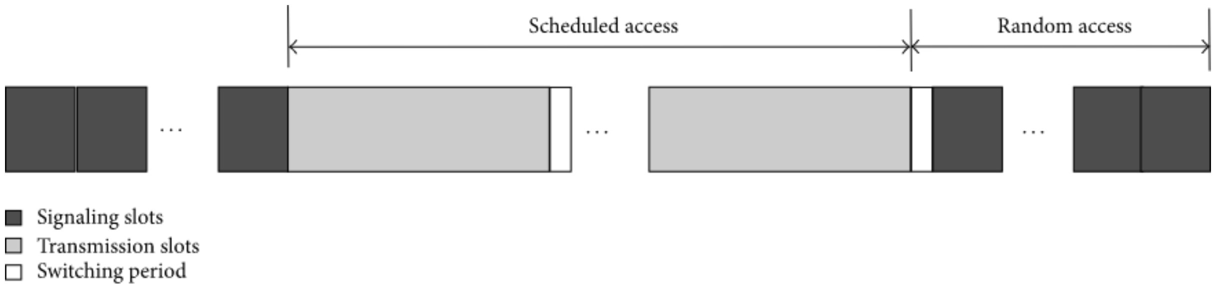
WiseMAC

WiseMAC is similar to B-MAC.
Preamble length is adapted to the wake-up period of neighbors listeners.



TRAMA

Energy consumption is reduced in this protocol by switching off when nodes are neither transmitting or receiving, that is, when they are free and therefore guaranteeing that a packet collision will not occur. TRAMA consists of three main components. First, the neighbor protocol (NP) gathers information from neighbor nodes. Schedule Exchange Protocol (SEP) allows nodes to exchange two-hop neighbor information and programs. Adaptive Election Algorithm (AEA) decides on the nodes that will transmit and receive in the current time zone by using neighbors and program information. This protocol is used for energy efficiency and applications requiring efficiency apart from the delay-sensitive applications. TRAMA provides higher efficiency and more energy than S-MAC. TRAMA leads to more latency.

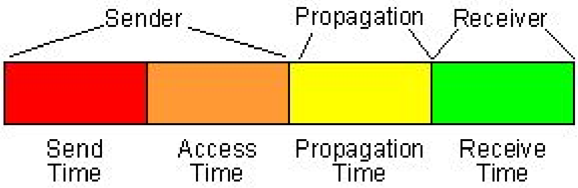


Z-MAC

Implemented on the top of B-MAC. Setup phase (doesn't occur again except if big change in topology) : neighbor discovery (1-hop neighbors and their own list of 1 hop neighbors -> 2 hops) , slot assignment with these two hops neighbors list (the algorithm is flexible to allow new nodes to join later.) , local frame exchange, global time synchronisation.
Better idle listening than B-MAC because of both high contention TDMA and CSMA low contention.
Not good for events driven applications. Overhead during network setup is very high (a lot of activities at the same time).
CSMA as the baseline MAC scheme and TDMA schedule to enhance channel utilization during high contention.

Clock synchronization

Time Synchronization in wireless networks is extremely important for basic communication, but it also provides the ability to detect movement, location, and proximity.
The synchronization problem consists of four parts: send time, access time, propagation time and receive time.



Note : CSMA protocols don't require clock synchronization to work properly as they can listen to the medium and retry if needed, however, to improve efficiency and packet collision, synchronization can be implemented to try to reduce uncertainty of presently described periods (send, propagation, receiver).

Major clock synchronization problem is not only to know if there is a packet delay, but also being able to predict the time spent on each transmission phase.
We need to know when to listen, when to send, to optimize sleep cycle and energy consumption.

Two types of network: Asynchronous networks, working with announcement packet (preamble) and independent schedule, and Synchronous ones, working with SYNC packet and schedule transmitted to neighbors.

Clock synchronized Protocols :

Protocols : S-MAC, T-MAC, P-MAC, DSMAC, Z-MAC

Schedules are shared between every neighbor. Timer synchronization needed (to have the 'same' schedule).
Periodic updates of synchro by using SYNC packet.
Synchronizer nodes (ones that create the original schedule) send SYNC packets to its followers (ones that receive and adopt the schedule).
Listening interval is divided into two parts : one for SYNC, one for RTS.

P-MAC : Time synchronization negotiated between neighbors nodes following the current traffic and other neighbors.

DSMAC : same as s-mac, nodes try to receive a wake up schedule from another node, and adapt to the existing system. All node maintains a local SYNC table to adjust its duty cycle according to load and energy consumption. Addition to S-mac : SYNC packet contains node's duty cycle.

Z-MAC : Time synchronization during setup phase

TRAMA : TRAMA, being a TDMA protocol, needs a strict clock synchronization due to the channel access of type requiring this synchronization.

Non-clock synchronized protocols :

Protocols : B-MAC, X-MAC, WiseMAC

Asynchronous network doesn't really need synchronization. Synchronization ensured by the announcement frame before each sending. Each node has its own schedule independently, using preamble schemes.

Localization

Goal is to assign geographic coordinates to each node with an unknown position in the deployment area.

Co-operative localisation: Small number of anchor nodes with given localisation, other nodes forming the network without localisation. For these nodes to have a computed location, we need:

- Rapid adaptation to topology changes due to mobile nodes
- Transmissions of periodic ranging probes are to be scheduled in such a way that they are received as tightly time clustered probes by each node.
- Probes should be sent during reserved time slots. (not broadcast or targeted to a specific node), ACK are not sent because retransmissions of probes are not desirable.

We need to estimate the distance between nodes, then triangulate the position.
Estimate distance: Propagation time between nodes (with clock synchronization).

Using an RSSI (radio signal strength indicator) signal to ‘compute’ the distance. Needs to know of offset of each node (clock synchronization necessary)

Localization is therefore possible with every protocol that has a clock synchronisation and that can allow to transmit additional information (either larger frame or one more frame with only RSSI information). Depends on the load of the network and its needs.

Security mechanisms

Broadcast wireless nature of communication : vulnerable to attacks

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CSMA/CA protocols are easy to attack:

- Keeping nodes awake by broadcast at right time (knowing schedule, or preamble)
- Replaying SYN packets for Synchronous Protocols, modification of schedules to prevent nodes to sleep.
- Using CTS/RTS packets to create collisions/conflicts.

Some security principle, mainly for authentication, are implemented:

Security into IEEE 802.15.4, three security mechanism, based on AES-128 bloc encryption:

- CTR, CounTeR mode, counter based encryption
- CBC-MAC, integrity and authenticity field added to frame.
- CCM, combination of both CTR and CBC-MAC.

Characteristics of a wireless channel can allow the wireless channel to be used as a means to authenticate the legitimate entity:

- The impulse response for time-variant wireless channel decorrelates quite rapidly in space.
- Wireless channel also changes in time, which results in a natural refresh for a channel-assisted security mechanism.
- The wireless channel is reciprocal in space.
- The time variation is slow enough so that the channel response can be accurately estimated within the coherent channel time.

Comparison of wavelengths, if they are close or not, allows the possibility to check if the wireless channel used for communication is close to the normal use (order of a wavelength close), or not, in this case, it’s probably not the original receiver/sender.

TDMA based protocols are hard to attack due to predefined time slots and long sleep periods.

Hybrid Protocols (Z-MAC) are hard to attack too, due to the assigned time slot for each node. Low contention level also makes attacks harder to do.

Nodes mobility

Mobile nodes into synchronized environments: need to resynchronize everything to integrate the mobile node: high cost in energy.

Synchronized protocols (neighbors schedules)

Mobile nodes keep the radio receiver awake until reception of the synchronisation frame (very energy consumptive).
Improvement: MS-MAC, more synchronization period, in function of node speed (detected with RSSI of sent messages), not optimal, but better.

MAC synchronised 802.15.4
- Nodes linked to a coordinator to exchange data with it
- Nodes can detect if they are out-of-range of a coordinator. (non-reception of 4 consecutives beacons leads the node to send a message to the coordinator, if there is no reponse, node try to associate himself with a new coordinator)

Unsynchronized protocols (preamble)

Preamble functioning really hard to adapt to mobility.
If the nodes are from another network, preamble length will differ and the communication will be impossible. In addition, transmission of preamble increases the length of the transmission, so the mobile node can be out of range of receivers after a certain time.

X-MACHIAVEL :
based on X-MAC, optimize the medium access for mobile nodes.
When a mobile node tries to access the medium but a fixed node is sending its preamble, the mobile node sends a special ACK to announce it will transmit its frame to the node transmitting its preamble. In addition, every node that sees the special ACK can ACK the preamble to become the new destination of the mobile node frame.

Power consumption

Power consumption is very variable for a given protocol, especially when we take different packet sizes, different traffic and different network sizes.

However, this is more or less accurate for medium packet size, traffic and nodes number:

Synchronous = P-MAC < S-MAC < T-MAC < DSMAC
Asynchronous = WiseMAC < B-MAC < X-MAC
Hybrid = Z-MAC
TDMA = TRAMA

Protocol	Energy Saving	Advantages	Disadvantages
S-MAC	Power savings over standard CSMA/CA MAC	Low traffic -> low energy consumption	Sleep latency
T-MAC	20% less than S-MAC	Adaptive active time	Early sleeping problems
X-MAC	Better than SMAC,BMAC,WMAC	Savings with LPL. Gains continues as network density increases	Unable to schedule small listening periods.
P-MAC	Low	Adaptable to traffic and neighbors	Renogiciation of schedule useless if the network is not changing
B-MAC	Better power saving, latency and thourghput than SMAC	Low overhead when the network is idle. Consume less power, easy to implement.	Overhearing bad performance when heavy traffic. Long latency.
DSMAC			
WiseMAC	Better than smac and classic LPL	Energy consumption both at sender and receiver, and at non target receiver, increase latency at each hop.	Low power for low traffic, Do not incur overhead due to synchronization
TRAMA	High	TDMA : no collisions Unicast	Latency
Z-MAC	Low	Adaptive to traffic	Poor handling of high frequency of topology change (setup phease)

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