Abstract—In this paper, we evaluate a novel contention-aware channel selection algorithm that focuses on energy efficiency improvement of a secondary network (SN) in a scenario where other non-cooperating SNs are also using the primary resources. We present a detailed energy efficiency analysis and we study how the time between two consecutive sensing periods affects the energy efficiency. Our analysis proves that a categorization of the idle channels based on their contention level and the selection of the less contended ones can result in up to 70% gain in energy efficiency. The model is further evaluated through simulations.

Index Terms—Cooperative Spectrum Sensing, Feature Detection, CSMA/CA, Green Communications.

I. INTRODUCTION

Cognitive radio (CR) has received much attention as a possible solution to the spectrum scarcity problem, as it enables the use of licensed bands by unlicensed users (i.e., secondary users (SUs)) for as long as they remain unused [1]. The energy-efficiency of CRs is also fundamental, as CRs nodes may be battery-power wireless devices. Thus, most research works focus on energy-efficient algorithms that mainly exploit the benefits of cooperative spectrum sensing (CSS) [2]–[4].

However, the majority of the works in the literature deals with scenarios where a single SN is considered. Nevertheless, the goal of studying the operation and performance of a SN in a scenario where other non-cooperating SNs are also using the primary resources opportunistically is twofold: Firstly, the ability of distinguishing whether the activity in a specific band is caused by primary users (PUs) or by SUs allows a more intensive reuse of the primary resources. Secondly, the amount of SUs contending for the same resources can have an impact both on throughput and energy consumption. Therefore, the proper selection of the frequency bands already used by other SNs can result in energy-efficient scenarios.

In [5], a contention-aware channel selection algorithm is proposed, but unlike our work, it focuses on connectivity, and not on energy-efficiency. To that end, in [6] we proposed an energy-efficient contention-aware channel selection algorithm, that focuses on throughput and energy efficiency improvement of a SN when it coexists with other non-cooperating SNs. In such scenarios, performing channel selection taking into account only the PU activity, as the state-of-the-art (SoA) does, is not optimal. Therefore, our algorithm further categorizes the idle licensed channels (LCs) based on their contention level (i.e., SU activity) and then selects the less contended ones to be accessed first. To achieve this, CSS is used, during which feature detection (FD) is combined with a technique that estimates the number of SUs in each LC. The performance gains of the algorithm were evaluated through simulations.

In this paper, we extend our work in [6] by deriving a novel analytical model for the energy efficiency of a SN when it coexists with other non-cooperating SNs. Furthermore, we study how the time between two consecutive sensing periods affects the aforementioned metric. The rest of the paper is organized as follows: In Section II, an overview of the algorithm is presented. In Section III, the energy efficiency analysis is given and in Section IV, the analytical and simulation results are presented. Finally, Section V concludes the paper.

II. ALGORITHM OVERVIEW

A SN of $N$ users and a set of $M$ LCs are considered, that are divided into $w$ different categories according to their contention level. The PU activity follows an exponential on-off traffic model, with the mean durations of on and off periods denoted by $T_{on}$ and $T_{off}$, respectively. An unlicensed channel (ULC) is also considered with a total of $N_{unic}$ users. Each CR node has a half duplex transceiver, while in-band signaling is considered. The transmissions of the SUs follow the CSMA/CA method [7], whereas the PUs use their own access method while accessing the LCs. The SN is assumed to be initially located in a highly congested ULC, where the coordinator triggers a sensing procedure (divided into three parts: $t_{ph1}$, $t_{ph2}$, $t_{ph3}$) to find new spectrum opportunities [6]. Thus, in the ULC only the initial set-up and the recovery of the SN (i.e., when no idle LCs are tracked) take place.

During $t_{ph1}$ as soon as the coordinator gains access to the ULC, it broadcasts a request for sensing (RFS). This packet defines how often the sensing procedure will be initiated ($T_S$). This parameter is constant and equals to the time between the beginning of operation in the first visited LC and the moment that the coordinator has a new RFS packet to send. The more quickly the PU activity changes, the lower this value is to keep the information for every LC updated. On the successful RFS reception only one of the SUs sends an ACK, whereas on erroneous reception the procedure of [6] is applied.

During $t_{ph2}$ all the SUs sense the LCs that was/were assigned to them in $t_{ph1}$. CSS using the OR fusion rule is applied. If the number of SUs of the SN is a multiple of
the LCs, each LC is sensed by the same number of SUs. Otherwise, a subset of LCs is sensed by more SUs, in order to achieve better missed detection and false alarm probability. Cyclostationary FD is used for sensing [8], which enables the SUs to distinguish between PUs’ and SUs’ signals, at the expense of more complexity and longer sensing time. The use of FD is very important, as otherwise (i.e., using energy detection) all the LCs used by other SUs would be considered busy resulting in very low spectrum efficiency.

During $t_{ph3}$ the exchange of the sensing results takes place. After gaining access to the ULC, the coordinator broadcasts a beacon and a contention-free period starts. During this period, each SN node waits $t_{SIFS}$ and then sends its sensing results [6]. Then, the coordinator constructs a list, which defines the order in which the idle LCs will be visited by the SN. Subsequently, the coordinator broadcasts a packet of length $l_{list}$ and the contention-free period ends.

Once the list is constructed, there are two possibilities: 1) if there are no LCs sensed as idle, the network stays in the ULC and another sensing procedure is initiated. 2) If there is at least one LC sensed as idle, the SN hops to the first LC in the list and operates there. Then, there are again two possible cases: 2.a) If the LC becomes busy, the SN has to leave the channel immediately in order not to interfere with the PU. We assume that the SN can detect the PU activity after $t_r$ and then react by hopping to the next LC in the list. In case there is no other LC in the list, the SN hops back to the ULC and triggers a new sensing procedure. 2.b) If it is time for the next sensing procedure to be initiated, the coordinator contends again to gain access to the LC to send a new RFS packet.

The list contains all the LCs that were sensed idle sorted by the number of contending nodes in ascending order (i.e., the LC with the least number of contending SUs takes the first place and thus higher priority). The main goal of the algorithm is to achieve energy efficiency improvement, by reducing the time that the SN under study spends in LCs with high contention. To that end, the use of FD allows the categorization of the LCs into those with PU activity, those with SU activity and those with no activity at all, while to further classify the LCs with SU activity according to their contention, the estimation technique described in [6] is applied.

III. ENERGY EFFICIENCY ANALYSIS

The energy efficiency of the algorithm can be expressed as:

$$Q = \frac{E[D]}{E[U] + E[L]}$$

where $E[D]$ is the expected payload transmitted by the SN in a period of time (i.e., the sum of the expected time spent in the ULC and LCs (denoted as $E[U]$ and $E[L]$, respectively) and $E[U]$, $E[L]$ the equivalent expected energy consumptions.

To better explain a period of time, an example is given in Fig. 1, where the SN remains in the ULC for $T_{U}$. Then, after completing the sensing procedure, it hops to the LCs, given that there is at least one sensed idle. There, it operates for two complete periods (CPs). A CP refers to the case that the SN remains in the LCs for $T_{S}$ and a sensing procedure has taken place. When all the LCs become busy, the SN hops back to the ULC and the last period was an incomplete period (INP). In the ULC, a new period starts. Thus, a period of time refers to the sum of the expected values of $T_{U}$ and $T_{L}$.

1) Given that there are $w$ categories of LCs, $E[D]$ equals:

$$E[D] = \sum_{k=1}^{w} E[N_{pack_k}]E[P]$$

$E[P]$ denotes the average packet payload size and $E[N_{pack_k}]$ the expected number of successfully transmitted packets by the SN in the category $k$ LCs in a period of time and equals:

$$E[N_{pack_k}] = \frac{E[T_k]}{E[T_{slot}]} P_{sk}$$

where $E[T_k]$ denotes the expected time required for operation (transmission, collision and idle slots) in category $k$ LCs, $E[T_{slot}]$ the average slot duration and $P_{sk}$ the probability of a successful transmission slot of the SN under study in category $k$ LCs. a) We define $X$ as the number of successive periods (CPs and an INP) operating exclusively in LCs. Thus, the probability of $x$ successive periods can be expressed as:

$$P(X = x) = P(T = T_{cp})^{x-1}P(T < T_{cp})$$

where $T$ denotes the time that, in every period, the SN remains in LCs, with a maximum of $T_{cp}$ ($0 \leq T \leq T_{cp}$) and thus $P(T = T_{cp}) = 1 - P(T < T_{cp})$ and $P(T < T_{cp})$ the probabilities of a CP and an INP, respectively, with $P(T < T_{cp})$ given by:

$$P(T < T_{cp}) = \sum_{n=1}^{M_{s}} P(n_i = n)P(T < T_{cp}|n_i = n)$$

where $M_{s}$ denotes the number of LCs, $n_i$ the number of LCs detected idle, $P(n_i = n)$ the probability of detecting $n$ LCs idle and $P(T < T_{cp}|n_i = n)$ the probability of having an INP, given that there are $n$ LCs detected idle. $P(n_i = n)$ equals:

$$P(n_i = n) = \frac{M_{s}^n}{n!} P_{idle}^{n}(1 - P_{idle})^{M_{s} - n}$$

$P_{idle} = (1 - P_{fa})P_{dte} + P_{md}(1 - P_{dte})$ is the probability that a LC is sensed idle, with $P_{dte}$ the probability of an LC being idle and $P_{md}$, $P_{fa}$ the probabilities of missed detection and false alarm.

When applying the OR fusion rule, $P_{md}$, $P_{fa}$ equal to:

$$P_{md} = 1 - \sum_{i=1}^{l} \binom{l}{i} (1 - P_{md})^{i} P_{md}^{l-i}$$

$$P_{fa} = \sum_{i=1}^{l} \binom{l}{i} P_{fa}^{i}(1 - P_{fa})^{l-i}$$

where $l$ is the number of cooperating SUs during sensing and $P_{md,u}$ and $P_{fa,u}$ the missed detection and false alarm probability of each one of the SUs, respectively [4]. Given that there are $n$ LCs sensed as idle, an INP occurs, when the SN operates for less than $T_{S} - S_{n-1}$ in the $n_{th}$ LC (i.e., the last LC of the list), where $S_{n-1} = \sum_{l=1}^{n-1} T_l + (n-1)\tau$ is the total time spent in the previous $n - 1$ LCs, $\tau_{i}$ is the operation time (transmission, collision or idle slots) in the $i_{th}$ visited LC and $\delta = t_r + t_{sw}$ the time required to detect the change of a LC ($t_r$) and switch to the following one ($t_{sw}$), when it becomes busy. Thus, $P(T < T_{cp}|n_i = n)$ equals to:
of \(E\) LCs idle. Then, the expected operation time in category \(k\), when having \(x\) successive periods equals:

\[
E[T_k] = \sum_{x=0}^{\infty} P(X = x)(x-1)E[T_k]_{cp} + E[T_k]_{inp} (10)
\]

with \(E[T_k]_{cp}\) and \(E[T_k]_{inp}\) the expected operation time in category \(k\) in a CP and in an INP, respectively, where \(E[T_k]_{cp}\) equals:

\[
E[T_k]_{cp} = \sum_{n=1}^{M_k} P(n_i = n) \sum_{j=0}^{\alpha} P(n_{(k-1),j} = j) \frac{\beta}{l} \sum_{i=1}^{l} [\tau_i | n_i = n] (11)
\]

where \(P(n_{i(k-1),j} = j)\) is the probability of having \(j\) LCs idle out of \(\alpha = \min(\sum_{k=1}^{K} M_k, n-j)\) in the previous \(k-1\) categories \((M_k, n)\) is the number of LCs in category \(y\), \(P(n_{ik} = l)\) the one of having exactly \(l\) LCs idle out of the \(\beta = \min(M_k, n-j)\) in category \(k\) and \(E[\tau_i | n_i = n]\) the expected operation time in the \(i_{th}\) channel visited LC when having a CP given that there are \(n\) LCs idle. Then, \(P(n_{i(k-1),j} = j)\) and \(P(n_{ik} = l)\) are given by:

\[
P(n_{i(k-1),j} = j) = \binom{\alpha}{j} P_{idle}^j (1 - P_{idle})^{\alpha-j} (12)
\]

\[
P(n_{ik} = l) = \binom{M_k}{l} P_{idle}^l (1 - P_{idle})^{M_k-l} (13)
\]

Then, \(E[\tau_i | n_i = n]\) can be expressed as:

\[
E[\tau_i | n_i = n] = \int_{0}^{T_S} f_{\tau_i}(\tau_i) \cdot \int_{T_S-S_{i-1}}^{T_S-S_{i-1-\delta}} f_{\tau_{i-1}}(\tau_{i-1}) \cdot \int_{T_S-S_{i-1}}^{T_S} f_{\tau_{i-1}}(\tau_{i-1})d\tau_{i-1} \cdot \cdots \cdot \int_{T_S-S_{i-1}}^{T_S} f_{\tau_{i-1}}(\tau_{i-1})d\tau_{i-1} + \int_{T_S-S_{i-1}}^{T_S} f_{\tau_{i}}(\tau_{i}) \cdot \int_{T_S-S_{i-1}}^{T_S} f_{\tau_{i}}(\tau_{i})d\tau_{i} \cdot \cdots \cdot \int_{T_S-S_{i-1}}^{T_S} f_{\tau_{i}}(\tau_{i})d\tau_{i} + \cdots \cdot \int_{T_S-S_{i-1}}^{T_S} f_{\tau_{i}}(\tau_{i}) \cdot \int_{T_S-S_{i-1}}^{T_S} f_{\tau_{i}}(\tau_{i})d\tau_{i} \cdot \cdots \cdot \int_{T_S-S_{i-1}}^{T_S} f_{\tau_{i}}(\tau_{i})d\tau_{i} (14)
\]

with \(S_i = S_{i-1} + \tau_i + \delta\). \(E[T_k]_{inp}\) is given also from (11), but instead of \(E[\tau_i | n_i = n]\), \(E[\tau_i’ | n_i = n]\) is used, that denotes the expected operation time in the \(i_{th}\) visited LC when having an INP given that there are \(n\) LCs idle and is expressed as:

\[
E[\tau_i’ | n_i = n] = \int_{0}^{T_S} f_{\tau_i}(\tau_i) \cdot \int_{T_S-S_{i-1}}^{T_S-S_{i-1}} \tau_i f_{\tau_i}(\tau_{i-1}) \cdot \int_{T_S-S_{i-1}}^{T_S-S_{i-1}} f_{\tau_{i-1}}(\tau_{i-1})d\tau_{i-1} \cdot \cdots \cdot \int_{T_S-S_{i-1}}^{T_S-S_{i-1}} f_{\tau_{i-1}}(\tau_{i-1})d\tau_{i-1} + \int_{T_S-S_{i-1}}^{T_S} f_{\tau_i}(\tau_i) \cdot \int_{T_S-S_{i-1}}^{T_S} \tau_i f_{\tau_i}(\tau_{i-1}) \cdot \int_{T_S-S_{i-1}}^{T_S} f_{\tau_{i-1}}(\tau_{i-1})d\tau_{i-1} \cdot \cdots \cdot \int_{T_S-S_{i-1}}^{T_S} f_{\tau_{i-1}}(\tau_{i-1})d\tau_{i-1} + \cdots \cdot \int_{T_S-S_{i-1}}^{T_S} f_{\tau_{i-1}}(\tau_{i-1}) \cdot \int_{T_S-S_{i-1}}^{T_S} f_{\tau_{i-1}}(\tau_{i-1})d\tau_{i-1} \cdot \cdots \cdot \int_{T_S-S_{i-1}}^{T_S} f_{\tau_{i-1}}(\tau_{i-1})d\tau_{i-1} (15)
\]

i) Calculation of \(f_{\tau_i}\): The pdf of the time that the LC remains in the same state (i.e., \(t_i\)) is given by: \(f(t_i) = \frac{1}{T} e^{-\frac{t_i}{T}}\) where \(A\) is equal to \(T_{idle}\) or \(T_{on}\) when \(t_i\) denotes the time in the idle or busy state, respectively. Then, the operation time in LC \(i\) which was previously denoted as \(\tau_i\) can be given by:

\[
\tau_i = \begin{cases} 
0, & \text{if } t_i \leq S_{i-1} \\
T_{idle} - S_{i-1}, & \text{otherwise} 
\end{cases} (16)
\]

As \(f_{\tau_i}(\tau) = \frac{1}{T} e^{-\frac{\tau}{T}} P(\tau_i \leq \tau)\), we should focus on \(P(\tau_i \leq \tau)\). All the channels included in the list have been perceived idle. However, due to missed detection probability, some of them are idle and some of them are busy. We define \(O_i(t)\) as the state of the \(i_{th}\) channel of the list at time \(t\). Therefore,

\[
P(\tau_i \leq \tau) = P(\tau_i \leq \tau | O_i(0) = idle) P(O_i(0) = idle) + P(\tau_i \leq \tau | O_i(0) = busy) P(O_i(0) = busy) (17)
\]

Let us focus on the first part of the equation (17).

\[
P(\tau_i \leq \tau | O_i(0) = idle) = P(\tau_i \leq \tau | O_i(0) = idle | t_i \leq S_{i-1}) P(t_i \leq S_{i-1}) + P(\tau_i \leq \tau | O_i(0) = idle | t_i > S_{i-1}) P(t_i > S_{i-1}) (18)
\]

\[
P(t_i \leq S_{i-1}) = \int_{0}^{S_{i-1}} f(t_i) dt_i = 1 - e^{-\frac{S_{i-1}}{T_{idle}}} (19)
\]

\[
P(O_i(0) = idle) = \frac{P_{idle}(1-P_{on})}{P_{idle}(1-P_{on}) + P_{on}(1-P_{idle})} (20)
\]

Now let us focus on the second term of (17), that considers the erroneously sensed as idle channels. We assume that the channel state can only change from busy to idle once before being visited by the SUs. Hence, if the activity changes from busy to idle before, the channel will be idle when visited.

\[
P(\tau_i \leq \tau | O_i(0) = busy) = P(\tau_i \leq \tau | O_i(0) = busy | \tau > S_{i-1}) P(\tau > S_{i-1}) + P(\tau_i \leq \tau | O_i(0) = busy | O_i(S_{i-1}) = idle) P(O_i(S_{i-1}) = idle | O_i(0) = busy) (21)
\]

\[
P(O_i(S_{i-1}) = idle | O_i(0) = busy) = e^{-\frac{S_{i-1}}{T_{on}}} (22)
\]

Finally, after some algebra and given that \(f_{\tau_i}(\tau | O_i(0) = idle \cap t_i \leq S_{i-1})\) and \(f_{\tau_i}(\tau | O_i(0) = busy \cap O_i(S_{i-1}) = idle)\) are equal to 1 if \(\tau = 0\) or 0 otherwise and \(f_{\tau_i}(\tau | O_i(0) = idle \cap t_i > S_{i-1})\) and \(f_{\tau_i}(\tau | O_i(0) = busy \cap O_i(S_{i-1}) = idle)\) equal to \(\frac{1}{T_{idle}} e^{-\frac{\tau}{T_{idle}}}\), the pdf of \(\tau_i\) is given in (23).

b) : The probability of a successful transmission of the SN in the category \(k\) LCs is: \(P_{sk} = N\tau(1-\tau)^N\) where \(N\) is the number of SUs, \(N_0\) the average number of the other nodes that operate in the category \(k\) LCs and \(\tau\) the probability that a node transmits in a randomly chosen slot time [7].
\[ f_r(\tau) = \begin{cases} 
\frac{1}{\tau_{off}} e^{-\frac{\tau}{\tau_{off}}} & \text{if } \tau = 0 \\
1 - e^{-\frac{\tau}{\tau_{on}}} - e^{-\frac{\tau_{off}}{\tau_{on}}} & \text{otherwixe} 
\end{cases} \] (23)

c) \( E[T_{slot}] \) can be expressed as:
\[ E[T_{slot}] = P_{空} \sigma + (P_{重} + P_{总}) T_{重} + (P_{重} + P_{总}^* T_{c}) \] (24)
where \( P_{空} \) is the probability of an idle slot in the category \( k \) LCs, \( P_{重} \) this of a collision slot of the SN and \( P_{总}^* \), \( P_{总} \) the probabilities that the other \( N_k \) users have a successful transmission and collision slot, respectively, in the category \( k \) LCs. \( \sigma \) denotes the empty slot duration, while \( T_{重} \) and \( T_{c} \) the durations of a successful transmission and collision slot [7]. Then, \( P_{空} = 1 - P_{重} \), where \( P_{重} = 1 - (1 - \tau)^{N_k + N} \) is the probability that there is at least one transmission in the considered slot time and \( P_{总}^* = N_k \tau (1 - \tau)^{N_k + N - 1} \). Then, we calculate the probabilities of collision by subtracting from the total number of collisions, the ones that involve only the \( N_k \) users for the calculation of \( P_{总} \) and the \( N \) users for \( P_{总}^* \). To that end, the total probability of collision is expressed as:
\[ P_{总} = \sum_{i=2}^{N_k} (N_k - i) \tau (1 - \tau)^{N_k + N - i} \] (25)
and thus
\[ P_{总} = P_{总} - (1 - \tau)^{N_k} \sum_{i=2}^{N_k} (N_k - i) \tau^i (1 - \tau)^{N_k - j} \] (26)
while \( P_{总}^* \) is derived from (26) by substituting \( N_k \) with \( N \).

2) \( E[E_{\text{tot}}] = E[E_{\text{unsuccess}}] E[E_{\text{success}}] + E[E_{\text{unsucc}}] \) where \( E[E_{\text{unsuccess}}] \) denotes the expected energy consumption in an unsuccessful slot and \( E[E_{\text{success}}] \) and \( E[E_{\text{unsucc}}] \) the energy consumptions during the successful transmission of the RFS packet and the list construction procedure, respectively. Then, \( E[E_{\text{unsuccess}}] = (1/P_{空}) - 1 \) where \( P_{空} \) is the probability of a successful transmission of the coordinator in the UL and \( E[E_{\text{success}}] \) can be expressed as:
\[ E[E_{\text{success}}] = \frac{1}{(1 - P_{空})} (NP_{idle}(P_{重} + P_{总} T_{重} + P_{总}^* T_{c}) + P_{重} (t_{data} (P_{总} + (N - 1) P_{rec}) + NP_{idle} t_{data})) \] (27)
where \( P_{总} \), \( P_{rec} \) and \( P_{idle} \) are the energy consumptions in transmission, reception and idle mode, \( P_{重} \), \( P_{总} \), \( P_{总}^* \) the probabilities of an idle, collision slot of the coordinator [7]. \( P_{总} \), \( P_{总}^* \) the probabilities of a successful transmission, collision slot of the \( N_{unsucc} \) nodes, equivalently. Then, \( E[E_{\text{unsuccess}}] \) and \( E[E_{\text{success}}] \) equal to:
\[ E[E_{\text{unsuccess}}] = E_{t_{data}} (P_{sum} + (N - 1) P_{rec}) + t_{ack} (P_{sum} + P_{rec} + (N - 2) P_{idle} + NP_{idle} t_{data}) \] (28)
\[ E[E_{\text{success}}] = E_{t_{data}} (t_{data} X_k P_{sum} + Y_k P_{rec} + (N - 1) P_{idle} + NP_{idle} t_{data}) \] (29)
where \( t_{data}, t_{ack}, t_{idle}, t_{rec} \) and \( t_{end} \) denote the time to send a beacon, report, list and end packet, respectively.

3) \( E[E_L] \) can be expressed as:
\[ E[E_L] = E[E_{\text{success}}] + \sum_{k=1}^{N_k} E[E_{contk}] \] (30)
where \( E[E_{\text{success}}] \) is the expected energy consumed by the SN during both the reaction periods and the sensing procedures in a period of time and \( E[E_{contk}] \) during the contention time in the category \( k \) LCs. \( E[E_{\text{success}}] \) can be expressed as:
\[ E[E_{\text{success}}] = \frac{1}{\delta} \sum_{x=0}^{\infty} P(x = x) ((x - 1) E_{\text{success}} + E_{data}) \] (31)
where \( E_{\text{total}} \), \( E[E_{\text{success}}] \) the expected energy consumptions both in the reaction periods and the sensing procedures in a CP and an INP, respectively, and can be expressed as:
\[ E[E_{\text{success}}] = \sum_{k=1}^{N_k} P_k E[E_{snk}] + \sum_{n=1}^{M_k} \sum_{i=1}^{N_k} P_{n_i} (i - 1) E_{\text{data}} + E_{data} \] (32)

Then, \( E[E_{contk}] = E[E_{snk}] + E[E_{inp}] \) and \( E[E_{inp}] \) the energy consumptions during \( \sigma \) and the sensing procedures in the LCs. \( P_{空} \) is given from (11) by substituting \( \tau [n_i = n] \) with \( P_{空} \). which can be expressed as:
\[ P_{空} = \sum_{k=1}^{N_k} P_k E[E_{snk}] + \sum_{n=1}^{M_k} \sum_{i=1}^{N_k} P_{n_i} (i - 1) E_{\text{data}} + E_{data} \] (33)

Then, \( E[E_{contk}] = E[E_{snk}] + E[E_{inp}] \) where \( E[E_{snk}] = \beta P_{空} E_{e}, E[E_{inp}] = \beta P_{空} E_{e}, E[E_{snk}] = \beta N_{idle} P_{idle} (P_{重} + P_{总}^* T_{重} + P_{total} T_{c}) \) the expected energy consumptions in the successful transmissions, collisions and idle slots of the SN in the category \( k \) LCs, respectively, with \( \beta = E[T_{空中}] / E[T_{slot}] \). \( E_{data} \) and \( E_{e} \) are the energy consumptions in a successful transmission and collision slot of the SN, respectively and are equal to:
\[ E_{数据} = (t_{data} + t_{ack}) (P_{sum} + P_{rec} + (N - 2) P_{idle} + NP_{idle} t_{data} + t_{sdfs}) \] (34)
\[ E_{e} = (t_{data} X_k P_{sum} + Y_k P_{rec} + (N - 1) P_{idle} + NP_{idle} t_{data} + t_{sdfs}) \] (35)

\( X_k, Y_k \) are the average numbers of SUs that are involved in a collision, in transmission or reception mode with \( X_k \) equal:
\[ X_k = \frac{1}{P_{空}} (N \tau (1 - \tau)^{N - 1} \sum_{i=1}^{N_k} (N_k - i)^{i} (1 - \tau)^{N_k - i} \] (37)

\[ + \sum_{j=2}^{N_k} (N_k - i)^{i} (1 - \tau)^{N - j} \sum_{l=0}^{N_k} (N_k - i)^{l} (1 - \tau)^{N_k - l} \] (37)
IV. PERFORMANCE EVALUATION

We consider a SN of $N=6$ and 12 SUs and a set of $M_s=6$ LCs, while $N_{unic}=50$. All the users are in saturated conditions (i.e., always having a packet to send). The channel conditions are assumed to be ideal for both our approach and the SoA to highlight the performance gains: no hidden terminals, no exposed terminals and no packet corruption are considered. The LCs are divided into four categories ($w=4$) according to the number of contending SUs already operating in the LC. Thus, for $N_{SUlic}=40$, two very low contended LCs (0-10 SUs), one low contended (10-20 SUs), one medium contended (20-30 SUs) and two high contended (30-40 SUs) are considered. The exact value of the actual number of SUs in a LC is randomly chosen between the interval of its category. The rest simulation parameters are summarized in Table I. As a reference algorithm, we consider a FD algorithm that uses no estimation technique for the number of contending SUs. Then, the list will include first the idle LCs with no activity (neither PU nor SU) and then those with SU activity in a random order.

In Fig. 2(a) we study how the time between two consecutive sensing periods (i.e., $T_S$) affects the energy efficiency (in bits/Joule). The analytical model for the energy efficiency is also presented and it is shown to be in good agreement with the simulations. There is a maximum energy efficiency achieved for $T_S=0.2s$. Before this value there is a lot of time and energy spent in frequent sensings and thus less time available for data transmission, whereas after it the list is not updated and the SN has to switch channels frequently. It can be also noticed that the energy efficiency gain of our proposal compared to the FD algorithm with $N=12$ and $N_{SUlic}=40$ is 46%.

In Fig. 2(b) and 2(c) the throughput and the energy efficiency of our proposal compared to the FD algorithm versus the maximum number of SUs in a LC, $N_{SUlic}$, are respectively depicted for different $N$. The analytical results are also presented in Fig. 2(c) and as it can be noticed, they match with the simulations. As $N_{SUlic}$ increases, both the throughput and energy efficiency decreases, as the contention in the LCs increases and thus the energy consumption. As a result, the relative gain in both throughput and energy efficiency increases compared to the FD algorithm, due to the contention-awareness of our proposal. Moreover, for given $N_{SUlic}$, as $N$ increases, the relative gain in both throughput and energy efficiency decreases, as the more users of the SN, the less the effect that the contention can have in throughput and the more the energy consumption. Thus, the proposed algorithm achieves the best relative gain under high contention and for a small SN (i.e., for $N=6$ and $N_{SUlic}=40$) it can present up to 71% improvement in throughput and 70% in energy efficiency.

V. CONCLUSION

We presented a detailed energy efficiency analysis of a SN, which shares the same PU resources with other non-cooperating SNs. We evaluated, both analytically and with simulations, the performance of a channel selection algorithm that selects the less contended idle LC for the SN to access and it has been proved that it can present up to 70% improvement both in throughput and energy efficiency without inducing any additional complexity compared to a simple FD algorithm.

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