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A multimode and multithreshold approach for energy efficiency in Internet of things systems

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Abstract

The IEEE 802.15.4 is designed for wireless personal area networks. Indeed, wireless personal area network turns out to help greatly in maintaining a flexible mode of communication within limited area networks. It is in this context that our present study can be set, in which the beacon-enabled mode is enabled with cluster tree topology to reach the scope of a rather extended network, whereby the network turns out to be clustered into several subgroups. Every single subgroup is characterized by its specific duty cycle which is configured by its correspondent personal area network coordinator. Therefore, many modes are enabled in the same network. Based on a very special mathematical model developed by us for energy consumption, the personal area network coordinator detects the actual level of energy in the battery of node. Then, an interesting comparison is made with the multiple thresholds which are already set. After that, both beacon order and superframe order (the standard IEEE 802.15.4 parameters) are recomputed with reference to the remaining energy.

Introduction

The Internet of things (IoT) has recently been established as a common terminology, frequently applied in the field of technology. Also dubbed Internet of Everything as well as Industrial Internet, IoT stands for a recently devised technology involving the entirety of devices capable of maintaining a particular mode of communication without the intervention of any human interference. Actually, the term Things in the Internet refers to all kinds of machines and devices destined for establishing a social life–based communication.[1]

The IoT is a newly coined term which has made its appearance in the very recently elaborated research works. Indeed, it could be considered as an extension of the revolution taking place in the area of machine-to-machine-based communication (M2M), helping in the establishment of communicative interactions between everyone and everything. It is actually these features which accord the IoT its global worldly character. In effect, these things are capable of detecting data and sending them wirelessly, which turns them out to be smart. These smart things have the capacity of

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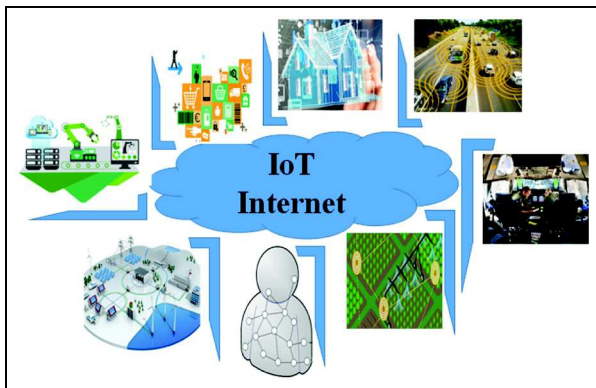Email: ayadihayfa.ing@gmail.com

Figure 1. Internet of thing application.

evaluating data collected from sensing materials, establishing communication with them, and taking appropriate timely decisions along with applying them. It allows different objects the opportunity to interact with their relating environment via the multiple senses available: hearing, sensing, and thinking. It is, therefore, due to this wide range of advantages that the IoT is presently implemented in a large array of domains such as the smart home,[2] transportation,[3] agriculture,[4] healthcare,[5] industry,[6] and entertainment,[7] as illustrated in Figure 1. Still, despite the various advantages it displays, the IoT is faced with diverse challenges, particularly, that associated with an immense number of connected devices, each entailing a specific identification. Such a state is likely to culminate in an immense range of nomenclatures that require the introduction of an effective identity management system. As a matter of fact, such a system needs to be dynamic enough for the identity's distinctiveness to be well safeguarded and preserved.

Indeed, the system has to be capable of managing and assigning a uniquely specific identity for such a wide range of objects. As the IoT contributes remarkably in connecting several devices to the various corresponding technologies and services with which they are intermingled and associated, numerous problems are most likely certain to emanate, owing to this noticeable diversity. Consequently, interoperability and standardization turn out to be serious issues associated with IoT systems. As it is the case within all information transmissions, an encryption system proves to stand as a critical necessity for data to be effectively transmitted from the physical environment. Similarly, the problem of fault detection[8,9] and energy provision also represents a very serious issue which contributes to developing many approaches in order to well control the energy consumed in the wireless sensor network (WSN) as well as the IoT systems.[10–12] In fact, as the IoT system associated data rate continues to grow, the consumed energy also increases remarkably, and in this respect, green energy would stand as an interesting
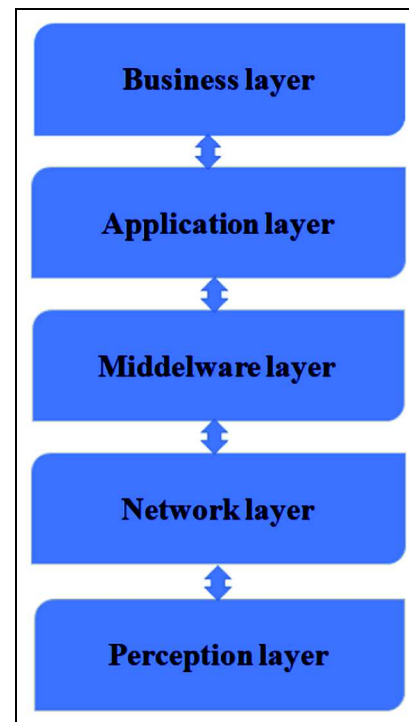

Figure 2. IoT system relating architecture.

alternative. Many applications consist of deploying billions, or trillions, of different objects and connecting them via the Internet network. The main problem always with the wireless communication is the energy consumption of the devices because of the wireless battery devices' capacity which is so limited. In addition to that in most of the cases, the wireless networks are deployed in a very special environment which is characterized by its inaccessibility. All the circumstances cited prove the importance of the energy in this field.[13] In this regard, several models have been proposed with the aim of devising a clear IoT system-relevant architecture but were met with several challenges, mainly those relating to the QoS, scalability, reliability, and interoperability. Still, certain basic layers appear to stand as too crucially critical to be incorporated in such an architecture, namely: the perception layer, network layer, middleware layer, along with the application layer, as illustrated in Figure 2.[14] Dubbed perception layer or device layer is responsible for maintaining the physical data,[15] and as such, the system's sensors are in their entirety connected to this layer. Their major task consists in identifying the data sources, and, naturally, sensing all the relevant environmental factors, such as temperature, humidity level, and vibration. In a second place, the collected data are transformed into digital data, prior to being diffused across the network.[14] Concerning the second layer, called network layer, it is assigned the role of receiving digital signals from the

perception sensors and transmitting it to the following layer, that is, the middleware layer via other technology means, such as 3G, wireless or wired media, for instance, ZigBee, WiMAX, Bluetooth, or WiFi, using specific protocols such as ipv6. Regarding the third layer, the middleware layer, it is allotted the task of managing the received information, prior to storing it in the database. The stored data are then processed and automated decisions are taken based on the results reached. As for the fourth layer, it consists in the application layer, which designates the appropriate application mode fit for the IoT system, for example, a healthcare application, smart farming, and industry. Finally, there comes the business layer, responsible for devising models, flowcharts, and graphs, based on the application layer emanating data. It is actually considered as the most important layer, owing mainly to the best business model selection it could provide, whereby the relevant analysis results may be displayed.

IoT systems pertaining technologies

The IoT network consists in a joint interaction among a wide range of various technologies, involving a large array of sensors, culminating in the emergence of the WSN. In effect, the WSN is considered as the major contributor of the IoT, whereby a great number of sensors are intricately interconnected and inter-nodal data turn out to be transmitted in such a way as to give birth to networks of smaller range. It is actually this interconnection between the small-range networks which lies at the origin of the creation of IoT networks. In its real sense, the IoT network is a collection of several diverse technologies, such as the IEEE 802.165.4 and ZigBee. Noteworthy, also, is that a wide array of protocols turn out to be established on the basis of the IoT, worth citing among which are the 6LoWPAN and Z-Wave.[15]

ZigBee and IEEE 802.15.4

As a matter of fact, even though the IoT network appeals to a wide range of technologies, the ZigBee remains still the most commonly appropriate one.

ZigBee technology. ZigBee is defined as a wireless communication technology destined to fit for application with low-rate sensors. It also englobes a physical layer, a medium access control (MAC) layer, a network layer, and an application layer. Just like the 6LoWPAN, the ZigBee is based on the IEEE 802.15.4 standards regarding both of its physical and MAC layers, while the upper layer is defined by its proper technology. It is also defined to comply well with three particular devices, specifically, the full function device (FFD) and the reduced function device (RFD), exclusively allowing for

three topologies to be maintained: the mesh, the tree, and the peer-to-peer topologies. Similarly, it undertakes a typical classification of nodes into three kinds enclosing the coordinator, end devices, and the router. The coordinator is responsible for paving the convenient route fit for maintaining data transmission. Besides, it serves to select the most appropriate topology useful for the network, in addition to initializing all the other parameters, including the operational parameters and the network's identifier, along with maintaining the channel's frequency.[15] As for the end device, it is characterized with a low-rate and low-power capacity, involving a number of environmental parameters detecting devices. Concerning the third component, that is, the routers, they constitute the major instruments responsible for ensuring the coordination of activities between the end devices and the coordinator. It can maintain easy connections with other routers in the network.

IEEE 802.15.4 standard. It is worth recalling that the IEEE 802.15.4 constitutes the major technology fit for equitable manipulation via the IoT networks.[16] Indeed, such technology displays the most appropriate choice fit for interaction with the IoT system's relating physical and MAC layers. Actually, this standard was initially invented for the purpose of solving similar challenges facing the WSN, particularly, the low-rate, versus the great area, coverage associated with the wireless local area network (WLAN) and wireless metropolitan area network (WMAN).

Still, energy constitutes the most serious trouble encountered by most of the wireless-based modes of communication, including the wireless personal area network (WPAN) family, simply formed of both physical and MAC layers. As it is the case with the ZigBee technology, its associated nodes could be of either an FFD or an RFD in type. The major related imposition is that the coordinator node must necessarily be of an FFD in type, while the end devices have to incorporate (RFD) pertaining nodes. To note, the FFD-related nodes are characterized by their remarkable energy storage capacity, with respect to the other RFD-associated nodes. As for the topological models enabled to fit well for an interactive co-integration with this particular technology, they are the peer-to-peer, tree, and mesh architectures. With respect to the tree topology, communication need be established between one personal area network (PAN) coordinator and at least a single end device. Regarding the peer-to-peer topology, however, communication could be established between a pair of nodes of the same type.[16] As for the mesh technology, every node is apt to communicate with any other node in the network, even if it does not pertain to the same range.

The IEEE 802.15.4 technology encompasses two main layers, namely, the physical layer and the MAC layer. The physical layer has two major roles to play, mainly, maintaining all data services required along with managing the physical layer. It is able to provide the possibility of applying up to 27 channels for the three bands available, specifically: a single channel within the 868 MHz range, 10 channels within the 915 MHz range, along with 17 channels within the 2.4 GHz range band. Noteworthy, also, is that a set of just three data rates could be provided via this standard mode, namely, 20, 40, and 250 kbps.[16] The same applies to the MAC layer, dedicated to perform such crucial functions as maintaining the MAC management service as well as the MAC data service, along with managing the beacon-relevant data, selecting the appropriate transmission channel, ensuring the link quality indication (LQI), energy detection (ED) in addition to monitoring and dealing with the radio transceiver's activity. Similarly, the MAC layer is mainly responsible for maintaining the beacon transmission process, in addition to managing the guaranteed time slot (GTS) and fulfilling the crucial role of ensuring the data transmission security.[16] In this respect, the IEEE 802.15.4 technology helps provide two modes of activities: the beacon-enabled mode and the non-beacon-enabled mode. Regarding the first mode, the PAN coordinator periodically sends a beacon frame to the entirety of the network's nodes to maintain a full range synchronization of their activities in addition to controlling the nodes' duty cycle through determining their relevant activity periods and sleeping spans, as defined via both of the superframe duration (SD) and the beacon interval (BI).[16] Both of the SD and BI are described in the formulas appearing below, that is, relation (1) and relation (2), respectively[16]

$$BI = a\ Base\ Superframe\ Duration \times 2^{BO}$$
$$1 \leq \text{BO} \leq 14 \qquad (1)$$

$$SD = A\ Base\ Superframe\ Duration \times 2^{SO}$$
$$0 \leq \text{SO} \leq \text{BO} \leq 14 \qquad (2)$$

The SD period indicates the node's activity duration throughout which it is able to send or receive data from other nodes in the network. Hence, intervening with the SD period would certainly contribute remarkably in monitoring the energy amount as consumed by the node. As for the second duration interval, it concerns the situation in which the node remains still in a sleeping state.[16] To note, the SD duration is characterized by its superframe order (SO). It also comprises 16 equal-size slots as presented by Figure 3.[16] It starts with the beacon frame, which plays a critical role within the IEEE 802.15.4, as it is assigned the task of synchronizing the entirety of the network involved members. In this context, a pair of successive beacons will help
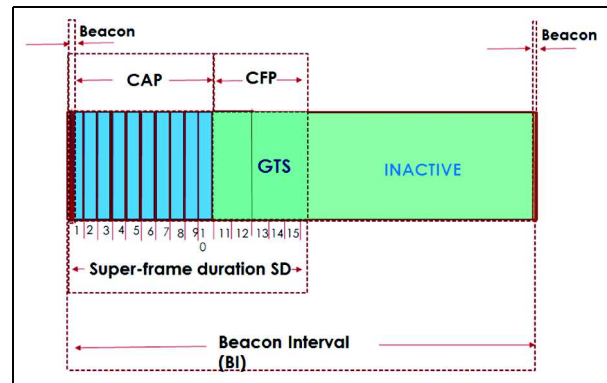

Figure 3. Frame composition.

define the actual BI. Regarding the active period, it consists of two different components, namely: the contention access period (CAP) and the contention free period (CFP). Throughout the CAP period, the node undertakes to send data via the carrier sense multiple access with collision avoidance (CSMA/CA) protocol. With respect to the CFP interval, however, appeal is made to the time division multiple access (TDMA) protocol, as exclusively deployed in this particular context. The two possible uses, relevant to the implementation of the CSMA/CA protocol, relate to the deployment of either of its associated versions: the slotted mode or the unslotted one. As far as this work is concerned, the focus of interest is exclusively laid on the slotted version of the CSMA/CA protocol, as illustrated in Figure 4.[15] In the first stage, we proceed with a small test which is done in order to discover the state of the battery life of the node. Then, the backoff exponent (BE) value is set to *macMinBE*. After that a small delay is chosen in which the node tries to proceed to the canal of transmission after exploring its state (idle or free). The next step is about defining the relevant parameters, which stand as follows: BE represents the backoff exponent, while NB denotes the number of times the slotted algorithm proves to request the congestion window backoff, and CW designates the congestion window. In the next stage, two clear channels are waiting to discover the transmission canal–associated potential. Then, based on the canal status, a relevant appropriate decision is taken.[17] Thus, either relevant data will be transmitted or an extra short-span duration is awaited, for a potentially possible appropriate canal availability to be checked.

Related work

It is worth highlighting that in association with the IEEE 802.15.4 technology, three possible approaches appear to be accessible for the node consumed energy to be effectively monitored, as applied within this
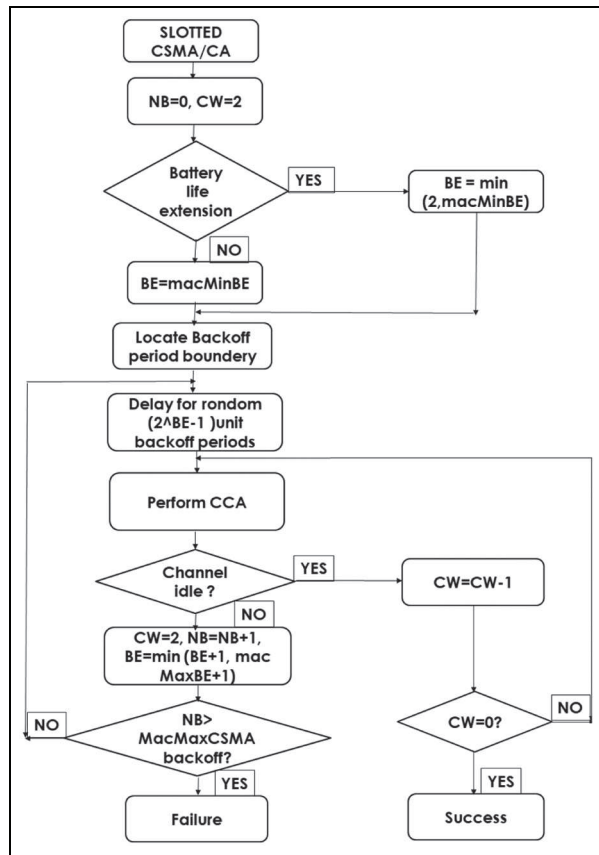
Figure 4. CSMA/CA slotted algorithm.

particular standard. They involve intervening with SD, intervening with BI, or else modifying both of the SD and the BI-associated intervals. Actually, restricting the active period could well stand as the most convenient and simplest alternative, whereby the communication span between the network members can be noticeably controlled. Many authors have demonstrated a remarkable interest in such a solution. Thus, on establishing a small-scale comparison with the initialized threshold, should the superframe occupation ratio (OR) turns out to be inferior to the initial threshold, a second test needs to be accessed, whereby the OR would be compared to a second threshold. A second proceeding lies in intervening with the beacon order (BO) in such a way as the SO value turns out to be fixed and the BO liable to manipulation, based on parameters such as the network traffic load adaptive algorithm (BOAA).[18] Indeed, they have devised a new approach, dubbed dynamic superframe adjustment algorithm (DSAA), whereby the SO value can be selected on the basis of a small comparison, to be established in terms of a certain network-associated parameters, such as the collision rate.[19] In turn, they have set up another approach which they called the duty cycle algorithm (DCA), whereby they considered adjusting the SO parameter with reference to the queuing delay, queue size, data

rate, and energy consumption. To this end, they used a fixed value of the BO, wherein a mere change in SO would lead to a conservation of the BI, which is likely to affect the sleeping period.[20] In addition, the adaptive algorithm to optimize the dynamics (AAOD) also stands as another model useful for dealing with the SO value management,[21] that rests on the same principle. Adaptation of the SO parameter proves to exclusively rely on the number of packets received. Should their number exceeds a predefined threshold, the SO value would then be decreased, and inversely, however (i.e. in the opposite case), the SO would increase. Another protocol, highly dependent on the superframe occupied period, is also considered to fit well with this very technique; it consists of the adaptive MAC protocol (AMPE).[22] Actually, this procedure is dedicated to just comply with small networks characterized by start topology and is predestined to help lengthen the beacon period. Similarly, relying on the same node sleeping-period maximization principle, the individual beacon order adaption algorithm (IBOAA) stands as a simple technique, whereby the node-associated lifetime could be managed.[23] Hence, it follows, in this respect, that the most effective method turns out to be that which helps in effectively and simultaneously managing both of the BO and SO relating values. Indeed, several approaches have been devised to address such a challenge. In the study by Oliveira et al.,[24] for instance, the authors try to control the duty cycle through intervening simultaneously with the BI and SD. Thus, the duty cycle self-adaptation algorithm (DBSAA) appears to stand as the most striking manifestation of this particular technique. Actually, the duty cycle proves to rely heavily on four network-related parameters, namely, the number of packets received by the coordinator, the number of source nodes, the superframe OR, along with the collision ratio (CR). Moreover, Salayma et al.[25] used cross-layer method named the battery aware and reliable beacon enabled IEEE 802.15.4 (BARBEI). This method proves its efficiency by the different simulation results published. Salayma et al.[26] change both the values of the BI and the SD and then study theirs impacts in the performance of the WSN. In addition to that, another approach was developed based on the traffic load of the network. The best results are presented by both ($BO = 7$, $SO = 5$) values.[27] All the approaches are summarized in Table 1. Most of the cited works do not give importance to the actual energy level in the battery, but in our approach, this level intervenes mainly in the manner of computation of the BO and SO.
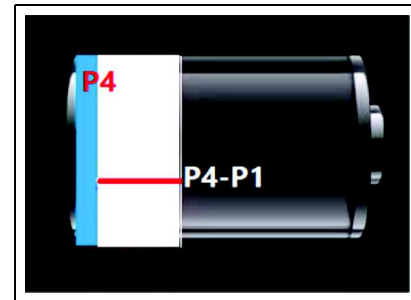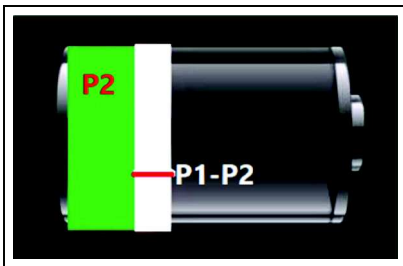
The proposed approach

This work's subject of interest lies in an attempt proposed to manage the last energy amount remaining in

Table 1. Related work.

	BO values	SO values	SO and BO values
Dynamic superframe adjustment algorithm (DSAA)[19]		*	
Duty cycle algorithm (DCA)[20]		*	
The network traffic load adaptive algorithm (BOAA)[18]	*		
The adaptive algorithm to optimize the dynamics (AAOD)[21]		*	
The adaptive MAC protocol (AMPE)[22]		*	
The individual beacon order adaption algorithm (IBOAA)[23]			*
The duty cycle self-adaptation algorithm (DBSAA)[24]			*
Reliable beacon-enabled IEEE 802.15.4 (BARBEI)[25]			*

BO: beacon order; SO: superframe order.
*The approach is included in the correspondent field (BO values, SO values or both).
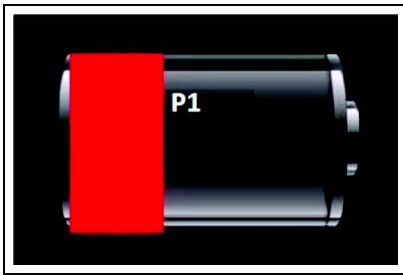
Figure 5. Threshold number 1.

Figure 6. Threshold number 2.
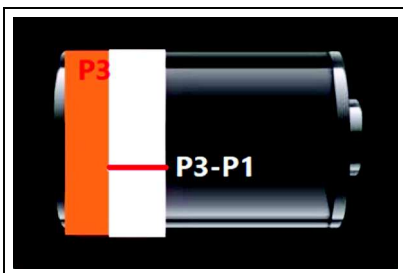
Figure 7. Threshold number 3.

the node's battery. The most effective option, we reckon, consists in monitoring both of the IEEE 802.15.4 beacon-enabled mode-associated parameters. The IEEE 802.15.4 is characterized by two different modes of activities as mentioned above, but the beacon-enabled mode is always the most conservative for

Figure 8. Threshold number 4.

energy consumption because both values (SO, BO) collaborate to control the activity and the sleep duration of the node which leads to minimizing the quantity of energy consumed. Moreover, the beacon data has many other advantages such as the synchronization between all nodes of the network. The framework envisages that every node should send its relevant data to the correspondent coordinator, which would proceed with computing the battery held E_R, prior to comparing it with the initial energy threshold $Et1$ as presented in Figure 5. Should it prove to record a decrease, the (BO1, SO1) are then computed. The same procedure is also reiterated with respect to the entirety of the remaining nodes N and thresholds M which are threshold 2, threshold 3, and threshold 4, as clearly illustrated in Figures 5–8. The figures describe the different levels (P1, P2, P3, and P4) manipulated by our approach which is named: a multimode and multithreshold approach for IoT systems (M2-ABEM). The levels (P1, P2, P3, and P4) are equal consecutively (1.5%, 1%, 0.8%, 0.6%) of the initial energy.

Energy formula

Our proposed model for energy consumption takes into consideration the different state of nodes: emission, reception, idle, sleep, and overhearing and overmitting.[25] It is actually during the transmission phase that the node appears to consume the most important

quantity of energy. Throughout the emission span, when the node undertakes to send its relevant data, the node proves to consume a certain quantity of power, dubbed emission energy $E_{em} \cdot E_{em}$, as described by expression below

$$E_{em} = (nbt_{sd} \times Ttt \times Eb) + 2 \times U \times I \times CCA \times Tp_{back} \tag{3}$$

where nbt_{sd} denotes the number of data frames existing in the SD, Eb stands for the binary energy, Ttt represents the frame size, I stands for the current value, U represents the voltage value, CCA is the clear channel assessment, and Tp_{back} is described by expression below

$$Tp_{back} = (2^{cst_{back}} - 1) \times 20 symbol \tag{4}$$

The $^{cst}back$ stands for the backoff period. Similarly, the node also appears to lose a certain energy quantity during the reception phase, dubbed E_{rc}, as depicted by expression (5), below

$$E_{rc} = nbr_{SD} \times Eb \tag{5}$$

where nbr_{SD} representing the number of bits acquired throughout the SD period. Moreover, and during both of the overhearing and overmitting phases, the energy consumed, as represented by E_o, turns out to be expressed by formula (6)

$$E_o = nbr_{tr} \times dtra \times Eb \times PER \tag{6}$$

where nbr_{tr} expressing the number of bits transmitted by node; $dtra$ representing the frames size (bit); Eb is the binary energy, while PER depicts the error rate attained in the form of packet average transmitted without being well received. As for the collision associated energy E_{col}, it is calculated in accordance with formula (7)

$$E_{col} = Tatt \times U \times I \times Nbpk \tag{7}$$

where $Tatt$ represents the little temporal period necessary to access to the transmission canal; $Nbpk$ denotes the number of attempts the node has made to send data without receiving any acknowledgment from the other side.

Hence, the sleep technique remains the best option useful for managing and intervening with the energy amount available in the node's battery, and, thereof, the network's lifespan as a whole. Actually, the IEEE 802.15.4 standard is well known for its disposition to make such a process achievable. Thus, the energy consumed throughout the sleep period E_{SLP} could be depicted in the expression below

$$E_{SLP} = Eb \times (BI - SD) \tag{8}$$

While the energy consumed during the idle state can be rendered through equation (9)

$$E_i dle = T_S IFS \times U \times I \tag{9}$$

where $T_S IFS$ represents the *SIFS* duration which is defined as the short interframe spacing (SIFS) periods, U denotes the voltage value, and I depicts the current value. Worth reminding is that our interest is focused on monitoring the nodes' associated life spans within a star topology, as manipulated via the IEEE 802.15.4 beacon-enhanced mode. The network is composed of several subgroups, each being made up of a PAN coordinator and a number of nodes. The network nodes are, in their entirety, interconnected through the node sink. It is at this level that our innovative approach can be set, as constructed around the idea that every node bears a number of specific IEEE 802.15.4 parameters (BO, SO) associated values within the cluster tree topology. At every interaction period or interval, the node issues a decision to send its specific parameters to the corresponding coordinator, which, in turn, undertakes to execute a computation procedure of the energy amount remaining in the node's battery E_R. Once the relevant value is discovered to be inferior or equal to the already preset threshold, the coordinator will then execute a computation procedure in relevance with the IEEE 802.15.4 initial parameters. The same algorithmic process is rehearsed for four times still getting all the thresholds machined, which is likely to culminate in the prevalence of a large array of modes within the network. Actually, for an effective management of the very last amount of power to take place, an auto-adaptive procedure of this energy quantity proves to be crucially imposed. In effect, such an approach turns out to be considered as a multi-threshold and multi-mode processing of activities within the IEEE 802.15.4 technology. Accordingly, the quantity of energy remaining in the battery appears to be computed via the expression (10)

$$E_R = Eini - Ec \tag{10}$$

Eini is the initial energy and the entirety of energy quantity consumed *Ec* could be calculated as the sum of all kinds of energy modes, as depicted by equation (11)

$$Ec = E_{em} + E_{col} + E_o + E_{SLP} + E_{rc} + E_{idle} \tag{11}$$

The IEEE 802.15.4 parameter's intervention

Within the context of a highly extended network, the first step consists in collecting the necessary parameters from the nodes so as to draw the nodes' consumed energy *EC*, thus getting the amount of battery remaining power. In the second stage, the reached amount is compared to a specified threshold, prior to computing the corresponding BO and SO values. Hence, with

respect to the Beacon-enabled duration, the node consumed power turns out to be provided by formula (12)

$$E_{BI} = \frac{BI}{T_{tt}} \times E_T \qquad (12)$$

where BI being the beacon interval period; $T_t t$ designating the length of the frame; and E_T representing the energy wasted in order to send a frame data. Still assuming that E_{BI} which presents the energy lost during the beacon interval is inferior to the remaining energy, as described by expression (13)

$$E_{BI} \leq E_R \qquad (13)$$

the relation (14) turns out to be attainable by means of both relations (12) and (13), such as

$$\frac{BI}{T_{tt}} \times E_T \leq E_R \qquad (14)$$

where the BI interval, as specified by the IEEE 802.15.4 standard, proves to be expressed through equation (15)

$$BI = 15,36 \times 10^{(-3)} \times 2^{BO} \qquad (15)$$

thereby, transforming expression (15) into expression (16)

$$(15,36 \times 10^{(-3)}) \times \frac{2^{BO}}{T_{tt}} \times E_T \leq E_R \qquad (16)$$

On the basis of equation (14), 2^{BO} appears to be defined by relation (17)

$$2^{BO} \leq \frac{E_R \times T_{tt}}{15,36 \times 10^{(-3)} \times E_T} \qquad (17)$$

and the BO value is given by equation (18)

$$BO \times \log(2) \leq \log\left(\frac{E_R \times T_{tt}}{15,36 \times 10^{(-3)} \times E_T}\right) \qquad (18)$$

In case of extra charge status, the BO turns out to be equation (19)

$$BO = \frac{\log\left(\frac{E_R \times T_{tt}}{15,36 \times 10^{(-3)} \times E_T}\right)}{\log(2)} \qquad (19)$$

For a rather effective management of the remaining quantity to last even longer, a proportion of just 10% of the remaining energy is manipulated, dubbed E_{R1}, as depicted by expression (20)

$$E_{R1} = E_R \times 0.1 \qquad (20)$$

and, consequently, BO turns out to shift to equation (21)

$$BO = \frac{\log\left(\frac{0.1 \times E_R \times T_{tt}}{15,36 \times 10^{(-3)} \times E_T}\right)}{\log(2)} \qquad (21)$$

Regarding the SD case, just 70% of the BI period appears to be exploited. Therefore, SO proves to be expressed through the relation (22)

$$SO = 0.7 \times \frac{\log\left(\frac{0.1 \times E_R \times T_{tt}}{15,36 \times 10^{(-3)} \times E_T}\right)}{\log(2)} \qquad (22)$$

When the level of energy reaches the level P1, the M2-ABEM starts and the node continues to send its information to its PAN coordinator periodically until the P2 is reached and the duty cycle is changed another time according to the M2-ABEM. The same step is repeated with all the levels.

The different steps of the M2-ABEM are presented clearly by the algorithm presentation below.

The Et_k presents the *kme* threshold energy.

Implementation and simulation results

In order to achieve our goals, an appeal is made to the INETMANET/OMNET++ simulator. It is worth noting that the OMNET++ simulator constitutes the Objective Modular Network Testbed in C++ and is considered as the most realistic wireless network–associated simulator. It stands as an object-oriented modular and a discrete event network-simulation framework. As a multidisciplinary tool, OMNET++ displays a wide range of advantages associated with modeling both modes of the communication networks:
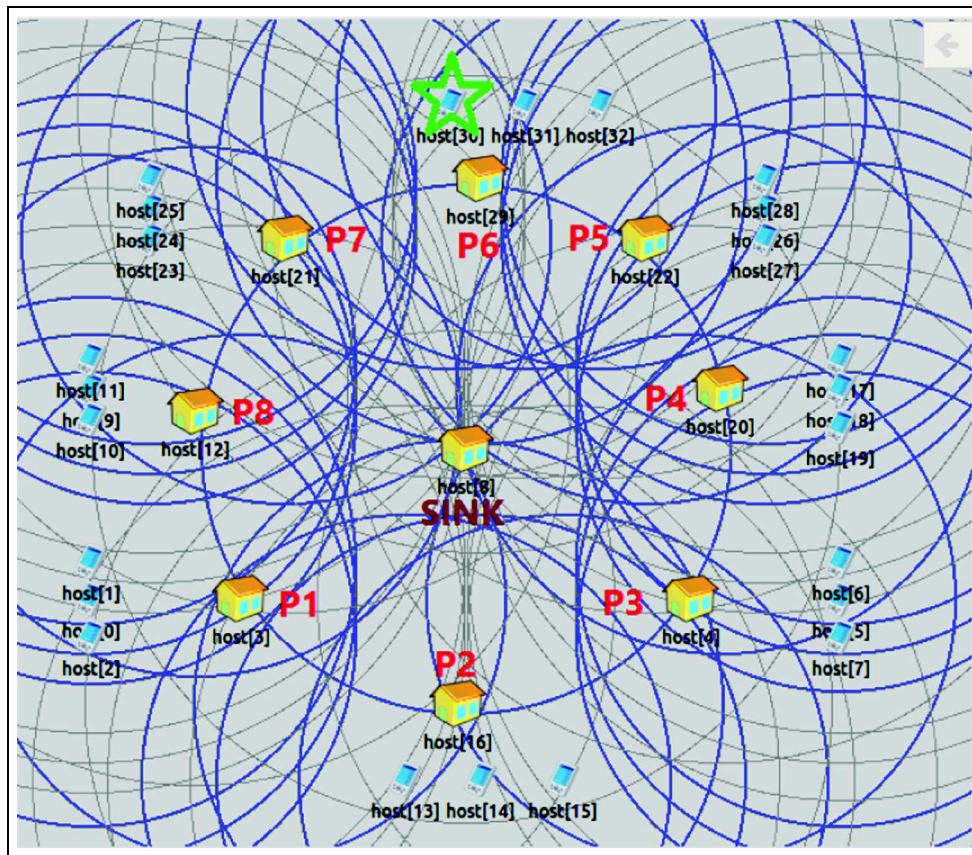
Algorithm 1. Proposed algorithm approach: M2-ABEM algorithm.

Input: *N* NODES NUMBERS
for $x \leftarrow 0$ **to** *N* **do**
  if *Coordinator_Receive_Energy_Consumption*
   = *true* **then**
    for $k \leftarrow 0$ **to** *M* **do**
     Storage_Energy_Remaining(E_R)
     if ($E\_R <= Et_k$) **then**
      Node_fault_energy = True;

$$BO_k = \frac{\log\left(\frac{0.1 \times E_R \times T_{tt}}{15,36 \times 10^{(-3)} \times E_T}\right)}{\log(2)}$$

$$SO_k = 0.7 \times \frac{\log\left(\frac{0.1 \times E_R \times T_{tt}}{15,36 \times 10^{(-3)} \times E_T}\right)}{\log(2)}$$

     else
      $BO_k = BO_{k-1}$;
      $SO_k = SO_{k-1}$;
     end
     send (BO_k, SO_k)
    end
  end
end

Figure 9. Multi-mode network.

Table 2. Simulation parameters.

Parameters	Values
Simulation time	100 s
Network size	(800, 400)
E initial (J)	18,720
Nodes number	29
PAN number	1
Channel frequency	2.4 GHz
Radio type	IEEE 802.15.4 radio

wired and wireless.[27] In addition to providing a small-scale prototype model to the relevant protocols, OMNET++ is also applicable for validation ends of the hardware architecture. Besides, it helps well in remarkably simplifying the software system–related complexities. The simulator-associated parameters are depicted in Table 2. With respect to our proposed network, it appears to enclose 25 nodes, along with 8 PAN coordinators and a node sink. It involves eight subgroups, each of them being made up of a single coordinator and three nodes. The simulation is triggered with the sink node sending of all the beacon frames to the PAN coordinator, for the entire network activities to be well synchronized. Then, as part of its assigned roles,

the PAN coordinator undertakes to dispatch the beacon frames to the network children. Every single subgroup is characterized by detaining specific IEEE 802.15.4 (BO, SO)-associated parameters. At this level, it is mandatory for the PAN coordinator and sinks to be FFD nodes in type, even though the remaining nodes could be RFD in type, as illustrated in Figure 9.

Thus, PAN node P1 stands as the major responsibility for the nodes (0, 1, 2) and, jointly, they form subgroup 1. As for PAN P2, it represents is the main parent for the nodes (13, 14, 15) making up, together, the subgroup 2. While subgroup 3 involves PAN P3 along with its three pertaining children (5, 6, 7). Concerning subgroup P4, it is modeled by PAN 4, along with the nodes (17, 18, 19), and PAN P5 stands as the major responsibility in charge of the nodes (26, 27, 28), forming subgroup 5. As for PAN P6, it serves as the parent of the nodes (30, 31, 32), forming together the subgroup 6 and the subgroup 7 is controlled by the P7 and composed by the nodes (23, 24, 25). However, PAN coordinator 8 is the response of the nodes (9, 10, 11) constituting the subgroup 8.

Accordingly, the PAN proceeds with sending beacon frames to its children, periodically, in a bid to synchronize the relevant activities. Each subgroup has its proper
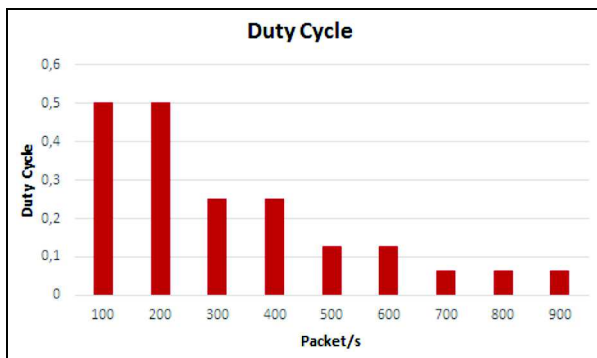
Figure 10. Duty cycle change.

Figure 11. Energy consumed of node 30.

Figure 12. Queue delay of the node with fault energy (node number 30).

specific BI and SD-associated parameters. Thus, three modes pertaining to the same network could be depicted. The peculiarity of this work lies in enabling every sub-group to self-manage the real energy range available to its nodes. Actually, the presence of eight subgroups within the network helps yield a variety of applicable modes, at a rate of about three modes per network. It is the PAN which sets the energy threshold values. In our particular context, four thresholds can be distinguished, helping to periodically change the IEEE 802.15.4-relevant parameters for four times. The duty cycle value is changed four times, $DC1$, $DC2$, $DC3$, and $DC4$, with the increase in the traffic loads as presented through Figure 10. In this way, the network's multimode and multi-threshold turns out to be simultaneously manipulated. In the first step, every node undertakes to send its pertinent data to the corresponding coordinator, and relying on the above-cited formula, the coordinator proceeds with computing the entirety of energy levels as consumed by the relevant nodes. It then continues with computing the remaining power amounts, while comparing them with the initial threshold.

Simulation results comparison

Once a node's consumed energy proves to be inferior to the set threshold, it will be marked as the risked node (fault energy). Its pertaining coordinator will, then, proceed with executing the second step, which deals with changing the node's both (BO, SO) values, for the sake of an effective exploitation of the remaining energy quantity. This procedure is repeated on a regular basis, and the quantity of battery residing power is regularly checked by the coordinator. In our case, the node number 30 suffers from energy fault. So the algorithm starts in order to postpone its death by decreasing its activity by intervening in its duty cycle. It is included in the subgroup number 6. Its IEEE 82.15.4 parameters are set by its PAN coordinator number 6. When it detects that the energy lasted in the battery of its child (node number 30) is less than the first threshold (Th1), it launches our
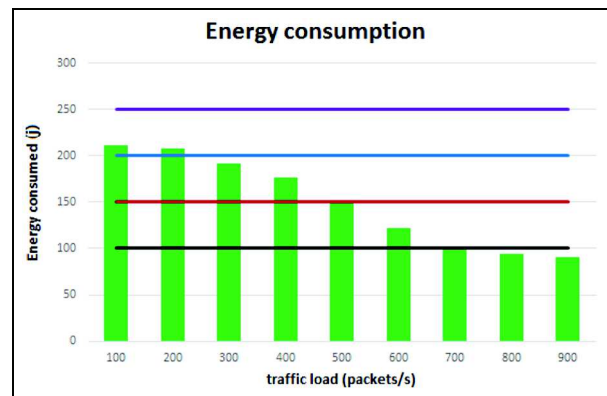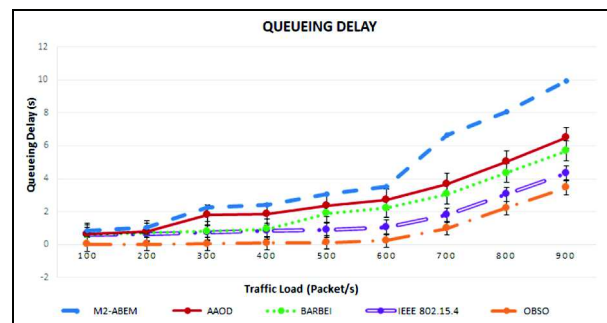
algorithm as presented by Figure 11. With 300 packets/s the energy consumed in this node also decrease under the second threshold (Th2) which set of the second intervention with the second duty cycle (DC2). Also, at 500 packets/s the *EC* becomes equal to Th3 which leads to our third intervention and finally our last try was at 700 packets/s used the *DC*4. The M2-ABEM is set on with node 30 and all the results performance of this node was even compared to four other approaches, already proposed to control the nodes' energy consumption process within the framework of IEEE 802.15.4 technology. The four methods, the subject of comparison, are: battery aware beacon enabled IEEE 802.15.4: the adaptive and cross-layer approach (BARBEI);[25] the AAOD of IEEE 802.15.4 Network (AAOD);[21] the optimal beacon and superframe orders (OBSO) in WSNs;[28] and IEEE 802.15.4 with (BO, SO) = (7, 5).[26] In this regard, a number of parameters were tested, namely, the queuing delay, end-to-end duration, in addition to all modes of energy consumption events, that is, those relating to the states of the collision, sleep, emission, and reception along with the overhearing and overmitting periods. The traffic load ranges from 100 packets/s to 900 packets/s. Figure 12, illustrates the queue delay evolution as scored with
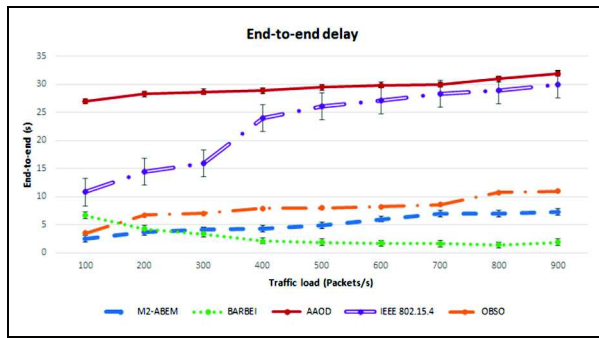
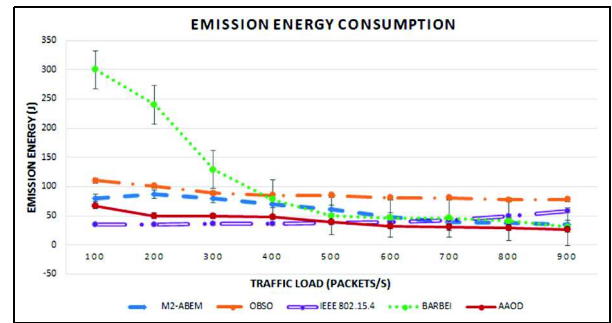**Figure 13.** End-to-end delay of the node with fault energy (node number 30).

Figure 15. Energy consumed in emission state of the node with fault energy (node number 30).
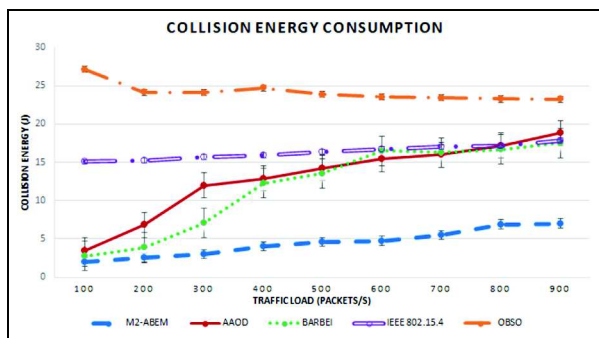

Figure 14. Energy consumed in collision state of the node with fault energy (node number 30).

respect to the entirety of observed approaches, concerning traffic load evolution within the node. The OBSO presents the best results for this performance compared to all other approaches which encourage to adopt this method in the applications which have problems concerning the queue delay. The end-to-end parameter, as shown in Figure 13, highlights the increase in the end-to-end characteristic delays with the increase in the network registered traffic load. The M2-ABEM appears to score the most effective results, as compared to the OBSO, IEEE 802.15.4, and the AAOD approaches.

The stable state–related energy consumption

It is worth reminding that for an effective data transmission, the node has to go through two different states: a transient state and a stable one. Throughout the first state, the node may well prove to be too busy transmitting or receiving information. Similarly, it might well suffer from a noticeable overhearing-overmitting associated problem. Besides, sleeping could be enabled in this case. In such a case, our proposed design turns out to be marked by the presence of four phases, as emanating from the four set up thresholds. Figure 14 depicts the simulation experiment results, as

recorded concerning the collision state–relevant data. Regarding that state, the consumed energy appears to mark an increase that coincides with the growth in the number of data packets. Except for the OBSO approach, all the other approaches (AAOD, BARBEI, and the IEEE 802.15.4) appear to score an increase in the energy lost throughout the collision incidence. Actually, the most striking results turn out to be displayed through our proposed M2-ABEM approach. The same applies to the evolution of energy as consumed during the node's emission state (Figure 15). All the cited approaches proved to display a consumption decrease with the increase in the number of message packets, except for the BARBEI approach, which proved to decrease throughout the entire simulation experiment. In addition, and within a very high traffic load, the M2-ABEM appears to yield nearly the best results, displaying the minimal energy consumption value. In effect, once the number of packets proves to rise, the M2-ABEM scored values appear to reach the same rates as those recorded by the AAOD method. Regarding the overmitting and overhearing cases, however, power loss, as scored via the different methods, turns out to increase with the evolution in the number of packets, except for the BARBEI approach (Figure 16). In this respect, the M2-ABEM appears, also, to exhibit the most effective results once the traffic load proves to be lower than 500 packets/s. In addition, the M2-ABEM-associated values are discovered to increase at a remarkably quicker pace than those recorded through the AAOD and OBSO architectures. Even in the reception state, the M2-ABEM seems to display the least values with respect to the other approaches in the high traffic load (Figure 17). Worth noting, also, is that owing to traffic load intensity and duty cycle increase, the node turns out to endure and suffers from a remarkable energy shortage, resulting in a noticeable increase in energy loss during the sleep period (Figure 18). Once again, the M2-ABEM is discovered to record effective increase scores with respect to energy consumption.
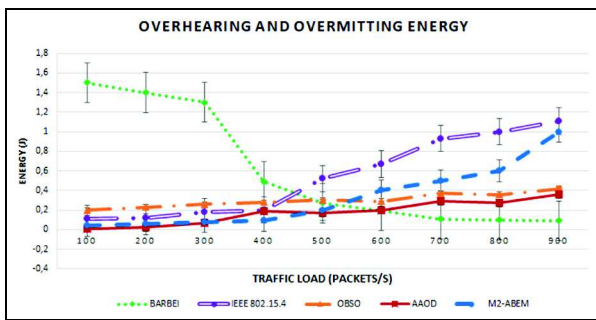
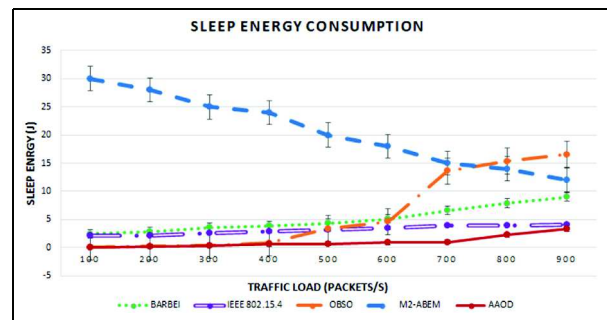**Figure 16.** Energy consumed in overhearing and overmitting state of the node with fault energy (node number 30).

Figure 18. Energy consumed during the sleep state of the node with fault energy (node number 30).
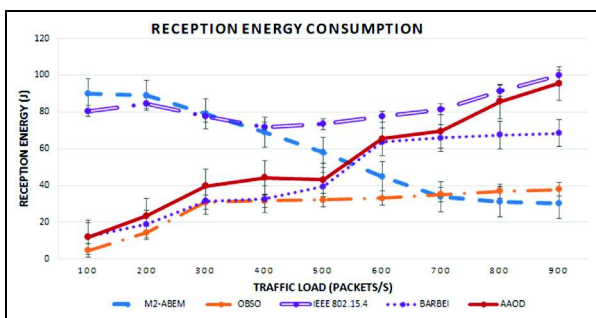

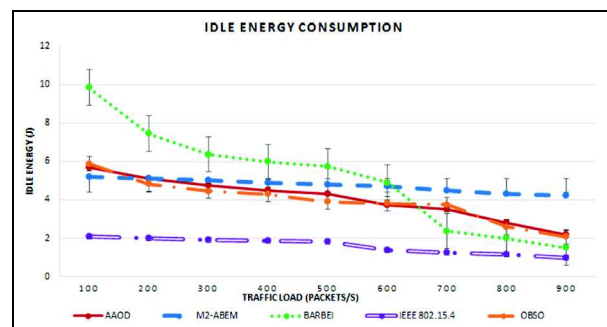**Figure 17.** Energy consumed in reception state of the node with fault energy (node number 30).

Figure 19. Energy consumed in idle state of the node with fault energy (node number 30).

The transient state–related energy consumption

To note, the idle state represents the unique case, a component of the transient state. Actually, all the cited approaches appear to demonstrate a decrease in energy consumed at this state level as presented by Figure 19. The M2-ABEM-associated values prove to indicate a decrease ranging from 5.2 to 4.9 J. As for the IEEE 802.15.4, it sounds to score the most effective results with respect to all the other models. Our proposed approach succeeds in reaching the best results compared to all other methods in many parameters studied such as the collision energy in addition to the reception energy. So the M2-ABEM presents the lowest results in the reception energy and collision energy. Moreover, it presents always the best results compared to the IEEE 802.15.4 (7,5) for the end-to-end parameter and to the overhearing and the overmitting. For the AAOD approach, our method describes the best results in the end-to-end parameter in addition of course to the reception and the collision states. The M2-ABEM presents also the best results compared to the OBSO in all kinds of parameters except the idle state and the overhearing and overmitting states. Finally, comparing to the BARBEI, our approach describes also the best results for emission state. Figure 20 describes the sum of all kinds of energy consumed by node 30: emission
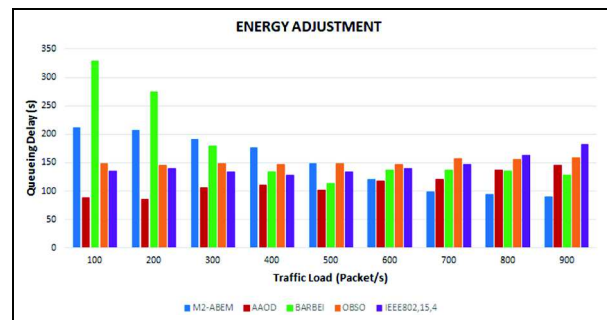

Figure 20. Energy adjustment of the node with fault energy (node number 30).

energy, reception energy, idle energy, sleep energy, as well as overhearing and overmitting energy. It is clear that our approach M2-ABEM presents the best results for energy consumed which is decreasing with the increase in the traffic loads.

Conclusion

The major contribution of this work lies, mainly, in the establishment of diverse modes interacting within the same network enabling the technology of IEEE

802.15.4. Therefore, the network was composed of many subgroups. Every subgroup turns out to be characterized with special IEEE 802.15.4-associated parameters (BO, SO). In addition to that, a wide range of thresholds are enabled by every PAN coordinator when it detects an energy fault in its subgroup in order to procure highly adaptive intervention. So periodical messages are sent by the nodes to their PAN coordinator in which they inform about their different pieces of information. At this level, every coordinator undertakes to compute the energy remaining in each node's respective battery and then detects the node displaying energy shortage fault when its remaining energy appears to be lower than the initially set threshold. After that, our proposed approach M2-ABEM is launched. So, the coordinator will intervene by changing the node's duty cycle through modifying both of the (BO, SO) values. In order to prove the efficiency of our algorithm, a comparison was established with four other approaches: battery aware beacon enabled IEEE 802.15.4, the AAOD of IEEE 802.15.4 network, the OBSO in WSNs, and the IEEE 802.15.4 with (BO, SO) = (7, 5). In future work, our proposed approach (M2-ABEM) will be validated with real testbed.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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