INSA Toulouse - 5ISS

Wireless sensor networks

MAC layer protocols dedicated to WSN & IoT

Students :
Remi Goalard

Teacher :
Daniela Dragomirescu

December 4, 2023

Contents

1 Introduction

15 billion, that is the number of IoT devices connected in networks all around the hearth. Due to recent advances in wireless technologies, the quantity of wireless IoT networks is exploding. As they rely on the interconnection of more or less sensor nodes, WSN (wireless sensor networks) comes with various requirements.
First, the system should answer to the problem it was created for, and therefore meet some requirements about coverage area, scalability, data rate, latency...
Then, a really important requirement to take into account is the energy efficiency. Most wireless nodes don't have any access to a permanent energy source. As a result, nodes and the protocols they rely on to communicate have to be developed with an energy efficiency mindset.
Last but not least, protocols improvement and complexity evolution, as well as the amplification of data transiting on WSN leads to a strong need of security.

A subset of the second layer of the OSI model, the so called MAC layer, plays a really important part in energy efficiency and characteristics requirement in a wireless network.

2 MAC layer definition

MAC, which stands for Medium Access Control, is a subset of the Data Link layer, the second one of the OSI model. As it is directly over the physical layer, MAC layer is responsible for controlling the access to the physical transmission medium. In a wireless environment, MAC layer is responsible of various tasks :

- **Addressing** : assigns unique MAC addresses to all the nodes & devices in the network.
- **Error detection** : to ensure the integrity of transmitted data, uses methods such as 'checksum'.
- **Frame management** : creates frames containing the data coming from above layers.
- **Frame filtering** : ensure that the received frames were sent for the receiving device.
- **Access control** : decide how the network nodes get access to the shared medium and ensure that only one node access the channel at a given time => avoid collisions. It is based on different methods, such as CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) for wireless networks.

To perform all those actions, MAC layer rely on a protocol. Actually, it can rely on many protocols, as many MAC protocols with various features have been proposed and developed thought the previous decade. It would be very long and complexe to present all the different MAC layer protocols, but they can be dispatched into 2 categories with sub-main-categories :

- **Contention-based** : Synchronous or asynchronous
- **Scheduled** : TDMA or FDMA

3 Contention-based protocols

The first category is **contention-based** protocols. In those networks, nodes are competing to have access to the transmission medium : when they have data to share they listen to the network to see if another node is already using the channel. If so, they wait for a certain period and do another check, until they find a moment when the channel is not busy. Let's see the pros & cons of contention-based protocols :

- **Advantages** :
  1. Mobility : allows changes in the network density, traffic load & topology => ensure nodes mobility.
- **Disadvantages** :
  1. Inefficient use of energy => often listen to the notworks so nodes receive packets they will not use just to know if they can use the medium ("overhearing") + many collision might occur in the network so packets should be re-sent. Need a lot of control which cost a lot of energy.
  2. Hard scalability, as a big number of nodes would cause lot of collisions & need lot of synchronization packets.

Furthermore, contention-based protocols can be divided into 2 subcategories : synchronous & asynchronous protocols.

3.1 Synchronous protocols

Synchronous protocols are based on a synchronization between the nodes of the network. The idea is that each node is aware weather other nodes are active or sleeping, so it can decide when to listen for packets or use the channel to send it's own ones. It is hard to implement a good synchronization protocol, as too many synchronization messages would cause an over-load of the network, while not enough messages would imply lot of collision and reduce network adaptability & node mobility.

Let's take the **Sensor MAC** protocol as an example :
It operates on the principle of synchronous duty cycling. Nodes alternate between active and sleeping periods to conserve energy (annex 1). The duty cycle, as well as the duration of active and sleep periods, remains fixed throughout the node's lifetime based on application requirements. During the SYNC period, nodes either wait for or broadcast a SYNC packet, containing the node's address and next sleep time. Close nodes sharing the same schedules forms clusters. The periodically synchronization minimize clock drift among those clusters.
S-MAC focus on energy-efficiency by employing RTS/CTS (Request to Send/Clear to Send) handshaking mechanisms to prevent collisions, overhearing, and hidden terminal issues during data transmission. According to a 2002 study, S-MAC nodes consumes around 450 mJ.

3.2 Asynchronous protocols

Unlike synchronous protocols, asynchronous ones do not require any scheduling/synchronization between nodes. The idea is to use low power listening or preamble sampling. In that case, receiver nodes are sleeping most of the time, while senders first send a preamble on the network when they have data to send. When a node waked up and receive a preamble, it knows some data will be sent on the network, so it stays awake until the data is received.

- **Advantages** :
  1. No explicit synchronization => no synchronization overhead.
  2. Reduce Idle listening of receivers.
  3. More flexible to topology changes
- **Disadvantages** :
  1. Over-emitting of transmitters prior to sending the data
  2. Increase of latency at each hop, especially when the receiver wakes up at the beginning of the preamble.
  3. Does not deal with collision.

Let's take the **WiseMAC** protocol as an example :
WiseMAC main objective is to focus on energy efficiency by reducing wake-up preamble length : the length is adjusted dynamically based on the frequency tolerance (tho) of the time-base quartz and the interval between communications (L) (Tp = min(4*tho*L, Tw)). Sensor nodes share their sampling schedules with others through ACK packets transmitted by the receiver at the end of data transmission (annexe 2). This information allows a sender to wake up precisely when the receiver becomes active, with a sampling period of TW.
During low traffic, the length of the preamble may exceed the data frame length (TD). In this case, WiseMAC repeats the data frame with the extended preamble. The receiving node only remains awake if it is the intended recipient of this data frame, and it sends an ACK message at the end of the transmission.

- **Advantages** :
  1. WiseMAC's dynamic preamble length adjustment improves performance under variable traffic loads, outperforming S-MAC.
  2. Overhearing is significantly reduced, particularly in high-traffic conditions.
- **Disadvantages** :
  1. In scenarios with frequently changing network topologies, WiseMAC may lead to high preamble overhead and increased latency.
  2. Some nodes may need to use long preambles after failing to communicate with the destination, contributing to latency and energy consumption.

4 Scheduled protocols

In scheduled protocols, node can access the network through two kind of resources : time & frequency. This access is scheduled among the nodes to prevent from collisions and energy loss (no idle listening nor message overhearing). Scheduling management cost a lot of energy, but those networks are nor very flexible, and therefore don't require much scheduling adjustment. In this case, managing the scheduling does not cost a lot during the network's lifetime.

- **Advantages** :
  1. Good node localization (because low mobility).
  2. Negligible overhead => energy saving.
  3. Collision avoidance
  4. Predictable latency
- **Disadvantages** :
  1. Low nodes mobility / less topology changes.
  2. Complex synchronization

Furthermore, schedule-based protocols can be divided into 2 subcategories : TDMA & FDMA

4.1 FDMA

In FDMA-based protocols, available frequency bandwidth is divided into several frequencies or sub-bands [Annex 3]. To prevent a collision, each node is assigned a unique physical frequency, based on some frequency assignment algorithm.

Let's take the **MMSN: MULTI FREQUENCY MAC** protocol as an example :
This focus on two aspects, frequency assignment & media access. In frequency assignment, each node is assigned a physical frequency for data reception. The assigned frequency is broadcast to its neighbours to inform other nodes of the frequency used to transmit unicasts packet to each of its neighbours. Frequency assignment is performed at the beginning of deployment and also infrequently at other times for adaption to system ageing. MMSN can use 4 different assigment schemes :

1. Exclusive Frequency Assignment (EFA) : assigns different frequencies to nodes within a two-hop neighborhood. Requires the number of frequencies to be at least as many as the nodes in the two-hop neighborhood.
2. Even Selection : an extension of EFA where the least chosen frequency is randomly assigned if physical frequencies are insufficient.
3. Eavesdropping : Nodes take a random back-off before broadcasting their frequency decision. Nodes record frequency decisions overheard during the back-off period.
4. Implicit Consensus : Similar to EFA but uses pseudo-random number generators for frequency number calculation.

Using this kind of protocols present various advantages but also disadvantages :

- **Advantages** :
  1. More than one node can transmit and receive at the same time => enhance channel utilization and so energy efficiency.

2. Avoid collision because frequency is exclusively assigned to nodes within two hops.

- **Disadvantages** :
  1. MMSN requires time synchronization during media access.
  2. A node snoops broadcast frequency for transmissions from other nodes during broadcast period.
  3. A node toggle between its self-frequency & the destination node's frequancy to check for ongoing transmissions.

4.2 TDMA

TDMA stands for Time Division Multiple Access. In this category, a single frequency channel is divided into time slots where each node is allocated a single transmission slot (Annex 4). Due to it, TDMA is a collision free protocol. TDMA need tight clock synchronization so time slots are respected and don't overlap each other. It require frequent message exchange and therefore high energy cost. When the channel contention is low, TDMA suffers from higher delays and lower channel utilization than other protocols, since TDMA only allows a node to transmit during the time slots allocated to the node.

Let's take the **Energy & Rate-MAC** protocol as an example :
This protocol includes a periodic listen and sleep mechanism similar to S-MAC and introduces the concept of energy criticality. This concept is here to balance energy consumption among nodes and extend the network lifetime : A node that is more active transmitting is allocated number of slots, and nodes with lower energy level are also critical and are allocated with more transmission slots than its neighbors. This protocol is based on 2 phases : 'normal phase' & 'voting phase' :

1. 'Normal phase' : In the normal phase, if a node owns the current slot, then it sends any available data or sleeps when there is no data available to transmit. If this node does not own the slot, it needs to be awake in order to receive data from its neighbors. If this slot is the second slot of the current leader, the slot is idle and this node goes to sleep.
2. 'Voting phase' : its locally triggered by a node when its energy criticality falls below a certain threshold (of the previous winner). This node becomes the new leader if its criticality is below the criticality of its neighbor. The leader will have more transmission slots allocated to it, while the rest of the nodes in the group only have one slot.

What are the advantages and disadvantages of this protocol :

- **Advantages** :
  1. No Packet Loss due to the TDMA nature more than this precise protocol.
  2. Voting phase is integrated into TDMA phase to save bandwidth and reduce overhead.
  3. More effective in higher load traffic => demonstrating energy savings.
- **Disadvantages** :
  1. Low nodes mobility due to it's schedule-based configuration.
  2. A node can only communicate during the activity of it's assigned slot => can lead to low bandwidth utilization.

A 2010 study shows that nodes emit less than 1 J during a packet transmission.

5 Conclusion

In this report, we have seen a few MAC layer protocols used to implement wireless sensor networks. Those protocols are only a small overview of the existing ones, but they illustrate the 4 main categories or MAC layer protocols :

- **Contained-based** :
  1. Synchronous
  2. Asynchronous
- **Schedule-based** :
  1. FDMA
  2. TDMA

The main points to remember are present in the following table :

	Synchronous S-MAC	Asynchronous WiseMAC	FDMA MMSN	TDMA ER-MAC
Clock synchro	Yes	No	Yes (infrequently)	Yes (local)
Localization	No	No	Yes (thx to low mobility)	Yes (same)
Node mobility	Easy	Easy	Hard	Hard
Energy	450 mJ	Effective low duty cycle S-MAC/7 (10%)		>1J/packet

Table 1: LTE-M features table

Finally we can discuss the security aspects. MAC layer itself can't assure the security of a network. It is usually done at a higher level (3 and above). However, some security points can be implanted, such as MAC address filtering or security protocols (WEP/WPA..). The issue here is that MAC layer security implies a huge increase of energy cost, which is not what we want. Indeed, it is hard to find the good balance between security and energy efficiency, but it seems better to optimize MAC layer protocols on energy consumption and use higher levels to ensure security.

6 References

1. El-Hoiydi, Amre, et Jean-Dominique Decotignie. « WiseMAC: An Ultra Low Power MAC Protocol for Multi-Hop Wireless Sensor Networks ». In Algorithmic Aspects of Wireless Sensor Networks, édité par Sotiris E. Nikoletseas et José D. P. Rolim, 3121:18-31. Lecture Notes in Computer Science. Berlin, Heidelberg: Springer Berlin Heidelberg, 2004. https://doi.org/10.1007/978-3-540-27820-7_4.

2. Kumar, Arun, Ming Zhao, Kai-Juan Wong, Yong Liang Guan, et Peter Han Joo Chong. « A Comprehensive Study of IoT and WSN MAC Protocols: Research Issues, Challenges and Opportunities ». IEEE Access 6 (2018): 76228-62. https://doi.org/10.1109/ACCESS.2018.2883391.

3. Sitanayah, Lanny, Cormac J. Sreenan, et Kenneth N. Brown. « ER-MAC: A Hybrid MAC Protocol for Emergency Response Wireless Sensor Networks ». In 2010 Fourth International Conference on Sensor Technologies and Applications, 244-49, 2010. https://doi.org/10.1109/SENSORCOMM.2010.45.

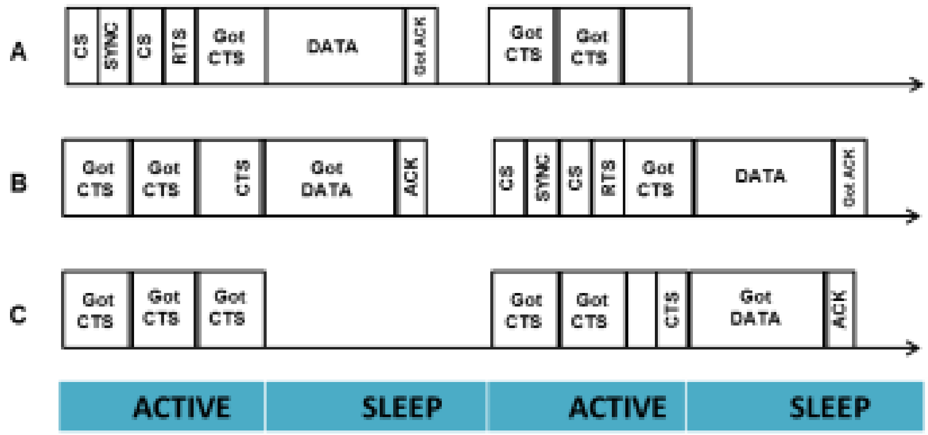
4. Ye, Wei, J. Heidemann, et D. Estrin. « An energy-efficient MAC protocol for wireless sensor networks ». In Proceedings.Twenty-First Annual Joint Conference of the IEE "computer and communications societies, 3:1567-76 vol.3, 2002. https://doi.org/10.1109/INFCOM.2002.1019408.

5. « Channel Access Method ». In Wikipedia. https://en.wikipedia.org/w/index.php?title=Channel_access_method&oldid=1094605369.

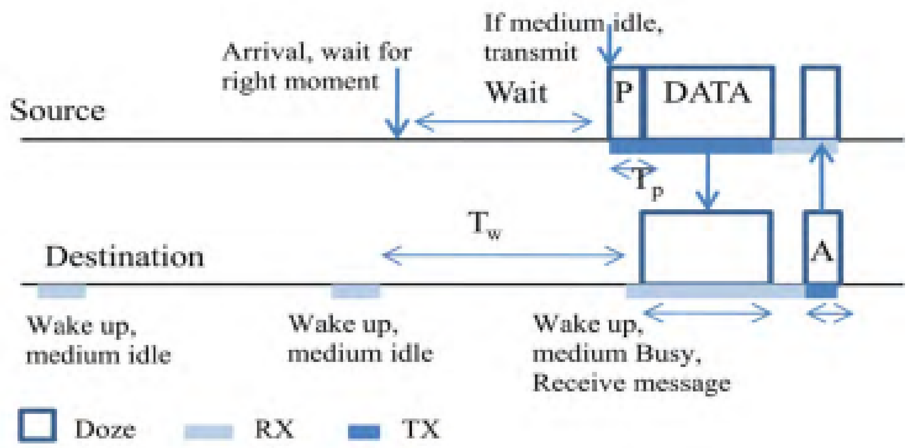
A Annexe :

Complementary information - additional resources

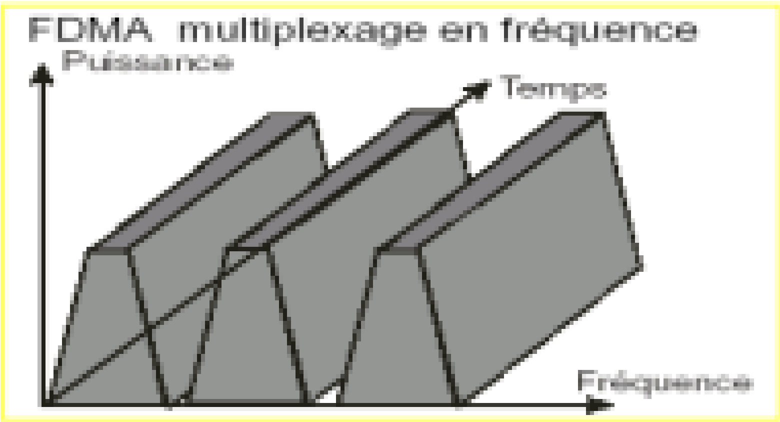
A.1 Example of S-MAC duty cycling



A.2 WiseMAC example



A.3 FDMA schema



A.4 TDMA schema