Analysis of existing MAC protocol layers for Wireless Sensor Networks

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1 Introduction : MAC-layer challenges for sensor networks

1.1 Important factors for sensor network MAC layer design

Energy consumption Sensors networks are usually based on low-range, low-power transmissions. That means that to cover a wide area, it is necessary to deploy a large number of sensors. The battery change operation can be costly, hard, or impractical when the number of sensors to replace is important [1]. That is why the energy consumption is a critical part, as the devices may be expected to last for several years. In the next section, we will see in which aspect the choice of the right MAC layer have an important role in energy consumption reduction.

Adaptability to changes In sensor networks, nodes can be added or removed (e.g. if running out of battery) from the network. The network needs to adapt quicky to the topology change induced by the addition or removal of nodes.

1.2 Sensor networks application characteristics

Sensor networks have a wide range of applications with a lot of different characteristics.

- Network density : the network can be made of high or low number of nodes in a small or big area.
- Network topology : there can be ad-hoc networks, or infrastructure networks.
- Delay : some applications may require very low latency.
- Throughput : some applications may require a high data throughput while other may send only a few short messages.

The power consumption of the nodes may vary depending on these characteristics and the used MAC layer protocol.

1.3 Energy waste on radio transmissions

According to [5], there are four main causes of energy waste in radio transmissions :

- Idle listening : it is the fact that a node is scanning the network while nothing happens on it. Staying in listening time for long period of times while there is no transmission is a waste of energy.
- Packet collisions : occur when a node receives several packets at the same time. For MAC layer protocols with acknowledgements, the packets needs to be transmitted again, which leads to energy waste.
- Overhearing : occur when a node receives packets that are destined to other nodes.
- Control Packet Overhead : the control packets are packets that are used to send information that is not payload data, but rather controls the way the data is sent. These include synchronization packets used by TDMA based protocols.

1.4 Why are there so many MAC layer protocols for wireless sensors ?

The answers to this question lies in the 3 previous subsections : there is currently no known protocol adapted for all kind of applications. Therefore, the protocols described in the next section are application specific : each protocol has its own advantages and disadvantages and perform optimally in a small subset of the applications.

2 Wireless Sensor Networks MAC protocols

The protocols presented in the next sections are mostly based on well known access schemas : Carrier Sense Multiple Access (CSMA) and Time Division Multiple Access (TDMA). Some of them are CSMA-based, while others make use of both CSMA and TDMA access schemes. The CSMA-based protocols are refered as asynchronous, while the TDMA-based protocols are refered as synchronous.

2.1 TDMA and CSMA principles

2.1.1 TDMA Principle

This paragraphs aims at briefly presenting TDMA principle, in order to better understand protocols based or inspired by TDMA.

TDMA allows multiple nodes to share the same frequency channel by dividing it into several time slots. Each node is periodically assigned a time slot, and can only emit during this time slot.

The benefits of TDMA are :

- No packet collisions : as the nodes have a specific time slot, they should not emit at the same time, therefore, should not produce any packet collision.

However, there are some drawbacks of using TDMA :

- Synchronization overhead : because of clock drift phenomenons, there is a need for synchronization packets.
- Bandwidth decreases as the the number of nodes sharing the same frequency channel grows.

2.1.2 CSMA Principle

Contrarily to TDMA, in CSMA there is no static allocation of slots for a node to emit. In CSMA, before the emitter node starts transmitting data, it tries to determine whether another node is currently transmitting on the same frequency channel by detecting the presence of a carrier signal. If the node detects that another node is currently transmitting, it waits until the end of the transmission before starting its own transmission.

CSMA has standard variants which are :

- CSMA/CA (Collision Avoidance) : in this variant, if node which wants to start a transmission senses that another node is transmitting, it will wait for a random duration before trying to emit again. This helps ensuring that 2 nodes waiting for a transmission to end will not emit at the send time at the end of the transmission.
- CSMA/CD (Collision Detection) : in this variant, if a node that is currently transmitting data senses another node, then it stops its transmission.

2.2 Synchronous / TDMA based protocols techniques

2.2.1 Node synchronization

According to [2], synchronous MAC protocols have two types of nodes : synchronizers and followers. If the node wakes up, listens to the channel and does not hear any schedule from the other neighboring nodes, it choses its next wake up time then broadcasts its schedule of wake up times. The node will stick to this schedule and become a synchronizer. If the node receives a schedule from another node, it sticks to its schedule and becomes a follower. This way, clusters are created that regroup a synchronizer and many followers. If the node receives another schedule after it has set itself its schedule, then it keeps both schedules. This node will wake up two times more than regular nodes.

Exemple : Sensor-MAC [4] S-MAC is a synchronous protocol designed for ad-hoc sensor networks. In S-MAC, the nodes are organized into clusters. Those clusters are composed of neighboring nodes, and have a schedule that is shared across all the nodes of the cluster. This schedule is composed of SYNC, DATA and SLEEP periods.

- SYNC : all nodes of the cluster wake up and synchronize clocks.
- DATA : Nodes which need to transmit packets send Request To Send (RTS) / Clear To Send (CTS) requests. This step is necessary to ensure that only one node will transmit a packet during the DATA time slot (otherwise collisions could occur).
- SLEEP : For each cluster, the node concerned by the CTS request transmits data them returns to sleep. All the other nodes (including those that wanted to transmit but received the CTS frame which didn't concern them) sleep immediately after the beginning of the sleep period.

Pros :

- sleep schedules ensures that the emitters / receivers will only sense the network when necessary.

Cons :

- Sleep schedules can induce high latency. This can be problematic when routing packets through long routes.

2.2.2 Overhearing avoidance

Overhearing avoidance is a technique used by T-MAC [5] to avoid the situation where a node is staying in listening state when no traffic will be sent to it. The idea is that when a node overhears an RTS or CTS destined to another node, it knows it will not be able to transmit data and doesn't need to listen to the data that will be transmitted by the other node. As a consequence it can enter sleeping mode to save energy. Altough this technique is good at saving power at low rates, collision overhead increases when the throughput is important, as some RTS/CTS packets might not be heard by nodes that entered the sleeping mode, causing these nodes to disturb the communication.

2.3 Asynchronous / CSMA based protocols techniques

In asynchronous protocols, there is no synchronization between nodes. All nodes choose their schedule independently of the other nodes [2]. The advantages of asynchronous protocols is that their is no Control Packet Overhead due to node synchronization and low duty cycles, which means low energy consumption. However the difficulty here is to be able to make the contact between two devices which have not their send/received windows synchronized.

2.3.1 Preamble sampling

The idea behind preamble sampling is to keep the nodes in sleep modes as long as possible and to wake them up sometimes to send or receive data.

All the nodes will wake up at regular constant intervals and sense the network during a certain period. If the medium is busy, then the sensor nodes will continue to listen until a data frame is received or the medium is no more busy. When transmitting, the access point will add a preamble before each frame. The preamble duration must be at least as long as the channel sampling interval to ensure that the receiving node will be set on active mode during the transmission of the preamble.

The problem with this technique is that the preambles cause an important reception overhead and loss of throughput. Also it causes overhearing because nodes must listen for the full data frame transmission before knowing if the frame was addressed to them.

2.3.2 Preamble sampling with Schedule learning

Schedule learning is an enhancement of basic preamble sampling in which nodes learn the schedule of the neighboring nodes in order to transmit shorted preambles. The idea is simple : if the source node knows when the destination nodes awakes, it can send the preamble just before it awakes instead of sending it through the whole sampling interval.

Exemple : WiseMAC [3] WiseMAC is designed for the downlink of infrastructure networks, that means there will be access point nodes and sensor nodes. WiseMAC is based on the preamble sampling technique. All the sensor nodes will wake up at regular constant and independant intervals and sense the network during a period called T_w. If the medium is busy, then the sensor nodes will continue to listen until a data frame is received or the medium is no more busy. When transmitting, the access point will add a (long) preamble before each frame. The problem with this technique is that the preambles cause an important reception overhead and loss of throughput. However WiseMAC makes the access points maintain a table of the sampling schedule of all the sensor nodes in range, in order to send frames when the destination node awakens, with a shorter dynamic-length preamble.

2.3.3 Receiver Wake up time estimation

Exemple : PW-MAC To optimize the time the sender stays awake, PW-MAC proposes a solution in which it predicts the receiver wake up time in order to wake up just before that time and start the transmission. The idea behing it is that PW-MAC uses a pseudo-random generator function to generate variable wake up intervals. This function has the particularity that given a seed, it will generate a predictable sequence of numbers. PW-MAC uses a beacon message to transmit the seeds from the receivers to the senders. Given that seed, the sender node can predict the receiver node's wake up time and wake up slightly before. "slightly before" is an interval that can be calculated from the receivers wake up time and an approximation of its clock drift relative to the sender node's clock.

3 References

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