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ESco: Eligibility Score-based Strategy for Sensors Selection in CR-IoT: Application to LoRaWAN

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Abstract

In this paper, a battery-powered Internet of Things assisting Cognitive Radio (CR-IoT) network is considered. In CR-IoT network, a set of IoT End Nodes (ENs) are assumed to cooperatively sense the channel. Each EN performs a Spectrum Sensing (SS) and reports its decision to a Fusion Center in order to reach the decision on the PU status. Such monitoring of PU comes at the cost of additional energy resources consumed by the EN to perform SS and reporting, and raises the need to set a suitable protocol to manage the data exchange. The extra operations may exhaust the energy of the EN battery, especially when Low Power Wide Area Networks (LPWAN) technology is used. In our manuscript, an Eligibility Score-based (ESco) Strategy is defined to reflect the eligibility of an EN to make a reliable SS taking into consideration its battery level. Our strategy is adapted to LoRaWAN Class-B protocol in order to handle real world scenarios. Necessary modifications are introduced to the existing protocol in order to support the synchronization between the ENs and the Application Server, (at which the SS need is identified), and the on-demand nature of the SS requests. To evaluate our strategy, LoRa sensors' parameters are considered in our simulations. The numerical results highlight the efficiency of the proposed strategy by showing the extension of the ENs' lifetime compared to classical strategies.

Keywords: Internet of Things, Network Lifetime, Cognitive Radio, Spectrum Sensing, LoRa Networks, LoRaWAN Protocol.

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1. Introduction

According to [1], 75 billions of Internet of Things (IoT) devices will be connected to the Internet by 2025. IoT will cover almost all the society life sectors, such as: urban, industry, medicine, transportation, security surveillance, etc [2, 3]. The expected huge number of devices will require special attention to the physical layer in order to maintain the service quality [4, 5].

In turn, Cognitive Radio (CR) is one of the most studied wireless technologies in the last two decades [6, 7, 8]. CR was introduced to mitigate the spectrum scarcity problem due to the ever increasing demand on the wireless communications. The CR system is based on sharing the spectrum between primary (PU) and secondary (SU) users. A PU has the exclusive right to access its spectrum band at any time, while SU, as an opportunistic user, can only access the spectrum whenever PU is absent. If PU resumes its transmission while SU is active, then SU should immediately vacate the channel. The decision on the PU channel availability is the mission of the Spectrum Sensing (SS) part of CR.

To tackle the needs of the additional frequency resources, the shifting to the CR-based communication requires SS to keep aware of the PU activity. Due to the deployment of IoT networks, their sensors may successfully perform the SS operation. Thus, the monitoring of the primary channel can be exploited according to two scenarios:

- CR-based Communication for IoT: In this scenario, IoT network performs SS for its interest due to its need for additional spectrum resources to send extra data [9]. This scenario may happen when the number of nodes in the IoT network is largely increased, which may cause high pressure on the frequency resources and require additional spectral bands. In this scenario, the EN may perform SS in addition to its initial task in sensing physical measures, such as: the temperature, the humidity, etc.
- Providing Spectrum Sensing as a Service (SSaaS): the CR-IoT may deliver a service of SS for another network. Hence, Sensing as a Service strategy is applied [10, 11]. In this case, CR-IoT receives a request from another network/operator asking about the status of a given channel within a geographical area. Accordingly, the CR-IoT asks the ENs to perform SS and report their decisions on the availability of a given frequency band for the sake of another network/operator. This second scenario is particularly covered in this paper.

1.1. CR-based Communication for IoT

In this section, an overview on related works to the CR-based communication for IoT is presented. Due to the huge expected number of IoT devices, CR

has been proposed as a major solution to tackle the problem of the scarcity of frequency resources on the physical layer [4]. CR considers the IoT nodes as
45 secondaries and provides them with a high flexibility since they may access any frequency band whenever PU is absent.

The scarcity of the spectrum and the static allocation policy are presented as main reasons to adopt the CR-based IoT in future radio technology generations [4]. The latter reference details the implementation of CR in IoT network in
50 addition to the standardization and the applications of the CR-based IoT.

Energy-Throughput trade-off of wireless sensor network is studied in [12] in the context of cooperative SS and dedicated to low-power devices. The main contribution of that study focuses on minimizing the consumed energy while satisfying the requirements of secondary throughput and the primary signal detection.

55 In [13], CR is extended to IoT networks in order to make a self-reconfigurable, interference-free, and intelligent IoT networks. CR can be helpful to Machine-to-Machine communications as suggested by [14, 15].

A dynamic spectrum allocation for IoT is proposed in [16], where a cognitive radio-based strategy is applied in order to avoid the interference among the IoT
60 nodes as SU and PU. To achieve such a goal, the proposed strategy aims to work in both licensed and unlicensed bands in a dynamic manner.

Last but not least, cognitive radio framework is proposed in [17] for IoT networks. The multiband cooperative SS is applied on IoT nodes, assumed to be environment-aware and self-reconfigurable, in order to reduce the energy consumption at every node. Multiband SS is adopted due to two main reasons: 1)
65 the need of the IoT networks to cover several frequency channels to fulfil their transmission requirement, and 2) having several available frequency channels makes the frequency handoff simpler and faster.

70 1.2. Spectrum Sensing as a Service

The SSaaS is inspired by the concept of Sensing as a Service which can be adopted by a Wireless Sensor Network or IoT network to deliver a service to another network or operator. Data like humidity, temperature, pressure, etc.
75 can be monitored by a WSN/IoT within a geographical area and provided to another operator. Similarly to the concept of Sensing as a Service, SSaaS has been proposed to provide another network/operator by the channel availability within a geographical area. The authors of [18] proposed the separation of the spectrum sensing task from the other tasks of a cognitive radio, by using the dedicated infrastructure of a WSN/IoT. In this case, the WSN/IoT outcomes
80 a list of available channels in response to a request of a Cognitive Radio-based network.

The SSaaS imposes several challenges related to the business model to be adopted between the WSN/IoT and the operator to be provided. Other challenges related to the nodes selection and the energy efficiency have been studied
85 in the literature in the sake of providing reliable and cost-effective service of SS [10, 11, 18, 19] .

Our manuscript mainly focuses on this scenario, where we aim at analysing the

selection strategy of the ENs of the IoT network in production, and adapt the
suitable protocol to exchange the data between the ENs and the upper entity
of the IoT network.

One of the main challenging issues when assigning the SS task to an IoT network, in both scenarios detailed above, is the energy autonomy which is related to the battery lifetime [20]. For instance, in Low Power Wide Area Network (LPWAN) IoT networks, the lifetime of a sensor is usually long and may exceed 5 years [20]. This is related to the battery technology and the transmission specifications of the IoT networks, especially the small duty cycle of less than 1% as in LoRa network [21]. The sensing operation required by the cognitive system reduces the IoT node's life due to the additional energy resources required by the SS function, where two major additional power consuming operations have to be done:

1. Making a decision on the channel by applying a sensing technique.
2. Reporting the decision to the Fusion Center (FC). This operation may rapidly consume the battery energy of the sensor due to the additional transmission operation.

However, the sensing of a given channel is the mission of several ENs in CR-IoT networks. This will positively impact both the energy efficiency and the performance since the consumed energy per node will be reduced and the spatial diversity will improve the sensing outcome [22]. Each EN makes a decision on the channel and sends it to the FC, which combines all decisions on that channel to output a final decision. Thus, the selection of the ENs performing the SS becomes an essential challenge of the FC. From one hand, selecting these ENs may be a function of the required number of ENs to perform the SS in order to fulfil the detection requirement (target false alarm and detection probabilities). On the other hand, this selection should take into consideration the battery level of the EN and its detection reliability, which is related to Signal to Noise Ratio (SNR) observed at that node. If an EN is about to be exhausted, it is recommended not to ask it to perform further SS. In addition, when the EN's SNR is bad, EN should treat a high number of received samples to outcome a reliable decision [23]. This fact may degrade the EN's battery. However, the ENs selected to perform the SS may vary from one SS operation to another. This fact will ensure a high participation of the node in the SSaaS task and to decrease the number of transmission of each node so it respects the LoRaWAN specifications related to the duty cycle.

In this paper, an Eligibility Score-based (ESco) strategy for IoT network providing SSaaS is proposed, where the selection of IoT ENs respects both the SS requirements and the energy level of the ENs. LoRaWAN is taken as case study to investigate the performance of our strategy, where we adapted the new strategy requirements to the LoRaWAN protocol. LoRaWAN is basically designed for uplink operations in which the ENs report the data to the Application Server (AS) after passing by the Gateway (GW) and the Network Server

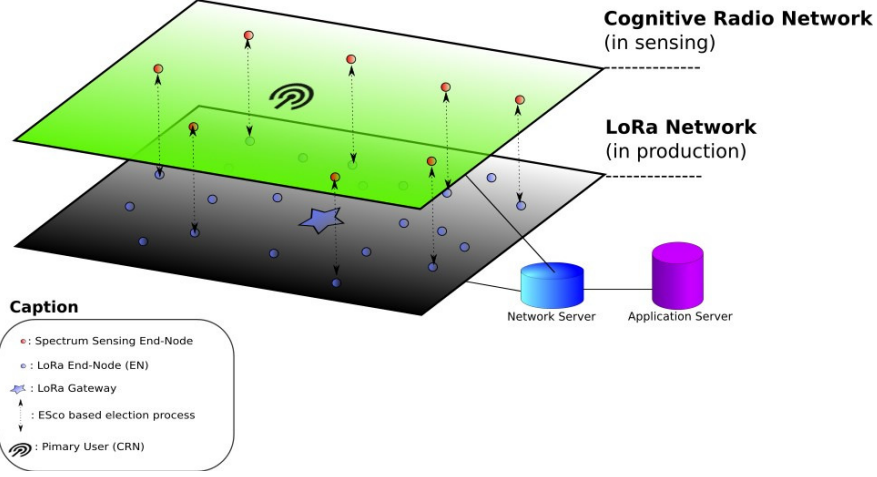


Figure 1: General view of the network topology for the proposed EScO solution: the elected End-Nodes from a standard LoRa network carry on the Spectrum Sensing for the Cognitive Radio Network layer

(NS) sparsely in time with a relatively low throughput. This fact ensures a long lifetime to the ENs measured in years instead of hours or months. In our application, the need for spectrum resources is identified at the AS, which requests the ENs to collect sensing data on a given channel. Then, the ENs should report their SS decisions on such channel to the AS, which plays the role of the FC in our work, upon request. Hence, we are in on-demand scenario [24], which is not fulfilled in existing LoRaWAN protocol. Therefore, we are suggesting to adapt the protocol to better fit our application. Figure 1 gives an overview of the adopted system model. The whole network is under the control of the NS and AS. NS manages the transmission parameters of the LoRa ENs such the Spreading Factor (SF) and the operating frequency. However, being the only entity in the LoRa network allowed to read the sensing content of the EN's message, AS elects the most eligible nodes to perform the SS using EScO strategy based on the data received from these nodes. A selected node participates in the CR operations and works at the CR network level to sense the PU activity. The main contributions of this manuscript can be summarized as follows:

1. Based on an evaluated Eligibility Score (ES) defining the eligibility of each EN to perform the SS, a new strategy called EScO of ENs selection is proposed. EScO ensures that the CR-IoT meets the detection requirements to achieve a high spectrum efficiency and a good protection of PU against the ENs transmission interference. In addition to the SS reliability, the

- new strategy respects the energy-related ability of the EN's battery to make SS.
2. The proposed strategy is adapted to the highly deployed LPWAN technology LoRa, where the LoRaWAN Class-B protocol is modified to meet the requirements of our strategy on exchanging the data between the AS and the ENs. Noting that in our paper, the LoRa network does not operate in cognitive way, but it holds its physical parameters, i.e. the operating frequency and the adopted Spreading Factors. The LoRa network in our study is SSaaS provider, which delivers the information on the primary channel to the AS upon a request of the latter.
 3. The PayLoad (PL) of the packets related to both SS and reporting from EN to AS is investigated in order to get an efficient performance while saving the EN battery.
 4. Numerical results show that long lifetime of the EN's battery is better ensured thanks to the proposed strategy compared to classical strategies.

The rest of this paper is organized as follows. In section 2, the system model is described and detailed. The proposed ESco strategy is explained in section 3; where we derive the ES and the related strategy to select the eligible ENs to establish the SS. Section 4 describes the adopted protocol to exchange the data between the ENs and the AS. LoRaWAN-based protocol is presented. Numerical simulations are presented in section 5; where we evaluate our proposed strategy based on the detection reliability, battery energy efficiency, and CR-IoT throughput. Section 6 concludes our work.

Table 1: List of Abbreviations and Symbols

Abbreviation/Symbol	Definition
AS	Application Server
BS	Base Station
BW	Bandwidth
CR-IoT	Cognitive Radio-based Internet of Things
CR	Cognitive Radio
EN	End-Node
ES	Eligibility Score
FC	Fusion Center
GW	Gateway
IoT	Internet of Things
IP	Internet Protocol
LoRa	Long Range
LoRaWAN	LoRa Wide Area Network
LPWAN	Low-Power Wide Area Network
NS	Network Server
PL	PayLoad
PU	Primary User
SF	Spreading Factor

SNIR	Signal to Noise and Interference Ratio
SNR	Signal to Noise Ratio
SR	Sensing-Reporting
SS	Spectrum Sensing
SU	Secondary User
TS	Test Statistic
C_0, C_1	The channel capacity of the secondary transmission when PU is absent and active respectively
CRC, I, DE	They stand respectively for: the presence or not of the CRC field in the physical message, the coding rate, and the low data rate optimization enabling.
D_i	The decision of the spectrum sensing made by the EN_i
ϵ	Quantization error
$E[\cdot]$	Mathematical expectation
f_s	Sampling frequency
$\mathcal{F}_i, \mathcal{F}_{II_i}$	The ES function of the EN_i and its quantization respectively
$\gamma_i, \sigma_{w,i}^2$	The SNR of the PU signal and the variance of the noise observed at EN_i
$\Gamma_{i,j}, y_{i,j}(n)$	The test statistic and the received signal of the channel j at the EN_i
H_0, H_1	Hypotheses that PU is absent or active respectively
l_i	Battery level of EN_i
λ	Threshold of comparison in spectrum sensing
N_{pre}, T_{pre}	Number of symbols in the Preamble message and its time respectively.
N_{symp}, T_{symp}	The number of transmitted symbols in a packet and their duration respectively.
$N_{s,i}, T_{SS}$	The number of samples and the needed time respectively needed by the EN_i in SS.
N_t, N_E	Total number of ENs and number of End-Nodes selected to make spectrum sensing
M_l, M_g	The bits number reserved to represent the battery levels and the SNR respectively
Q_l, Q_γ	Set of quantization levels of the battery levels and the SNR respectively
$Q(\cdot)$	Gaussian Q -Function
B_i, ζ_i	The i th level of quantization of the battery levels and the SNR respectively
P_d, P_{fa}	Probability of detection and false alarm respectively
p_0, p_1	Probability that PU is active or absent respectively.
P_c, P_{cf}	Probability of collision and collision-free respectively
$P_{d,i}, P_{fa,i}$	Probability of detection and false alarm respectively of the EN_i
P_r	Probability that PU returns active
R_0, R_1	The useful and the colliding throughputs of the secondary transmission respectively

$Rx1, Rx2$	First and second receiving windows respectively
$s_{i,j}(n), w_{i,j}(n)$	The PU received signal and the noise at the channel j at the EN_i
T_{bcn}	Beacon's period
T_{Tx}	Duration of the transmission time
T_x	Transmission window in LoRaWAN protocol
U_i	The i th user selected to perform the spectrum sensing
W	Bandwidth of the secondary transmission
\bar{x}	The target value of x

2. System Model

The considered CR-IoT consists of a certain number of ENs, with N_t ENs are able to make the SS. The N_t nodes serve as spectrum sensors by reporting their measured decisions to the [FC \(Application Server\)](#), which makes the final decision. Note that the channel to be sensed is different from the actual channel used by the AS and ENs to exchange the data through the GW. To reach this goal, the nodes are assumed to be equipped with a cognitive radio module allowing them to configure their frequency parameters to observe a certain channel as per the request of AS.

In order to exploit the spatial diversity of the N_t ENs, cooperative SS is used. These N_t nodes, or some of them, must cooperatively report their decisions on a given channel to the [AS via the GW and the NS](#). In turn, AS considers the decisions of the ENs to reach a final decision on that channel.

In our scenario, the CR-IoT networks may sense a set of N_c channels. The sensing operation of each channel is the task of $N_E \leq N_t$ ENs, where each of them evaluates a Test Statistic (TS). The i th EN (denoted by EN_i), $i \in [1, N_E]$, should discriminate between two hypotheses H_0 : PU is idle and H_1 : PU is active:

$$y_{i,j}(n) = w_{i,j}(n) \text{ under } H_0 \quad (1)$$

$$y_{i,j}(n) = s_{i,j}(n) + w_{i,j}(n) \text{ under } H_1 \quad (2)$$

where $y_{i,j}(n)$, $s_{i,j}(n)$, and $w_{i,j}(n)$ are respectively the received signal, the received PU signal including the channel effect, and the noise observed at the i th EN at the channel $j \in [1, N_c]$.

In this paper, the widely used non-coherent Energy Detector (ED) is adopted [25]. ED consists in evaluating the TS $\Gamma_{i,j}$ on the received signal $y_{i,j}(n)$ at the channel $j \in [1, N_c]$ and compare it to a predefined threshold λ to make a binary decision: 1 if PU is detected as active, and 0 if PU is diagnosed absent.

$$\Gamma_{i,j} = \frac{1}{N_{s,i}} \sum_{n=1}^{N_{s,i}} |y_{i,j}(n)|^2 \underset{0}{\overset{1}{\gtrless}} \lambda \quad (3)$$

where $N_{s,i}$ is the number of received samples at the i th EN used to evaluate $\Gamma_{i,j}$.

185 The ENs should inform the AS by their decisions. Thus, the decision D_i of EN _{i} should be reported using a control channel to the AS in order to make a final decision [22, 26]. In our work, the "Or" logic rule, i.e. the minimum risk strategy, is applied on the received decisions of the ENs. The overall probability of detection P_d and false alarm P_{fa} can be evaluated as follows [22]:

$$P_d = 1 - \prod_{i=1}^{N_E} (1 - P_{d,i}) \quad (4)$$

$$P_{fa} = 1 - \prod_{i=1}^{N_E} (1 - P_{fa,i}) \quad (5)$$

where $P_{d,i}$ and $P_{fa,i}$ are the probability of detection and the probability of false alarm at i th EN respectively.

Assuming that the received signal samples are independent and identically distributed (i.i.d.), thus $P_{d,i}$ and $P_{fa,i}$ are presented as follows [27]:

$$P_{d,i} = Q\left(\frac{\sqrt{N_{s,i}}\left(\frac{\lambda}{\sigma_{w,i}^2} - \gamma_i - 1\right)}{\gamma_i + 1}\right) \quad (6)$$

$$P_{fa,i} = Q\left(\sqrt{N_{s,i}}\left(\frac{\lambda}{\sigma_{w,i}^2} - 1\right)\right) \quad (7)$$

190 where $Q(\cdot)$ ¹ is the Gaussian Q -function, and $\sigma_{w,i}^2$ and γ_i are the variance of $w_{i,j}(n)$ and the observed SNR at the the EN _{i} respectively.

195 As it can be shown from previous equations, N_E , $N_{s,i}$ and γ_i control the SS performance. However, for target P_d and P_{fa} , $N_{s,i}$ and N_E become functions of γ_i . More γ_i increases more the required N_E and $N_{s,i}$ decrease. In turn, high $N_{s,i}$ leads to a high consumption of the battery of the EN, and usually $N_{s,i}$ decreases with N_E . The optimal solution that takes both the SS performance and the power consumption into consideration is to fulfil the target P_d and P_{fa} with low $N_{s,i}$ and N_E . Thus, the FC should be able to select the best ENs to perform the SS taking into consideration the battery level of these ENs and their SNRs.

200 3. Proposed ENs Selection Strategy

In order to optimize the consumption of the energy related to SS among the network's ENs, we propose to evaluate an Eligibility Score (ES) $\mathcal{F}_i(\gamma_i, l_i)$ of each EN, which takes into consideration the needed $N_{s,i}$ to fulfil the SS requirements at the EN _{i} and its battery level l_i . In fact, in the classical cooperative

¹ $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{+\infty} \exp(-\frac{u^2}{2}) du$ [28]

205 SS, all the ENs can participate in sensing a channel in order to maximize the sensing reliability. Even though such a strategy presents high performance with a relative low consumed power by SS operations, it may exhaust the ENs with low l_i [22, 29]. The same problem may be encountered when only ENs with the highest SNR performs the SS [30]. In this scenario, an efficient sensing
 210 performance is obtained, however, the energy level cannot be respected. Another strategy is to select the ENs with high l_i to perform the SS. The weak point is to not respecting the SNR, which may lead to low accuracy or to fast consumption of the EN's battery due to the need of high $N_{s,i}$ when performing SS at low SNR. Finally, a proposed strategy is based on randomly selecting
 215 the ENs participating in the SS [31, 32]. This strategy is adopted to avoid the selection of two correlated ENs. However, in IoT scenario, this procedure requires the cooperation between several GWs² to specify the location of EN [33]. This may add additional computational complexity which is not always feasible.

220 3.1. Evaluating the Eligibility Score of a Node

Our proposed ESco aims at evaluating the eligibility of the EN to perform the SS based on $N_{s,i}$ and l_i . At a good SNR, low $N_{s,i}$ is required to fulfil the detection requirements, and subsequently reduce the sensing power. In contrast, even with a low $N_{s,i}$ the EN may be unable to make SS due to a low l_i . In other
 225 words, low $N_{s,i}$ is not sufficient to consider an EN as eligible. In contrast, even with a high l_i , the EN may highly consume its battery to fulfil the detection requirements when the SNR is low. Thus, l_i solely neither $N_{s,i}$ are sufficient to select the eligible ENs.

Motivated by the discussion above, we define the ES $\mathcal{F}(l_i, N_{s,i})$ as follows:

$$\mathcal{F}_i(l_i, N_{s,i}) = \frac{l_i}{N_{s,i}} \quad (8)$$

230 $\mathcal{F}_i(l_i, N_{s,i})$ is a positive-valued function since $l_i > 0$ and $N_{s,i} > 0$, and its unit is *Joule/Sample*. Such ES indicates how much the EN could spend energy for one sample. Thus, more the ES increases more the EN proves itself to be eligible. In addition, in the equation (8), N_E and γ_i are represented by $N_{s,i}$, since the latter inversely changes with N_E and γ_i for target P_d and P_{fa} . The optimal
 235 choice derived from equation (8) corresponds to a high l_i with a low $N_{s,i}$.

3.2. Setting of Sensing Parameters

The main goal of the CR network is to reach a high spectrum efficiency while protecting as possible the PU from the secondary interference. This goal can

²In LoRa technology, several GWs may cooperatively localize an EN using a triangulation technique.

be reformulated as follows:

$$P_d \geq \overline{P_d} \quad (9)$$

$$P_{fa} \leq \overline{P_{fa}} \quad (10)$$

where $\overline{P_{fa}}$ and $\overline{P_d}$ are the target false alarm rate and detection probability in the CR-IoT network respectively.

Assuming all the ENs involved in the SS have the same target $\overline{P_{d,i}}$ and $\overline{P_{fa,i}}$, then by satisfying equations (4) and (5) we obtain:

$$\overline{P_{d,i}} = 1 - \sqrt[N_E]{1 - \overline{P_d}} \quad (11)$$

$$\overline{P_{fa,i}} = 1 - \sqrt[N_E]{1 - \overline{P_{fa}}} \quad (12)$$

Here, N_E represents the number of ENs which have the highest N_E ESs:

$$[U_1, U_2, \dots, U_{N_E}] = \max_{\mathcal{F}_i(\gamma_i, l_i)} \text{EN}_i, \quad i \in [1, N_t] \quad (13)$$

where U_i is the i th user selected to perform the SS, and N_t is the total number of ENs in CR-IoT network. These ENs must meet $\overline{P_{d,i}}$ and $\overline{P_{fa,i}}$. To do so, the EN should take into consideration the number of samples $N_{s,i}$ to adopt. Using equations (6) and (7), we can obtain:

$$N_{s,i} = \left[\frac{\alpha_i - \beta_i}{\gamma_i} - \beta_i \right]^2 \quad (14)$$

where $\alpha_i = Q^{-1}(\overline{P_{fa,i}})$ and $\beta_i = Q^{-1}(\overline{P_{d,i}})$.

As per the equation above, $N_{s,i}$ and γ_i are inversely proportional. Low SNR necessitates high $N_{s,i}$ to converge to an accurate decision of SS. This requires additional power resources. Thus, ENs with low γ_i are dying faster than ENs with high SNR. However, this issue can be controlled by the ES: when the AS selects two ENs of the same ES to perform the SS, if the first EN is of higher l_i than the other one, then it performs the SS with a higher $N_{s,i}$. In this case, the second EN uses certainly lower $N_{s,i}$, and subsequently it does not require to spend a large amount of energy as such as the first one. Thus, the proposed EScO is dynamic and adaptable with respect to both needed number of samples and the available battery's energy.

4. Application to LoRa Network

LoRa (Long Range) is a spread spectrum modulation technique derived from Chirp Spread Spectrum (CSS) technology. The Gateway (GW) coverage of LoRa network may achieve up to 20 Km in rural areas and 5 km in urban areas. The data rate of LoRa network may vary from 0.3 to 50 kbps depending on the Spreading Factor (SF), which varies between 7 and 12, and the adaptive data

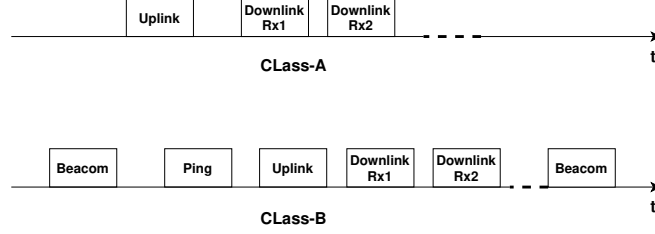


Figure 2: Time windows of LoRaWAN classes A and B: Class-B ensures a synchronization between FC and EN thanks to the Beacon.

rate algorithm. The SF selection has a great impact on the lifetime of the EN and may depend on several factors such as the distance from the EN to the GW, the network capacity, the packet error ratio, etc. [34, 35]. On the other hand, LoRaWAN defines the communication protocol of the LoRa technology. LoRaWAN networks are defined in a star topology, where the GW receives the data from the EN inside the network and forwards it to the NS and AS. The communications between EN and GW are done using LoRa, while communications between GW and NS use Internet Protocol (IP)-based technologies such as 4G or WiFi. NS is considered as the manager of the LoRaWAN network, where it controls the selection of SF, the operating frequency, the network capacity, etc.. NS controls the network parameters while the Application Server (AS) is the only entity that could read the message content of the ENs. For that reason, AS could manage the proposed ESc strategy since the selection process is based on the data sent by the ENs. Thus, AS play the role of the FC of the ENs participating in the SS.

4.1. Protocol of data exchange between FC and ENs

As previously mentioned, AS plays the FC role in our network. Therefore, the need for spectral resources should be identified at the AS, which sends a request to the ENs via the NS and the GW respectively. The communication between GW and ENs is assumed to be established on a reserved control channel. The AS, playing the role of FC, is assumed to be equipped with a database to save data on the ENs especially $\mathcal{F}_i(l_i, N_{s,i})$. Thus, the ENs, eligible to make the SS, should be ready once the AS sends a request following on-demand fashion of the data exchange. This insists a synchronization between the AS and the ENs. As per LoRa regulations the GW broadcasts a Beacon each 128 sec [36]. Then, to respect this regulation, the ENs may report a decision on a channel every 128 sec at least.

For LoRaWAN case study, we can distinguish two main classes: Class-A and Class-B [37, 38]. In Class-A, no synchronization is made between GW and EN, thus, it becomes hard to apply in our scenario since the ENs should response once the AS requests. By contrast, in Class-B, the synchronization is ensured thanks to a Beacon sent by the GW to the ENs. This Beacon is considered as a timing reference to the ENs, which can be used by the AS to initiate SS

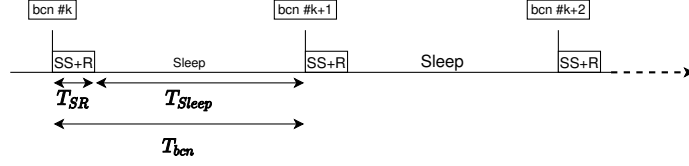


Figure 3: The behavior of the ENs during the SR operations: ENs wakes up for T_{SR} , then sleep till the next SR operation

operation. Then, the ENs can periodically open receive windows called “ping slots” to initiate an uplink operation Tx from the EN. Following each uplink transmission, the EN opens two short reception windows, $Rx1$ and $Rx2$, to receive data from the NS (see figure 2).

Upon the request of the AS, the N_E ENs make SS and Reporting (SR) operations in Tx ³. The ENs participating in the sensing operation send their decisions in addition to the updated l_i and γ_i . γ_i lets the AS calculates $N_{s,i}$ as per equation (14), and subsequently evaluate $\mathcal{F}(l_i, N_{s,i})$. Evaluating $\mathcal{F}(l_i, N_{s,i})$ at the AS reduces the computational complexity at the EN and ensures that EN meets the detection requirement, i.e., \bar{P}_d and \bar{P}_{fa} , since the SS requirements reflected by equation (14) could be changed from a primary channel to another according to the tolerable collision rate between PU and SU [39, 40]. Regarding the remaining ENs, which do not participate in SR, they remain silent but receive from the AS through the NS and the GW.

In turn, after receiving the SS-related data in Tx , AS makes the final decision on the PU channel and updates the database of the ENs based on the received data to select the most eligible N_E to perform the SS in the next round. These N_E ENs are selected based on their $\mathcal{F}_i(l_i, N_{s,i})$. The SR operation is terminated by informing the N_E ENs of the next SR operation by their task, and providing them with $N_{s,i}$ to be used in the next round within $Rx1$ time slot. Indeed, other parameters are sent by the NS to the EN according to the classical LoRaWAN protocol such as the SF and the operating frequency to be adopted in the next transmission operation. Once SR operation is done, the ENs go to sleep mode with a time T_{Sleep} to save energy till the next Beacon arrives (see figure 3).

Figure 4 shows the process of data exchange between EN participating in SR and the FC (AS). EN must send D_i , l_i and $N_{s,i}$, and receives from the FC whether it is selected to perform SR in the next round and $N_{s,i}$ to be used.

Diagram of figure 5 resumes the steps to be followed in the proposed strategy for the participating and the not participating ENs in the network during one SR operation.

³In LoRa network, at each uplink operation, the EN uses channel parameters, i. e. SF and operating frequency, fixed by the NS in the previous operation and sent within $Rx1$.

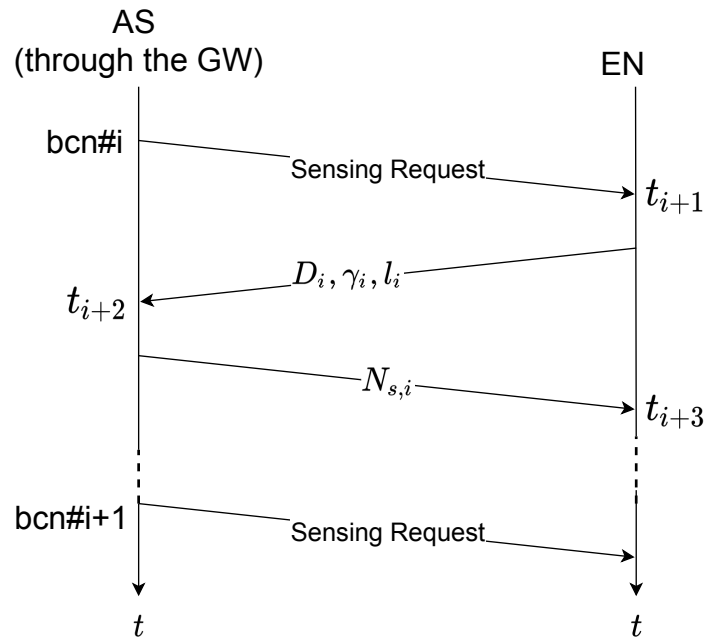


Figure 4: Our ESco strategy: After requesting the ENs to make SS, they respond to the AS request by D_i , l_i and γ_i . AS makes a final decision on the PU channel availability and chooses the ENs with the N_E highest ESs to establish SS in the next round.

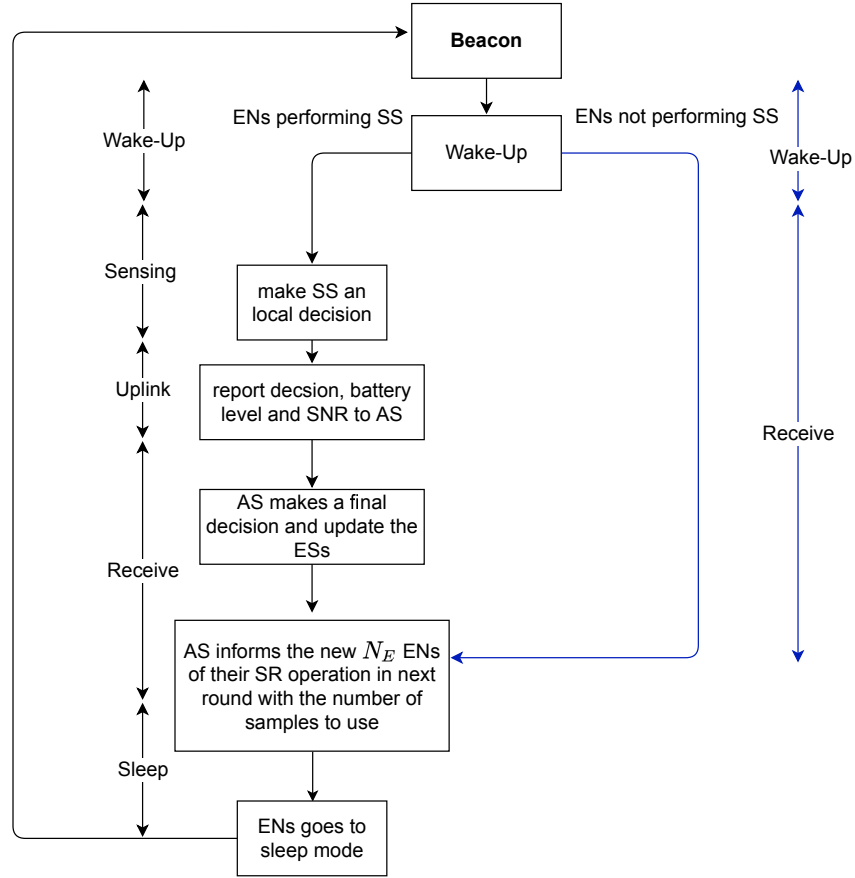


Figure 5: The behavior of the ENs during the SR operations: ENs wakes up for T_{SR} , then sleep till the next SR operation

4.2. Data Encoding of SNR and Battery Level

For our application, the LoRaWAN packet is composed from the PayLoad (PL) and other bytes related to the communication identification between the EN and the AS. It must report to the AS three parameters: the decision on the channel D_i , the SNR γ_i and the battery level l_i . Subsequently PL length depends on the number of bits on which D_i , l_i and γ_i measures are represented. Given that D_i can be represented using one bit: 0 if PU is detected absent and 1 otherwise, the two other measures are not one-bit represented.

We assume that the battery level and SNR are quantized on Q_l and Q_γ levels respectively as follows:

$$Q_l = [B_0, B_1, B_2, \dots, B_{Q_{M_l}-1}] \quad (15)$$

$$Q_\gamma = [0, \zeta_1, \zeta_2, \dots, \zeta_{Q_{M_g}-1}] \quad (16)$$

with: $Q_\gamma = 2^{M_l}$ and $Q_\gamma = 2^{M_g}$, where M_l and M_g are the bits number reserved to represent the battery levels and the SNR respectively. B_0 represents a battery level very close to zero, while B_{Q_l} represents the full energy. ζ_1 represents the minimum SNR, i.e. any SNR lower than ζ_1 the SNR is considered null, and $\zeta_{Q_{M_g}-1}$ is the maximum SNR, where it represents the saturation level. The following equation summarizes the the quantization process of γ_i :

$$\gamma_i \rightarrow \begin{cases} 0; & \text{if } \gamma_i < \zeta_1 \\ \zeta_k; & \text{if } \zeta_1 \leq \gamma_i \leq \zeta_{Q_\gamma} \\ & \text{and } \|\gamma_i - \zeta_k\|_2 \leq \|\gamma_i - \zeta_p\|_2, \quad k \neq p; k, p \in [1, Q_\gamma] \\ \zeta_{Q_\gamma}; & \text{if } \gamma_i > \zeta_{Q_{M_g}-1} \end{cases} \quad (17)$$

Forcing SNR to be 0 as shown in the above equation makes the ES null, since $N_{s,i} \rightarrow 0$ as $\gamma_i \rightarrow 0$ (see equation (14)). This will help the CR-IoT network to avoid selecting ENs with very low SNR and prevents the SNR-wall phenomenon [23], which may happen when performing SS at low SNR values. In addition, low values of SNR highly consumes the battery since a huge number of samples is required to meet the detection requirement. Regarding the maximal value ζ_{Q_γ} , this saturates the SNR value. In fact, at very high SNR, the EN could fulfil the detection requirement with a few number of samples. Thus, it positively impacts the amount of consumed energy by the SS operation.

5. Simulation results

In our simulations, we use real parameters related to the SS, the transmit/receive, and the Micro-Controller Unit (MCU). For the SS operation, the parameters of RTL-SDR-based RadioHound are used [41]. It can scan from 25 MHz to 6 GHz, with a power less than 3 W. For transmit/receive and MCU operations, we use respectively the parameters of transceiver SX1272 and the Semtech STM32L073 MCU [42, 43].

According to the experimental results of [44], the energy is mainly consumed

335 by the four following functions of the EN: (1) The Measurement (Sensing of
the channel in our application), (2) the transmission, (3) the Micro-Controller
Unit (MCU) running, and (4) the receiving. Even though in Sleep mode the
EN consumes a very low power, but it becomes considerable due to the long
time taken by this mode. Table 2 gives the electrical specifications of the sys-
340 tem under the following parameters: Supply voltage = 3.3 V, Capacity = 1000
mAh, Operating Frequency = 868 MHz, Power of transmission = 10 dBm, and
the bandwidth (BW) of LoRa communication = 125 KHz.

Table 2: Power consumption specifications of the four main functions of the LoRa EN

Mode	Unit	Current
Receive mode	SX1272	10.5 mA
Transmit mode	SX1272	31 mA
Spectrum Sensing	RadioHound	0.9 A
MCU Running	STM32L073	1.8 mA
Sleep mode	SX1272	0.1 μ A

Receive Mode. In the receive mode, EN is active to hear from the AS two kinds
of operations: (1) when receiving the Beacon from the GW considered as request
345 to make the SS, the Beacon lasts for 16 ms [36]. And (2), when receiving
data in *Rx1* informing the EN whether it is selected to make the SS in the
next round or not. The time of *Rx1* depends on the SF used by the EN in the
transmission. *Rx2* is used by the NS to send some updates to the ENs, and it
is disregarded in this work.

350

Transmit Mode. The duration of the transmission operation is related directly
to the number of transmitted symbols N_{symp} :

$$N_{symp} = 8 + \max \left[\mathcal{H}, 0 \right] \quad (18)$$

where $\mathcal{H} = \left\lceil \frac{28+8PL+16CRC-4SF}{4(SF-2DE)} \right\rceil (CR+4)$, where $\lceil X \rceil$ rounds X to the nearest
integer greater than or equal to X .

PL represents number of bytes in the PL. *CRC* indicates the presence or not
of the CRC field in the physical message (CRC is set to 0 if the CRC field is
not present; otherwise, CRC is equal to 1). *CR* denotes the coding rate and
can take values from 1 to 4, for 4/5 to 4/8 coding rate, respectively. Finally,
DE = 1 when the low data rate optimization is enabled (for SF=12 and SF=11)
and *DE* = 0 elsewhere.

The transmission time T_{Tx} is evaluated using the duration T_{symp} of the N_{symp}
symbols and the preamble message time T_{pre} (refer to [38, 44] for more infor-

mation), where:

$$T_{symb} = N_{symb} \times \frac{2^{SF}}{BW} \quad (19)$$

$$T_{pre} = (N_{pre} + 4.5) \times \frac{2^{SF}}{BW} \quad (20)$$

$$T_{Tx} = T_{symb} + T_{pre} \quad (21)$$

N_{pre} is the number of preamble symbols, and it is fixed in this study to 8.

Spectrum Sensing Mode. The energy consumed by SS depends on the number of samples needed for the energy detector before making the decision. We assume that the band to be monitored is 125 KHz BW, and the sampling frequency f_s is twice the BW. Thus the sensing time T_{SS} at the EN_i becomes:

$$T_{SS} = \frac{N_{s,i}}{f_s} \quad (22)$$

355 Even though the power of SS is relatively high compared to other modes, the time of SS is very short, which leads to a comparable consumed energy to other modes.

Micro-Controller Unit Running Mode. This mode is activated once the system wakes up and lasts till the end of the receiving mode.

360 *Sleep Mode.* After receiving the data from the NS and AS in $Rx1$, the EN system goes to Sleep mode till the time of the next SS round.

5.1. Simulation scenarios

ESco is compared to two other strategies: (1): N_E ENs are randomly selected to make the SS, and (2) ENs with the N_E maximal energy level make the SS.

365 For the three strategies, the network is considered dead when the last number of ENs with $l_i > 0$ is smaller than N_E . The total number of nodes in the networks is fixed to $N_t = 500$ throughout the upcoming simulation results.

The ENs are assumed to be equipped with the same battery capacity, and l_i is considered at 100% of the full battery capacity at the beginning of the simulations. The battery lifetime is considered to evaluate the proposed mechanism. This lifetime is related to the initial energy of the battery as well as the adopted SF and the SNR at the node. High SF means that the transmission time becomes large, and subsequently the consumed energy increases compared to the scenario when low SF is used. On the other hand, low SNR leads to the need of a large number of samples to make an accurate SS, which increases the consumed energy of the SS as shown in equation (22).

370 Regarding the parameters of SS, the target $\overline{P_d}$ and $\overline{P_{fa}}$ are fixed to 0.9 and 0.1 respectively. The SNR is assumed to be log-normal distributed among the ENs, with a mean γ_m and a standard deviation σ_g .

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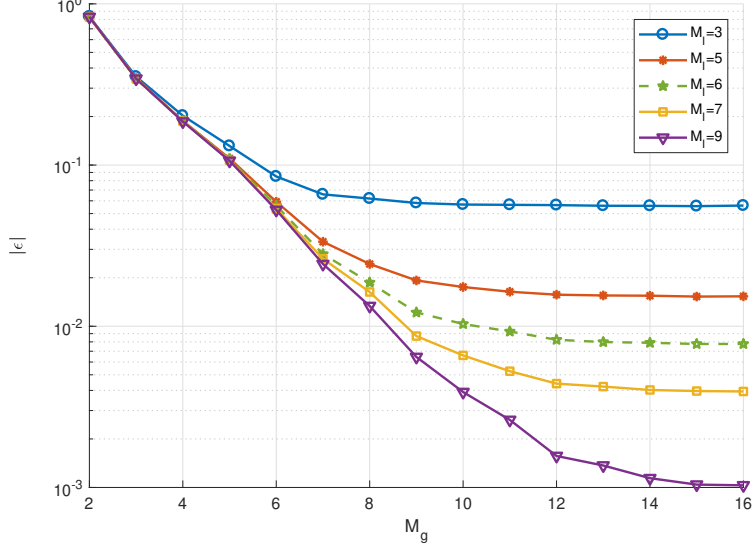


Figure 6: Variation of the error of quantization ϵ is terms of the number of bits used in Q_γ and Q_l .

5.2. Investigation on the size of PL

The precision of the quantization of SNR and the battery level is necessary to make a reliable decision at the AS. From one hand, the quantization error may adversely affect the ES, leading to wrong selection of the ENs. On the other hand, $N_{s,i}$ of ENs participating in the SR is calculated at the AS based on the quantized SNR for target \bar{P}_d and \bar{P}_{fa} . If the SNR's quantization is badly done, the EN may not meet the detection requirements since $N_{s,i}$ becomes irrelevant to the real SS conditions of the EN. Given that D_i is represented on one bit, we aim at investigating the number of bytes to be loaded by the PL in the transmitted packet. γ_i is log-normal distributed with $\gamma_m = -10$ and $\sigma_m = \sqrt{10}$ dB. The minimum SNR is set to -20 dB. The maximal value of SNR is set to 5 dB, beyond this value the SNR is saturated as per the model of (17).

The evaluation of the reliability of the quantization is based on the error ϵ :

$$\epsilon = \frac{E[|\mathcal{F}(l_i, N_{s,i}) - \mathcal{F}_q(l_i, N_{s,i})|]}{E[\mathcal{F}(l_i, N_{s,i})]} \quad (23)$$

where $\mathcal{F}_q(l_i, N_{s,i})$ is the ES evaluated based on the quantized γ_i and $N_{s,i}$, and $E[\cdot]$ stands for the mathematical expectation.

Figure 6 presents the evolution of ϵ for several values of Q_γ and Q_l . As expected, ϵ decreases with the increase of M_g and M_l . For $M_l = 9$ bits and $M_g \geq 9$ the error becomes lower than 1 %. At $M_l = 9$ bits and $M_g = 12$, the error becomes close to 0.1 %.

Throughout the rest of the paper $M_l = 9$ and $M_g = 12$ are fixed to evaluate the performance of the proposed strategy ESco.

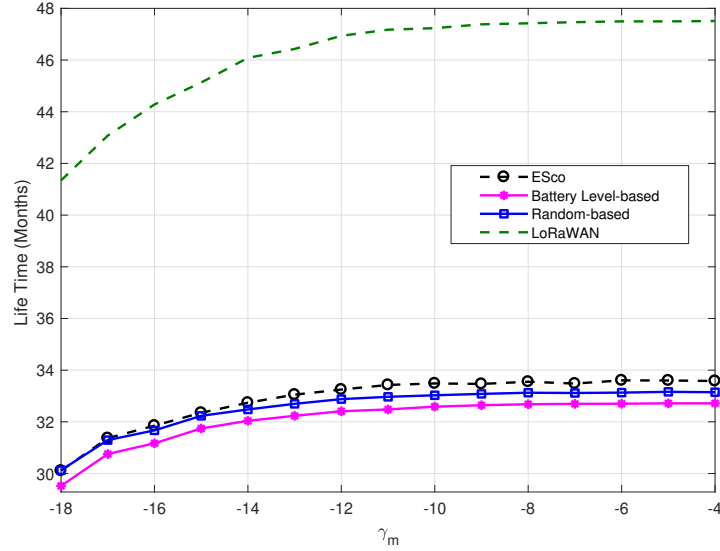


Figure 7: The lifetime of the network in terms of the mean SNR γ_m . $P_{fa} = 0.1$; $P_d = 0.9$; $N_t = 500$

5.3. Lifetime and sensing performance evaluation

In this subsection, we analyse the performance of the CR-IoT from the sensing and the lifetime points of view.

Due to the modifications on the LoRaWAN protocol, especially the need of all the ENs to be awake at the beginning of each transmission period, the energy efficiency may be changed. Figure 7 shows the network lifetime for several values of γ_m while comparing with the standard LoRaWAN, where not all the ENs wake up at the beginning of the period. σ_g is fixed to $\sqrt{10}$ dB and the number of nodes participating in each SR operation is fixed to $N_E = 8$. The lifetime of the network increases with γ_m for all the presented strategies since the number of samples to be treated decreases. Thus, the energy spent by the SS operation decreases. On the other hand, the proposed ESco outperforms both Random-based and Battery level-based strategies by achieving highest lifetime. The variation of γ_m from -18 dB to -4 dB leads to increase the lifetime of ESco by more than three months and a half, and about three months for both Random-based and Battery level-based strategies. Compared to LoRaWAN, the lifetime of the ENs adopting ESco exhibits a decrease of 25 %, from 47 months at $\gamma_m = -14$ to around 33 months for the same SNR. This is due to the fact of the waking up of all the ENs at the beginning transmission period. This paid cost comes at providing the LoRaWAN with the ability to apply on-request data transmission which is not available for the actual LoRaWAN protocol, and, on the other hand, to make the LoRa network work cooperatively to select the ENs with the best ESs.

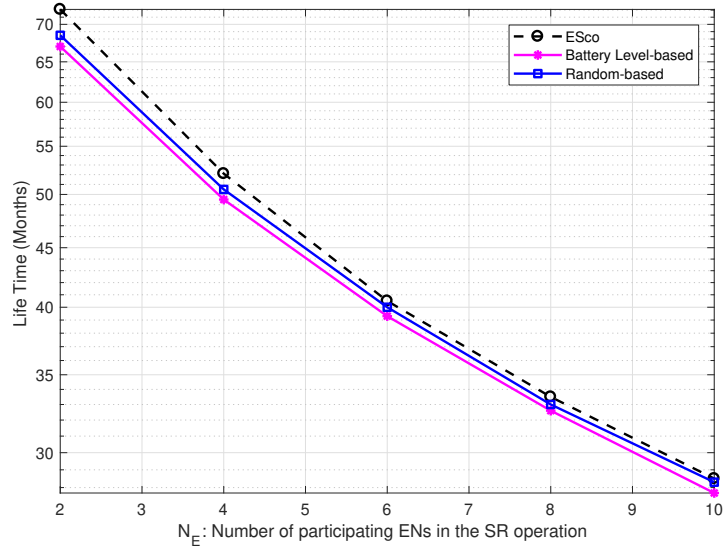


Figure 8: The impact of N_E on the network lifetime when $P_{fa} = 0.1$; $P_d = 0.9$; $N_t = 500$, and SF=9.

The chosen number of the participating ENs, N_E , may play an essential role in the SR process since this parameter is related to the spatial diversity to be ensured by the cooperative SS. Figure 8 shows the evolution of the network lifetime in terms of N_E . The lifetime decreases as N_E increases. However, for all the considered values of N_E our proposed strategy reaches the longest lifetime compared to other considered strategies. Even though the sensing time decreases with N_E , leading to reduce the consumed energy of SS, the lifetime is decreasing with N_E because the participating ENs consumes a high transmission energy to report the sensing results to the AS. However, a sufficiently high number of the ENs is required in order to ensure the spatial diversity that overcomes the problem of the hidden PU problem [22].

Figure 9 shows the impact of the adopted SF on the lifetime of the network. SF varies from 7 to 12 according to the specifications of LoRaWAN. The lifetime decreases with the increase of SF for the three presented strategies. This refers to the fact that the transmission time increases with SF, which leads to increase the transmission energy. However, the proposed EScO outperforms the two other strategies for all the used SFs.

Figure 10 depicts the impact of N_t on the lifetime of the network. $N_E = 8$ is adopted. As N_t increases the network lifetime increases. This is because the probability of an EN is selected to perform the SS decreases with N_t for all the presented strategies. This leads to extend the lifetime of the sensor and subsequently the one of the network. Our proposed EScO preserves better the lifetime of the network compared to the two other strategies as show in figure 10.

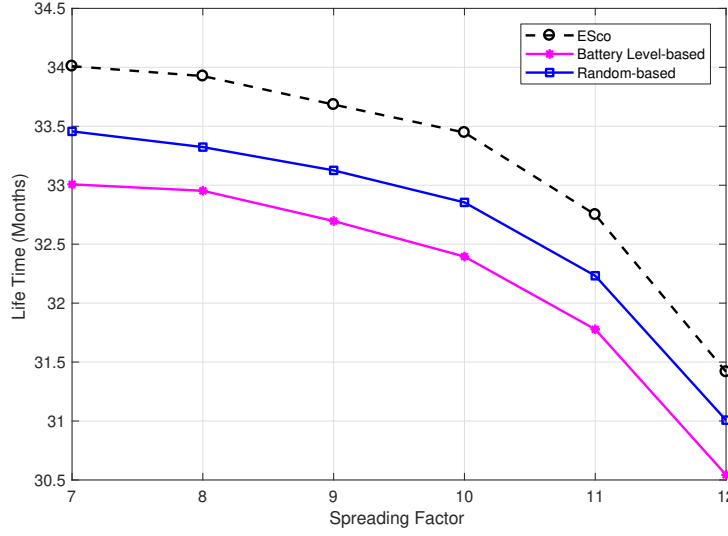


Figure 9: The evolution of the network lifetime with respect to SF. $N_E = 8$, $N_t = 500$

One of the essential parameters to be set in any CR-based network is the time between two consecutive SS operations. This is related to the rate of a tolerable collision time between SU and PU, and this collision rate may differ from one primary channel to another. In the proposed protocol, AS should request a SS operation each T_{bcn} using a Beacon, where the request rate may highly impact the lifetime of the ENs. Figure 11 shows the evolution of the lifetime of the network for several of T_{bcn} . As depicted, the lifetime is highly impacted by T_{bcn} since at each SR operation the EN must spend energy for sensing, receiving and reporting. For ESco, which outperforms the two other strategies, achieves a lifetime of 34 months for $T_{bcn} = 128$ sec, while this lifetime is reduced to 18 months when $T_{bcn} = 32$ sec. The lifetime becomes almost the double when using $T_{bcn} = 128$ instead of $T_{bcn} = 32$. Thus, increasing T_{bcn} the lifetime of the network increases; however, this may increase the collision risk with the PU since the latter may return active between two consecutive Beacons. Further discussion on the collision is given in the next subsection.

5.4. Throughput and Collision Analysis

In this section, we analyse the impact of the length of T_{bcn} on the throughput and the collision rate between the secondary transmission and PU. Secondary transmission is based on the decision made by the CR-IoT. Useful throughput R_0 of the secondary transmission is done without any interference with PU, while the colliding throughput R_1 is considered when SU sends the data with an active PU on the same channel. R_0 happens when the CR-IoT makes a true decision on the absence of PU and the latter does not return back during T_{bcn} . R_1 takes place in two cases: (1) if the CR-IoT makes a miss-detection on PU

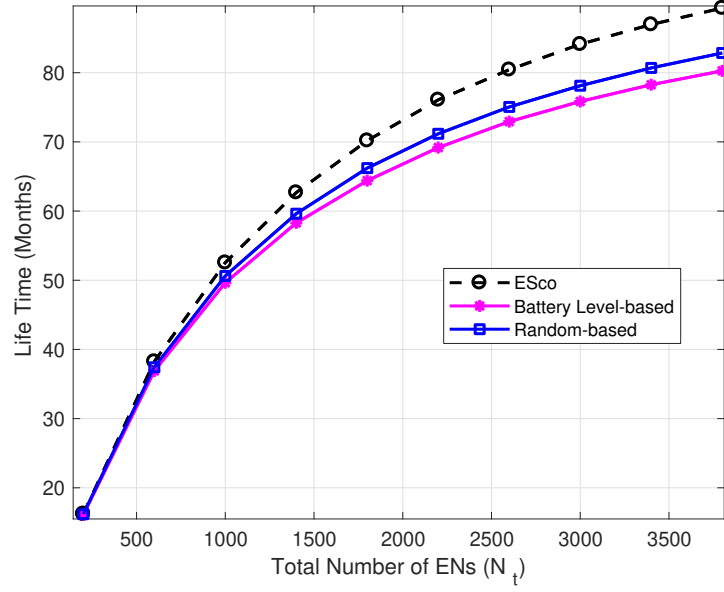


Figure 10: The impact of N_t on the network lifetime when $N_E = 8$.

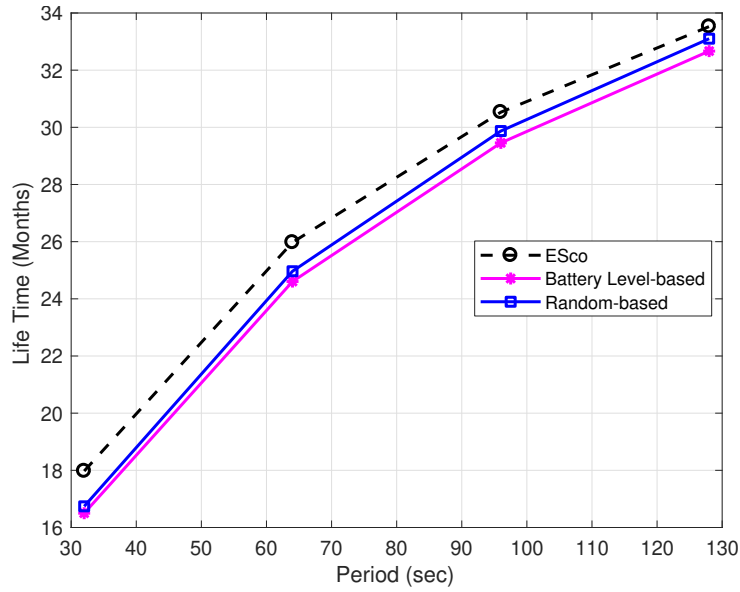


Figure 11: The impact of the length of Beacon period on the network lifetime with $N_E = 8$.

presence, and (2) CR-IoT makes a true decision on the absence of PU when doing the SS, but PU returns back during T_{bcn} . Given that the PU can change its state (active to idle or idle to active) once during T_{bcn} , the probability of collision P_c and collision-free P_{cf} are given as follows [39, 45]:

$$P_c = (1 - P_d)p_1 + (1 - P_{fa})p_0P_r \quad (24)$$

$$P_{cf} = (1 - P_{fa})p_0(1 - P_r) \quad (25)$$

$$(26)$$

where p_0 and p_1 are the probabilities that PU is absent and active respectively when the SS is performed. P_r is the probability that PU reappears during $T_{bcn} - T_{SS}$, and it is given by:

$$P_r = 1 - \exp\left(-\frac{T_{bcn} - T_S}{\lambda}\right) \quad (27)$$

where λ is defined as the average idle duration of the PU. Subsequently, R_0 and R_1 are given is the following equations:

$$R_0 = C_0P_{cf} \quad (28)$$

$$R_1 = C_1P_c \quad (29)$$

C_0 and C_1 are the channel capacities related to R_0 and R_1 respectively:

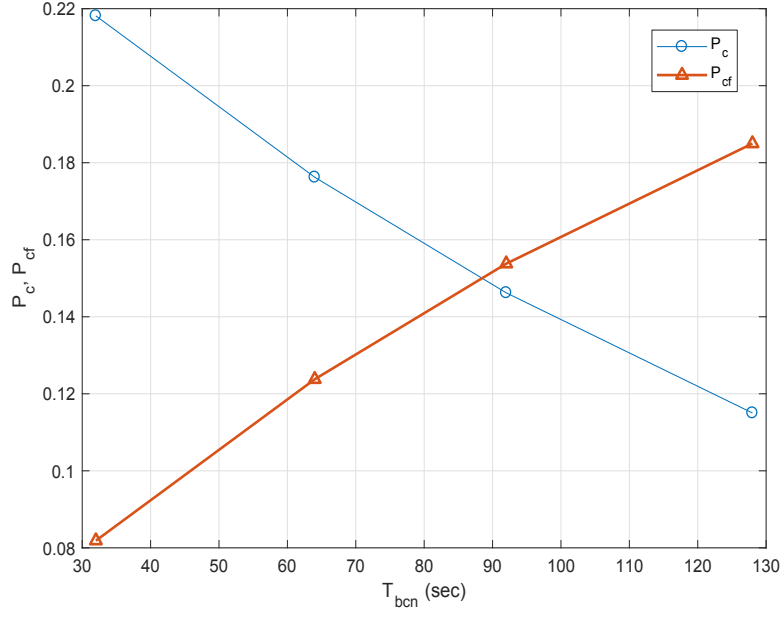
$$C_0 = W \log_2(1 + Z_0) \quad (30)$$

$$C_1 = W \log_2(1 + Z_1) \quad (31)$$

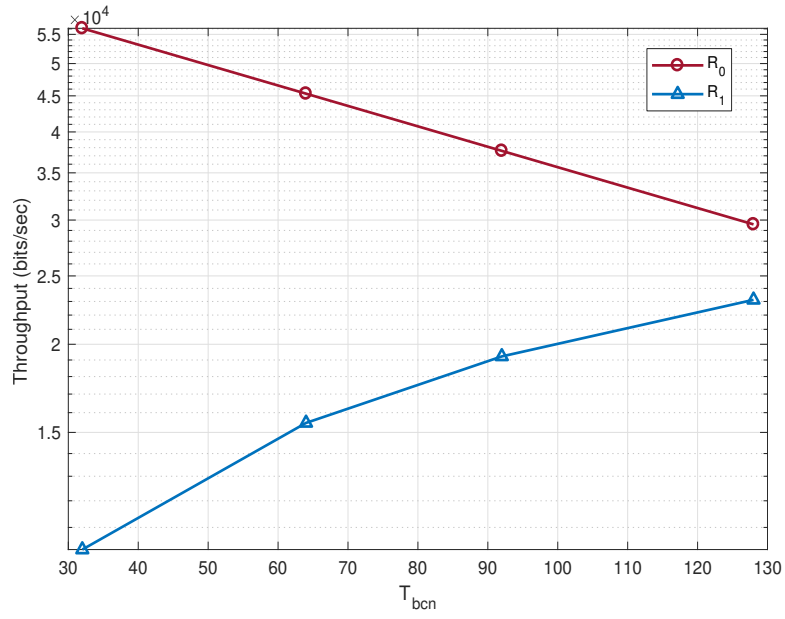
455 where W is the transmission bandwidth (in our case $W = 125$ kHz), Z_0 and Z_1 are the SNR and the Signal to Noise and Interference Ratio (SNIR) of the secondary transmitted signal at the secondary receiver respectively.

Figure 12 presents the evolution of the collision probability, collision-free probability, and the throughputs of the secondary system. $Z_0 = 5$ dB and $Z_1 = 3$ dB are fixed. $\lambda = 130$ sec, $p_0 = 0.3$ and $p_1 = 0.7$ are adopted. As shown in figure 12(a), P_c increases with T_{bcn} from 0.08 at $T_{bcn} = 32$ sec to greater than 0.18 at $T_{bcn} = 128$ sec. This reflects the adverse impact of a long T_{bcn} on the collision between the secondary and the primary transmissions. On the other hand, P_{cf} decreases with T_{bcn} . Thus, low T_{bcn} reduces the secondary collision 460 to the primary transmission while enhances the collision-free activity of the secondary system.

Figure 12(b) depicts the evolution of both the useful and the colliding throughputs of the secondary transmission. R_0 decreases with T_{beacon} while R_1 increases. In fact, a long T_{bcn} may reduce the frequency efficiency of the secondary system, since it takes a long time to re-establish a SS after a decision 470 of the presence of PU. During this time, PU may leave the channel, thus a lost in exploiting the available frequency resources happens. In turns, the long time may also increase the collision probability since PU may return active between two consecutive SS operation, when the secondary system is unaware of PU activity. Thus shortening this time leads to reduce the collision rate.



(a) The probability of Collision



(b) The Throughput

Figure 12: The evolution of the collision and collision-free probability, and the useful and colliding throughputs in terms of T_{bcn}

6. Conclusion

In this paper, Eligibility Score-based (ESco) strategy is proposed to handle the sensing-reporting process in a battery-powered CR-IoT network providing Spectrum Sensing as a Service. LoRaWAN protocol is taken as case study to implement the proposed strategy. The SS operation performed in such network may largely consume the battery of the ENs. Thus the ENs involved in the SS should be carefully selected so that the lifetime of the CR-IoT network is extended as possible. The selection process is done based on an efficient Eligibility Score (ES) evaluated at each EN in the network. This ES takes into consideration both SS decision reliability and the battery level of the EN. In addition, we studied the data exchange between Network Server and EN of proposed ESco as per the LoRaWAN Class-B protocol, where we introduce needed modifications to make this protocol responsive to the on-demand model of the Spectrum Sensing as a Service. Numerical results depict the efficiency of the proposed strategy by respecting high protection of PU against the interference, high spectrum efficiency and long extended network lifetime. The compatibility of ESco with other IoT technologies such as Sigfox and NB-IoT are to be explored and investigated in future work.

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