A PERFORMANCE EVALUATION OF THE SMAC PROTOCOL

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ABSTRACT

In this paper we study the main performance characteristics of SMAC, a media access control protocol for sensor networks (WSN). SMAC was designed keeping in mind the characteristics of energy scarcity and processing capacity of the sensor nodes and achieves reduction in energy consumption at the expense of other performance parameters such as delay, throughput and bandwidth usage. Our contributions through this work are: first,a model of physical layer corresponding to the transmitter/receiver CC2420 radio including a model of energy consumption and a model of the SMAC protocol based on the specifications of the authors implemented in Qualnet® and second, a detailed analysis of protocol performance based on different metrics. Through our study we provide to designers of sensor networks operating parameters and performance information.

Keywords: throughput, latency, wireless multimedia sensor network, medium access control - MAC.

1. INTRODUCTION

A wireless sensor network - WSN, is composed of a set of sensor devices of different types, with different useful features to collect information from an environment. WSN are considered a particular type of ad hoc network composed of hundreds or thousands of simple and inexpensive devices (sensor nodes) cooperating to establish and maintain the network, measure and monitor physical parameters of the environment where they are deployed. According to application requirements and characteristics of the environment, the sensor nodes could process in any way the collected information and perform tasks such as reconfiguration, routing, etc.; or simply operate as information gatherers. The range of applications is very broad and may include wildlife monitoring, detection of structural defects, security, agriculture, health, etc. Although it is a relatively new area of research it has generated much interest in the academic community, given the large number of applications in which the WSN prove to be useful. However, although the state of art of the area is changing rapidly, there are still many challenges to overcome.

A special feature of the sensor nodes that make up the WSN is that they are devices with very limited resources. Among the resources that stand out for their rarity in these nodes are, energy mainly because these nodes are powered by batteries and in some scenarios recharging or replacing is an impossible task, memory storage and processing capacity. These aspects are primarily responsible for the protocols used in these networks must be carefully optimized to prolong their life. For this reason the traditional stack of TCP/IP protocols used on the Internet and most of today's networks is inadequate for WSN, especially for the large number of headers that are transmitted with each packet. It is then necessary to use different protocols used in TCP/IP networks in each of the layers, specially designed keeping in mind the optimum energy consumption, in addition to its simple operation.

In WSN and ad hoc networks generally the tasks associated with transmitter/receiver radio are responsible for the increased power consumption [1-2], so the media access strategy is one of the most critical aspects when optimizing the operation of the network. While in operation within the network, these radios can be in one of four modes: transmitting, receiving, listening (but not receiving or transmitting data) or off (low power mode). It has been adopted as the primary method to put the radio off mode as long as possible to achieve further reduction in power consumption.

The following causes have been identified as the major causes of energy waste [3-5]:

- **Collisions:** When a packet is corrupted by a collision it should be discarded, making it necessary retransmission, generating additional energy consumption.
- **Over listening:** (Listening transmissions directed to other destinations). Since the transmission medium is broadcast, nodes receive packets that are destined for other nodes, which should be discarded.
- **Overhead and control packets:** Send and receive control packets can mean additional energy consumption. It is therefore necessary to use the fewest possible headers, as the minimum amount of control packets.
- **Idle listening:** (Listen when there is nothing to hear). A node in this state is ready to receive a package that probably has not been sent. This is a state of considerable energy consumption, which should be avoided when there is no data to receive.

Although many aspects of sensor networks and some others regarding the SMAC [3] protocol have already been investigated [6], in this article we present a detailed performance evaluation of SMAC protocol proposed by the SCADDS group of the USC/ISI [7] also complement the work already done. We give light on the performance characteristics of the protocol, which to our knowledge have not been presented in the literature found.

2. THE SMAC PROTOCOL

SMAC is the medium access control protocol for sensor networks most cited in the literature. This protocol has as main objective, the conservation of energy and network auto configuration; latency, transmission speed and bandwidth utilization have lesser importance. SMAC aims to reduce energy consumption attacking its four main sources of waste: collisions, over listening, overhead andcontrol packets and idle listening.

SMAC protocol supposesthat in sensor networks applications, nodes remain inactive for long periods of time, due to events of interest occur infrequently. Because of this, generation rate packets on the network is very low and during these long periods of inactivity is more appropriate to keep the nodes in a state of low power consumption. SMAC put the nodes in idle mode periodically as shown in Figure-1. Each node is in an inactive state for some time and then moves to the active state to hear if any other node wishes to communicate. These periods allow idle states substantially reduce energy consumption in the network, but the price paid is a further increase in transmission delay.

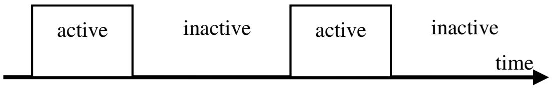

Figure-1. Active and inactive states in SMAC [3].

In SMAC a complete cycle is defined as a frame and includes an inactive period and another inactive period. The active interval is defined taking into account the characteristics of the physical layer, the parameters of the MAC layer, the bandwidth of the radio and the size of the contention window. All nodes are free to choose the start time of the frame.

Since in a multi-hop network not all neighboring nodes can be synchronized together two neighboring nodes may have different scheduling frame. Each node must make sure to speak to each of its neighbors, even if they have different timing. In Figure-2, for example nodes A and B may have different frame timing given that communicate with different nodes C and D. When A wants to communicate with B, it must wait until B starts its active period.

Figure-2. A and B nodes have different synchronization time

During the active period nodes contend for access to the medium. The nodes inform their neighbors about their scheduling sending a synchronizationpacket-SYNC-periodically to all (broadcast) at the beginning of the active period. To avoid collisions SMAC follows a similar to 802.11procedures, including virtual and physical carrier sensing and an exchange procedure of RTS/CTS packets to fix the problem of hidden terminal.

Each time a packet is transmitted, a field indicates the rest of the transmission delay. When any node receives a packet destined to another, check how long the channel is busy and stores this value in a variable called NAV (Network Allocation Vector). Then, the node puts a timer and turn off your radio to save power. Before each transmission node checks the timer status to ensure that there is no transmission in progress; this is called virtual carrier sensing,but additionally the physical sensing this is done too. The channel is considered free if in both cases node has success.

Communication between transmitter and receiver has the following sequence of packets, RTS/CTS/DATA/ACK, when the exchange of RTS/CTS is successful the two nodes use the next sleep period for packet transmission. Figure 3 shows the communication process when the node A wishes to transmit a data packet to node B.

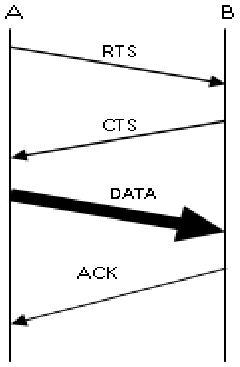

Figure-3. Packets exchange between nodes A and B.

Each node maintains a table to schedule frames which stores the programming of all neighbors it knows. To synchronize your own frame each node follows these steps:

- Initially hear channel during a fixed amount of time, which is at least equal to a full period (one frame). If it hear no SYNC choose its frame and start to follow. In addition it announced its frame regularly through a SYNC package.
- If the node receives a SYNC from another node before announcing its own or start following other; then follows this and announce it in the next period. That is, discardsits own.
- If the node hears a new SYNC, but before scheduled, announced its own and also already has neighbors then it must take the two frames. If it did not have neighbors discards all frames and follows the new.

In order that the nodes receive synchronization and data packets, the listening interval is divided into two parts, one for synchronization and one for data packets.

Figure 4 shows the distribution of the listening interval and illustrates the exchange of packets between receiver and transmitter.

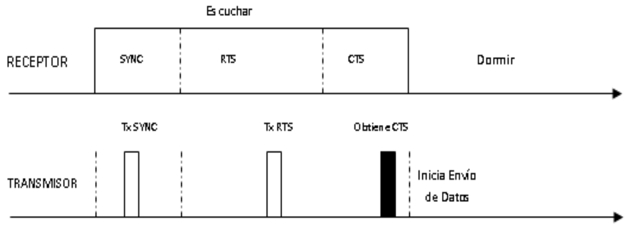

Figure-4. Distribution of the listening interval.

Adaptive listening

The network delay is proportional to the length of the frame and is generally high. To improve this situation in the protocol a mechanism called adaptive listening is implemented. It works as follows: when an event occurs some nodes attempt to transmit data bursts and therefore some hear many transmissions; these nodes are left in a state of active for an additional period of listening to broadcast data immediately should be the next leap in the way of these. If they do not receive anything during the adaptive period again they return to idle state until its new period of activity begins.

It can be shown that the average delay introduced by N hops in the network without adaptive listening is given by the following equation:

$$E[D(N)] = NT_f - \frac{T_f}{2} + t_{CS} + t_{tx} \qquad (1)$$

Where:

T_f : Time length of the frame.
t_{CS} : Time delay introduced by the physical sensing of the carrier.
t_{tx} : Transmission delay between two nodes.

The average delay introduced by N hops in the network with adaptive listening period is given by the following equation:

$$E[D(N)] = \frac{NT_f}{2} - \frac{T_f}{2} + 2t_{CS} + 2t_{tx} \qquad (2)$$

From there it can guess that the average delay with adaptive listening grows softer than without it.

3. SMAC IMPLEMENTATION IN QUALNET

The implementation of S-MAC protocol was performed in Qualnet® version 4.0 according to the description of the protocol presented in [3], an implementation developed by the authors in NS-2 version 2.28 [8] and sQualnet [9]. The S-MAC communication with other network layers is via the APIs included in QualNet making it compatible with other protocols of different levels of the stack. In addition to the standard APIs to communicate with the physical layer, which include functions for sending and receiving packets between the two layers, an additional feature that allows the change of state of the physical layer from the MAC layer to include control on and off the radio. The function that performs the state change is within the physical layer model. S-MAC model implemented uses the adaptive listening mechanism to reduce delay in multi-hop as described in the previous section.

In simulations a duty cycle of 10% was specified, for exchanging of synchronization packets a contention window of $32ms$was set and for data exchangesa window of $63ms$. With the duty cycle and the windows of contention specified the duration of a cycle or frame is 1.144 seconds. To validate the model the results obtained were compared with those obtained by the authors with the model written in NS2 with the model Qualnet 4.0.

Implementation of the physical layer model

At the level of physical layer a model it was implemented to simulate the Chipcon CC2420 radio transceiver designed for low-power wireless applications [10]. The physical layer CC2420 model can use a receiving packets model based on the threshold of the signal to noise ratio, which was used in the simulations, or one based on the bit error rate. The radio can be in one of five possible states: "idle", "sensing", "receiving", "transmitting" or "sleep". The "sleep" state simulates the radio turned off, in this state cannot receive or transmit packets. The characteristics of the model fit the CC2420 radio specifications; the main parameters are presented in Table-1[11].

Table-1. CC2420 radio transceiver characteristics.

Parameter	Value
Transmission power	10dBm
Sensitivity	-95dBm
Reception threshold	-77dBm
Transmission bit rate	250kbps
Time from Tx to Rx mode	195µseg
Energy consumption	59.1 mWin Rx state 91.4 mWinTx state 59.1 mWin “Idle” state 15 µWin “Sleep” state

* A Temperatureof 25 °Cis assumed.

Furthermore, the model implemented can calculate thepower consumption of the node during simulation. The calculation of the energy consumed is based on the time of the node in each of the states.The total energy consumed since the beginning of the simulation to the time t_n can be simply expressed as:

$E_{t_n} = \sum_i E_i t_i$(3)

Where

E_{t_n} = Energy consumed by the node to the timet_n.
E_i = Average energy consumed during state i.
t_i = Time in state i.

The power consumed in each of the states is shown in Table-1. The energy consumption during simulation is updated dynamically in each state change.

4. PERFORMANCE EVALUATION AND SIMULATIONS RESULTS

This section describes the chosen simulation scenario for our evaluation and the results obtained. I was chosen a linear network configuration in which the performance of the protocol with light and heavy traffic was analyzed. This configuration despite being simple is sufficient to evaluate the main features of the protocol. We define a scenario of heavy traffic, as one in which the period between packet generation in sources is less than or equal to a frame.

Implementation of linear network with constant traffic

The chosen scenariois a linear network with 11 nodes and 10hops as in Figure 5. The node 1 operates as source and node 11 operates as a sink. A traffic source added to the node 1 sends packets to the node 11 at a constant rate (CBR). In Table 2the simulation parameters are summarized.

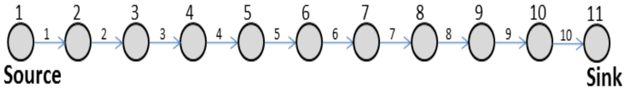

Figure-5. Linear network.

Table-2. Simulation parameters.

Traffic type	Constant bit rate (CBR)
Packet size	100 bytes
Data generation interval	1 to 10 seconds
Routing	Static
Duty cicle	10%

The intervaltime to send packets from the CBR source was varied from 1 to 10 seconds. The evaluation metrics chosen in this article were: energy, delay, throughput, delay variation and queues length.

Energy consumption

The chosen simulation time was 3000 seconds, so that at least 200 packages were received by the sink. Figure 6 shows the average power consumption for each simulation with respect to data generation interval at source. These values correspond to the average energy consumed per node.

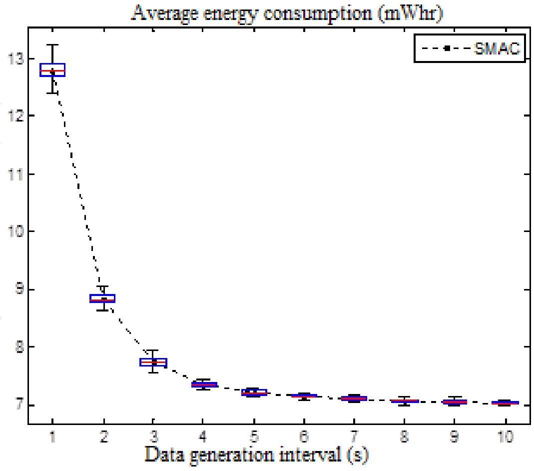

Figure-6. Average energy consumption at the network nodes.

Notice that as the frequency of packet generation at the source increase, also the energy consumption and thevariabilityofenergy consumption increases in each simulation. The length of the choose frame is 1.14 seconds, so we believe that for equal intervals between sending packets or less than 1 second, the network traffic is heavy. Under conditions of heavy traffic network metrics evaluated in this article may have greater variation and show poor performance.

Delay

Adaptive listening was used in all simulations, and the average delay found agrees with the expectancy, as shown in Figure-7. For intervals of sending greater than a frame, the average delay is around 4.5secondsfor this scenario, since under these conditions the traffic is light. While for heavy traffic conditions, the delay is growing rapidly and its variation as well. It should be noted that the additional delay occurs by long waits in queues of nodes.

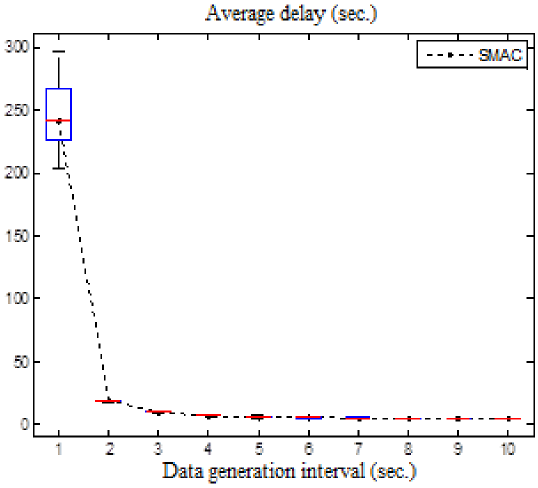

Figure-7. Average delay from source to sink.

Throughput

SMAC is a medium access control protocol designed for applications of sensor networks with low traffic and delay tolerant. In our simulation scenario by simple intuition one can see that the maximum flow expected arrival is equal to the size of each packet divided by the time between data generation interval at the source. As shown in Figure 8 in our simulation the arrival throughput tends to the expected value for packet generation intervals greater than a frame in the source, it means for light traffic. As the frame size decreases the arrival throughput differs from the expected value and variability also grows.

Although the physical layer model supports transmission speeds up to 250 kbps, channel utilization is affected by two reasons. First because the duty cycle is 10% and second because SMAC allows each node to transmit at most 2 packages for a frame when the adaptive listening mechanism is used.

Delay variability and queue length

The results of our simulation show greater variation of delay fordata generation intervals value close to the frame length. For extreme values a variation of delay smoother and less variance is observed, as shown in Figure-9.

A key parameter in network performance is the size of the queues at the nodes for different operating scenarios. The size of the queue can influence the reliability in the delivery of packages and size of storage required at the nodes. Figures 10 and 11 show the average queue length at the source node and intermediate nodes in the transmission path of the packets. Note that the average size of the queues at intermediate nodes is much larger than the average size of the queue at the source. On the other hand, this size varies much more for heavy network traffic.

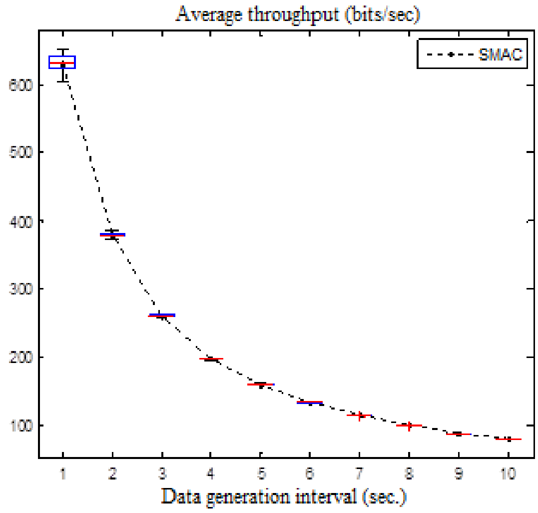

Figure-8. Average throughput.

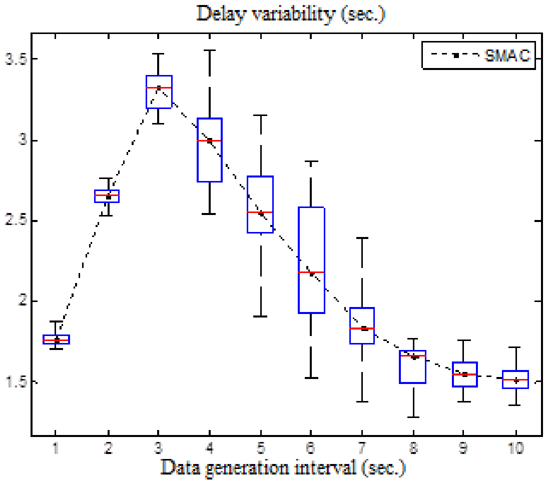

Figure-9. Delay variability.

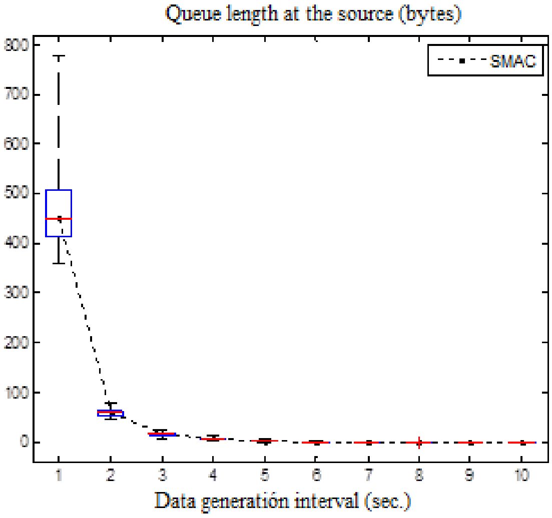

Figure-10. Average queue length at the source.

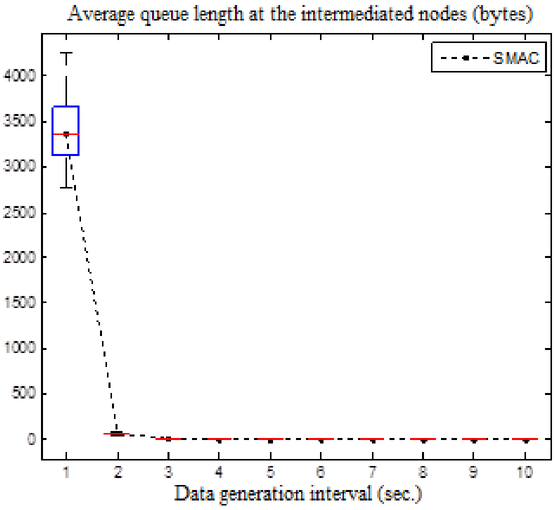

Figure-11. Average queue length at the intermediated nodes.

CONCLUSIONS

This article presents a simulation study of the SMAC protocol using Qualnet® version 4.0. Specific details of the implemented models in this simulation tool are presented. The results of this study and the implemented models allow to revealing the relationship between energy consumption, delay, throughput, delay variation and long queues. This can be useful for sensor network engineers when adjusting its design parameters. Notice that the performance of SMAC is very traffic on the networkdependent. For heavy traffic performance metrics studied here show deterioration. Finally it is concluded that SMAC can perform well in light traffic applications with scalar sensors and delaytolerants, such as agriculture in the measurement of temperature, pH and other environmental variables.

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