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# An Energy-Efficient MAC Protocol for Wireless Sensor Networks for Wide Area Large Scale Environmental Monitoring

**Miguel A. Erazo, Ing**
*Student of Computer Engineering, University of Puerto Rico at Mayagüez, Mayagüez, Puerto Rico, miguel.erazo@ece.uprm.edu*

**Yi Qian, PhD**
*Professor in Computer Engineering Department, University of Puerto Rico at Mayagüez, Mayagüez, Puerto Rico, yi.qian@ece.uprm.edu*

## Abstract
In this paper, we propose a new energy aware medium access control (MAC) protocol for wireless sensor networks with wide-area large scale environmental monitoring applications. The proposed MAC scheme is specifically designed for wireless sensor networks that follow a query-based data gathering paradigm and at the same time takes into consideration event-based data packets. Latency and energy studies are detailed for analysis. The proposed wireless sensor network MAC protocol is tested using simulations

## Keywords
Wireless Sensor Network, MAC Layer Protocol, Energy Aware

## 1. Introduction

Wireless sensor networks have recently come into prominence because they hold the potential to revolutionize many segments of our economy and life, from tasks as surveillance, to widespread environmental monitoring, to manufacturing and business asset management, to automation in the transportation, to security, and health-care industries. They can be used in virtually any environment, especially in those where wired connections are not possible, the terrain inhospitable, or physical placement difficult. Wireless sensor networks consist of battery-operated sensor devices with computing, data processing, and communicating components. Energy conservation is a critical issue in wireless sensor networks since batteries are the only limited life energy source to power the sensor nodes.

Like in all shared-medium networks, medium access control (MAC) protocols enable the successful operation of the network. The MAC protocol in a wireless sensor network must achieve two goals. The first is the creation of the network infrastructure. Since thousands of sensor nodes are densely scattered in a sensor field, the MAC scheme must establish communication links for data transfer. This forms the basic infrastructure needed for wireless communication hop by hop and gives the sensor network self-organizing ability. The second objective is to fairly and efficiently share communication resources between sensor nodes.

Constraints on energy resources made researchers look for energy-efficient MAC protocols. Several MAC protocols for wireless sensor networks with an ultimate goal of increasing the network lifetime by conserving energy have been proposed in the literature.

Our goal in this paper is to develop a new MAC protocol for wireless sensor networks deployed for wide area environmental monitoring. In our scheme, sensors are organized into virtual clusters after deployment (Ye, 2004). After synchronization, they will follow an adjustable second listen-sleep schedule based on the former schedule. As will be explained later in this paper, this will reduce the energy spent on idle listening. Nodes only wake up on specific times when a sample of an environmental variable is to be taken. If events that occur between two samples meet a given criteria a packet is generated and nodes wake-up so the packet can be transmitted to the nearest Base Station. In this way, query and event based packets are transmitted with the primary goal of reducing energy consumption.

The main contributions of this paper are:

- Design of a listen-sleep schedule that works on top of previously negotiated schedule in similar fashion as that of S-MAC (Ye, 2004). With this, it is intended to simplify re-synchronization activities; which consume energy resources and plenty of time to complete.
- Design of a mechanism to wake up nodes only when event-based packets are generated.
- Comparison of the proposed scheme's performance with S-MAC in terms of energy consumption and throughput.

In the remainder of the paper, a brief survey of related works is presented in Section 2. The detailed description of our new MAC protocol is in Section 3. Performance analysis and simulation results are presented in Section 4. Finally, the conclusions are discussed in Section 5.

## 2. Related Work

Many energy efficient wireless sensor network MAC protocols have been proposed in the past. Most of them use a contention mechanism for nodes to transmit in the shared medium. The CSMA mechanism is widely used for the contention based MAC protocols.

Ye et al., 2004, proposed S-MAC, a medium access control (MAC) protocol designed for wireless sensor networks. S-MAC uses a few novel techniques to reduce energy consumption and support self-configuration. It enables low-duty-cycle operation in a multihop network. Duty Cycle (DC) is the ratio of the time the radio is *on* to the duration of a cycle. Nodes form *virtual clusters* based on common sleep schedules to reduce control overhead and enable traffic-adaptive wake-up. Finally, S-MAC applies *message passing* to reduce contention latency for applications that require in-network data processing.

Dam et al., 2003, proposed T-MAC, a contention-based Medium Access Control protocol for wireless sensor networks. To handle load variations in time and location, T-MAC introduces an adaptive duty cycle in a novel way: by dynamically ending the active part of it. This reduces the amount of energy wasted on idle listening, in which nodes wait for potentially incoming messages.

Lu et al., 2003, proposed D-MAC, a protocol whose objective is to achieve very low latency and still be energy efficient. The solution proposed is a *staggered active/sleep* schedule. Low latency is achieved by assigning subsequent slots to nodes that are consecutive in the data transmission path. With this scheme it is expected that a packets do not suffer from sleep delay at all because the next intended receiving node must always be awake when transmitting node wants to transmit a packet to it.

Mainwaring et al., 2002, provide an in-depth study of applying wireless sensor networks to real-world habitat monitoring. A set of system design requirements are developed that cover the hardware design of the nodes, the design of the sensor network, and the capabilities for remote data access and management.

## 3. The Proposed MAC Layer Protocol and Analysis

The proposed protocol is described in this section. First, protocol basic overview is explained. Then, the new synchronization scheme is detailed as well as the corresponding energy consumption. Finally, the proposed mechanism to meet the requirements of triggered packets communication is analyzed.

### *A. Overview of the Proposed Protocol*

The objective of this protocol is to save as much energy as possible in transmitting packets from nodes to the base station while fulfilling all the requirements of a wireless sensor network. The basic assumption is that most traffic is correspondent to periodic samples of environmental variables like temperature or humidity. This is a reasonable assumption if we think of a sensor network for environmental monitoring based on queries where samples are taken periodically to collect statistics for further analysis.

It is important to characterize the classes of data traversing the network. *Sampling* data is obtained by sampling a certain parameter a given number of times every day while *triggered* data is disseminated after a certain event has happened. Sampling or triggered data is carried in correspondent sampling and triggered packets. We will further refer to them as *packets* instead of *data*.

Initially, after the nodes have been deployed, nodes organize themselves into virtual clusters according to a clustering algorithm that is similar to the algorithm proposed in (Ye, 2004). Each virtual cluster will have its own synchronization scheme. Later, proposed protocol assumes a second layer of synchronization that will run on top of the first one. This second layer of synchronization is the one proposed in this paper.

Proposed Synchronization scheme will save energy and meet the requirements of sampling packets generated periodically by each node. The basic idea is that nodes in the network should only be awake when samples are about to be taken from the environment. The rest of the time, node must be slept to prevent energy consumption in idle listening.

To meet latency requirements of triggered packets it is also proposed a mechanism that is useful to wake up the network to disseminate triggered packets. It is the objective that triggered packets be disseminated and reach the Base Station with minimum latency; but optimizing the energy consumption as well. For this purpose the mechanism introduced a new time variable called *Tone Time*. Nodes which have generated triggered packets signal other nodes to wake up in this time interval.

### *B. New Synchronization scheme*

The proposed synchronization scheme has two objectives: 1) Make the synchronization be configurable to meet the requirements of specific applications with the appropriate choice of parameters and 2) Meet the requirements of sampling packets by allowing nodes to send the packets at specific times, saving energy by avoiding idle listening.

In order to make the synchronization scheme configurable, it must be easy to change the parameters. Thus, we made this new synchronization sit on top of S-MAC-like synchronization. Synchronization must make nodes to awake only to disseminate sampling packets. Figure 1, shows the proposed synchronization scheme.

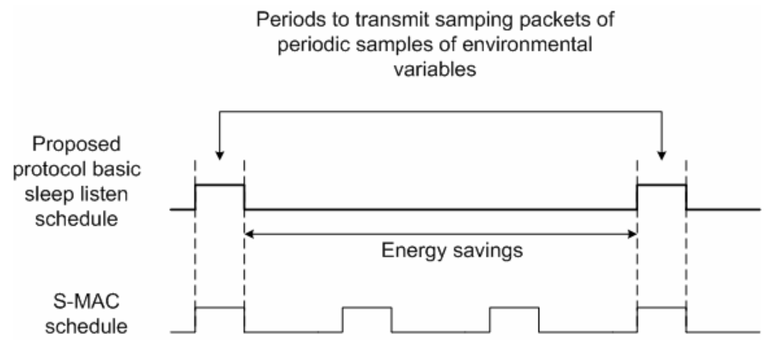


**Figure 1. Basic synchronization of Proposed Protocol**

A single active period (radio turned on) may not be enough to disseminate a packet from the source node to the Base Station, particularly in multi-hop networks. In this way, a synchronization that takes into account this fact must be configured to meet the objectives. Figure 2 shows an improved synchronization scheme from that shown in Figure 1, which has more than one active period.

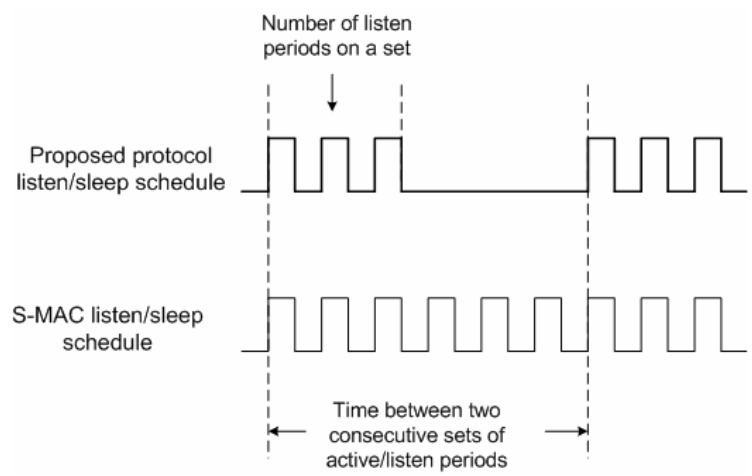


**Figure 2. A more efficient synchronization**

Figure 2 plots a more efficient synchronization that saves energy by avoiding idle listening and makes it be configurable by setting different *Number of SMAC-Listen periods in a set* and/or *Time between consecutive sets of active listen periods* (see Figure 3).
The completed characterization of the proposed synchronization is shown in Figure 3.

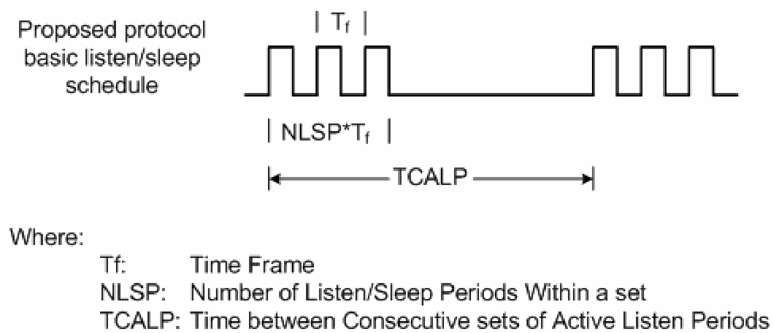


**Figure 3. Time intervals in basic proposed listen/sleep schedule**

*C. Mechanism for Triggered Packets*

The synchronization proposed in Figure 2 is not adequate for triggered packets since such packets must meet the requirement of the minimum latency. With the synchronization shown in Figure 2, triggered packets would suffer a long delay since they would have to wait a time in the interval [0, TCALP-NLSP*$T_f$] to be transmitted. In the following paragraphs a solution for this issue is proposed.

The proposed energy efficient MAC protocol introduces a new time interval to be used for a node that has detected an extraordinary event to signal other nodes in the wireless sensor network that there are triggered packets that need to be disseminated through the network as soon as possible. With this scheme, triggered packets will be sent in the next active listen period of the underlying S-MAC synchronization (see Figure 1). The proposed approach is plotted in Figure 4.

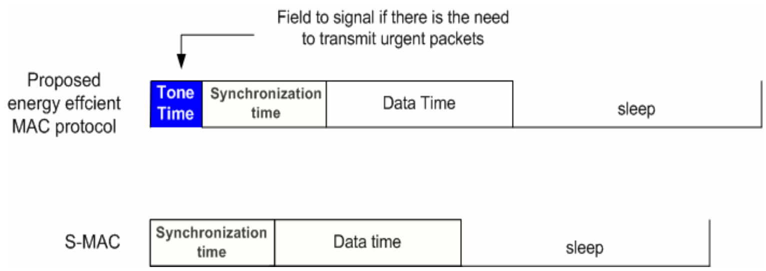


**Figure 4. Proposed energy-efficient protocol vs. SMAC listen- time structure**

Figure 5 shows how this mechanism works:

- A node that has sensed an interesting event generates a triggered packet.
- If the node has its radio off, then it signals other nodes in Tone Time to wake up by sending a very small packet that we call *tone-packet* (see Figure 5).
- A node that receives a tone-packet wakes up and at the same time broadcast another tone packet in Tone-Time.
- The Triggered packet is sent in Data Time.

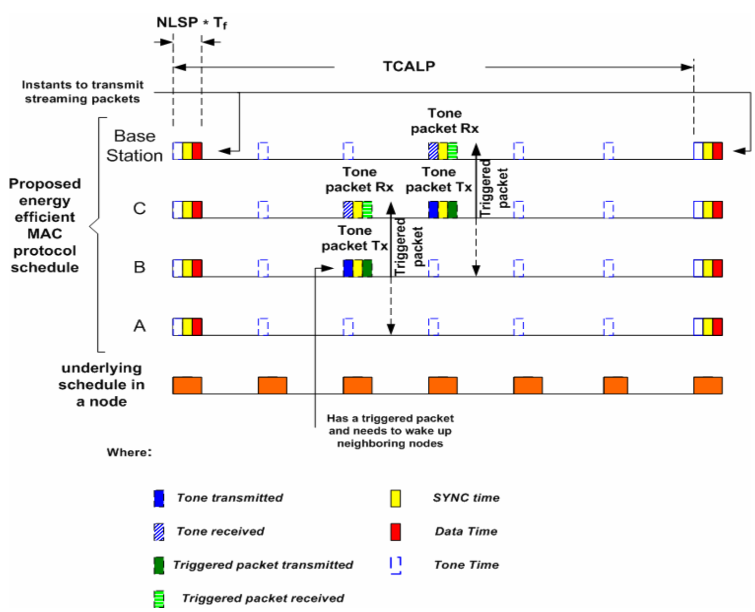


**Figure 5. Energy efficient MAC protocol listen/sleep schedule optimized to avoid idle listening and decrease latency, collisions and queue usage for triggered packets.**

*D. Energy Analysis for Proposed Synchronization scheme*

In this section, we analyze the energy consumption of the proposed MAC protocol. In the analysis we use a simplified network configuration shown in Figure 6.

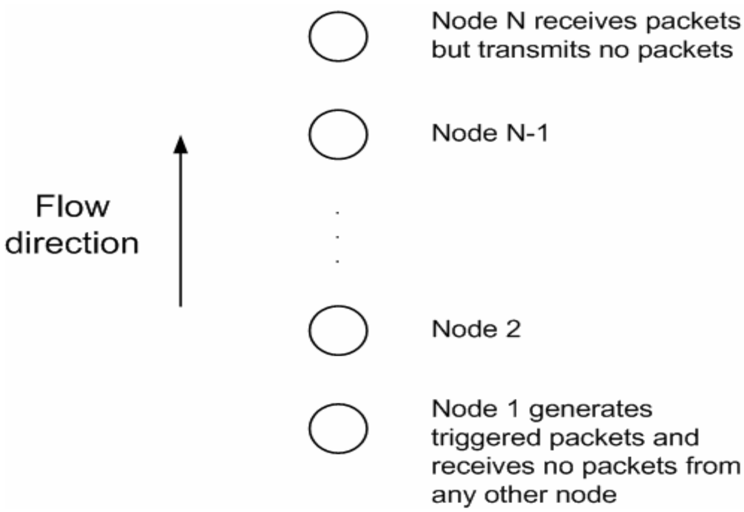


***Figure 6. Configuration used for analysis***

Following are the assumptions made for energy analysis:

- Sampling packets are small enough to be transmitted in a single listen interval
- Only one node in the network generates sampling packets (node 1)
- There is a route from the nodes to Base Station (node N)
- Each node has only two neighbors (except node 1 and N)
- There is no collisions
- There is no retransmissions

We define the following items:

$\rho(n)[\frac{packets}{s}]: Rate\ of\ packets\ sampled\ by\ second\ in\ node\ n$

$E_{IL}(n)[joules]: Energy\ spent\ in\ idle\ listening\ in\ a\ T_f\ in\ node\ n$

$E_{TX}(n)[joules]: Energy\ spent\ in\ transmitting\ a\ packet\ in\ node\ n$

$E_{RX}(n)[joules]: Energy\ spent\ in\ receiving\ a\ packet\ in\ node\ n$

$E_{ON}[joules]: Energy\ spent\ to\ turn\ on\ radio$

$T_0(n): Period\ of\ observation\ n$

$E_S(n)[joules]: Energy\ spent\ on\ sleep\ time\ within\ a\ T_f\ in\ node\ n$

$N: Number\ of\ nodes\ in\ the\ network$

*E(n):Energy consumed in node n in the period of observation $T_0$*

*TCALP: Time between Consecutive sets of Active Listen Periods (see Figure 3)*

*NLSP: Number of Listen Periods within a TCALP (see Figure 3)*

$E_{TONE}$ *: Energy consumed by a node in idle listening in a Tone Time (see Figure 3)*

$\frac{T_0}{TCALP} NLSP$ *: Number of active listen periods on $T_0$*

$\frac{T_0}{TCALP} NLSP - 2\rho T_0$ *: Number of active listen periods*

The energy consumed in node n:
*E(n) = Energy-transmit-packets + Energy-idle-listening + Energy-turn-on-radio + Energy-receive-packets + Energy-sleeping* (1)

We can derive the total energy consumed in the network of Figure 6 is:

$$E_N = \sum_{n=1}^{N} E(n) \qquad (2)$$

$$E[E_N] = (N-1)T_0\rho(E_{TX} + E_{RX}) - \ldots$$
$$-(N-1)T_0\rho\rho_{IL}T_D + \frac{N \times T_0}{TCALP} NLSP \times E_{ON} + \ + \frac{N \times T_0}{TCALP} NLSP \frac{\rho_{IL}T_D}{2} + N\frac{T_0}{T_f}E_{TONE} \qquad (3)$$

If we compare these results to S-MAC, we conclude that the condition for the Proposed Protocol to consume less energy than S-MAC is:

$$\frac{NLSP}{TCALP} < \frac{1}{T_f} \qquad (4)$$

*E. Latency Analysis for Triggered Packets*
We use Figure 7 to derive the expression to calculate the latency for triggered packets.

The delay experimented in node *n* since the reception of a packet to the time it is forwarded is:

$$D(n) = t_s(n) + t_{TONE} + t_{CS}(n) + t_{TX} + t_{SYNC} \qquad (5)$$

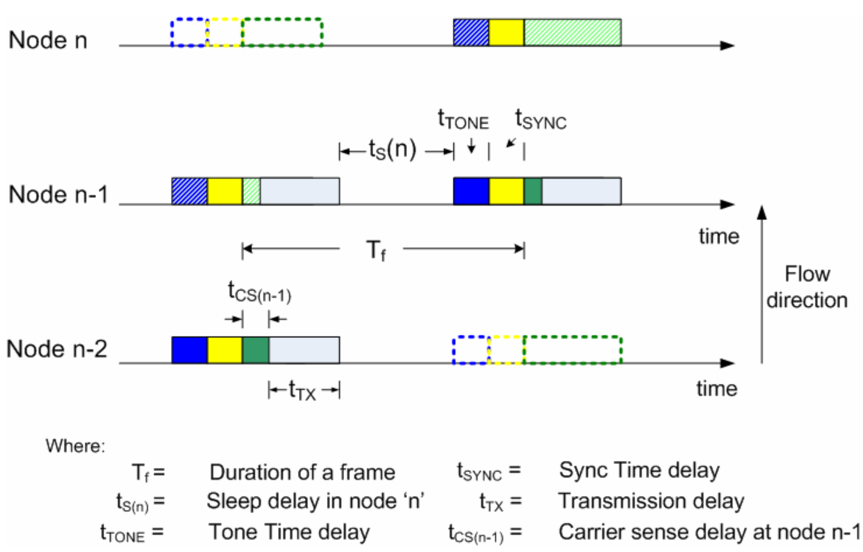


**Figure 7. Identification of existing delays to transmit triggered packets**

The average delay in each node can be expressed as:

$$E[D(N)] = N \times T_f - \frac{T_f}{2} + t_{TX} + t_{SYNC} + t_{TONE} + t_{CS} \qquad (6)$$

## 4. Simulation Results

We have evaluated the Proposed Protocol and compared it to S-MAC using the ns-2 simulator ("The network simulator").

Network simulation is shown in Figure 8 and has the following characteristics:

- Four nodes are placed on a straight line with equal distance of 150 meters.
- Node 1 can reach only node 2, 2 can reach 1 and 3, 3 can reach 2 and Base Station and Base Station only 3.
- The objective of each node is to transmit its data packets to node 3 (the Base Station). Only synchronization and control information is exchanged between neighbors.

Simulation is designed as described in the following:

- Nodes spend about 50 seconds in synchronizing themselves
- Transmission pattern is constant rate which can be described as a constant message inter-arrival time.
- Simulation time (**$T_0$**): Time to send 100 packets[s], max 100000[s]
- Initial energy of each node: 100,000
- Each node use the following parameters in the ns-2 simulator: NLSP =5, StatusModifiedProtocolTimer = 20, syncTime = difs + slotTime * SYNC_CW + durSyncPkt + guardTime, toneTime = 0.6*syncTime.
- All logs are saved in the trace file. The total energy consumed is computed by adding the energy consumed by all four nodes.
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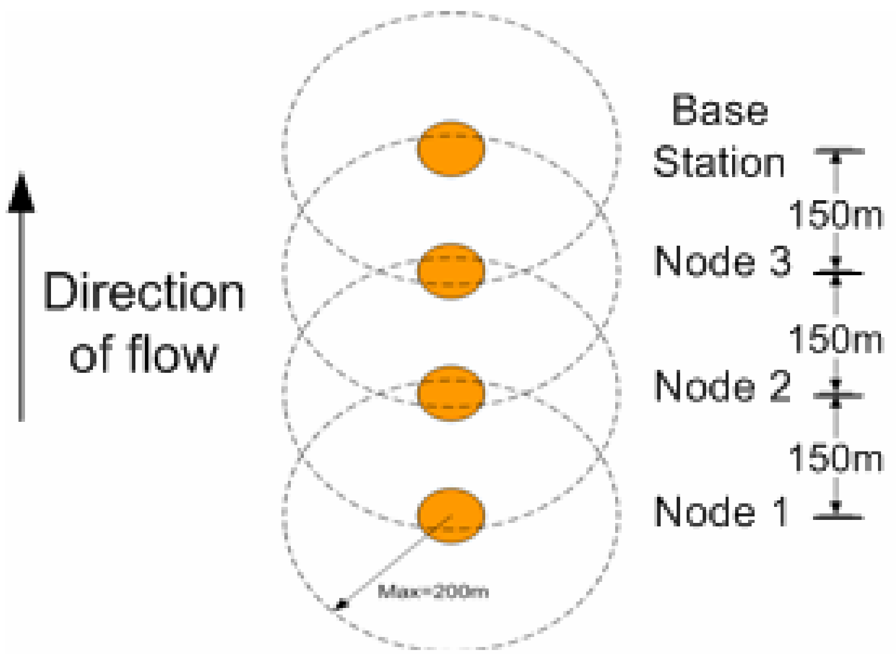


**Figure 8 Network configuration of simulation**

Figures 9 and 10 show the results of the energy consumed vs. the message inter-arrival time at 40 and 50% DC. Message inter-arrival time is the time between two transmissions of the node 1 (see Figure 6).

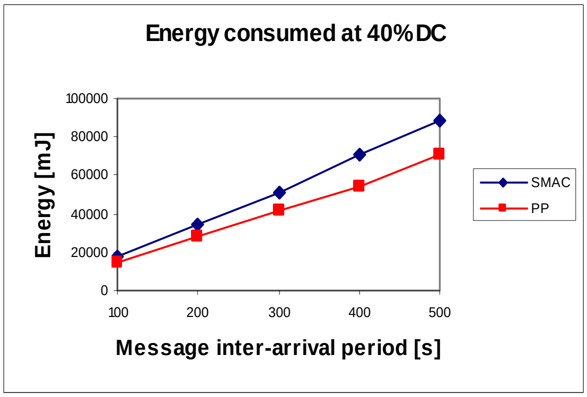


Figure 9: Energy consumption at 40% DC

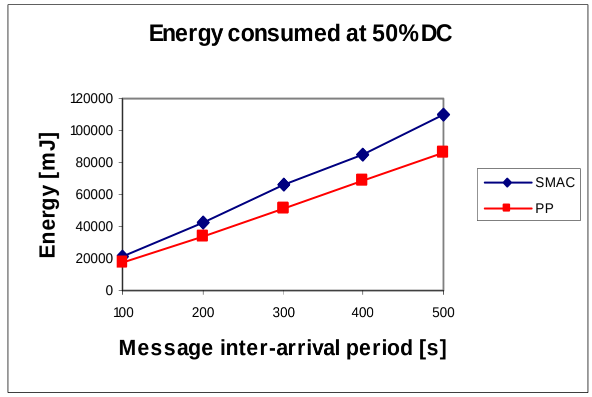


Figure 10: Energy consumption at 50% DC

At a fixed Duty Cycle (DC), the higher the message inter-arrival period the greater the difference between Proposed Protocol and SMAC (the better the proposed protocol is). Figures 9 to 10 show clearly this fact.

From Figure 3, the higher is the message inter-arrival period, the higher is the Time between Consecutive sets of Active Listen Periods (TCALP) and remembering that $T_f$ is constant and so is NLSP, the "better" the inequality (4) satisfies.

The inequality (4) is the basic requirement for energy savings. The more the difference between the two sides of the inequality the more energy savings will result in the wireless sensor network.

Figure 11 shows the energy consumed for different DCs vs. the rate of transmission of node-1 in bits/s.

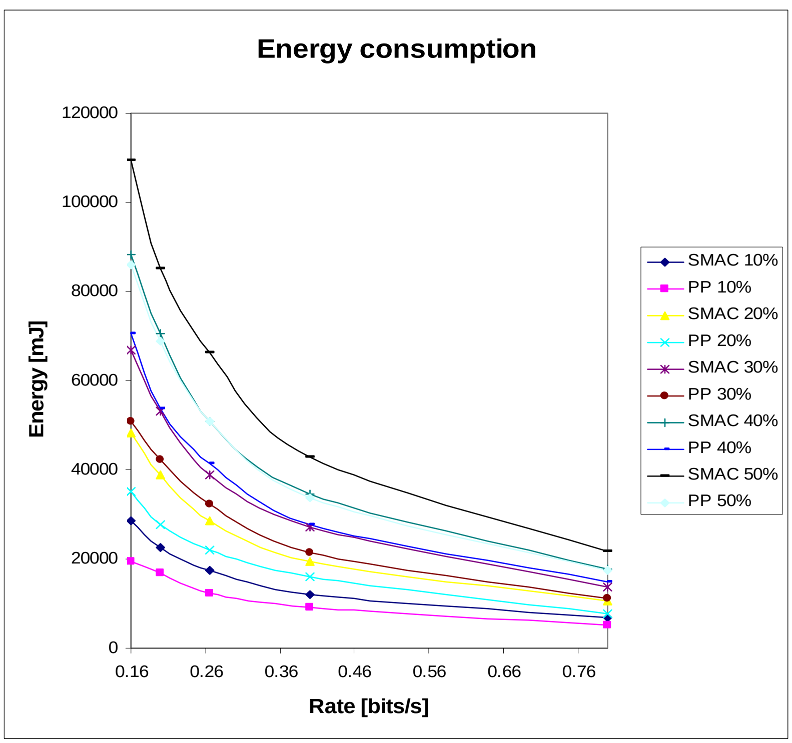


**Figure 11. Energy consumption vs. rate of transmission**

In Figure 11 it is observed that the higher the rate of transmission of packets the less the consumption of energy. This also agrees with equation (3):

$$E[E_N] = (N-1)T_0\rho(E_{TX} + E_{RX}) - (N-1)T_0\rho\rho_{IL}T_D + \ldots \quad + \frac{N \times T_0}{TCALP} NLSP \times E_{ON} + \ldots$$
$$+ \frac{N \times T_0}{TCALP} NLSP \frac{\rho_{IL}T_D}{2} + N \frac{T_0}{T_f} E_{TONE}$$

According to this equation, if rate of transmission increases, $\rho$ increases which makes increase the first term of the equation: $(N-1)T_0\rho(E_{TX} + E_{RX})$. However, the protocol has an anti-overhearing mechanism in which a node goes to sleep if it listens a transmission not intended for it and also a node that transmit a packet simply goes to sleep before the end of the cycle so the higher $\rho$ the less energy is consumed in idle listening, this fact is expressed in the second term of the equation: $-(N-1)T_0\rho\rho_{IL}T_D$.

Thus, the reason why the higher the rate of transmission the less energy is consumed is because the term x $\rho_{IL} T_D$ is more dominant than $(E_{TX} + E_{RX})$. Remember that the majority of energy is consumed in idle listening and not in transmission nor reception of packets.

If the rate increases dramatically, there will be some other effects in the network such as retransmissions due to collisions which have not been included in this analysis. In this case the energy consumption may increase instead of reduce.

## 5. Conclusions

We have proposed an energy aware MAC protocol for wireless sensor networks that gathers data for wide-area large scale environmental monitoring. The scheme saves energy by organizing the networks usage changing the running synchronization. The proposed scheme is observed to perform better in terms of achievable network lifetime and responsiveness to events as compared to similar existing schemes like S-MAC.

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