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MAC Protocol Design Based on Satellites Presence for Low-Energy Wireless Sensor Networks

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Abstract A satellite is a way that allows a system administrator to receive data collected by sensors in different geographical areas. To realize this task, a medium access control (MAC) protocol in sensor networks must minimize power consumption in order to extend the lifetime of sensor nodes. To remedy this problem, we first assumed an architecture based on a Low Earth Orbit satellite and a network of heterogeneous sensors (*Ordinary Nodes 'ONs' and Cluster Heads 'CHs'*). We proposed a MAC protocol, called Satellite Sensor MAC (SS-MAC), which avoids the different causes of energy dissipations. The basic idea behind our protocol is to minimize the number of communications. This number is based on the data quantities collected by each *ON* (or each *CH*) in order to extend the lifetime of *ONs*, which means extend the network lifetime. Our protocol uses four periods: a period for the grouping nodes to form clusters, a Transmission/Reception period between *ONs* and their *CHs*, a period when the satellite allocates slots to *CHs* and a period when *CHs* send their data to the satellite. Finally, the energy consumption in each period was evaluated through its protocol analysis, numerical results and *Markov* chain models. All these results have shown the energy-efficient of the *SS-MAC* protocol.

Keywords Sensor network · MAC protocol · Energy-efficient · Network lifetime · Low Earth Orbit (LEO) satellite · Markov chain

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1 Introduction

A wireless sensor network (WSN) is a specific class of wireless ad-hoc networks in which hundreds or thousands of sensor nodes are collaborating together to accurately measure a physical phenomenon from the environment or to monitor a remote site [1]. The sensor nodes constituting the network are battery-powered devices with limited energy, computation capability and storage [1]. *WSNs* are widely used in many applications such as military target tracking and surveillance [2, 3], natural disaster relief [4], biomedical health monitoring [5, 6], hazardous environment exploration and seismic sensing [7].

The success of a sensor network is heavily dependent on two key resources, namely communication bandwidth and nodes energy [8]. To tackle these two resources, a large body of pioneering research work has been done. Most of this research considers the design of sensor networks where sensors are interconnected via a wireless terrestrial network (e.g. terrestrial base stations). Compared to wireless networks, satellite communication systems offer a multitude of advantages [9–16].

Effectively, in addition to their inherent multicast capabilities and flexible deployment features, satellite systems are able to provide coverage to extensive geographic areas and interconnect among remote networks. As a consequence, there is a major interest to use satellites in large-scale deployment of sensors [17–20].

Due to low power support of sensor nodes, energy efficiency becomes one of the core problem. From analysis of sensor nodes, the communication module is the part consuming most energy, which is the main optimization goal. The medium access control (MAC) protocol directly controls the communication module, so it has important effect on the nodes' energy consumption. Many reasons related to MAC paradigms lead to energy waste and *WSN* life reduction, such as: Collision, Overhearing, Packet Overhead, Overemitting, Idle listening, etc. [21–27].

In this paper, we will take the advantage of using satellites for sensor network deployment, as means of master controllers, to design an efficient and energy-aware MAC protocol for wireless sensor networks called Satellite Sensor MAC (SS-MAC). The aim of this paper is to maximize the lifetime of the network by avoiding major energy waste causes. While saving energy is always of great importance, achieving that goal at the expense of throughput and/or latency unnecessarily compromises the utilization and performance of *WSNs*. Therefore, our MAC protocol focuses on energy conservation, while achieving at the same time high performance in term of delays.

The rest of the paper is organized in the following way. In Sect. 2, we give an overview of the proposed network structure. Section 3 exhibits the details of *SS-MAC*. Section 4 provides an analysis of the proposed protocol together with its advantages. Numerical results are provided in Sect. 5. Section 6 presents a *Markov* chain model to analyze the proposed protocol and it provides a performance evaluation of *SS-MAC*. Finally, Sect. 7 concludes the paper.

2 Overview of the Architecture

The proposed deployment architecture consists of the coverage area of a satellite constellation made by $\boldsymbol{M}$ Low Earth Orbit (LEO) satellites. The satellites are set in an orbit distant from the earth surface by an altitude H. A number of sensor nodes are dispersed over the entire network area. Two types of sensor nodes are considered. Ordinary Nodes (*ON*) are low power, relatively inexpensive, and small-sized sensors. The other type of nodes has complex software and higher hardware with enough power to communicate directly with satellites. As the network is organized into clusters, these nodes act as Cluster Heads (*CH*) and sinks with the *ONs* in their local cluster.

ONs gather the necessary data from the studied field and transmit data directly to their corresponding cluster head. *CH* nodes aggregate data from *ONs* according to specific signal processing functions and send them directly to the system administrator (Base station) via the satellites.

In the followings, some assumptions are made for network model:

- All nodes are immobile, i.e., all nodes remain stationary after deployment.
- The energy of ONs can not be recharged. That means that ON will die if its energy is exhausted.
- All ONs are homogeneous in terms of energy, communication and processing capabilities.
- The ONs can estimate the approximate distance using the received signal strength.

3 SS-MAC Protocol Design

The main goal of a MAC layer protocol [28–30] is to allocate the shared wireless channels among sensor nodes as fairly as possible and to guarantee that no two interfering nodes transmit at the same time. The proposed *SS-MAC* is adapted to the architecture of a global sensor network based on a constellation of *LEO* satellites (see Fig. 1). It exploits the inherent features of Time Division Multiple Access (TDMA) [31, 32], to avoid the main sources of energy wastage: collision and control packet overhead. It uses the concept of periodic listen and sleep in order to avoid idle listening and overhearing. The novel idea in *SS-MAC* is to minimize the number of communication (i.e., Each node is assigned a number of *TDMA* slots. This number is based on the data quantities collected by each ON or each *CH*) in order to extend the lifetime of sensor nodes. *SS-MAC* uses four periods (see Fig. 2): a period for the grouping nodes to form clusters (*Regr-Clu*), a Transmission/Reception (TX/RX) period between *ONs* and their *CHs* ($TX/RX_{CH/ON}$), an Allocation (Alloc) period where the satellite allocates slots to *CHs* ($Alloc_{Sat/CH}$) and a Communication (Comm) period where *CHs* send their data to the satellite ($Comm_{CH/Sat}$).

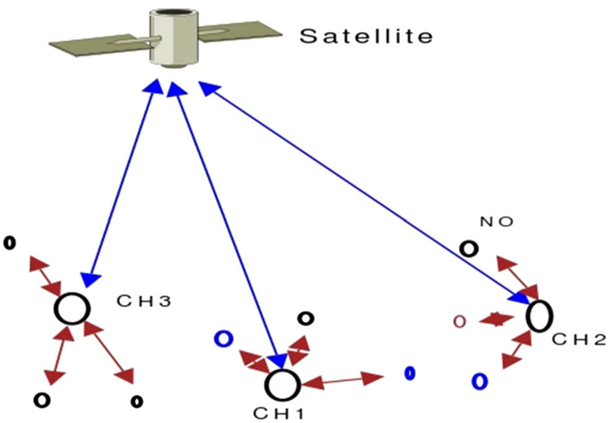


Fig. 1 Satellite sensor network architecture

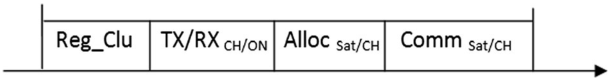


Fig. 2 Frame format of SS-MAC protocol

The time of *SS-MAC* frame is defined by the following formula:

$$T_{frame} = T_{Reg-\mathrm{Clu}} + T_{TX/RX_{CH/ON}} + T_{Alloc_{Sat/CH}} + T_{Comm_{Sat/CH}} \tag{1}$$

In SS-MAC, the ON may be just in one of the four states at any time: Transmission, Reception, Idle and Sleep. In the first state, the ON sends data or other messages to its CH. In the Reception state, the ON receives the different messages from its CH. When the ON is in the Idle state, it does not do anything but its radio is on. In the Sleep state, the ON turns off its radio transceiver and saves its energy.

On the contrary, the second type of nodes (CHs) has only three states: Transmission, Reception and Idle. The CH must be awake all the time in order to manage its cluster.

3.1 Regr-Clu Period

The satellite broadcasts a grouping message for all *CHs*. At the reception of this message, each *CH* executes the proposed Algorithm 1 in order to be organized in clusters. There is no optimal number of clusters in the network. This is because no assumptions about the size and topology of the network are made. The number of clusters depends on the number of *ONs* and *CHs*. In other words, the Number of clusters N_{CHs} depends on the Number of the ordinary nodes N_{ONs} as well as number of the *CHs* according to [33]: $N_{CHs} = \sqrt{N_{ONs}}$. Each *CH* broadcasts the *INVITATION* message across the network, while the *ONs* receive all *INVITATION* messages and decide which *CH* to *JOIN*. The metric for *ONs* to make decisions is the distance metric (see the proposed Algorithm 2), each ON can compute the approximate distance to the *CH* based on the received signal strength.

Algorithm 1 : Send the *INVITATION* message by CH_i

Let CH_i be the cluster head of the $cluster_i$
At the reception of the satellite message coming from the reception channel of CH_i ;
Broadcast (CH_i, *INVITATION* message) ;
For all $ON_j \in Transmission\ Range(CH_i)$ **do**
Send *INVITATION* (CH_i, ON_j) ;
At the reception of *JOIN* message of ON_j ;
$Cluster_i = Cluster_i \cup \{ON_j\}$;
end for

Algorithm 2 : Cluster Head Election

Let *NI* be the number of *INVITATION* message
if $(NI = 1)$ **then**
  Send JOIN (ON_j, CH_i) ;
else
  if $(NI > 1)$ **then**
    For $k = 1$ to *NI* **do**
      $Compute\ minimal\ distance\ (ON_j, CH_k)$
    end for
    NO_j chooses the CH_k that requires minimum communications according to the received signal strength
    Send JOIN (NO_j, CH_k) ;
  end if
end if

3.2 $TX/RX_{CH/ON}$ Period

The $TX/RX_{CH/ON}$ period is divided into three subperiods: a subperiod of *verification* of the number of data packets collected by *ONs*, a subperiod for the *allocation* of slots for *ONs* using SLOT packet and a subperiod *RECeption* to transmit data packet, called REC packet, to the *CH*. In the $TX/RX_{CH/ON}$ period, the time $TX/RX_{CH/ON}$ is as follows:

$$T_{TX/RX_{CH/ON}} = T_{verif} + T_{alloc} + T_{rcv}f \tag{2}$$

Formula (2) indicates that the time of $TX/RX_{CH/ON}$ period is composed of three parts: *Verification* time (T_{verif}), *Allocation* time (T_{alloc}) and *Reception* time (T_{rcv}).

- During the *Verification* subperiod, each *CH* sends Account Query (AQ_{CH}) message to its *ONs* to know the number of collected data. Each ON_i has a buffer and a counter of data called cpt_{ON_i}.

When the *ON* senses data, it will thread this data in its buffer, and it will increment its counter $(cpt_{ON_i} = cpt_{ON_i} + 1)$.

When *ON* receives AQ_{CH} message of *CH*, it will answer by a Response Query (RQ_{ON}) message which contains the source address (ON address), the destination address (*CH* address) and the value of its counter (cpt_{ON_i}).

- The time of *Allocation* subperiod is not fixed, it varies according to the amount of data that cluster's ONs have collected:

$$T_{alloc} = \sum_{i=1}^{n} cpt_{ON_i} \times T_s \tag{3}$$

  The time slots of each ON (called T_{ON_i}) is computed by the following formula:

$$T_{ON_i} = cpt_{ON_i} \times T_s \tag{4}$$

  where T_s is the necessary time to send or receive data of given length.
- During the *Reception* subperiod, ON sends its data to its *CH* in its time slots. As in the case of the *ONs*, the *CHs* have also a buffer where they save their received data and a counter which corresponds to the value of the number of data received (cpt_{CH_j}) which is given by:

$$cpt_{CH_j} = \sum_{i=1}^{n} cpt_{ON_i} \tag{5}$$

When CH receives ON data, it will thread it in its buffer and it will increment its counter:

$$cpt_{CH_j} = cpt_{CH_j} + 1. \tag{6}$$

3.3 $Alloc_{Sat/CH}$ Period

The allocation period between the satellite and the set of *CHs* is not fixed. Before a satellite allocates a time slots, it sends the Account Query (AQ_{Sat}) message to each *CH* in order to know the number of data received by its *ONs* (the time to send a amount of data depends on the counter value).

If *CH* has completed the aggregation of its data, it will answer to the base station by a Response Query (*RQ*) packet, where it includes the value of its counter cpt_{CH}. When the satellite receives *RQ* of CH_i, it will allocate to the latter a time slots equivalent to the value of its counter cpt_{CH_i}. A *RQ* message contains a geographic localization of the *CH* and a cpt_{CH} value.

3.4 $Comm_{\ CH/Sat}$ Period

During this period, *CHs* send their data to the satellite in their time slots. In other words, once the CH receives all the data, it performs data aggregation to enhance the common signal and reduces the uncorrelated noise among the signals. Then, the resultant data are sent from the CH to the satellite.

4 SS-MAC Analysis

This section presents the analysis and benefits of the proposed protocol *SS-MAC*.We first discuss the message complexity of Algorithms 1 and 2.

Lemma 1 *The message complexity of Algorithms 1 and 2, in the network, is O(N).*

Proof The number of *INVITATION* and *JOIN* messages exchanged in the network is upper-bound by $N \times CHs$ where N is the number of nodes in the cluster. Given that the number of *CHs* is a constant as mentioned by Heinzelman et al. [33], the total of all messages is $O(N)$ and all other iterations have a $O(1)$ time complexity. Therefore, the total processing complexity is $O(N)$.

4.1 The SS-MAC Advantages

The main advantages of *SS-MAC* are the followings:

- *SS-MAC* avoids the collisions:
  The collision appears when a transmitted packet is corrupted. It has to be discarded and the follow-on retransmissions increase energy consumption. Collision also increases latency. *SS-MAC* uses *TDMA* technique, so, each node has its own assigned time slots.

- *SS-MAC* avoids the overhearing:
  The overhearing means that a node picks up packets that are destined to other nodes. In order to reduce overhearing in *SS-MAC*, the *ONs* that are not in the *Reception* period will go to sleep (In the sleep mode, a node will turn off its radio).
- *SS-MAC* avoids the overemitting:
  The overemitting is caused by the transmission of a message when the destination node is not ready. Synchronization between each phase should be guaranteed that each node has enough time to complete the procedure. While within each phase, synchronization among the nodes is not necessary and idle nodes will turn to sleep till the phase ends. *SS-MAC* avoids the overemitting by having the *CHs* periodically broadcast synchronization signals to all nodes.
- *SS-MAC* avoids idle listening:
  The Idle listening is defined by listening to receive possible traffic that is not sent. As *SS-MAC* protocol uses *TDMA* technique, it avoids then the idle listening.
- *SS-MAC* minimizes the latency:
  With *SS-MAC*, each ON has a time slots according to its collected data. If an *ON* has no data to be sent, then it will not have a time slots.
- *SS-MAC* ensures the scalability:
  The *Regr-Clu* period ensures the scalability of our *SS-MAC* protocol.

4.2 SS-MAC Energy Consumption

Given that the *CH* is not as energy-constrained as the *ON*, it is better to compute the energy consumption just in the *Regr-Clu* and $TX/RX_{CH/ON}$ period, since, in the other periods the *ON* can turn itself off.

Thus, the energy consumption per *ON* in *SS-MAC* is:

$$E_{total} = E_{rc} + E_{verif} + E_{alloc} + E_{rcv} \tag{7}$$

4.2.1 Energy Consumption in Regr-Clu Period

We apply the most used energy model introduced by Heinzelman et al. [33] in our protocol. Based on this model, the transmitted and received energy costs for the transmission of a x-bit data packet between two nodes separated by a distance of d meters are given, respectively, by Eqs.(8) and (9).

$$E_{tx} = x \times E_{elec} + x \times \mu \times d^2 \tag{8}$$

$$E_{rx} = x \times E_{elec} \tag{9}$$

where E_{elec} denotes the electronic energy. It is needed to operate the transmitter or receiver circuit and μ represents the transmitter amplifier.

The energy necessary for this period called E_{rc} is as follows:

$$E_{rc} = E_{tx} + E_{rx} \tag{10}$$

In *SS-MAC* protocol, the energy necessary to send an *INVITATION* message is:

$$E_{tx} = x \times E_{elec} + x \times \mu \times d^2 \tag{11}$$

and the energy necessary to receive a *JOIN* message is:

$$E_{rx} = x \times E_{elec} \tag{12}$$

So, E_{rc} energy can be given by:

$$E_{rc} = x \times (2 \times E_{elec} + \mu \times d^2) \tag{13}$$

where x is a common size of the *INVITATION* and the JOIN message.

4.2.2 Energy Consumption in $TX/RX_{CH/ON}$ Period

Given that this period is divided into three subperiods, then, the energy consumption in $TX/RX_{CH/ON}$ period is defined by the total of the energy consumption in these subperiods.

- Energy consumption in the Verification subperiod
During this period, *CH* sends *AQ* packet to ON. After *AQ* packet reception, the *ON* replies to the *CH* by a *RQ* packet. To facilitate computations, we suppose that *AQ* packet and *RQ* packet have the same size x_1.
The energy dissipated in this period, called E_{verif}, is defined as follows:

$$E_{verif} = E_{tx2} + E_{rx2} \tag{14}$$

The energy necessary to transmit *RQ* packet, called E_{tx2}, is given by:

$$E_{tx2} = x_1 \times E_{elec} + x_1 \times \mu \times d^2 \tag{15}$$

The energy necessary to transmit *AQ* packet, called E_{rx2}, is as follows:

$$E_{rx2} = x_1 \times E_{elec} \tag{16}$$

From these three last formulas, E_{verif} becomes:

$$E_{verif} = x_1 \times (2 \times E_{elec} + \mu \times d^2) \tag{17}$$

- Energy consumption in the Allocation subperiod
In this subperiod, the *ON* does not transmit any data, it receives only its time slots. The energy necessary for *Allocation* subperiod, called E_{alloc}, is given by the formula:

$$E_{alloc} = E_{rx3} = x_2 \times E_{elec} \tag{18}$$

where x_2 is the size of the *SLOT* packet witch contains the *CH* address, the *ON* address, the beginning and the end of the slot.
- Energy consumption in the reception subperiod
In this subperiod, an *ON* sends its data during its time slots. The energy necessary for an ON_i, to send its data, called E_{rcv} is given by:

$$E_{rcv} = cpt_{ON_i} \times x_3 \times E_{elec} + (\mu \times d^2) \tag{19}$$

where x_3 is the data size.

We conclude that the energy consumption per *ON* in *SS-MAC* is:

$$\begin{aligned} E_{total} = {} & x \times (2 \times_{Eelec} + \mu \times d^2) + x_1 \times (2 \times E_{elec} \times \mu \times d^2) + \\ & + x_1 \times E_{elec} + cpt_{ON_i} \times x_3 \times (2 \times_{Eelec} + \mu \times d^2). \end{aligned} \tag{20}$$

4.3 The Delay Optimization of *ON*

As the energy of *ON* is computed during the *Regr-Clu* period and Communication period between an *ON* and its *CH*. Then, the time when *ON* is active called T_{actif} is also computed during these two periods and it is obtained by the following formula:

$$T_{actif} = T_{rc} + T_{verif} + T_{alloc} + T_{rcv} \tag{21}$$

where

$$T_{rcv} = cpt_{ON_i} \times T_s \tag{22}$$

5 Numerical Results

The performance evaluation of *SS-MAC* protocol is based on formula 20.

We used the following both performance measures:

- The energy consumption versus a number of packets that *ONs* have collected,
- The energy consumed by *ONs* in each period of *SS-MAC* protocol.

The energy consumed by *ONs* is computed using the following parameters values:

- The initial energy and communication range of each *ON* are set respectively to *5* J and *50* m.
- E_{elec} and μ are set respectively to *50* pJ/bit and 100 nJ/bit/m^2.

Table 1 illustrates the format and the size of each *SS-MAC* packet.

5.1 Energy Consumption Versus a Number of the Collected Packets

Using the formula 20, we draw a graph of the number of the collected packets to determine the relationship between the energy consumption and the number of collected packets (see Fig. 3).

Figure 3 shows a high and positive correlation between the consumed energy and the number of collected packets. Then, we can say that when the collected packets increase, the consumed energy increase as well. We can then deduce that the lifetime of *ONs* depends linearly on the number of collected packets.

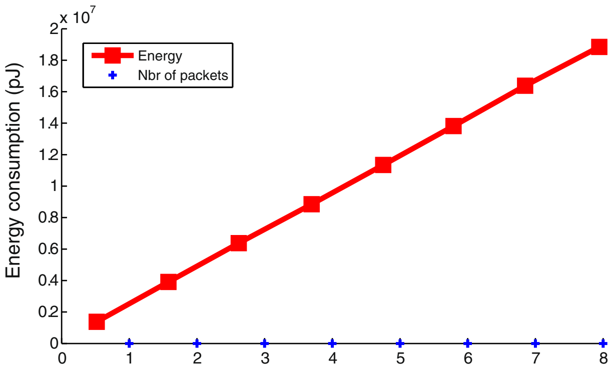
5.2 Energy Consumption in Each Period of SS-MAC

Figure 4 illustrates the energy consumption by *ONs* in each period of *SS-MAC*. We can see from this figure that energy consumption in *Regr-Clu* period, *Verification* subperiod, and

Table 1 The contents and size of the different type of messages exchanged between the *ONs* and the *CHs*

Message	Contents and size
INVITATION	ID of CH (1 Byte), ID of ON (1 Byte) and data (4 Bytes)
JOIN	ID of CH (1 Byte), ID of ON (1 Byte) and data (4 Bytes)
AQ	ID of CH (1 Byte), ID of ON (1 Byte) and data (6 Bytes)
RQ	ID of CH (1 Byte), ID of ON (1 Byte) and data (6 Bytes)
SLOT	ID of CH (1 Byte), ID of ON (1 Byte) and time slots (5 Bytes)
REC	ID of CH (1 Byte), ID of ON (1 Byte) and data (1-256 Bytes)

Fig. 3 The energy consumption versus a number of the collected packets



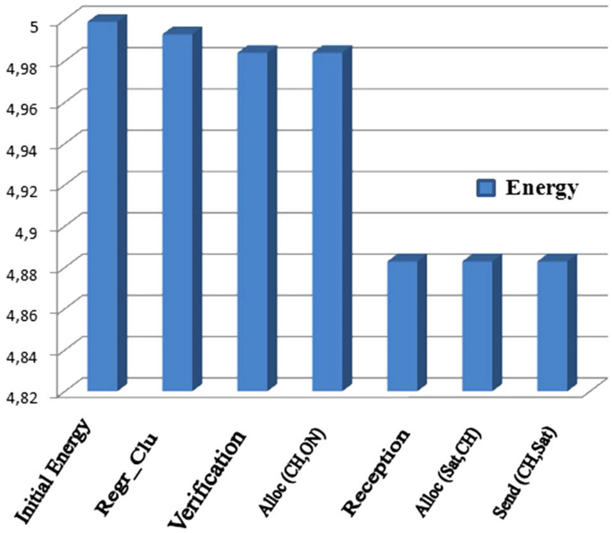


Fig. 4 Energy consumption in each period and subperiod of SS-MAC

Allocation subperiod is more than twice the energy consumption in the *Reception* subperiod. In $Alloc_{Sat/CH}$ and $comm_{CH/Sat}$ periods, *SS-MAC* puts *ONs* into sleep state for energy savings. In the sleep state, the radio is completely turned off. We conclude that the consumed energy by *ONs* is related to *Regr-Clu* period, *Verification* subperiod, *Allocation* subperiod and *Reception* subperiod.

6 Markov Chain Model of SS-MAC Protocol

The model building of *SS-MAC* protocol is obtained by the different *Markov* chains over different periods or subperiods. All the *Markov* chains consider some of the five possible states:

- Idle state denoted by *I*,
- Transmission state denoted by *T*,
- Reception state denoted by *R*,

- Sleep state denoted by S,
- The state of period i denoted by F_i, $i = \overline{1,3}$ where i stands respectively for *Regr-Clu* period, *Verification* subperiod and *Allocation* subperiod.

In the next subsection, we will compute the transition probabilities between different states using the following probabilities:

- λ_i: Probability of a message arrival, where i represents the type of message,
- s: Probability to be in the suitable slot,
- f: Probability to be at the end of the message,
- k_i: Probability to be at the end of period i, $i = \overline{1,3}$ where i stands respectively for *Regr-Clu* period, *Verification* subperiod and *Allocation* subperiod.
- γ: Probability to be at the end of the frame.

6.1 Markov Chain of Each Period

Like in the analysis of *SS-MAC* protocol (Sect. 4), we are still interested in the *Regr-Clu* period and the *TX/RX*$_{CH/ON}$ period for the same reason.

6.1.1 Markov Chain of Regr-Clu Period

In this period, each *CH* broadcasts the 'INVITATION' message across its cluster, while the *ONs* receive all the 'INVITATION' messages and decide which cluster to join (send the '*JOIN*' message). The transition graph of the *Markov* chain, given in Fig. 5, represents the conditions for passage of different states during the *Regr-Clu* period, where the considered states are Idle, Reception, Transmission and *F1*.

If there is an INVITATION message, the ON moves from the Idle state to the Reception state with a probability λ_I. Otherwise, it stays in the same state with a probability $(1 - \lambda_I)$. Then, from the reception state, this node will move certainly to the Transmission state, because it will transmit its JOIN message towards the selected CH. If it is the end of the Regr-Clu period, the ON moves to the *F1* state with a probability *k1* and it will move certainly to the Idle state, else it will move to the Idle state with a probability $1 - k1$.

The system of equations associated to this period is defined as follows:

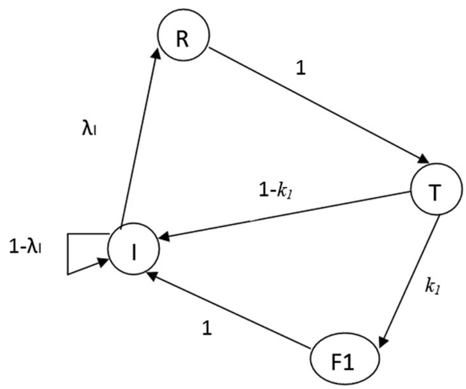


Fig. 5 The transition graph of Markov chain under the *Regr-Clu* period

$$\begin{cases} \lambda_I P(I) = P(F_1) + P(1-k_1)P(T) \\ P(R) = \lambda_I P(I) \\ P(T) = P(R) \\ P(F_1) = k_1 P(T) \end{cases} \quad (23)$$

Given that $P(I) + P(R) + P(T) + P(F_1) = 1$, then,

$$\begin{cases} P(R) = \dfrac{\lambda_I}{1+\lambda_I(2+k_1)} \\ P(T) = \dfrac{\lambda_I}{1+\lambda_I(2+k_1)} \\ P(I) = \dfrac{1}{1+\lambda_I(2+k_1)} \\ P(F_1) = \dfrac{k_1\lambda_I}{1+\lambda_I(2+k_1)} \end{cases} \quad (24)$$

6.1.2 Markov Chain of TX/RX$_{CH/ON}$ Period

For this period, we present the different *Markov* chains related to the three subperiods.

- *Markov chain of Verification subperiod*: In this period, there are messages exchange *(AQ, RQ)* between each *CH* and its *ONs*.

The transition graph of the *Markov* chain, given in Fig. 6, represents the conditions for passage of different states during the *Verification subperiod*, where the considered states are *Idle*, *Reception*, *Transmission* and *F2*.

If the *AQ* message has been received, the ON moves from Idle sate to Reception state with a probability λ_{AQ}. Otherwise, it remains in the Idle state with a probability $1-\lambda_{AQ}$, because its *CH* sends sequentially the *AQ* message to others *ONs* of the same cluster. Then, when ON is in the Reception state, it will go certainly to the Transmission state. When the ON is in the Transmission state, it moves from this state to F2 state with a probability k_2

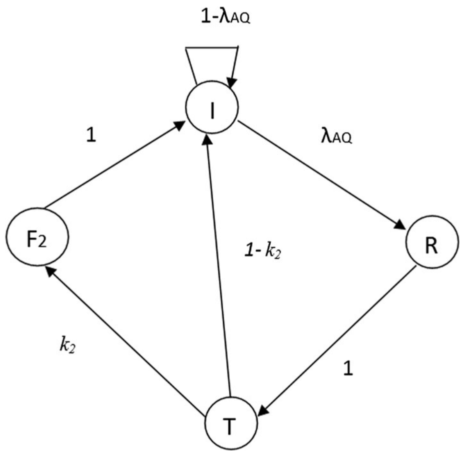


Fig. 6 The transition graph of Markov chain under the *Verification* subperiod

(the end of the Verification subperiod) or it moves to Idle state with a probability $1 - k_2$ (if the Verification subperiod is not completed).

The system of equations associated to this subperiod is defined as follows:

$$\begin{cases} \lambda_{AQ} P(I) = P(F_2) + (1 - k_2) P(T) \\ P(R) = \lambda_{AQ} P(I) \\ P(T) = P(R) \\ P(F_2) = k_2 P(T) \end{cases} \tag{25}$$

Given that $P(I) + P(R) + P(T) + P(F_2) = 1$, then,

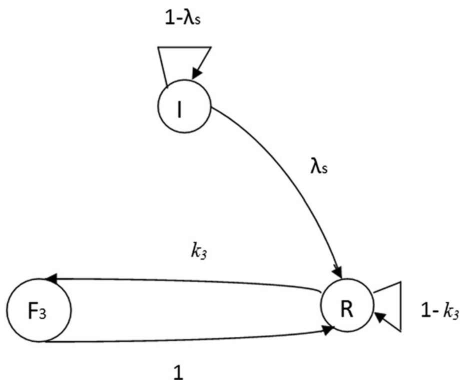
$$\begin{cases} P(R) = \dfrac{\lambda_{AQ}}{1 + \lambda_{AQ}(2 + k_2)} \\ P(T) = \dfrac{\lambda_{AQ}}{1 + \lambda_{AQ}(2 + k_2)} \\ P(I) = \dfrac{1}{1 + \lambda_{AQ}(2 + k_2)} \\ P(R) = \dfrac{k_2 \lambda_{AQ}}{1 + \lambda_{AQ}(2 + k_2)} \end{cases} \tag{26}$$

- *Markov chain of Allocation subperiod*: During this subperiod, the *CH* sends to each *ON* its time slots (the beginning and the end of its time slots).The transition graph of the *Markov* chain, given in Fig. 7, represents the conditions for passage of different states during the *Allocation* subperiod, where the considered states are *Idle*, *Reception*, and *F3*.

The ON leaves the Idle state to the Reception state with a probability λ_s, if it receives a message sent by its CH. Otherwise, it remains in the same state with a probability $(1 - \lambda_s)$. If this subperiod is finished, the ON moves from the Reception state to the *F3* state with a probability k_3. Otherwise, it remains in the same state with a probability $(1 - k_3)$. Then, the ON will return certainly to the Reception state.

The system of equations associated to this subperiod is defined as follows:

Fig. 7 The transition graph of Markov chain under the *Allocation* subperiod



$$\begin{cases} k_3P(R) = P(F_3) + \lambda_s P(I) \\ F3 = k_3P(R) \end{cases} \tag{27}$$

Given that $P(I) + P(R) + P(F_3) = 1$, then,

$$\begin{cases} P(R) = \dfrac{1}{1+k_3} \\ P(F_3) = \dfrac{k_3}{1+k_3} \end{cases} \tag{28}$$

- *Markov chain of Reception subperiod*: During this subperiod, each *ON* sends its data to its *CH*. The transition graph of the *Markov* chain, given in Fig. 8, represents the conditions for passage of different states during the Reception subperiod, where the considered states are *Transmission*, *Reception*, and *Sleep*.

If the ON is in its time slot, it moves from the Reception state to the Transmission state with a probability s. Otherwise, it moves to the Sleep state with probability $(1 - s)$. If the ON is at the end of the frame, it moves from the Transmission state to the Reception state with a probability γ. If the ON has sent all its data, it moves from the Transmission state to the Sleep state with a probability $(f(1-\gamma))$. If the ON has still data to send and the end of frame is not arrived yet, it remains in the Transmission state with a probability $((1-f)(1-\gamma))$. If the ON is in the Sleep state and the end of the frame is arrived, this ON moves from this state to the Reception state with a probability γ. Otherwise, if this node is always in Sleep state and it is in its time slot, it moves from the Sleep state to the Transmission state with a probability $(s(1-\gamma))$. Else, while the time slot of the ON is not arrived yet, it remains in the Sleep state with a probability $(1-\gamma)(1-s)$.

The system of equations associated to this subperiod is defined as follows:

$$\begin{cases} P(R) = \gamma P(T) + \gamma P(S) \\ (\gamma + f(1-\gamma))P(T) = sP(R) + s(1-\gamma)P(S) \\ (\gamma + s(1-\gamma))P(S) = (1-s)P(R) + f(1-\gamma)P(T) \end{cases} \tag{29}$$

Given that $P(R) + P(S) + P(T) = 1$, then,

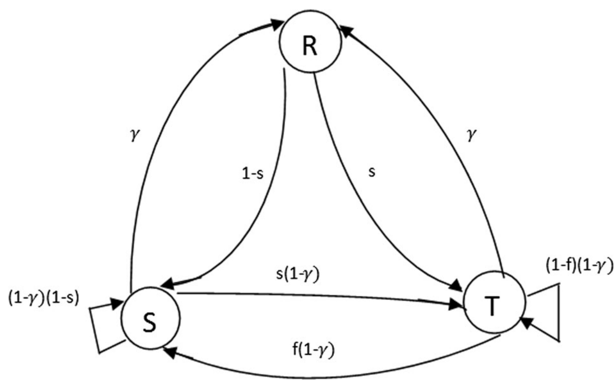


Fig. 8 The transition graph of Markov chain under the *Reception* subperiod

$$\begin{cases} P(S) = \dfrac{\gamma + f(1-\gamma)}{\gamma + f(1-\gamma) + s\theta_m + s(1-\gamma) + (\gamma + f(1+\gamma))\theta_m} = \rho_m \\ P(R) = \rho_m \theta_m \\ P(T) = \dfrac{s\rho_m \theta_m}{\gamma + f(1-\gamma)} + \dfrac{s(1-\gamma)\rho_m}{\gamma + f(1-\gamma)} \end{cases} \tag{30}$$

where $\theta_m = \frac{\gamma(\gamma+f(1-\gamma))+s\gamma(1-\gamma)}{\gamma(1-s)+f(1-\gamma)}$.

6.2 Performance Evaluation of SS-MAC

In *SS-MAC*, the energy consumption per *ON* is given by the following formula:

$$E = \sum_{i=1}^{4} E_{(i)} \tag{31}$$

where E indicates the total energy consumed in *SS-MAC* and $E_{(i)}$ indicates the energy consumed during each period i.

The power consumptions used for the performance evaluation of *SS-MAC* are taken according to wireless LAN module (IEEE 802.11/2 Mbps) [34].

The power consumption in the *sleep* state is equal to *zero* since ON can turn itself off.

To compute the energy consumption in each period, we assume that the energy consumption in each F_i is equal to that consumed in the *idle* state.

6.2.1 The Energy Consumption in Regr-Clu Period

The energy consumption in this period is given by the following formula obtained by its *Markov* chain model:

$$E(1) = P(I)P_{WI} + P(R)P_{WR} + P(T)P_{WT} + P(F_1)P_{WF_1} \tag{32}$$

where Pw_X is the power consumption in a given state X as showin in the Table 2.

Figure 9 represents the energy consumption $E_{(1)}$ in *Regr-Clu* period against the probability λ_i.

Figure 9 illustrates that the energy consumption in the *Regr-Clu* period differs from node to node, depending on the *INVITATION* messages that *ONs* have received from the *CHs*. We notice that the consumed energy can vary from 0.07 to 0.69.

6.2.2 The Energy Consumption in Verification Subperiod

The energy consumption in this subperiod is given by the following formula obtained by its *Markov* chain model:

Table 2 Power consumption in each state of the module IEEE 802.11/2 Mbps

State	Power consumption: P_W (W)
Idle	0.75
Reception	1.55
Transmission	1.90

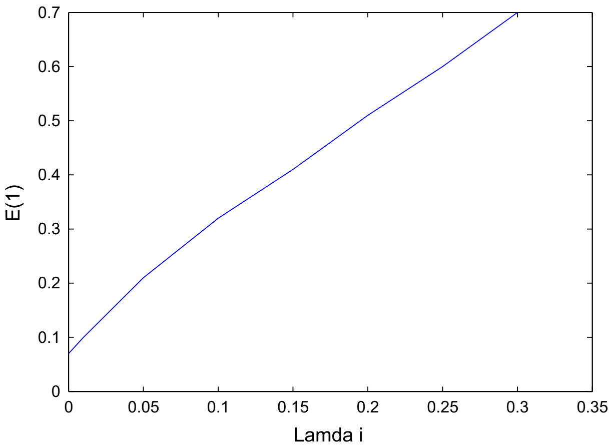


Fig. 9 Energy consumption in Regr-Clu period

$$E(2) = P(I)P_{WI} + P(R)P_{WR} + P(T)P_{WT} + P(F_2)P_{WF_2} \tag{33}$$

Figure 10 represents the energy consumption $E_{(2)}$ in *Verification* subperiod against the probability to be at the end of this subperiod. This figure shows that the energy consumed by *ONs* can vary from *Verification* period to another, depending on its time which is a necessary time to the *Verification* subperiod. We notice that the consumed energy can vary between 0.66 and 0.71.

6.2.3 The Energy Consumption in Allocation Subperiod

The energy consumption in this subperiod is given by the following formula obtained by its *Markov* chain model:

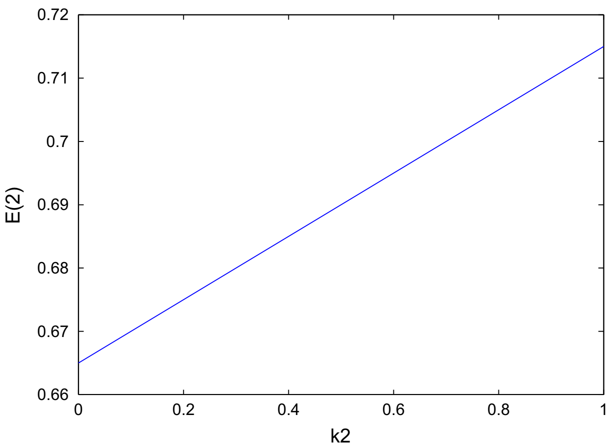


Fig. 10 Energy consumption in Verification subperiod

$$E(3) = P(I)P_{WI} + P(R)P_{WR} + P(F_3)P_{WF_3}. \tag{34}$$

Figure 11 represents the energy consumption $E_{(3)}$ in *Allocation* subperiod against the probability to be at the end of this subperiod. This figure shows that the energy consumed by *ONs* can vary from *Allocation* period to another, depending on its time which is a necessary time to the *Allocation* period. We notice that the consumed energy can vary between 0.22 and 0.62.

6.2.4 The Energy Consumption in Reception Subperiod

The energy consumption in this subperiod is given by the following formula obtained by its *Markov* chain model:

$$E(4) = P(R)P_{WR} + P(T)P_{WT} + P(S)P_{WS} \tag{35}$$

Figure 12 represents the energy consumption $E_{(4)}$ in *Reception* subperiod against the probability to be in the suitable slot. Figure 12 shows that the energy consumption in this period can vary from *Reception* period to another, depending on its time slots which

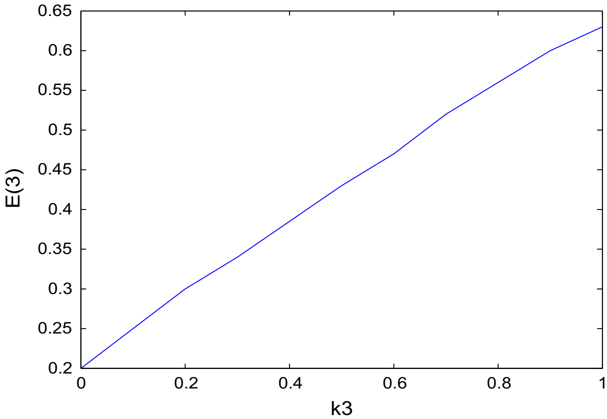


Fig. 11 Energy consumption in Allocation subperiod

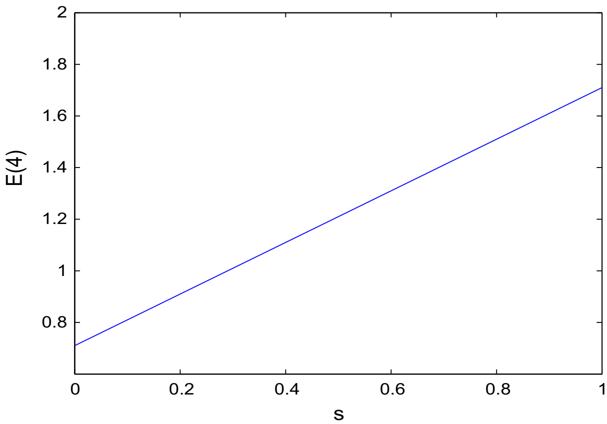


Fig. 12 Energy consumption in Reception subperiod

depends on the number of data collected. We notice that the consumed energy can vary between 0.74 and 1.69.

7 Conclusion

The proposed *SS-MAC* for energy management in *WSNs* is based on a LEO satellite and a network heterogeneous sensor. It uses *TDMA* technique together with periodic listen and sleep to avoid major sources of energy dissipations. However, the key feature of our protocol is the assignment of time slots to each sensor node following the quantity of data collected by the latter. *SS-MAC* protocol incorporates delay guarantee into energy efficient by limiting the time slots for the *ONs* which have the data to be sent.

From the protocol analysis, we can deduce that our protocol avoids the different causes of energy dissipations such as collisions, overhearing, overemitting and idle listening.

From the graphical results, we deduce that there is a high and positive correlation between the energy consumption and the number of collected packets. In other words, the lifetime of *ONs* depends linearly on collected packets. We also deduce that the consumed energy by *ONs*, in our protocol, is related to *Reg-Clu* period, *Verification* subperiod, *Allocation* subperiod and *Reception* subperiod. As a consequence, we used *Markov* chain models to evaluate the energy consumption in this period and these subperiods. We conclude that the energy consumption can vary from one period to another.

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