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Energy Consumption Modeling for Heterogeneous IoT-WSN Devices: Entire Modes and Operation Cycles considerations

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Abstract: Wireless Sensor Network (WSN) and the sensing devices are considered part of the core components of the Internet of Things (IoT). Hence, the modeling of IoT-WSNs is fundamental to having a better understanding, management, and deployment of this kind of technology. A fundamental issue in WSN is energy consumption due to the inherent limitations of this resource in the sensor devices. On the other hand, several issues arise in heterogeneous scenarios due to the coexistence of different sensor devices. Therefore, the modeling process becomes challenging and must consider the different transmission and operation cycles and modes that the transmission protocol implements to assure successful functioning in terms of transmission, synchronization, and energy savings. A duty-cycled MAC WSN protocol (PSA-MAC) has been modeled based on a pair of two-dimensional Discrete-Time Markov Chain (2D-DTMC), whose solution in terms of stationary probability distribution is used by expressions that have been derived to evaluate the energy consumption of sensor devices that could be used for WSN-based IoT applications. Analytical results of average energy consumption are obtained, where the synchronization, data, and sleep periods of a full transmission cycle are considered in a heterogeneous scenario with different node classes and priority assignments. Also, the normal and awake operation cycles are considered to assure synchronization and energy savings. Moreover, the transmission schemes of SPT (transmission of single packets) and APT (transmission of packets in aggregation) are also considered in the model. These results are validated through discrete event-based simulations, and the obtained results are accurate.

Keywords: energy consumption modeling; wireless sensor network; WSN MAC protocol; internet of things

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1. Introduction

The Internet of Things (IoT) has been powered by the growth of smart systems and WSN technologies. In fact, sensing devices are considered part of the core components of IoT [1]. Several examples of WSN-based IoT applications can be listed. One of them is the IoT-based sensor infrastructure that is used in precision agriculture applications, where wireless agriculture sensors are dispersed across the agriculture field to sense moisture, temperature, and humidity in the soil [2]. Moreover, in environmental applications, IoT is largely dependent on WSNs, where sensors continuously monitor the environment in IoT WSNs and alert the base station immediately if any event is detected, even if there is an emergency alert [3]. Also, in the industry application called Industrial Internet of Things (IIoT), the focus is on network automation processes through proper communication and data collection between sensors, actuators, and processing units [4].

On the other hand, because energy is a limited resource in sensor nodes, there are many research efforts to find solutions that contribute to optimizing energy consumption and using it more efficiently [5]. In that sense, there are different approaches focused on assessing diverse communication protocols, routing methods, Medium Access Control (MAC) solutions, and aggregation schemes [6,7], and [8] with the objective of extending the network lifetime.

Considering that energy consumption is a key factor, it is important to model and analyze energy behavior, which contributes to a better understanding, management, and design of sensor networks.

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To this end, several models have been developed to analyze energy consumption in WSN networks with IoT applications. For example, in [9], a very complete deterministic model is carried out where a simple MAC is considered, focusing more on the consumption of the PHY layer and considering operating modes or classes.

In [10], the authors present a model with a stochastic component, where they model energy consumption as a random variable with their respective probability distribution function (PDF) and maximum and minimum limits of expected energy values. Physical layer issues are the main ones taken into account in the model, but there is also a part of the MAC that is relatively simple. In [11], they do stochastic modeling, where they modify topologies and perform analyses and simulations for validation. They consider random variables and their corresponding probability distribution of communication jumps between nodes, distances, and the number of nodes in the network. But the approach is physical and routing (without specifying any protocol) and does not take into account media access protocols.

There are approaches where they model and analyze energy consumption [12] and try to predict such consumption [13] based on Markov process tools. They consider consumption in various states and during transitions, not taking into account the MAC or incorporating it very basically into the model. In [14], they mention that they incorporate the duty cycle mechanism into the model. They consider sleep and active modes as principal phases and two more intermediate phases in their energy calculation. They use joint probability to model the number of data packets and a multidimensional Markov process to model sensor phases. No medium access protocol or any synchronization algorithm is observed to be incorporated.

The inclusion of a robust medium access procedure is important in modeling, as the nature of the shared medium leads to conflict processes that can cause collisions to a greater or lesser extent depending on traffic conditions and node density [15]. Of all the models mentioned above, they have in common that the considerations of the MAC layer are very basic, where conflict situations or measures against possible collisions are not considered. This mentioned would definitely have an impact on energy consumption. In the previous models, there are no scenarios where there is heterogeneity that gives way to priority assignments. Another feature of these models is that the operating states of the sensor node were established to analyze its energy consumption, but without considering that these states would be affected by other active nodes around. The nature of the scenario where nodes coexist and share the medium involves a certain degree of dependence among nodes, consequently affecting the energy they could consume. Moreover, if we consider heterogeneous environments where there is more than one type of sensor in the network, in the calculation of energy consumption, the complications that may arise from this type of coexistence in the different phases or states should be considered. Even scenarios where there is a priority allocation option and the incorporation of a packet aggregation scheme.

From other related works focused on the study of energy consumption in WSNs that use similar modeling tools, we have found [16], where a stochastic analysis of energy consumption is carried out. Even a Markov chain is built, but without considering heterogeneous scenarios or any APT scheme. On the other hand, very few jobs have been found for the development of analytical models for WSN evaluation with packet aggregation schemes (APT). However, in [17], an energy analysis of a WSN is carried out considering APT and deriving Markov models, but focused on a routing perspective and without considering any specific layer MAC protocol. Other studies include the energy analysis of the WSN with a duty-cycle (DC) MAC, considering APT, and even some degree of heterogeneity in the nodes [18,19], but these studies have been accomplished mainly by simulations or by testing with laboratory prototypes.

In [20], the authors have developed DTMC models to evaluate performance parameters for a WSN with MAC operating with DC, including energy consumption and considering the APT scheme. However, this study does not consider heterogeneous scenarios or any priority assignment.

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Furthermore, although the energy analysis considers different node operation cycles and operation modes, the present study is more direct with the resulting stationary probability distribution, which is used in the expressions to determine energy consumption. In [21], with the introduction of the Priority Sink Access MAC Protocol(PSA-MAC) model, we have proven this new approach to the determination of energy that allows for more accurate results with a more systematic method of calculation. Additionally, the performance of a heterogeneous network using a DC MAC protocol has been evaluated. In these models, the established transmission scheme is one packet per cycle (SPT).

In [22] we have enhanced the model in order to support the APT scheme, including the energy approach used in [21]; nevertheless, in all these models, only the energy consumption during the data transmission period of the transmission cycle is considered.

For that reason, in [23], we derived exhaustive expressions to determine the energy consumption of the sensor nodes during the full transmission cycle, including the data transmission period, the synchronization and sleep periods. Moreover, the awake and sleep operation modes of nodes were contemplated. However, the model does not support heterogeneous scenarios that include different classes of nodes conforming to the network. On the other hand, the incorporation of an aggregated transmission scheme was not contemplated.

A contribution of this work is the analytical modeling and comprehensive assessment of power consumption performance for a WSN whose MAC operates with the DC mechanism in scenarios where the nodes have different loads, access priorities, and APT and SPT transmission capabilities. The model is based on two two-dimensional Markov discrete time chains (2D-DTMC), whose solution in terms of stationary probability distribution is used with comprehensive expression for determining the energy consumption of nodes, considering all the above-mentioned scenarios but also considering the heterogeneous scenarios and the issues involved in the coexistence of different nodes.

For the determination of energy consumption expressions, we have considered *awake* operating cycles, whose aim is for nodes to listen to the transmission of possible SYNC packets from neighboring nodes and, thus, to be updated in their synchronization calendar. The activity of the reference node of each class and the other neighboring nodes is taken into account (from the same or different classes). This generates different combinations for each class of nodes, which we call types, and for each one, an expression is generated for the energy calculation. Similarly, expressions are established to determine the energy consumption (for each type of node) in the so-called *normal* cycles, in which, to save energy, nodes are disabled and enter *sleep* mode for the rest of the transmission cycle after a successful or failed transmission.

For the total energy consumption calculation, the energy consumption during the *awake* cycles and the energy consumption during the *normal* cycles are added to the energy used during the synchronization period at the beginning of the transmission cycle and the energy consumption during the *data* transmission period. The node activity during the synchronization period is necessary for nodes to create the transmission schedule at the beginning of the transmission cycle. The activity of nodes during the data transmission period includes the CSMA/CA contention mechanism and the RTS/CTS/FRAME/ACK interchange packets.

The remainder of the article is organized as follows: In Section 2, the heterogeneous and APT transmission model and scenarios are resumed. The analysis to obtain the energy performance is developed in Section 3. The results and their discussion are set out in Section 4. Finally, the conclusions are presented in Section 5.

2. Heterogeneous and APT Transmission Model and Scenarios

Before specifying the procedure for determining the energy consumption, it is necessary to review some aspects in relation to the WSN scenario, the transmission procedure, the transmission cycle and operation modes of the nodes. The heterogeneous model is resumed from [21], where two classes of nodes coexist in the WSN, as shown in Figure 1, and where there will be a pair of reference nodes, one for each of the classes considered (RN1 and RN2).

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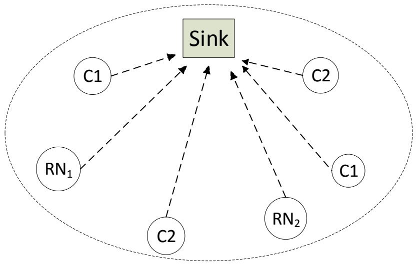

Figure 1. Heterogeneous WSN with two classes of nodes. class 1 (C1) nodes have channel access priority over Class 2 nodes (C2). A reference node (RN) is defined for each class.

class 1 nodes are given priority in medium access, as explained in detail in [21], and according to the transmission process that can be seen in Figure 2. The transmission process is structured in cycles, which are composed of the *active* and *sleep* periods; furthermore, the *active* period is subdivided into the *sync* and *data* periods. In Figure 2, you can also observe the different periods that constitute the cycle, showing the scheme of a transmission where the two types of nodes of the WSN are considered. With respect to [21], the synchronization period is now included, and now is possible to send mode than one packet embedded in frames.

Consequently, in this model, the energy consumption contribution of the *sync* period procedure is considered. In addition, the energy contribution during the data period, used by the nodes to transmit the DATA packets, is contemplated. Moreover, nodes have the ability to transmit both in SPT and with APT. On the other hand, the transmission procedure involves the exchange of control packets (RTS, CTS, and ACK), which is illustrated in Figure 2.

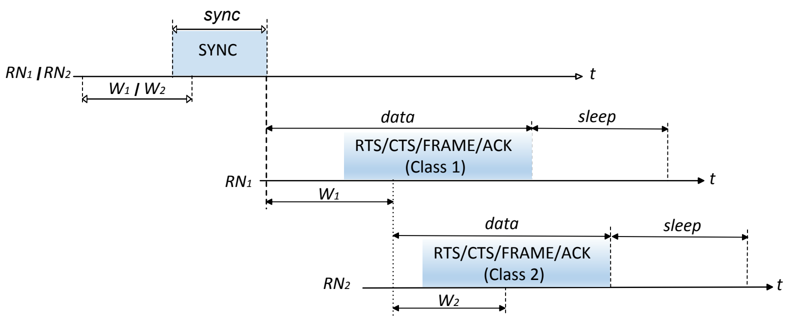

Figure 2. Transmission process in a transmission cycle for a heterogeneous WSN with two classes of nodes.

On the other hand, the contribution during the sleep period is also taken into account. During this period, nodes fall asleep to save energy or wake up to listen to SYNC packets that have been transmitted, according to the corresponding cycles of *normal* operation or *awake*, respectively. It should be noted that during the sleep period there are two possible cycles of operation: the normal cycles that occur most frequently, in which the nodes are put to rest (also called sleep mode), and the *awake* cycles, which occur less often, in which the nodes remain awake and serve to maintain synchronization between nodes (also called awake mode). Finally, the modeling of the system and its solution is carried out in the same way as in [22]. Furthermore, in this model, the nodes can perform the aggregation of packets according to the packets they have in their queues. It is important to note that the packet aggregation capability applies to each class of nodes, regardless of their priority. The model considers both coupled Markov chains and their solution in terms of stationary probability distribution and is used by the expressions to evaluate the energy performance in a more precise and systematic way.

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3. Energy Consumption

The entire transmission process occurs during a cycle that consists of an active period and a sleep period. The active period is subdivided into the sync and data periods. In this section, we derive expressions to determine the average energy consumed by the RN per cycle, considering the different periods and contributions.

3.1. *Average Energy Consumption in the* Sync *Period*

It should be noted that for the purpose of synchronization, the nodes consume energy due to the transmission and reception of SYNC packets during the sync period of the transmission cycle. The equations 1 and 2 allow to determine the energy consumption of RN_1 and RN_2 during that period (N_{sc}):

$$T_{sync} = (W-1) + t_{SYNC} + D_p\,, \tag{1}$$

$$E_{sc} = \frac{1}{N_{sc}} \cdot \left[\left(t_{SYNC} \cdot P_{tx} + \left(T_{sync} - t_{SYNC}\right) \cdot P_{rx}\right)\right] + \frac{N_{sc}-1}{N_{sc}} \cdot \left(T_{sync} \cdot P_{rx}\right)\,, \tag{2}$$

where T_{sync} is the duration of the *sync* period, W is the size of the contention window, t_{sync} is the transmission duration for a *SYNC* packet, and D_p is the one-way propagation delay.

In addition, P_{rx} and P_{tx} are the power levels of reception and transmission, respectively. The N_{sc} parameter indicates the cycle periodicity of the transmission of *SYNC* packets. Suppose the *RN*, of the corresponding class, transmits one *SYNC* packet every N_{sc} cycles and may receive one packet per cycle in the remaining cycles ($N_{sc} - 1$).

3.2. *Average Energy Consumption in the* Data *Period*

The entire process required for the transmission of the DATA packets, which takes place in the data period, involves an energy consumption, which is determined by the expressions (3), (4) and (5). In this section, the analytical process for determining the energy consumed by the reference nodes, RN_1 and RN_2, is shown in the *data* period of the transmission cycle. It should be remembered that only the energy consumed by the radio frequency transceiver is studied; therefore, the energy consumption due to events related to specific detection or monitoring tasks, depending on the application of the sensor node, is not included in the calculation. The average energy consumed by the *RN* of the corresponding class during the *data* period of a cycle is generally the sum of the energy consumed when the node successfully transmits its frame ($E^d_{tx,s}$), and the energy used by the node when it fails to transmit because it encounters a collision ($E^d_{tx,f}$).

$$E_d = E^d_{tx,s} + E^d_{tx,f}\,. \tag{3}$$

The consumption due to a successful transmission, $E^d_{tx,s}$, for class 1 nodes is obtained by the expression (4).

$$\begin{aligned} E^d_{tx,s} &= \sum_{i=1}^{Q_1}\sum_{k=0}^{M_1} \pi_1(i,k) P_{s_1,k}\left(E^d_1 + \alpha_1 t_{DATA} P_{1,tx} + BT_{s_1,k} P_{1,rx}\right), \\ E^d_1 &= t_{RTS} P_{1,tx} + [t_{CTS} + t_{ACK} + 4D_p] P_{1,rx}\,, \\ \alpha_1 &= min(i, F_1)\,. \end{aligned} \tag{4}$$

where t_{RTS}, t_{DATA}, t_{CTS}, and t_{ACK} are the transmission times of the corresponding packets. The factor α is defined as the number of packets added to the transmission when the node is in state i. The factor

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π is the stationary probability distribution; therefore, π_1 is the corresponding to class 1. The energy consumption due to collision ($E^d_{tx,f}$) for class 1 nodes is obtained by the expression (5).

$$E^d_{tx,f} = \sum_{i=1}^{Q_1} \sum_{k=0}^{M_1} \pi_1(i,k) P_{f_1,k} (E^d_2 + BT_{f_1,k} P_{1,rx}) ,$$
$$E^d_2 = t_{RTS} P_{1,tx} + 2D_p P_{1,rx} . \tag{5}$$

For class 2 nodes, the energy consumption due to success transmissions (E^{tx}_s) and collision transmissions (E^{tx}_f) is calculated in the same way. In this case, the stationary probability distribution corresponding to the class 2 node (π_2) is used in calculations. In addition, the multiplication should be considered by the factor $R_{1,0} = \pi_1(0,0)$, which is the probability that there are no active classes 1 nodes in a cycle (fractions of cycles in which classes 1 nodes are inactive) [21].

3.3. Average Energy Consumption During Awake Cycles

It should be noted that *awake* cycles are those in which the nodes, during the *sleep* period, must remain awake, even if they have completed their transmission process, or must wake up if they were not awake. When a node is in *awake* mode, it wakes up at the beginning of the *awake* cycles and remains *awake* until the cycle ends. When the node hears the start of a successful transmission, it reads the *RTS*, calculates the time the channel remains occupied, and moves to *sleep* mode. When the broadcast ends, it returns to the *awake* state. The aim of the above is for the nodes to listen to the transmission of the possible *SYNC* packets of the neighboring nodes; thus, to be updated in their synchronization schedule. We refer to these cycles as *awake* cycles. It is desired to calculate the energy consumed by node and by cycle of each class in the *awake* cycles. It is supposed that in these cycles, the node activates the *awake* mode at the beginning of the cycle (after the *sync* period, which is the same for both classes). Note that for cycles in which class 1 nodes collide, Class 2 nodes are considered to detect activity and not participate in the channel access contention.

3.4. Awake Consumption Scenario for class 1 Nodes

For class 1 nodes, in particular RN_1, the following types of cycles are considered:

Cycle 1A: RN_1 is ACTIVE ($i_1 > 0, k_1 \geq 0$): class 1 nodes access the channel in the same cycle than RN_1 is in *awake*. Access to the channel can be from the same RN_1 or from other class 1 nodes. In the first case, the RN_1 performs channel detection or channel sensing, and the following cases can occur: (a) the RN_1 performs a transmission successfully; (b) the RN_1 collides; (c) another node performs the transmission with success; (d) other nodes collide.

Cycle 1B: RN_1 is INACTIVE ($i_1 = 0, k_1 > 0$). class 1 nodes access the channel in the same cycle that RN1 is awake. Access to the channel can only come from other class 1 nodes. The RN_1 listens to the channel to decode the *RTS* and determine the duration of the frame. The following cases may occur: (a) another node performs a transmission successfully; (b) other nodes collide.

Cycle 1C: RN_1 and the rest of the class 1 nodes are INACTIVE ($i_1 = 0, k_1 = 0$). There are class 2 nodes active that access the channel in the same cycle that RN_1 is *awake*. The RN_1 listens to the channel to decode the *RTS* and determine the duration of the frame. The following cases may occur: (a) a class 2 node performs a successful transmission; (b) several class 2 nodes collide.

Cycle 1D: RN_1 and the rest of class 1 and Class 2 nodes are INACTIVE, in the same cycle that RN_1 is awake, $i_1 = k_1 = i_2 = k_2 = 0$.

3.5. Energy Consumed in Awake by RN1

The following are the expressions used in the calculation of the energy according to the scenarios corresponding to the cycles mentioned in the previous subsection.

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3.5.1. Energy Consumption in Cycles of Type 1A

The energy consumption in cycles of type 1A is obtained from the sum of the expressions (7), (8), and (9). With the addition of the results of the above expressions, we obtain the energy consumption in cycle 1A, as observed in expression (6).

$$E_{aw}[1A] = E^{aw}_{tx,s}[1A] + E^{aw}_{tx,f}[1A] + E^{aw}_{oh}[1A] \,, \tag{6}$$

where $E^{aw}_{tx,s}[1A]$, $E^{aw}_{tx,f}[1A]$ and $E^{aw}_{oh}[1A]$, are the terms of energy consumption when the RN successfully transmits, transmits with failure (collision), and overhears transmissions from another node, respectively. During a successful transmission, the consumption of $E^{aw}_{tx,s}[1A]$ is given by the expression (7).

$$\begin{aligned} E^{aw}_{tx,s}[1A] &= \sum_{i=1}^{Q_1}\sum_{k=1}^{N_1} \pi_1(i,k)P_{s_1,k}\left[E^{aw}_1 - (\alpha_1\, t_{DATA} + BT_{s_1,k})P_{1,rx}\right], \\ E^{aw}_1 &= \left[T - T_{sync} - (t_{RTS} + t_{CTS} + t_{ACK} + 4D_p)\right]P_{1,rx}\,, \end{aligned} \tag{7}$$

where T is the duration of the cycle. When collisions occur, the energy $E^{aw}_{tx,f}[1A]$ is obtained with the expression (8).

$$\begin{aligned} E^{aw}_{tx,f}[1A] &= \sum_{i=1}^{Q_1}\sum_{k=1}^{N_1} \pi_1(i,k)P_{f_1,k}\left[E^{aw}_2 - BT_{f_1,k}P_{1,rx}\right], \\ E^{aw}_2 &= \left[T - T_{sync} - (t_{RTS} + 2D_p)\right]P_{1,rx}\,. \end{aligned} \tag{8}$$

The power consumption due to *overhearing*, $E^{aw}_{oh}[1A]$, is determined by the expression (9).

$$\begin{aligned} E^{aw}_{oh}[1A] &= \sum_{i=1}^{Q_1}\sum_{k=1}^{N_1} \pi_1(i,k)kP_{s_1,k}[E^{aw}_3 - f_{1,k}\, t_{DATA}(P_{1,rx} - P_{sl})] \\ &+ \sum_{i=1}^{Q_1}\sum_{k=2}^{N_1} \pi_1(i,k)\widehat{P}_{f_1,k}(T - T_{sync})P_{1,rx}\,. \end{aligned} \tag{9}$$

$$\begin{aligned} E^{aw}_3 &= (T - T_{sync})P_{1,rx} - (t_{CTS} + t_{ACK} + 3D_p)(P_{1,rx} - P_{sl})\,, \\ \widehat{P}_{f_1,k} &= \sum_{i=1}^{W_1}\left[\sum_{n=2}^{k}\binom{k}{n}\left(\frac{1}{W_1}\right)^n\left(\frac{W_1 - i}{W_1}\right)^{k-n+1}\right]. \end{aligned} \tag{10}$$

It is assumed that $\widehat{P}_{f_1,k}$ is the probability that other nodes will collide their packets in cycles where RN_1 is active. $\widehat{P}_{f_1,k}$ defines the probability that one of the k nodes, other than RN_1, will gain access to the channel but transmit with collision when RN_1 is active. P_{sl} is the power level in sleep mode. During consumption due to *overhearing*, it is necessary to know how long the RN_1 will be in *sleep* mode while the transmission of another node occurs. Upon completion of such transmission, the RN will return to the *awake* state. Therefore, it is important to estimate the duration of the transmission, whose duration depends on the size or number of packets aggregated. The parameter $f_{1,k}$ is the average package size of the frame that the RN_1, or any other node of the same class, would transmit conditioned to the RN_1 contends with other k nodes in the same cycle, and is determined by the following expressions (11):

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$$
\begin{aligned}
f_{1,k} &= \frac{1}{G_{k_1}} \sum_{i=1}^{Q_1} \alpha_1 \cdot \pi_1(i,k) \;, \\
G_{k_1} &= \sum_{i=1}^{Q_1} \pi_1(i,k) \;.
\end{aligned}
\tag{11}
$$

$f_{1,k} = 1$ if only one package is sent per plot (SPT transmission mode).

3.5.2. Energy Consumption in Cycles of Type 1B

The energy consumption in cycles of type 1B is obtained by the expression (12).

$$
\begin{aligned}
E_{aw}[1B] = &\sum_{k=1}^{N_1} \pi_1(0,k) k P_{s_1,k-1} [E_3^{aw} - f_{1,k-1}\, t_{DATA}(P_{1,rx} - P_{sl})] \\
&+ \sum_{k=2}^{N_1} \pi_1(0,k) \widehat{P}'_{f_1,k} (T - T_{sync}) P_{1,rx} \;,
\end{aligned}
\tag{12}
$$

$$
\widehat{P}'_{f_1,k} = \sum_{i=1}^{W_1} \left[\sum_{n=2}^{k} \binom{k}{n} \left(\frac{1}{W_1}\right)^n \left(\frac{W_1 - i}{W_1}\right)^{k-n} \right] , \tag{13}
$$

where $\widehat{P}'_{f_1,k}$, defines the probability that one of the k nodes, other than RN_1, wins access to the channel but transmits with collision when RN1 is inactive.

3.5.3. Energy Consumption in Cycles of Type 1C

The energy consumption in cycles of type 1C is obtained with the expression (14). The $RN1$ is *awake* from the beginning of the cycle; it goes to sleep when it hears the transmission of a class 2 node and wakes up again at the end of this cycle.

$$
\begin{aligned}
E_{aw}[1C] = &\sum_{i=1}^{Q_2} \sum_{k=1}^{N_2} \pi_2(i,k)(k+1) P_{s_2,k} [E_3^{aw} - f_{2,k}\, t_{DATA}(P_{1,rx} - P_{sl})] \\
&+ \sum_{k=1}^{N_2} \pi_2(0,k) k P_{s_2,k-1} [E_3^{aw} - f_{2,k-1}\, t_{DATA}(P_{1,rx} - P_{sl})] \\
&+ \sum_{i=1}^{Q_2} \sum_{k=2}^{N_2} \pi_2(i,k) \widehat{P}_{f_2,k} (T - T_{sync}) P_{1,rx} \\
&+ \sum_{k=2}^{N_2} \pi_2(0,k) \widehat{P}'_{f_2,k} (T - T_{sync}) P_{1,rx} \;.
\end{aligned}
\tag{14}
$$

Each of the terms in the above expression indicates the energy consumption according to the possible events that may occur. The first term expresses the energy consumed when one of the $k+1$ active nodes (the RN_2 and other k) successfully transmits; the second term defines energy consumption when a k active node other than the RN_2 has successfully transmitted in a cycle with the RN_2 inactive; the third and fourth terms indicate consumption when two or more of the k nodes, different from the RN_2, gain access to the channel but transmit with collision when the RN_2 is active or inactive, respectively.

Note that the stationary probability distribution used is $\pi_2(i,k)$, so the average frame size, $f_{2,k}$, is calculated as indicated in the expression (15).

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$$f_{2,k} = \frac{1}{G_{2,k}} \sum_{i=1}^{Q_2} \alpha_2 \cdot \pi_2(i,k) \; ,$$
$$G_{2,k} = \sum_{i=1}^{Q_2} \pi_2(i,k) \; , \tag{15}$$

where $\alpha_2 = min(i, F_2)$. Note that if $f_{2,k} = 1$, only one packet per frame is sent (SPT transmission mode). The probabilities of failure in transmission $\widehat{P}_{f_{2,k}}$ and $\widehat{P'}_{f_{2,k}}$ are calculated using the expressions (10) and (13), respectively, but taking into account the contention window parameter for the class 2 nodes (W_2).

3.5.4. Energy Consumption in Cycles of Type 1D

The energy consumption in cycles of type 1D is obtained with the expression (16). In this cycle, energy consumption is accounted for when there is no activity at the nodes.

$$E_{aw}[1D] = \pi_1(0,0)\pi_2(0,0)\left(T - T_{sync}\right)P_{1,rx} \,. \tag{16}$$

3.5.5. Consumption in the Awake State for *RN1*

The final value of energy consumed is given by the expression (17), which consists of the sum of the different energy consumptions in the cycles considered above.

$$E_{1,aw} = E_{aw}[1A] + E_{aw}[1B] + E_{aw}[1C]R_{1,0} + E_{aw}[1D] \, ,$$
$$E_{1,aw} = E^{aw}_{tx,s}[1A] + E^{aw}_{tx,f}[1A] + E^{aw}_{oh}[1A] + E_{aw}[1B] + E_{aw}[1C]R_{1,0} + E_{aw}[1D] \, . \tag{17}$$

Note that $E_{aw}[1C]$ is multiplied by the $R_{1,0}$ factor, which defines the fraction of cycles where class 1 nodes are inactive. Remember that the transmissions in this cycle are due to Class 2 nodes; therefore, class 1 nodes will be inactive during this transmission process.

3.6. Awake Consumption Scenario for Class 2 Nodes

For class 2 nodes, in particular for RN_2, the following cycles are considered:

Cycle 2A: class 1 nodes are INACTIVE ($i_1 = 0, k_1 = 0$), but RN_2 and other Class 2 nodes are active ($i_2 > 0, k_2 \geq 0$): Class 2 nodes access the channel in the same cycle as RN_2 is awake. Access to the channel can be from the same RN_2 or from other Class 2 nodes. In the first case, the RN_2 performs channel detection or channel sensing, and the cases that may occur are: (a) the RN_2 performs a transmission successfully; (b) the RN_2 collides; (c) another class 2 node performs the transmission with success; (d) other class 2 nodes collide.

Cycle 2B: class 1 nodes are INACTIVE; RN_2 is also inactive, but other Class 2 nodes ($i_2 = 0, k_2 > 0$) are active. Class 2 nodes access the channel in the same cycle that RN_2 is awake. Access to the channel can only be performed by other Class 2 nodes. The RN_2 listens to the channel to decode the RTS and determine the duration of the frame. The following cases may occur: (a) another Class 2 node performs transmission successfully; (b) other Class 2 nodes collide.

Cycle 2C: class 1 nodes are ACTIVE ($i_1 \geq 0, k_1 \geq 0$). The RN_2 listens to the channel to decode the RTS and determine the duration of the frame. The following cases may occur: (a) a class 1 node performs a transmission successfully; (b) several class 1 nodes collide.

Cycle 2D: RN_2 and the rest of the class 1 and Class 2 nodes are INACTIVE; in the same cycle that RN_2 is awake, $i_1 = k_1 = i_2 = k_2 = 0$. In one of these cycles, RN_1 and RN_2 could coincide in the awake state.

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3.7. *Energy Consumed in* Awake *by RN2*

The expressions used in the calculation of energy according to the scenarios for the cycles mentioned in the previous paragraph are set out below.

3.7.1. Energy Consumption in Cycles of Type 2A

The energy consumption in cycles of type 2A is obtained from the sum of the expressions (19), (20) and (21). The addition of the results of the previous expressions throws us into energy consumption, as observed in the expression (18).

$$E_{aw}[2A] = E^{aw}_{tx,s}[2A] + E^{aw}_{tx,f}[2A] + E^{aw}_{oh}[2A]\,, \tag{18}$$

where $E^{aw}_{tx,s}[2A]$, $E^{aw}_{tx,f}[2A]$ and $E^{aw}_{oh}[2A]$, are the terms of energy consumption when the *RN* successfully transmits, transmits with failure, and listens to transmissions from another node (overhearing), respectively. During a successful transmission, the $E^{aw}_{tx,s}[2A]$ consumption is given by the expression (19).

$$\begin{aligned} E^{aw}_{tx,s}[2A] &= \sum_{i=1}^{Q_2}\sum_{k=1}^{N_2} \pi_2(i,k) P_{s_2,k}\left[E^{aw}_{1,2} - \left(\alpha_2\, t_{DATA} + BT_{s_2,k}\right) P_{2,rx}\right], \\ E^{aw}_{1,2} &= \left[T - T_{sync} - \left(t_{RTS} + t_{CTS} + t_{ACK} + 4D_p\right)\right] P_{2,rx}\,, \\ \alpha_2 &= min(i, F_2)\,. \end{aligned} \tag{19}$$

When collisions occur, the energy $E^{aw}_{tx,f}[2A]$ is obtained with the expression (20).

$$\begin{aligned} E^{aw}_{tx,f}[2A] &= \sum_{i=1}^{Q_2}\sum_{k=1}^{N_2} \pi_2(i,k) P_{f_2,k}\left[E^{aw}_{2,2} - BT_{f_2,k} P_{2,rx}\right], \\ E^{aw}_{2,2} &= \left[T - T_{sync} - \left(t_{RTS} + 2D_p\right)\right] P_{2,rx}\,. \end{aligned} \tag{20}$$

The energy consumption due to *overhearing*, $E^{aw}_{oh}[2A]$, is determined by the expression (21).

$$\begin{aligned} E^{aw}_{oh}[2A] &= \sum_{i=1}^{Q_2}\sum_{k=1}^{N_2} \pi_2(i,k) k P_{s_2,k}\left[E^{aw}_{3,2} - f_{2,k}\, t_{DATA}\left(P_{2,rx} - P_{sl}\right)\right] \\ &+ \sum_{i=1}^{Q_2}\sum_{k=2}^{N_2} \pi_2(i,k) \widehat{P}_{f_2,k}\left(T - T_{sync}\right) P_{2,rx}\,, \\ E^{aw}_{3,2} &= \left(T - T_{sync}\right) P_{2,rx} - \left(t_{CTS} + t_{ACK} + 3D_p\right)\left(P_{2,rx} - P_{sl}\right). \end{aligned} \tag{21}$$

It is assumed that $\widehat{P}_{f_2,k}$ is the probability that other nodes will collide their packets in cycles where RN_2 is active. $\widehat{P}_{f_2,k}$ defines the probability that one of the k nodes, other than RN_2, will gain access to the channel but transmit with collision when RN_2 is active. P_{sl} is the power level in sleep mode. As mentioned earlier, during *overhearing* consumption, it is necessary to know how long the node will be in *sleep* mode, listening to the transmission from another node, and waiting for such transmission to conclude in order to be able to wake up during the rest of the cycle. Therefore, it is important to estimate the duration of the frame transmission, whose duration depends on the size or number of packets aggregated. The parameter $f_{2,k}$ is the average packet size of the frame that the RN_2, or any other node of the same class, would transmit, conditioned on it contending with other k nodes in the same cycle, and is determined by the expressions of (15). It should be remembered that with $f_{2,k} = 1$, only one packet per frame is sent (SPT transmission mode).

3.7.2. Energy Consumption in Cycles of Type 2B

The energy consumption in cycles of type 2B is obtained with the expression (22).

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$$
\begin{aligned}
E_{aw}[2B] &= \sum_{k=1}^{N_2} \pi_2(0,k) k P_{s_2,k-1} \left[E_{3,2}^{aw} - f_{2,k-1}\, t_{DATA} (P_{2,rx} - P_{sl}) \right] \\
&+ \sum_{k=2}^{N_2} \pi_2(0,k) \widehat{P}'_{f_2,k} (T - T_{sync}) P_{2,rx} \,.
\end{aligned} \tag{22}
$$

$\widehat{P}'_{f_2,k}$ defines the probability that one of the k nodes, other than RN_2, will gain access to the channel but transmit with collision when RN_2 is inactive.

3.7.3. Energy Consumption in Cycles of Type 2C

The energy consumption in cycles of type 2C is obtained with the expression (23). The RN_2 is *awake* from the beginning of the cycle, turns to *sleep* mode when it hears the transmission of a class 1 node, and wakes up again at the end of the transmission.

$$
\begin{aligned}
E_{aw}[2C] &= \sum_{i=1}^{Q_1} \sum_{k=1}^{N_1} \pi_1(i,k)(k+1) P_{s_1,k} \left[E_{3,2}^{aw} - f_{1,k} t_{DATA} (P_{2,rx} - P_{sl}) \right] \\
&+ \sum_{k=1}^{N_1} \pi_1(0,k) k P_{s_1,k-1} \left[E_{3,2}^{aw} - f_{1,k-1}\, t_{DATA} (P_{2,rx} - P_{sl}) \right] \\
&+ \sum_{i=1}^{Q_1} \sum_{k=2}^{N_1} \pi_1(i,k) \widehat{P}_{f_1,k} (T - T_{sync}) P_{2,rx} \\
&+ \sum_{k=2}^{N_1} \pi_1(0,k) \widehat{P}'_{f_1,k} (T - T_{sync}) P_{2,rx} \,.
\end{aligned} \tag{23}
$$

Each of the terms in the above expression indicates the energy consumption according to the possible events that may occur. The first term expresses the energy consumed when one of the $k+1$ active nodes (the RN_1 and other k) successfully transmits; the second term defines energy consumption when a k active node other than the RN_1 has successfully transmitted, in a cycle with the RN_1 inactive; the third and fourth terms indicate consumption when one k node, other than the RN_1, gains access to the channel but transmits with collision when the RN_1 is active or inactive, respectively.

Note that the stationary probability distribution used is $\pi_1(i,k)$, so the average size of the frame, $f_{1,k}$, is determined by the expression (11). The probability of failure in transmission $\widehat{P}_{f_1,k}$ and $\widehat{P}'_{f_1,k}$ (expressions (10) and (13), respectively), are calculated considering W_1.

3.7.4. Energy Consumption in 2D Cycles

The energy consumption in cycles of type 2D is obtained with the expression (24). In this cycle, energy consumption is accounted for when there is no activity at the nodes.

$$
E_{aw}[2D] = \pi_1(0,0) \pi_2(0,0) (T - T_{sync}) P_{2,rx} \,. \tag{24}
$$

3.7.5. Consumption in the Awake State for RN2

The final value of energy consumed is given by the expression (25), where it is observed that it consists of the sum of the different energy consumptions in the cycles considered.

$$
\begin{aligned}
E_{2,aw} &= (E_{aw}[2A] + E_{aw}[2B]) R_{1,0} + E_{aw}[2C] + E_{aw}[2D] \,, \\
E_{2,aw} &= \left(E_{tx,s}^{aw}[2A] + E_{tx,f}^{aw}[2A] + E_{oh}^{aw}[2A] + E_{aw}[2B] \right) R_{1,0} \\
&+ E_{aw}[2C] + E_{aw}[2D] \,.
\end{aligned} \tag{25}
$$

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Note that $E_{aw}[2A]$ and $E_{aw}[2B]$ are multiplied by the $R_{1,0}$ factor, which defines the fraction of cycles where class 1 nodes are inactive. Remember that the transmissions in these cycles are due to Class 2 nodes; therefore, class 1 nodes are inactive during this transmission process.

3.8. Average Energy Consumption During Normal Cycles

Usually, to save energy, the nodes are disabled and enter the *sleep* mode during the rest of the transmission cycle, after a successful or failed transmission. These types of cycles are called *normal* cycles. The following expressions are used to determine the energy consumption of the *RN* during these *normal* cycles. Furthermore, in this calculation, the energy consumption due to *overhearing* during the *data* period is included.

$$E_{nr} = E^{nr}_{tx,s} + E^{nr}_{tx,f} + E^{nr}_{oh} \,. \tag{26}$$

where $E^{nr}_{tx,s}$, $E^{nr}_{tx,f}$ and E^{nr}_{oh} are the terms of energy consumption when the *RN* successfully transmits, transmits with failure (collision), and incurs in ((overhearing)), respectively.

3.8.1. For class 1 Nodes

When successfully transmitted, $E^{nr}_{tx,s}$ consumption for class 1 nodes is determined by the expression (27).

$$\begin{aligned} E^{nr}_{tx,s} &= \sum_{i=1}^{Q_1}\sum_{k=0}^{M_1} \pi_1(i,k) P_{s_1,k} \left[E^{nr}_1 - (\alpha_1\, t_{DATA} + BT_{s_1,k}) P_{sl}\right], \\ E^{nr}_1 &= \left[T - T_{sync} - \left(t_{RTS} + t_{CTS} + t_{ACK} + 4D_p\right)\right] P_{sl}\,, \\ \alpha_1 &= min(i, F_1)\,. \end{aligned} \tag{27}$$

When a failed transmission occurs, the $E^{nr}_{tx,f}$ consumption for class 1 nodes is given by the expression (28).

$$\begin{aligned} E^{nr}_{tx,f} &= \sum_{i=1}^{Q_1}\sum_{k=1}^{M_1} \pi_1(i,k) P_{f_1,k} \left[E^{nr}_2 - BT_{f_1,k}\, P_{sl}\right], \\ E^{nr}_2 &= \left[T - T_{sync} - \left(t_{RTS} + 2D_p\right)\right] P_{sl}\,. \end{aligned} \tag{28}$$

The consumption due to *overhearing* (E^{nr}_{oh}) for class 1 nodes is obtained with the following expressions (29):

$$\begin{aligned} E^{nr}_{oh} &= \sum_{i=1}^{Q_1}\sum_{k=1}^{M_1} \pi_1(i,k) k P_{s_1,k} \left[\left(E^{nr}_3 + BT_{s_1,k}\, P_{1,rx}\right) + \left(E^{nr}_4 - BT_{s_1,k} P_{sl}\right)\right] \\ &+ \sum_{i=1}^{Q_1}\sum_{k=2}^{M_1} \pi_1(i,k) \widehat{P}_{f_1,k} \left[\left(E^{nr}_3 + BT_{f_1,k}\, P_{1,rx}\right) + \left(E^{nr}_4 - BT_{f_1,k} P_{sl}\right)\right] \\ &+ \sum_{k=0}^{M_1} \pi_1(0,k) \left(T - T_{sync}\right) P_{sl}\,, \\ E^{nr}_3 &= \left[D_p + t_{RTS}\right] P_{1,rx}\,, \\ E^{nr}_4 &= \left[T - T_{sync} - D_p - t_{RTS}\right] P_{sl}\,. \end{aligned} \tag{29}$$

The *RN* goes to *sleep* mode when it is inactive, $i = 0$. Note that in E_{nr} only the energy consumed in addition to $E^{d}_{tx,s}$ and $E^{d}_{tx,f}$ is considered in normal cycles.

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3.8.2. For Class 2 Nodes

For class 2 nodes, the power consumption due to successful transmissions ($E^{nr}_{tx,s}$), transmissions with collision ($E^{nr}_{tx,f}$), and the consumption by *overhearing* (E^{nr}_{oh}) is calculated in the same way, but the stationary probability distribution corresponding to class 2 nodes is used in the calculations (π_2). In addition, the multiplication by the factor $R_{1,0} = \pi_1(0,0)$ should be considered, which is the stationary probability distribution that there are no active class 1 nodes in a cycle (a fraction of cycles in which class 1 nodes are inactive).

When the frame is successfully transmitted, $E^{nr}_{tx,s}$ consumption for class 2 nodes is determined by the expression (30).

$$\begin{aligned} E^{nr}_{tx,s} &= \sum_{i=1}^{Q_2}\sum_{k=0}^{M_2} \pi_1(i,k) R_{1,0}\, P_{s_2,k} \left[E^{nr}_1 - (\alpha_2\, t_{DATA} + BT_{s_1,k}) P_{sl}\right], \\ E^{nr}_1 &= \left[T - T_{sync} - \left(t_{RTS} + t_{CTS} + t_{ACK} + 4D_p\right)\right] P_{sl}, \\ \alpha_2 &= min(i, F_2). \end{aligned} \tag{30}$$

When a failed transmission occurs, the consumption $E^{nr}_{tx,f}$, for class 2 nodes is given by the expression (31).

$$\begin{aligned} E^{nr}_{tx,f} &= \sum_{i=1}^{Q_2}\sum_{k=1}^{M_2} \pi_1(i,k) R_{1,0}\, P_{f_2,k} \left[E^{nr}_2 - BT_{f_2,k}\, P_{sl}\right], \\ E^{nr}_2 &= \left[T - T_{sync} - \left(t_{RTS} + 2D_p\right)\right] P_{sl}. \end{aligned} \tag{31}$$

The consumption per *overhearing* (E^{nr}_{oh}) for class 2 nodes is obtained with the expressions of (32).

$$\begin{aligned} E^{nr}_{oh} &= \sum_{i=1}^{Q_2}\sum_{k=1}^{M_2} \pi_1(i,k) R_{1,0}\, k P_{s_2,k} \left[\left(E^{nr}_3 + BT_{s_1,k}\, P_{2,rx}\right) + \left(E^{nr}_4 - BT_{s_2,k} P_{sl}\right)\right] \\ &+ \sum_{i=1}^{Q_2}\sum_{k=2}^{M_2} \pi_1(i,k) R_{1,0}\, \widehat{P}_{f_2,k} \left[\left(E^{nr}_3 + BT_{f_1,k}\, P_{2,rx}\right) + \left(E^{nr}_4 - BT_{f_2,k} P_{sl}\right)\right] \\ &+ \sum_{k=0}^{M_2} \pi_1(0,k) R_{1,0} \left(T - T_{sync}\right) P_{sl}, \\ E^{nr}_3 &= \left[D_p + t_{RTS}\right] P_{2,rx}, \\ E^{nr}_4 &= \left[T - T_{sync} - D_p - t_{RTS}\right] P_{sl}. \end{aligned} \tag{32}$$

The *RN* goes to *sleep* mode when it is inactive, $i = 0$. Note that in E_{nr} only the energy consumed in addition to $E^{d}_{tx,s}$ and $E^{d}_{tx,f}$ is considered in normal cycles.

3.9. Average Total Energy Consumption

To calculate the average total energy, the energy consumption contributions from the previously considered periods are added and determined by the equation 33.

$$E = E_{sc} + E_d + E_{sl}. \tag{33}$$

In the previous expression, E_{sc} is determined in accordance with subsection 3.1. E_d consumption is calculated as shown in subsection 3.2. To determine the last term of 33, which refers to consumption during the sleep period (E_{sl}), the following expression is used (34):

$$E_{sl} = E_{nr}\frac{(N_{aw} - 1)}{N_{aw}} + E_{aw}\frac{1}{N_{aw}}. \tag{34}$$

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Remember that in the *sleep* period, a node can go to a *sleep* to save energy, but it may also not sleep and stay awake or wake up to receive SYNC packages and maintain synchronization with its neighboring nodes. Note that N_{aw} is the variable that determines the fraction of cycles in which the node will sleep or remain awake. Finally, the sum of energy expenditure due to the activities mentioned in that period is what reflects the expression (34).

4. Numerical Results

4.1. Scenario and Parameter Configuration

The analytical results have been obtained using the two-dimensional Markov chain model (2D-DTMC). Simulation results have been obtained using a customized discrete event simulator developed in the C language that mimics the physical behavior of the system (SPT or APT schemes). That is, in each cycle, a node receives packages according to a given discrete distribution, competes for access to the channel with other nodes if it has packets in the queue, and if it wins, it transmits a frame according to the transmission scheme (one packet for SPT or a set of packets for APT). The results of the simulation are completely independent of those obtained by the analytical model. The configuration of the parameters for the WSN scenario is carried out according to the specifications shown in Table 1.

Table 1. Parameter configuration [24].

Cycle time (T)	60 ms	Propagation delay (D_p)	0.1 μs
t_{SYNC}, t_{RTS}, t_{CTS} and t_{ACK}	0.18 ms	*Slot* time (ts)	0.1 ms
t_{DATA}	1.716 ms	Contention window (W)	128 slots
DATA packet size (S)	50 bytes	Queue size (Q)	10 packets
SYNC packet Tx period (N_{sc})	20 cycles	Awake period (N_{aw})	80 supercycles
Transmission power (P_{tx})	52 mW	Reception power (P_{rx})	59 mW
Sleep power consumption (P_{sl})		$P_{sl} = 3\mu W$	
Maximum frame size		$F = \{2, 5, 10\}$ packtes	
Nodes number $N_1 = 5$, $N_2 = 20$		Packets arrival rate (packets/s) $\lambda_1 = \{0.5\}$, $\lambda_2 = [0.5, 4.5]$	

The following sections present figures with the results derived from the analytical and simulation models. In the figures, the lines with markers represent the analytical results, while the simulation results are represented only by markers.

4.2. Components of Energy Consumption

This section presents the results of the components of energy consumption; a breakdown is made of the contributions due to consumption by data transmission in the *data* period and contributions owed to the *awake* and *normal* operating cycles during the *sleep* period. Figure 3 shows these power consumptions for class 1 nodes configured to transmit in SPT. A constant behavior in the consumption of the three energy components is observed, and a more significant contribution of the nodes entering the *awake* cycle during the *sleep* period is observed compared to the data period and the *normal* operating cycle.

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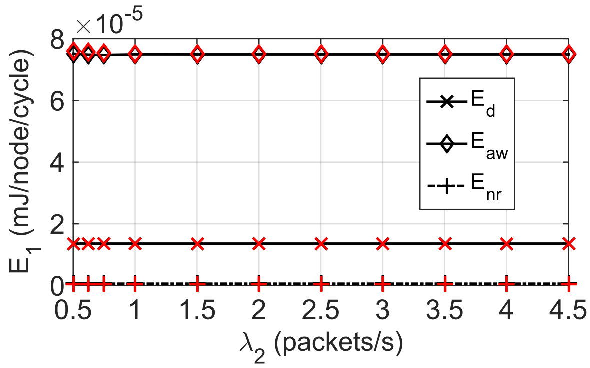

Figure 3. Components of energy consumption for class 1, during the *data* period, and the *awake* and *normal* cycles. Transmission mode: SPT (both classes) and $Q_1 = Q_2 = 10$.

Figure 4 shows the power consumption for Class 2 nodes, also under the SPT transmission scheme. In relation to Figure 3, there is an increase in consumption in the normal operation phase or normal cycle, which consists of the energy spent by the nodes when they go to sleep or remain in sleep mode and the energy due to *overhearing*. There is also a decrease in data transmission, as evidenced by a reduction in energy consumption during the *data* period. It is considered that the above is the effect observed as a result of an increase in congestion due to the fact that it is a non-priority class, in addition to having a greater number of nodes than class 1.

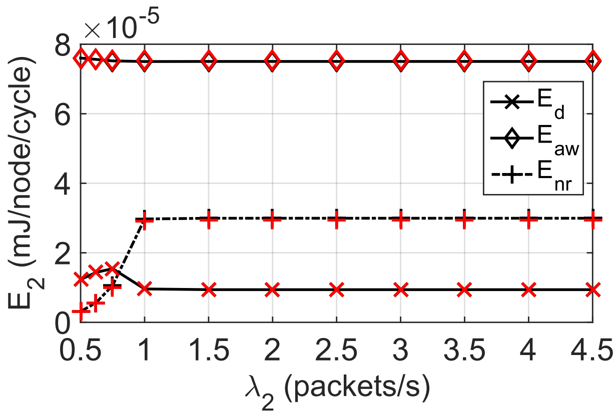

Figure 4. Components of energy consumption for class 2, during the *data* period, and the *awake* and *normal* cycles. Transmission mode: SPT (both classes) and $Q_1 = Q_2 = 10$.

Figure 5 and Figure 6 show the components of power consumption when transmitted in APT, with a maximum size of $F_1 = F_2 = 2$ packets per frame for class 1 and Class 2 nodes, respectively. Figure 5 shows that there is virtually no change in the results for class 1, when compared with the results of the same class but with the SPT transmission scheme, as shown in Figure 3.

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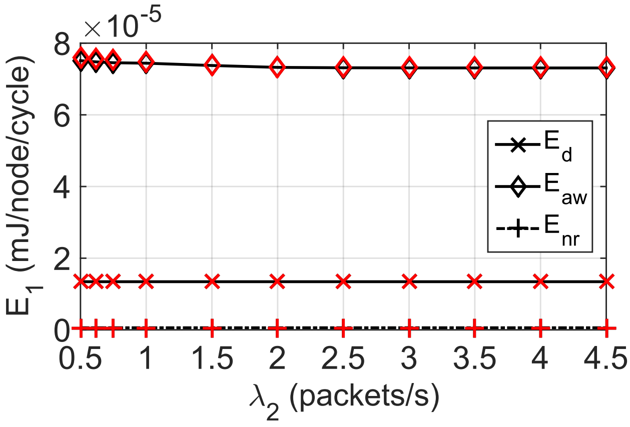

Figure 5. Components of energy consumption for class 1, during the *data* period, and the *awake* and *normal* cycles. APT transmission mode ($F_1 = F_2 = 2$) and $Q_1 = Q_2 = 10$

However, for Class 2 (Figure 6), a higher transmission of packets is gained, as a higher energy consumption is observed in the data period, when compared with Figure 4, whose results correspond to the SPT transmission scheme. Clearly, increasing the transmission of information in one more packet ($F_2 = 2$) has a positive impact on relieving the congestion of the medium of transmission. In the same way, comparing the results of Figure 4, it is observed that in Figure 6, the maximum values of energy consumption are achieved during the *data* period and the *normal* cycle at higher traffic rates.

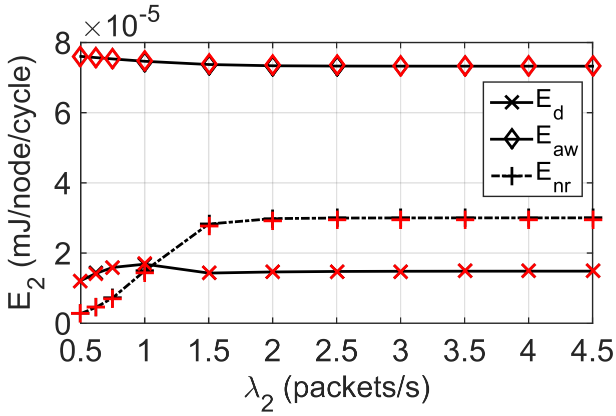

Figure 6. Components of energy consumption for class 2, during the *data* period, and the *awake* and *normal* cycles. APT transmission mode ($F_1 = F_2 = 2$) and $Q_1 = Q_2 = 10$.

Figure 7 and Figure 8 show energy consumption by considering the APT scheme, when the maximum frame size a node can transmit $F_1 = F_2 = 5$ packets for class 1 and class 2 nodes, respectively. Figure 7 shows a decrease in *awake* consumption towards the end of the graph as traffic increases.

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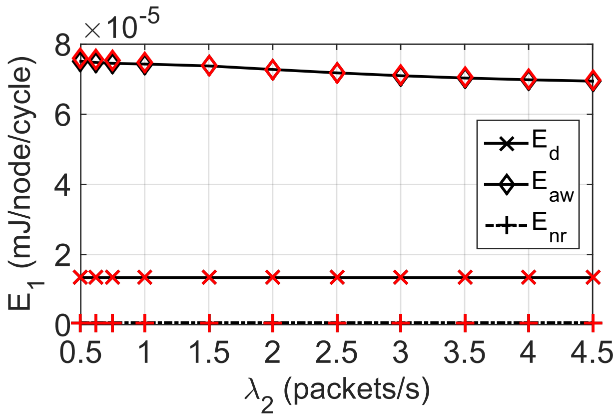

Figure 7. Components of energy consumption for class 1, during the *data* period, and the *awake* and *normal* cycles. APT transmission mode ($F_1 = F_2 = 5$) and $Q_1 = Q_2 = 10$.

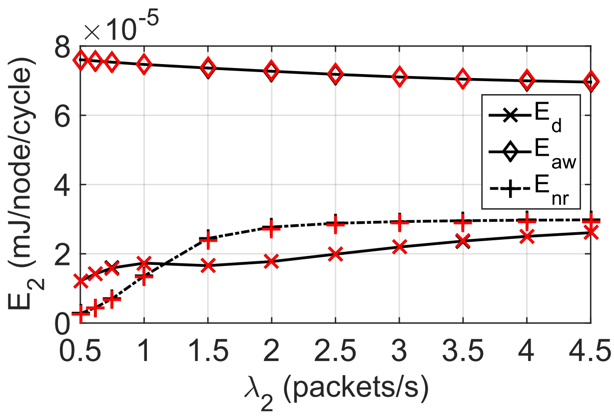

Figure 8. Components of energy consumption for class 2, during the *data* period, and the *awake* and *normal* cycles. APT transmission mode ($F_1 = F_2 = 5$) and $Q_1 = Q_2 = 10$.

On the other hand, the consumption due to the inactivation of the node in the *normal* operating phase is very small. This trend has been observed in all the results for class 1. The above is considered to be due to the fact that there is virtually no contention, as class 1 is the priority class and there are a small number of nodes in this class. As there is virtually no contention, the packet or frame that reaches the queue is transmitted immediately, deactivating the node immediately during the rest of the cycle to save energy, but for a shorter time, because when there is a successful transmission, the node has to wait until the transmission of the frame is finished to deactivate itself. Clearly, there is a lower consumption when the nodes deactivate themselves after they have failed in transmission or have lost contention. In the latter case, they do not need to wait anytime to become inactive, lasting longer asleep and consuming for longer that minimal sleeping energy.

In Figure 8, and in all that has been seen for class 2 nodes, a significant consumption is observed for the normal operation phase, when the nodes go to sleep or fall to rest. This is because there is greater competition given that there are more nodes in this class, and an increase in this congestion is observed as traffic increases. As there is greater contention, the nodes are more likely to lose the competition for media access more often, or the transmitted packets will collide with a higher probability. This implies that more nodes go to sleep more times immediately after failing to transmit or losing the contest, and consequently, there is an increase in normal energy consumption.

Figure 9 and Figure 10 show energy consumption by considering the APT scheme, when the maximum frame size that a node can transmit in packets is F1 = F2 = 10, for class 1 and class 2 nodes, respectively. From Figure 9, we can comment on the decrease in energy consumption as traffic increases.

This is clearly observed in cases where traffic aggregation transmission (APT) is used, especially for $F_1 = \{5, 10\}$.

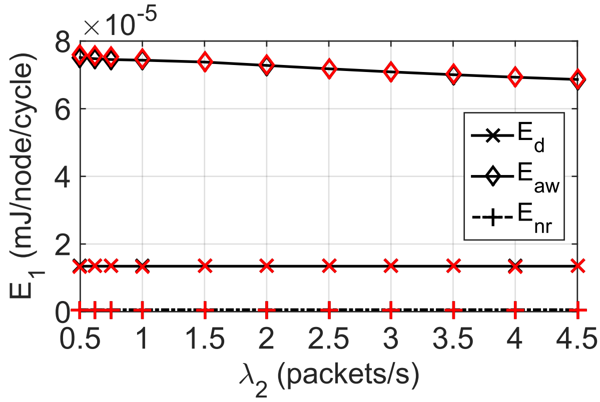

Figure 9. Components of energy consumption for class 1, during the *data* period, and the *awake* and *normal* cycles. APT transmission mode ($F_1 = F_2 = 10$) and $Q_1 = Q_2 = 10$.

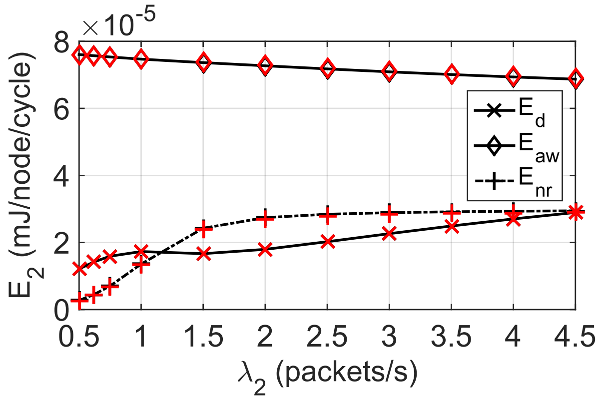

Figure 10. Components of energy consumption, for class 2, during the *data* period, and the *awake* and *normal* cycles. APT transmission mode ($F_1 = F_2 = 10$) and $Q_1 = Q_2 = 10$.

By improving the efficiency of the transmission of information, as the number of packets per frame increases, it also increases the likelihood that nodes will successfully transmit their frames because it contributes to decongestioning the transmission channel. According to the scenario described in Section 3.3, a node that is in the *awake* phase and that has successfully transmitted subsequently consumes less energy than an *awake* cycle node that has been transmitted with collision. This is because the time of energy consumption for packet reception is shorter when there has been success in transmission. When a node in the *awake* cycle fails transmission, the node turns its receiver on in advance (compared to a successful transmission) and keeps it on for the rest of the cycle. Therefore, by increasing the successful packet transmission frequency, nodes entering the *awake* cycle will tend to consume less energy. This causes a decrease in energy consumption in the *awake* cycle, as seen towards the end of the corresponding curve in Figure 10. The energy consumed in this phase is significant, as a certain amount of power is needed to keep the receiver on Table 1. Figure 10 confirms the trend that has been observed towards an increase in energy consumption due to data transmission as the number of packets sent by frame increases.

5. Conclusions

A comprehensive energy consumption model for heterogeneous IoT WSN-based devices has been developed that considers the entire operation modes and cycles of sensor nodes. The model is based on two concatenated 2D-DTMCs that are solved and whose solution in terms of stationary probability distribution is used by derived expressions in order to determine the energy consumption. The model considers a synchronized duty cycle MAC protocol for a heterogeneous network with priority assignment and the possibility to transmit packets in aggregation (APT transmission mode). The entire transmission cycle and the different operating modes, including synchronization consumption, data transmission consumption, and the energy due to *normal* and *awake*, operations cycle, are considered. Due to the heterogeneous scenario and the necessary coexistence of different classes of nodes, we have obtained exhaustive expressions, especially for the *awake* and *normal* operation cycle.The average energy consumption results are obtained from the analytical model and validated through simulations based on discrete events, obtaining very accurate results. With regard to the energy results, an analysis of the different components of the energy consumption of the nodes is carried out.

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References

1. Mansour, M.; Gamal, A.; Ahmed, A.I.; Said, L.A.; Elbaz, A.; Herencsar, N.; Soltan, A. Internet of Things: A Comprehensive Overview on Protocols, Architectures, Technologies, Simulation Tools, and Future Directions. *Energies* **2023**, *16(8):3465*, 1–39.
2. Ahmed, S. Energy Aware Software Defined Network Model for Communication of Sensors Deployed in Precision Agriculture. *Sensors* **2023**, *23(11):5177*, 1–19.
3. Pedditi, R.B.; Debasis, K. Energy Efficient Routing Protocol for an IoT-Based WSN System to Detect Forest Fires. *Applied Sciences* **2023**, *13(5):3026*, 1–22.
4. Chi, H. R.; Wu, C. K.; Huang, N.; Tsang, K.; Radwan, A. A Survey of Network Automation for Industrial Internet-of-Things Toward Industry 5.0. *IEEE Trans. Ind. Informatics* **2023**, *19*, 2065-2077.
5. Guiloufi, A.; El khediri, S.; Nasri, N.; Kachouri A. A comparative study of energy efficient algorithms for IoT applications based on WSNs. *Multimed. Tools Appl.* **2023**, *82*, 42239–42275.
6. Abdul-Qawy, A.; Alduais, N., Saad, A.; Taher, M.; Nasser, A.; Saleh, S.;Khatri, NB. An enhanced energy efficient protocol for large-scale IoT-based heterogeneous WSNs. *Sci. Afr.* **2023**, *21 e01807*, 1–24.
7. Abdulzahra, A.; Al-Qurabat, A.; Abdulzahra, S. Optimizing energy consumption in WSN-based IoT using unequal clustering and sleep scheduling methods. *Internet Things* **2023**, *22 100765*, 1–37.
8. Banti, K.; Karampelia, I.; Dimakis, T.; Boulogeorgos, A.; Kyriakidis, T.; Louta M. LoRaWAN Communication Protocols: A Comprehensive Survey under an Energy Efficiency Perspective. *JTelecom* **2022**, *3*, 322–357.
9. Ghaderi, M.R.; Amiri, N. LoRaWAN sensor: energy analysis and modeling. *Wirel. Netw.* **2024**, *30*, 1013–1036.
10. Correia, F. ; Alencar, M.; Assis, K. Stochastic Modeling and Analysis of the Energy Consumption of Wireless Sensor Networks.*IEEE Lat. Am. Trans.* **2023**, *21(3)*, 434–440.
11. Nguyen, M.T.; Nguyen, H.M.; Masaracchia, A.; Nguyen, C.V. Stochastic-Based Power Consumption Analysis for Data Transmission in Wireless Sensor Networks. *EAI Endorsed Trans. Ind. Networks Intell. Syst.* **2019**, *6 (19) e5*, 1–11.
12. Xu, D.; Wang, K. Stochastic Modeling and Analysis with Energy Optimization for Wireless Sensor Networks. *Int. J. Distrib. Sens. Networks* **2014**, *10(5) 672494*, 1–6.
13. Rahimifar, A.; Kavian, Y.; Kaabi, H.; Soroosh, M. Predicting the energy consumption in software defined wireless sensor networks: a probabilistic Markov model approach. *J. Ambient. Intell. Humaniz. Comput.* **2021**, *12(10)*, 9053–9066.
14. Zhang, Y.; Li, W. Energy consumption analysis of a duty cycle wireless sensor network model. *IEEE Access* **2019**, *7*, 33405-33413.

 doi:10.20944/preprints202405.1658.v1

15. Xiao, W.; Kaneko, M.; El Rachkidy, N.; Guitton, A. Integrating lora collision decoding and mac protocols for enabling iot massive connectivity. *IEEE Internet Things Mag.* **2022**, *5(3)*, 166–173.
16. Wang, Y.; Vuran, M.C.; Goddard, S. Stochastic Analysis of Energy Consumption in Wireless Sensor Networks. In Proceedings of the 2010 7th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON), Boston, Massachusetts, USA, 21-25 June, 2010; 1-9 pp.
17. Gallucio, L.; Palazzo, S. End-to-End Delay and Network Lifetime Analysis in a Wireless Sensor Network Performing Data Aggregation. In Proceedings of the 2010 In 2009 IEEE Global Telecommunications Conference (GLOBECOM 2009), Honolulu, Hawaii, USA, 30 November-4 December, 2010; 1-6 pp.
18. Li, Z.; Peng, Y.; Qiao D.; Zhang, W. Joint Aggregation and MAC design to prolong sensor network lifetime. In Proceedings of the 2013 21st IEEE International Conference on Network Protocols (ICNP), Goettingen, Germany, 2013, 7-10 October, 2013; 1-10 pp.
19. Li, Z.; Peng, Y.; Qiao D.; Zhang, W. LBA: Lifetime balanced data aggregation in low duty cycle sensor networks. In Proceedings of the The 31st Annual IEEE International Conference on Computer Communications (IEEE INFOCOM 2012), Orlando, Florida, USA, 2013, 25-30 March, 2012; 1844-1852 pp.
20. Guntuplli, L.; Martinez-Bauset, J. Li, F.Y.; Weitnauer, A. Aggregated packet transmission in duty-cycled WSNs: Modeling and performance evaluation. *IEEE Trans. on Vehicular Technology* **2016**, *66(1)*, 563–579.
21. Portillo, C.; Martinez-Bauset, J.; Pla, V.; Casares-Giner, V. Modeling of Duty-Cycled MAC Protocols for Heterogeneous WSN with Priorities. *Electronics* **2020**, *9 (3):467*, 1–19.
22. Portillo, C.; Martinez-Bauset, J.; Pla, V.; Casares-Giner, V. Heterogeneous WSN Modeling: Packet Transmission with Aggregation of Traffic. In Proceedings of the Interdisciplinary Conference on Mechanics, Computers and Electrics (ICMECE 2022), Barcelona, Spain, 6-7 October 2022; 278-283 pp.
23. Portillo, C.; Martinez-Bauset, J.; Pla, V.; Casares-Giner, V. Energy Modeling and Analysis for IoT Sensor Devices: A DTMC-Based Approach. In Proceedings of the Workshop on Innovation on Information and Communication Technologies (ITACA-WIICT 2018), Valencia, Spain, 13 July, 2018; 126-142 pp.
24. MICAz Data Sheet. Crossbow Technology Incorporated, San Jose, CA, USA. Available online: $http://courses.ece.ubc.ca/494/files/MICAz_Datasheet.pdf$ (accessed on 1 April 2024).