Comparative Study of Energy-Efficient MAC Protocols in Wireless Sensor Network (WSN)

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***Abstract*— Wireless Sensor Networks (WSN) are self-organized networks that use several small sensor nodes to sense physical characteristics of their surrounding environment and share them with the user(s) of the network. Dealing with energy constraints is the main challenge of Wireless Sensor Networks, because of their low battery power. Using the Omnet++ framework it was possible to simulate the performance of three WSN energy-saving MAC protocols: TMAC, SMAC and ZigBee. It was observed how sample rate and node density impacted energy consumption when implementing said protocols. In this paper, the results of these simulations are analyzed and discussed.**

I. INTRODUCTION

A Wireless Sensor Network (WSN) is a network comprised of tiny devices called sensor nodes. There can be even thousands nodes in a WSN, and they are able to perceive conditions such as sound, temperature, pressure, etc., monitor the environment around them and share the acquired information with a more powerful sensor called sink node, which will further process the data. WSN's usage has been increasing thanks to the technological development as sensors became smaller and more affordable, and it is now possible to implement them for increasingly more situations such as home, office, transportation, environmental monitoring, healthcare, logistics, military activities [1]. Although WSNs' areas of application keep increasing, sensor devices are limited in memory, battery power, processing power compared to other devices such as cell phones, and thus energy consumption is their main issue. WSN lifetime can be defined as the length of the time period from the deployment of the network to the ending of the battery lifetime of the nodes when the battery is unable to provide sufficient energy required for sensing, processing, or communicating [2]. Considering this, developing a Medium Access Control (MAC) protocol that can accommodate such needs and avoid energy wastes has become essential. The main features of WSNs are scalability, low complexity, self-healing, and most notably low cost and long network lifetime [2,3].

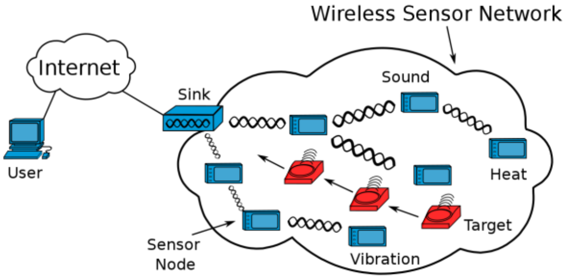

Figure 1. WSN

The rest of this paper is organised as follows. Section II briefly describes the MAC common protocols in WSN, with a further discussion in the appropriate subsection regarding the three protocols compared in the simulation: SMAC, TMAC and ZigBee. The simulation framework and the scenarios are explained in section III. The results of the simulations are analysed and discussed in section IV. Finally, section V concludes the paper.

II. MAC PROTOCOLS IN WSN

The Medium Access Control protocol (MAC) is used to regulate the access to the shared channel in order to increase the efficiency when sharing limited resources. A MAC protocol must try to lower the impact of the five principal causes of energy waste and consumption:

- Overhearing: it occurs when a device receives packets which they are not destined for.
- Collision: when more than one node tries to send packets at the same time over the same medium collision may occur. When this happens, packets need to be retransmitted, which increases energy consumption.
- Overemitting: it may occur when a sensor node sends packets to a receiver that is not yet ready to receive them.
- Idle listening: it happens when a node keeps listening for a large fraction of time to receive possible traffic from its neighbours while nothing is sensed.
- Control Packet Overhead: some protocols require the exchange of control packets that do not contain any application data. This causes energy consumption, and this phenomenon is called overhead.

A high-quality MAC control must also obtain [4]:

1. Throughput: it represents the number of packets successfully sent or received in a given period. A high throughput indicates a fast network.
2. Latency: it describes the time between the moment a packet is sent and the moment it is received. The lower the latency, the faster the network.
3. Adaptability: a MAC protocol must be able to adapt to sudden changes in the topology of the network, which is one of the main features of wireless networks.

MAC protocols can be divided into two main categories, scheduled-based and contention-based.

Schedule-based: schedule-based protocols schedule both transmit and listen periods to avoid idle listening, collisions, and overhearing. They can be centralized, where a cluster head (CH) assigns the different timeslots, and every time a node enters or leaves the network, the CH re-assigns the time slots for every node. They also can be distributed, in which case each node schedules itself. Common schedule-based protocols include LEACH, TDMA, FDMA, CDMA. Despite the numerous advantages, they also have some drawbacks. Some of them include network overhead caused by the fact that topology changes make rescheduling necessary, and higher memory capacity is required for the nodes to maintain their schedule [5]. However, distributed protocols are intrinsically more energy efficient, as the absence of a CH reduces the general traffic needed for rescheduling and thus reduces the overhead.

Contention-based: these are protocols based on the Carrier Sense Multiple Access (CSMA) technique: the nodes will contend for the same transmission medium, therefore risking collisions. The sender listens to the medium and waits for a given amount of time and will then either send the message if the medium is clear or keep waiting for the same amount of time until the medium is found to be clear. These protocols use a technique called Duty Cycling to regulate the operation activity, switching from active state to sleeping state, trying to stay active for the lowest possible amount of time in order to maintain the node's battery. Maintaining a low duty cycle can reduce energy consumption, at the cost of increasing delay as the waiting period in each hop increases. Contention-based MAC protocols can be divided into synchronous and asynchronous protocols. In synchronous protocols, nodes will regularly wake up and communicate during common active periods. This synchronisation allows for a more energy efficient communication between the nodes but produces more overhead. On the other hand, asynchronous protocols solve the overhead problem that's common in synchronous protocols by allowing nodes to select their own active schedule. However, since there is no synchronisation, senders use preambles to let the receivers know about incoming communications, and this can cause overhearing in the network therefore potentially increasing the energy consumption [6]. Examples of contention-based protocols may include SMAC, TMAC, DMAC, STEM, SWMAC.

A. SMAC

The Sensor-MAC (SMAC) protocol offers collision avoidance and good scalability. It uses a fixed duty cycle to establish a listen period and a sleep period. During the listen period, nodes can communicate between each other and then switch to a sleep period once their active time is over. This cycle is repeated until the batteries of the sensors run out, and this provides an energy saving function. Sensor nodes are also able to send control packets such as Request to Send (RTS), Clear to Send (CTS) SYNC and ACK packets. Studies show that SMAC has better energy-conserving characteristics compared to other 802.11 protocols [4] but it is not exempt from drawbacks, notably in the form of high latency and lower throughput caused by the periodic sleep times.

B. TMAC

The Timeout-MAC protocol (TMAC) uses an adaptive duty cycle method to reduce energy consumption on idle listening. It was stated above that SMAC uses a fixed duty cycle with active periods of constant length, and while that brings many advantages it also means that if no communication occurs during that period (or even for just a portion of it) then the involved nodes would have needlessly stayed awake, wasting resources. This is the idle listening problem and can be a major issue under increasing network loads. TMAC aims to minimise this issue by introducing a duration of TA which represents the minimum possible duration of idle listening, and if no communication occurs before it ends then it will put the node to sleep prematurely [10]. While this adaptability allows for further energy saving, it opens to the early sleeping problem.

C. ZigBee

The ZigBee technology is built on top of the 802.15.4 IEEE standard protocol and operates on different layers. Regarding the physical layer, it supports a 2.4GHz band with 16 channels, a 902-928MHz band with 10 channels, and an 868MHz band with 1 channel. It is adopted for solutions that require low data rate, low power consumption and low costs. It uses the CSMA/CA for accessing the channel, and there are two possible variations [7]: the Beacon Enabled Network which uses the slotted CSMA/CA, and the Non-Beacon Enabled Network which uses the unslotted CSMA/CA. For the network layer, it provides a network address of 16 bits, allowing for a network that can contain up to 65535 devices, and utilises a hierarchical structure. Devices have three possible operation modes [8]:

- PAN Coordinator.
- The Coordinator.
- The End Device.

Any device can communicate with other devices, except the PAN Coordinator. This creates the possibility of a mesh topology, offering high scalability and flexibility. It has however a few disadvantages, such as the short range, low data rate capped at 250kbps, and high maintenance costs.

III. Simulation Framework and Scenario

OMNET++ is a simulation library and framework primarily used for building network simulators [9] adopted for the simulations presented in this paper. The parameters setup is explained as follows.

Parameter	Value
Simulation Time	300 Seconds
Application	Bridge Test
The Sink Node (0)	true
Number of nodes	19 including the Sink
Field Size	100m x 40m
Battery	18,720 J (2x AA Batteries)
Mobility	No mobility used
Radio Transmitter Power	-10dBm
Radio Type	CC2420 and CC1000 Radio
MAC Algorithm	ZigBee, TMAC and SMAC
Vary Sample rate	10,20,30,40,50
Vary Node Density	10,20,30,40,50,60
Data Rate	1024Kbps
Sample Rate	100ms default
Initial Power Consumption	Two AA Batteries
Path Loss Map	Yes
Routing Protocol	Bypass Routing

Table 1. Simulation parameter setup

As for the energy saving, two parameter are considered to greatly impact energy consumption: sample rate and node density. This simulation is based on four different scenarios which are described as follows.

A. MAC Test 1

This simulation compares the three MAC protocols discussed, focusing on the impact of sample rate on energy consumption while using the CC1000 radio model.

	CC1000
Frequency	300 – 1000 MHz
Transmit Bit Rate	76.8 kbps
Power Control	Programmable
Output Power Range	-20 to 10 dBm
RF Module	Zigbee
Supply Voltage	2.1 to 3.6 V

Table 2. CC1000 Properties

B. MAC Test 2

This simulation will observe the same parameters as the MAC test 1 simulation; however, it will implement the CC2420 radio model.

	CC2420
Frequency	2.4 GHz
Transmit Bit Rate	250 kbps
Power Control	Programmable
Output Power Range	-24 to 0 dBm
RF Module	Zigbee
Supply Voltage	2.1 to 3.6 V

Table 2. CC2420 Properties

IV. RESULTS AND ANALYSIS

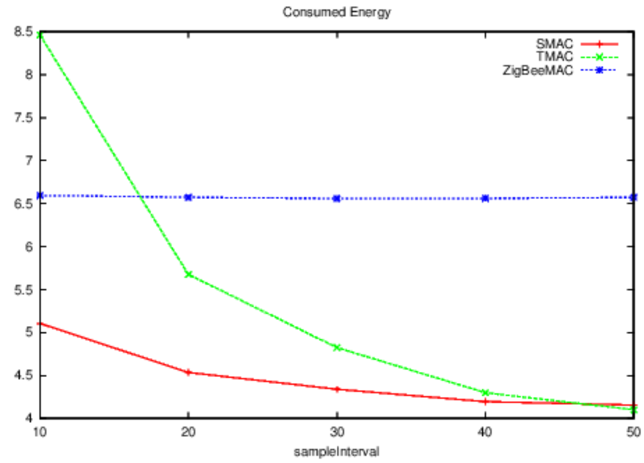

Figure 2. Energy Consumption vs Sample Rate CC1000

The above results belong to the MAC Test 1 scenario, involving an increasing sample rate while the number of nodes is fixed at 19 including the Sink.

ZigBee keeps a steady power consumption around a value of 6.6 with very small fluctuations despite the increase of the sample rate.

While SMAC starts with a much lower initial power consumption (almost half as much) as TMAC, TMAC's decrease in power consumption is much greater than SMAC's, managing to reach a lower value after a sample rate of 50ms, this can be attributed to TMAC's ability to adapt its active cycle to the rate of communication happening in the network.

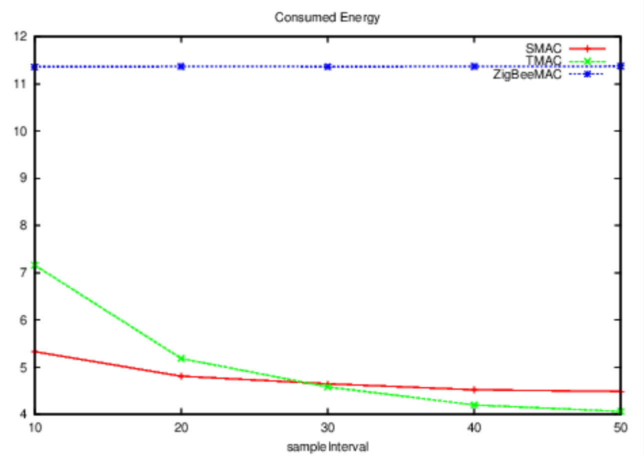

Figure 3. Energy Consumption vs Sample Rate CC2420

Figure 3 shows the results of the MAC Test 2 simulation, implementing the CC2420 radio model. The trend is very similar to the first test, where ZigBee maintains a steady value over the course of the simulation, SMAC starts as the lowest initial power consumption that despite the decrease in power consumption, tends to maintain a steady course and it is probably due to fixed duty cycle that keeps a regular idle listening waste of power. TMAC manages to quickly drop its power consumption reaching the lowest amount of the three after a sample rate of 30ms and maintaining a steep, regular decrease over the duration.

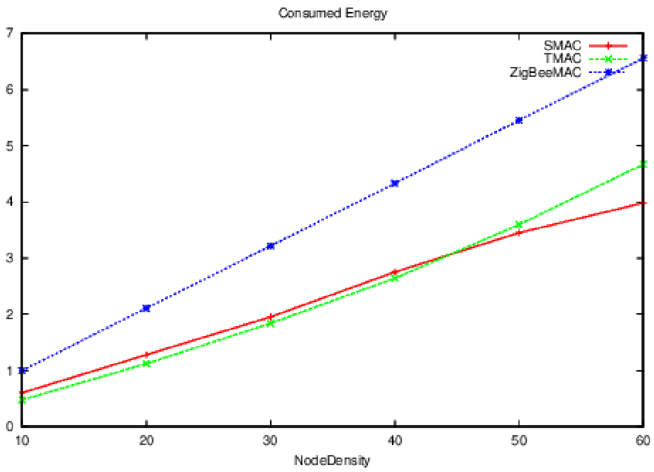

Figure 4. Energy Consumption vs Node Density CC1000

Figure 4 describes the results of MAC Test 3. It was observed that ZigBee maintains a regular increase in power consumption as the node density increases. TMAC and SMAC begin with almost identical values but as the density reaches higher values, SMAC performs slightly better and this is probably due to the increase in risks for TMAC of generating early sleeping problems, oppositely to SMAC which lowers the risks of idle listening as the number of nodes increases.

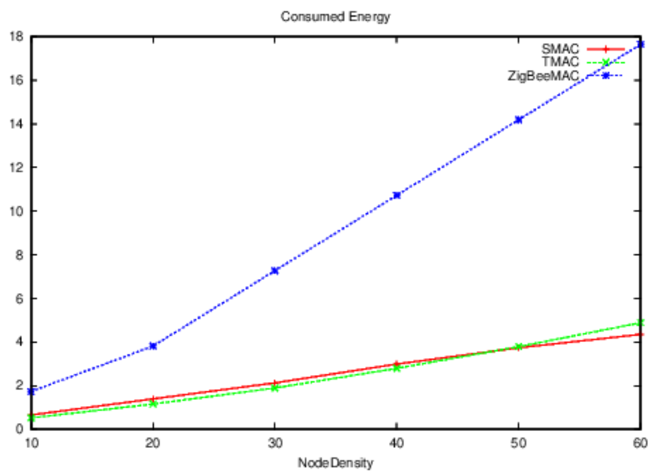

Figure 5. Energy Consumption vs Node Density CC2420

Figure 5 outlines the results of MAC Test 4, using the CC2420 radio model. It was observed that ZigBee increases its consumption even more than with the CC1000 model, reaching almost double its previous energy consumption, probably correlated with the natural higher transmission rate and frequency of the CC2420 model. However, SMAC and TMAC performed very similarly to the previous test, with SMAC performing better once again as the number of nodes increases.

V. CONCLUSION

All simulations produced different results but similar trends as to how protocols react to increasing sample rates and node density.

It is always important to note that the use of the protocol depends on the situation where they will be used. ZigBee is more suitable for larger situations where it can offer several solutions, while TMAC does not scale as well as SMAC and SMAC has issues with latency and throughput and its staticness can lead to performance issues.

However, the results show that with a relatively low number of nodes and a sample rate above 30ms, TMAC can outclass both protocols in power consumption by far, while SMAC is able to perform best as the number of nodes increases.

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