Time-domain Cognitive Sensor Networking

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Abstract

Cognitive wireless networking is often considered in scenarios where a "secondary" network exploits opportunistically the frequency resources which are left unused by a "primary" network. In this book chapter, we consider the application of the cognitive networking paradigm to resource-constrained Wireless Sensor Networking (WSN) scenarios. In particular, we propose a time-domain cognitive sensor networking approach, where the secondary nodes transmit during time intervals left unused by a primary WSN. Assuming that both primary and secondary WSNs are IEEE 802.15.4, we first derive the exact statistical distribution of the idle times of the primary WSN. Then, we optimize the transmission time of the secondary WSN in order to minimize the probability of interference with the primary WSN, highlighting the existing trade-off with the throughput of the secondary WSN.

Index Terms

Discrete Time Markov Chain (DTMC); IEEE 802.15.4; sensor networking; time-domain cognitive networking.

I. INTRODUCTION

Because of the increasing number of low-cost wireless applications, the unlicensed spectrum is quickly becoming a scarce resource. In voice-oriented wireless networks, e.g., cellular systems, it has been shown that a relevant portion of the licensed spectrum is under-used [1], thus yielding significant inefficiencies. A better performance can be obtained using new techniques, such as Dynamic Spectrum Access (DSA), that allow a secondary network to exploit the white spaces in the licensed spectrum of a primary network, owing to cognitive capabilities. Most of the research activity on cognitive systems focuses on efficient spectrum utilization, considering cellular systems. However, in the case of Wireless Sensor Networks (WSNs), a network typically generates bursty traffic over the entire available bandwidth.

In this book chapter, we propose a cognitive sensor networking strategy such that a secondary WSN transmits in the inactivity periods of a primary WSN, using all the (common) shared bandwidth. Clearly, one of the main problems of the secondary WSN is to decide when to transmit its packets, in order to maximize its throughput while, yet, minimizing the interference with the primary WSN. In order to tackle this problem, we consider a cognitive system similar to the scheme presented in [2]. The reference scenario is given by a primary IEEE 802.15.4 WSN coexisting with a secondary WSN which tries to exploit the inactivity periods of the primary one. More precisely, both WSNs share the same bandwidth and the cognitive coexistence is carried out in the time domain. In particular, assuming synchronization between the nodes of the secondary WSN, upon waking up, they sense the channel and act accordingly: if the channel is busy, the secondary WSN defers any activity (namely, data collection, i.e., transmissions from the sensor nodes to the sink); otherwise, i.e., if the channel is idle, the secondary WSN transmits for an "optimal" time interval. By relying on a rigorous queueing-theoretic approach, the length of this interval is optimized in order to minimize the probability of interference with the primary WSN, yet maximizing the throughput of the secondary WSN.

This book chapter is structured as follows. In Section II, we present an overview of related works. In Section III, we derive an accurate queuing model for a single hop IEEE 802.15.4 WSN. In Section IV, we study the exact distribution of idle times in IEEE 802.15.4 WSNs. By using the developed analytical models, in Section V we characterize the performance trade-offs involved by time-domain cognitive sensor networking. Finally, Section VI concludes this book chapter.

II. RELATED WORK

The interest in the application of cognitive principles to wireless networks dates back to the end of the Nineties, after the introduction of the basic concept of cognitive radio by Mitola [3]. In the last decade, the ever increasing demand for data exchange (in particular, Internet access in the presence of mobility) has led to a higher and higher need to access the electromagnetic spectrum (in particular, some portions of it, e.g., the ISM band) [4]. Cognitive networking is an approach which tries to exploits the "empty" (temporarily unused) spaces in the electromagnetic spectrum. In particular, a cognitive radio follows a cognitive cycle [5], which attributes to a node both the ability to perceive the surrounding environment and the intelligence required to identify spectral holes and exploit them efficiently.

The FCC has attributed various characteristics to cogntive radios [6]. In particular, spectrum *sensing* and *sharing* play key roles. In [1], spectrum sensing techniques are classified into three groups: identification of a primary transmitter; identification of the primary receiver; interference temperature measurement. In the same paper, spectrum sharing is classified according to the used access technology: in the presence of *overlay* spectrum sharing the secondary nodes access the spectrum using portions of the spectrum currently unused by the primary nodes; with *underlay* spectrum sharing, spread spectrum techniques are used to make a primary user perceive the transmissions by the secondary users as noise.

Various approaches to the design of communication protocols able to exploit opportunistically the electromagnetic spectrum have been proposed. In [7], the authors propose a Medium Access Control (MAC) protocol, relying on the theory of alternating renewal processes, for a cognitive (secondary) network, which opportunistically use the channels of a primary network with the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) MAC protocol (e.g., a WiFi network). According to this approach, a pair of secondary nodes estimate the duration of an idle period and, then, try to maximize the secondary throughput by maximizing the number of frames transmitted during idle periods. In [8], a proactive channel access model is proposed, such that secondary nodes, on the basis of sensing, build a statistical model of the spectral availability for each channel. The proposed approach is validated considering a primary network given by a television broadcast network. In [9], the authors present a similar proactive approach to the estimation of the availability by the secondary nodes, followed by intelligent commutation (between available channels) on the basis of a proper prediction step based on renewal theory. Three statistical models of busy/idle times are considered: (i) busy and idle times have both exponential distributions; (ii) busy and idle times have fixed duration; (iii) the idle time has an exponential distribution, while the busy time is fixed. In [10], the authors, exploiting the theory of alternate renewal processes, derive the optimized duration of the channel sensing phase in order to maximize the identification of spectral holes. In [11], the authors investigate the coexistence of cognitive radios and WiFi nodes, modeled through a Continous Time Markov Chain (CTMC)-based model. In [12], the authors investigate the busy and empty times in an IEEE 802.11 network experimentally, in order to identify accurate statistical models: in particular, it is concluded that a hyper-Erlang distribution provides the most accurate fit, but an exponential distribution allows to design MAC protocols more efficiently. In [13], with reference to IEEE 802.11 networks, the CSMA/CA protocol of secondary users is modified to be able to operate in the intermittent manner of spectrum pooling. In [14], the authors propose a cognitive scenario where secondary users adjust their communication protocols by taking into account the locations of the primary users. By introducing "preservation regions" around primary receivers, a modified multihop routing protocol is proposed for the cognitive users.

The features of cognitive radios can be exploited also by WSNs, which are typically designed to use fixed portions of the electromagnetic spectrum in a bursty manner and are formed by nodes with limited communication and processing capabilities. The focus of [15] is on the coexistence of IEEE 802.11 Wireless Local Area Network (WLAN) and IEEE 802.15.4 WSNs in the ISM band. Distributed adaptation strategies, based on spectrum scanning and increased cognition through learning, are proposed for IEEE 802.15.4 nodes, in order to minimize the impact of the interference from IEEE 802.11 nodes.

In [16], it is shown that a WSN, provided that the nodes are equipped with a cogntive radio interface, can have several benefits, such as: DSA (which may avoid the acquisition of expensive licenses to transmit a very limited amount of data); opportunistic use of the available channels for a bursty traffic; adaptivity to channel conditions (leading to a reduced energy consumption); feasibility of coexistence of competing WSNs (partially or totally sharing given spectrum portions). In [17], the authors formulate the sensing-throughput tradeoff problem mathematically and use an energy detection sensing scheme to prove that the formulated problem allows to identify an optimal sensing time which yields the highest secondary network throughput. This optimal sensing time decreases when distributed spectrum sensing is applied. In [18], a cognitive radio sensor combines multiple sensing results obtained at different time points, i.e., time-diversity, to make an optimal decision on the existence of spectrum access opportunity.

In [19], [20], the authors propose a time-domain cooperative spectrum sensing framework, in which the time consumed by reporting for one cognitive user is also utilized for other cognitive users' sensing, i.e., space diversity is exploited. The obtained results show that optimal sensing settings allow to maximize the throughput of the secondary network, under the constraint that the primary users are sufficiently protected. In [21], a novel and comprehensive metric, denoted as the Coexistence Goodness Factor (CGF), is introduced to accurately model the inherent tradeoff between uninterfered primary users and unlicensed access efficiency (from secondary users) for time-domain DSA-based coexistence.

III. AN ACCURATE QUEUING MODEL OF A SINGLE-HOP IEEE 802.15.4 WSN

In order to derive the optimal transmission time that a secondary IEEE 802.15.4 WSN should adopt, we first develop an accurate queuing model for the primary IEEE 802.15.4 WSN. More precisely, by leveraging on the theory of the renewal process and Discrete Time Markov Chains (DTMCs) [22], the primary WSN is modelled as an M/G/1/N queue, where N is the number of primary nodes and the service time distribution depends on the IEEE 802.15.4 standard. An illustrative scheme of the (general)

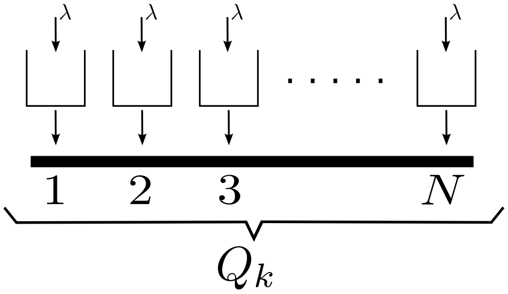


Fig. 1. Queuing model for a multiple access scheme with N nodes.

queuing model is shown in Fig. 1. More specifically, the M/G/1/N queue models the overall number of packets in the system and is solved using its embedded DTMC. The time is discretized in minislots, and the length of each minislot coincides with the duration of the backoff unit of the IEEE 802.15.4 MAC protocol. Each primary node acts as a Bernoulli traffic source with parameter p: more precisely, in each minislot a source node generates a packet with probability p. Each node transmits packets of fixed size D_{pck} (dimension: [b/pck]) and, under the assumption of fixed transmit data-rate, duration (corresponding to a given number of minislots). The final corresponding transition diagram of the process $\{Q_k\}$ is shown in Fig. 2. It is then possible to determine all transition probabilities $\{P_{i,j}\}$ (for all admissible pairs (i,j)) shown in the diagram in Fig. 2 and, then, determine the stationary distribution $\boldsymbol{\pi} = \{\pi_n\}_{n=0}^{N}$, such that

$$\boldsymbol{\pi} = \boldsymbol{P}\boldsymbol{\pi}. \tag{1}$$

Solving equation (1) corresponds to identifying the eigenvectors of $\boldsymbol{P}$ associated with the eigenvalue 1—note that $\boldsymbol{P}$ has for sure the unitary eigenvalue as the transition matrix is stochastic [23]. The existence and uniqueness of the steady-state distribution are guaranteed by the ergodicity of the considered DTMC. It can be shown that the obtained solution depends on the probability with which a packet, arriving in an idle minislot at a given node, is transmitted at the beginning of the next minislot. This probability, denoted as q, depends on the particular back-off algorithm under use. In order to determine the value

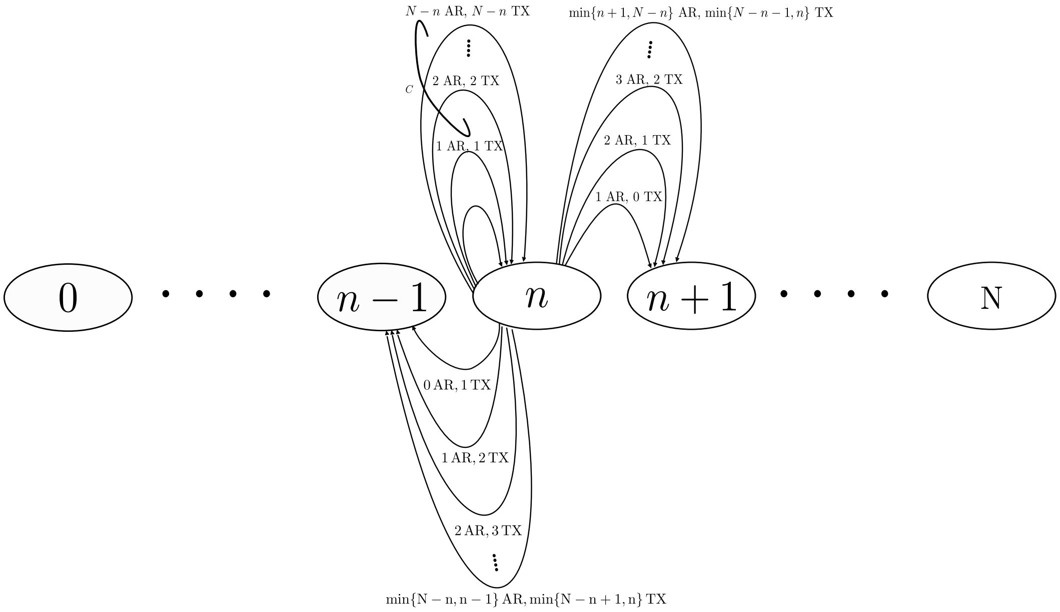


Fig. 2. Transition diagram of the process $\{Q_k\}$ in a single-hop IEEE 802.15.4 network.

of q, we apply the renewal theoretic approach proposed in [22], where the three-level renewal process shown in Fig. 3 (in the illustrative case with maximum number of retransmissions $M = 5$) is proposed.

- The first level renewal cycle is defined as the period between two consecutive instants at which the selected node starts with the back-off stage 0. In particular, two types of first level cycles can be observed: the X_1 cycle does not contain any transmission because of M consecutive busy CCAs, whereas the X_2 cycle contains one transmission (either successful or not) which is carried out after an idle CCA.
- The second level renewal cycle Y is defined as the period between the end of the first level cycle X_2 and the end of the consecutive first level cycle X_2. Note that there could be j ($j \geqslant 0$) X_1 cycles before the X_2 cycle. The cycle Y can be either of type Y_1 (if the transmission reduces to a collision) or Y_2 (if the transmission is successful).
- The third level renewal cycle Z is defined as the period between the end of the second level cycle Y_2 and the end of the consecutive second level cycle Y_2. As for the previous case, there could be k

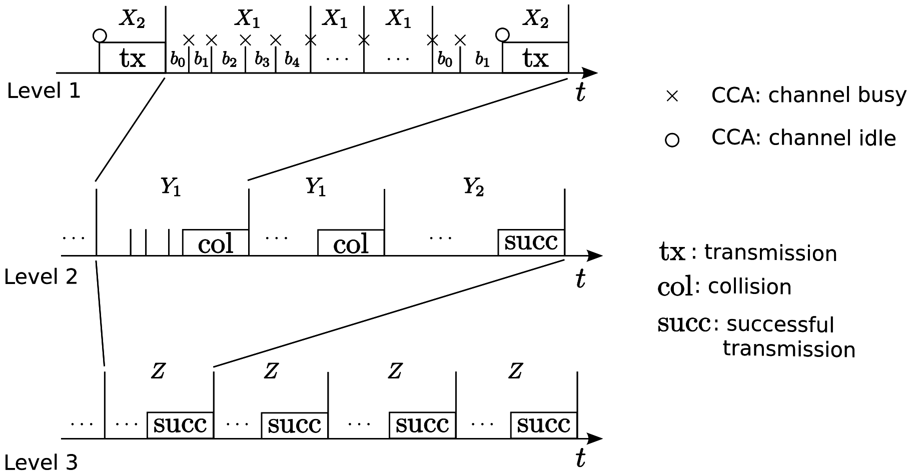


Fig. 3. Three-level renewal process proposed in [22], with maximum number of retransmissions equal to $M = 5$.

$(k \geqslant 0)$ Y_1 cycles before a Y_2 cycle. The successful transmissions carried out in the Z cycle can thus be considered as the "reward" for the third level renewal process. The throughput of the selected node can thus be computed as the average reward in the Z cycle.

According to the theory of renewal processes with reward, one can derive the following two equations for the case with double CCA [22]:

$$\tau = \frac{\overline{R}}{\overline{X}} = \frac{\sum_{m=0}^{M-1} \alpha^m}{\overline{X}} \tag{2}$$

$$\alpha = \frac{L\left[1-(1-\tau)^N\right]}{1+L\left[1-(1-\tau)^N\right]} \tag{3}$$

where: τ is the sensing probability; α is the "failure" probability, i.e., the probability of finding the channel busy in a minislot; N is the number of nodes; L is the packet length (in minislots); and M is the maximum number of backoff cycles. If L, N, M are known, then equations (2) and (3) are a set of fixed point equations and can be solved. In particular, the probability τ corresponds to the probability q introduced in our model.

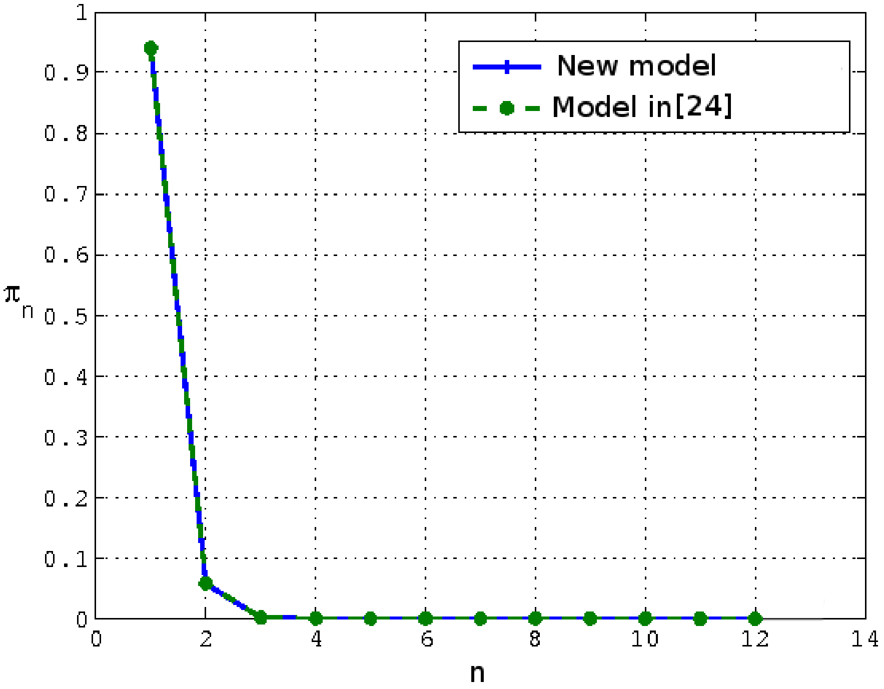


Fig. 4. Distribution of the number of packets in the system in a scenario with $p = 0.0002$.

In order to verify the validity of the proposed framework, we have compared the predicted results with the Markov chain-based model proposed in [24]. In Fig. 4, we compare the steady-state distribution predicted by our model with that predicted by the model in [24], in a scenario with $p = 0.0002$, $N = 12$ nodes, and $L = 10$.

IV. EXACT IDLE TIME DISTRIBUTION IN SINGLE-HOP IEEE 802.15.4 WSN

Unlike the approximate model presented in [2], we propose an innovative analytical approach to numerically derive the exact distribution of the idle channel times of the IEEE 802.15.4 primary WSN, by using the queueing model presented in Section III. The basic idea consists of the application of the total probability theorem for the evaluation of each term of the Probability Mass Function (PMF) of the idle time, by conditioning on the starting states and assuming that they have the steady-state probabilities

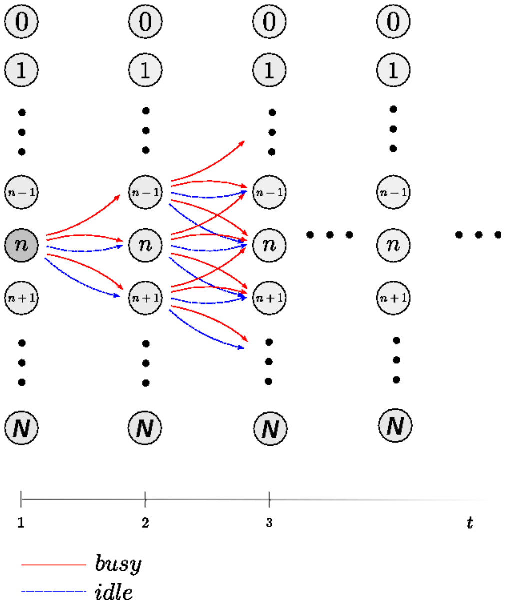


Fig. 5. Full trellis diagram associated with the transition diagram in Fig. 2.

$\{\pi_n\}_{n=0}^{N}$ of the DTMC associated with the process $\{Q_k\}$. More precisely, one obtains:

$$\mathrm{P}\{I=i\} = P\{I=i \,|\, Q_k=0\}\pi_0 + \mathrm{P}\{\mathrm{I}=i \,|\, Q_k=1\}\pi_1 \quad + \ldots \quad + \mathrm{P}\{I=i \,|\, Q_k=N\}\pi_N \qquad \forall i>0. \quad (4)$$

The terms $\{\mathrm{P}\{I=i \,|\, Q_k=n\}\}$ are obtained through a recursive algorithm which “runs” over a particular trellis diagram, derived from the transition diagram in Fig. 2—in networking theory, the transition diagram is commonly considered, as steady-state transition probabilities are of interest; the use of a trellis diagram, which takes into account the time evolution through the specific sequence of states (i.e., a “path”), is often used in transmission theory [25]. Instead of considering the “full” trellis diagram (i.e., with all possible transitions), we consider a “reduced” trellis diagram with only the transitions associated with the idle events. Illustrative rapresentations of full and reduced trellises are shown in Fig. 5 and Fig. 6, respectively.

Assuming to start from the state n in the trellis diagram, the sum of the state probabilities at the i-th

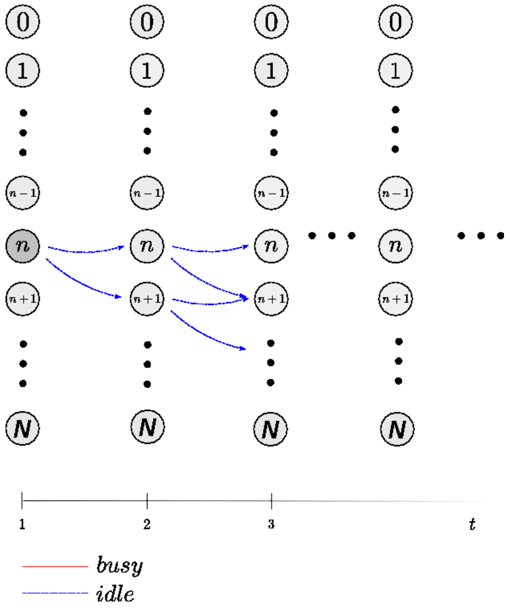


Fig. 6. Reduced trellis diagram, with only branches associated with idle minislots, derived from the full trellis diagram in Fig. 5.

step corresponds to the probability $\mathrm{P}\{I \geqslant i \mid Q_k = n\}$. Therefore, it follows that

$$\mathrm{P}\{I = i \mid Q_k = n\} = \mathrm{P}\{I \geqslant i \mid Q_k = 1\} - \mathrm{P}\{I \geqslant i+1 \mid Q_k = n\}. \tag{5}$$

At this point, the complete PMF (4) of the idle time duration (in minislots) can be derived—the accuracy of this calculation can be made as high as desired simply by considering a sufficiently large number of trellis steps, in order to correctly estimate the tail of the PMF.

We remark that in the derivation of the idle time distribution, we assume that the channel is busy immediately before becoming idle. Moreover, the distribution starts from one minislot as we decided to consider the two idle CCA minislots as belonging to a busy period.

In the remainder of this section, we investigate the idle time distribution considering a fixed network scenario with: $N = 12$ nodes directly connected to the sink; fixed packet duration of $L = 10$ minislots (of data), with 2 supplementary CCA minislots related to the CSMA/CA MAC protocol. All remaining parameters of the CSMA/CA parameters are set to their default values. The network load will be set to two values representative of low and high traffic situations. We recall that the traffic generation at each node has a Bernoulli distribution with parameter p (dimension: [pck/minislot]). In general, the aggregate and normalized network load can be expressed as [24]

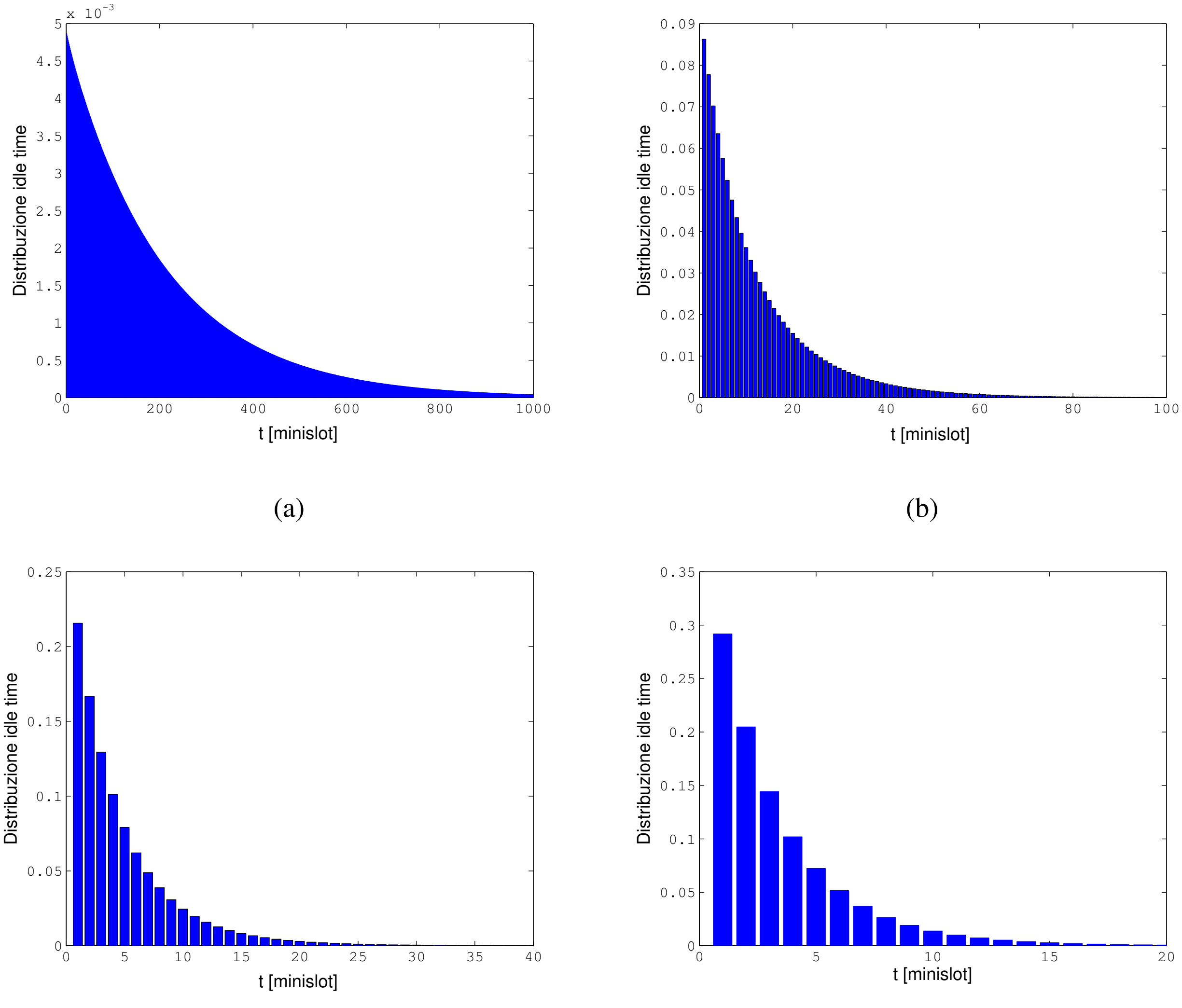
$$G = NLp. \tag{6}$$

By fixing the values of N and L (as will be done in the following), G depends only on p.

In Fig. 7, we show the idle time distribution associated with four values of p: (a) 0.0002, (b) 0.003, (c) 0.007, and (d) 0.01. In all cases, $N = 12$ and $L = 10$. From the results in Fig. 7, it can be observed that the PMF of the idle time concentrates to smaller and smaller values for increasing values of p. However, it can also be observed that the "shape" of the PMF tends to remain the same. This suggests that there might exist a closed-form distribution which approximates the exact idle time distribution. Heuristically, the results in Fig. 7 suggest that the shape of the PMF looks like a translated geometric with properly set parameter p_{idle}, i.e.:

$$\mathrm{P}\{I = i\} = p_{\text{idle}}(1 - p_{\text{idle}})^{i-1} \qquad \forall i > 0. \tag{7}$$

In particular, it can be concluded that $p_{\text{idle}} = P\{I = 1\}$ and this probability can be computed by relying on the proposed trellis-based approach run only for the first step. The average idle time duration is thus $1/p_{\text{idle}}$. In Fig. 8, we compare directly the exact and approximate (geometric) distributions of the idle time considering various values of p: (a) 0.0002, (b) 0.003, (c) 0.01. An excellent agreement can be observed. This result compares favorably with the results, relative to an IEEE 802.11 network, presented in [26], where the idle time distribution is assumed to be geometric. In [26], it shown that the assumption of constant access probability per minislot is confirmed. Moreover, the geometric idle time distribution determined by our framework is in agreement with the results presented in [7], [11], where the channel occupancy is modeled as exponential (continous time approach). We remark, however, that our recursive trellis-based approach is *exact* and, thus, confirms the validity of the geometric approximation.

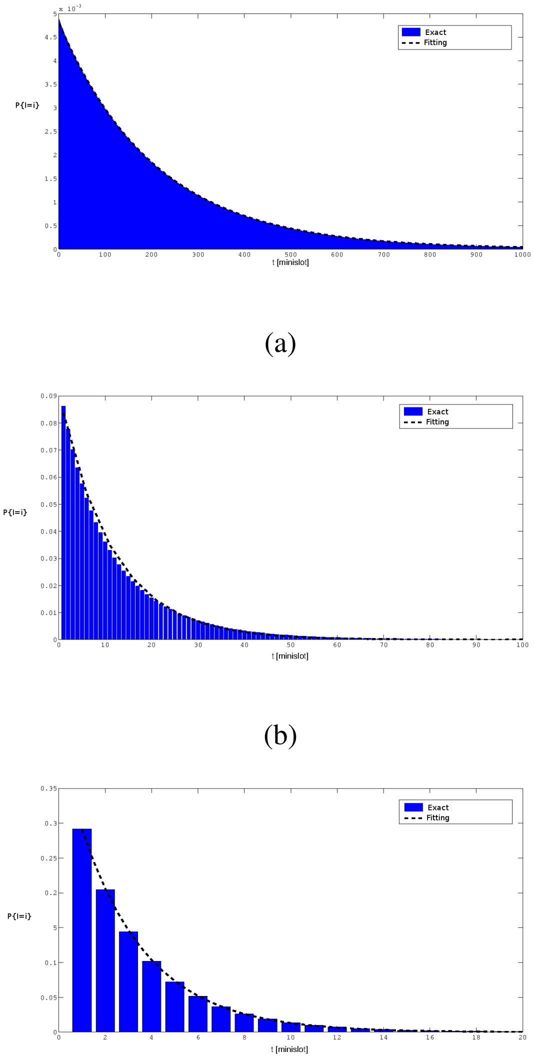


(a) (b)

(c) (d)

Fig. 7. Idle time distributions corresponding to various values of p: (a) 0.0002, (b) 0.003, (c) 0.007, and (d) 0.01. In all cases, $N = 12$ and $L = 10$.

In Fig. 9, the parameter p_{idle} is shown as a function of the aggregate (normalized) load G of the primary WSN. As before, $N = 12$ and $L = 10$. It can be observed that, as intuitively expected, p_{idle} is approximately a linearly increasing function of G. In Fig. 10, the average idle time duration $\bar{I}$ is shown as a function of G. It can be observed that the average idle time $\bar{I}$ decreases very quickly for increasing values of the traffic load in the primary WSN.



(a)

(b)

(c)

Fig. 8. Direct comparison between exact and approximate (geometric) idle time distributions for various values of p: (a) 0.0002, (b) 0.003, (c) 0.01. In all cases, $N = 12$ and $L = 10$.

V. TIME-DOMAIN COGNITIVE SENSOR NETWORKING

Even if not surprising, the fact that the idle time distribution is accurately modeled as geometric has a relevant consequence for the considered cognitive system. In fact, thanks to the memoryless property of the geometric distribution of the idle times of the primary WSN, when the secondary WSN wakes up in the middle of an idle interval, the elapsed portion of this idle time is irrelevant, as the distribution of the

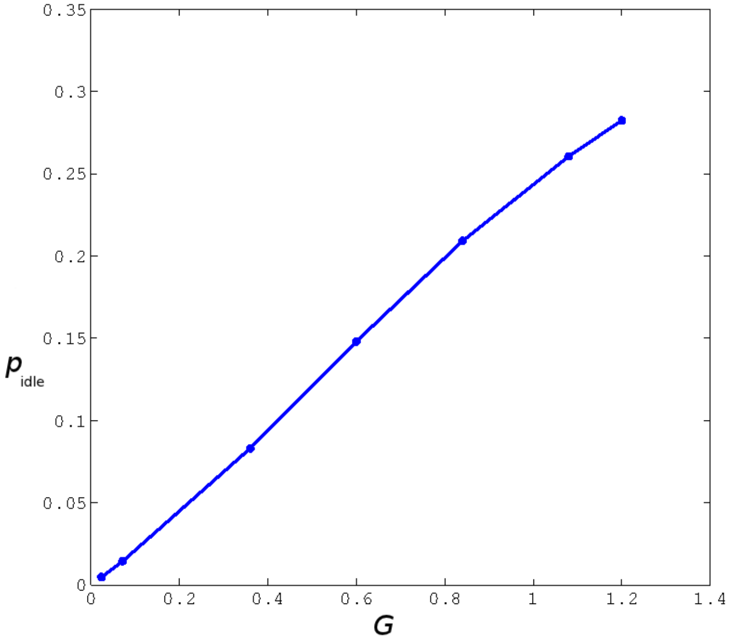


Fig. 9. p_{idle} as a function of the aggregate (normalized) load G of the primary WSN.

remaining portion of the idle time does not change. On the other hand, the optimal transmission strategy for the secondary WSN simply requires to estimate the average per-node traffic load of the primary network, together with its number of nodes. An illustrative representation of the overall cognitive sensor networking system is shown in Fig. 11.

Depending on the adopted strategy, the estimation of the primary WSN activity behaviour can be carried out in several ways: (i) by the primary node sink (in a very accurate way), (ii) by the secondary sink or a generic node of the secondary network. Clearly, these solutions lead to different levels of performance and complexity. The first approach implies cooperation between the primary and secondary sinks. The second approach seems more appealing for typical scenarios relative to coexisting sensor networks.

In order to evaluate the performance of a cognitive system where the secondary nodes is aware of the geometric idle time distribution of the primary IEEE 802.15.4 WSN, we carry out simulations where the idle times of the primary network are generated according to the geometric distribution. The overall

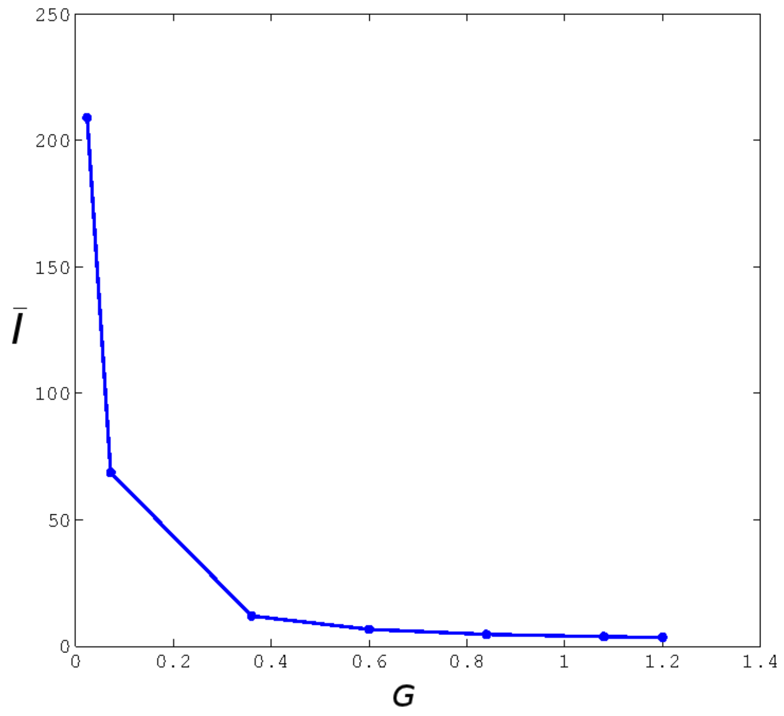


Fig. 10. Average idle time duration $\bar{I}$ as a function of G.

simulation time is $T_{\text{sym}} = 100000$ minislot—the duration is such that the arithmetic average of the idle times is sufficiently close to $1/p_{\text{idle}}$. We assume that the secondary nodes have always packets to transmit, but are allowed to transmit only by Access Point (AP) of the secondary WSN (sort of polling mechanism). Once the channel is sensed idle by the secondary AP, the transmission in the secondary network, of duration equal to L minislots, can start: if, during the entire transmission, the channel remains idle, then the transmission is considered successful; otherwise (i.e., if the primary network starts its activity), then there is a failure. In Fig. 12, an illustrative example of the interaction between the two WSNs is shown.

In order to evaluate the performance of the proposed cognitive system, various parameters need to be considered: the load of the primary network, the packet duration L (in minislots), and the duty cycle of the secondary network. The duty cycle of the secondary WSN is defined as the percentage of time

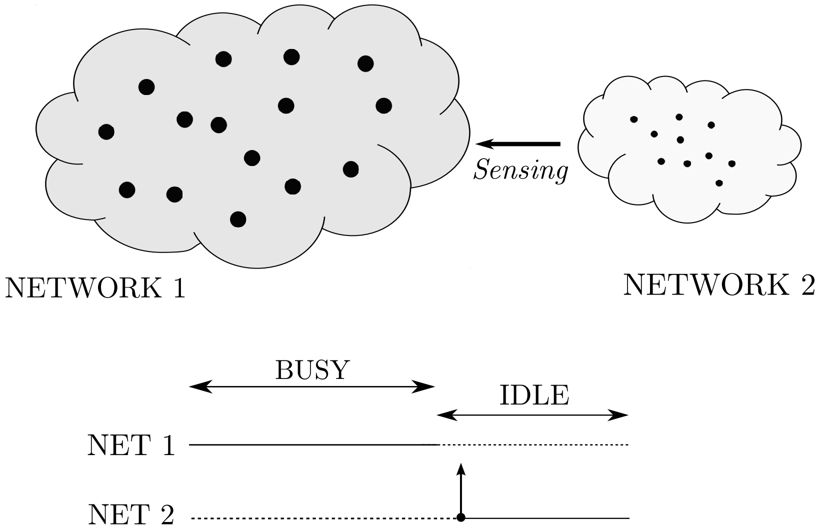


Fig. 11. Cognitive sensor networking system.

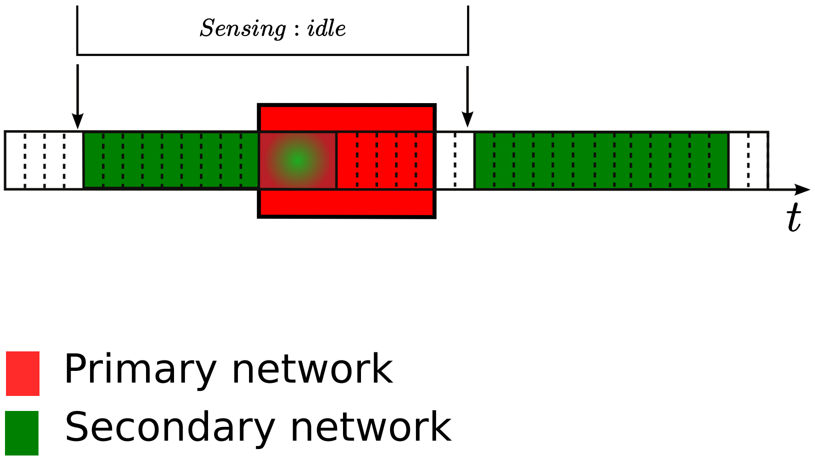


Fig. 12. Illustrative representation of channel utilization by the primary and secondary WSNs.

during which this WSN is active. A low duty cycle is attractive in scenarios where the secondary WSN generates a sporadic traffic (e.g., it is dedicated to low-rate background measurement of specific physical quantities).

The following two performance metrics are considered for performance analysis.

- The probability of interference, denoted as P_i, of the secondary network on the primary network.

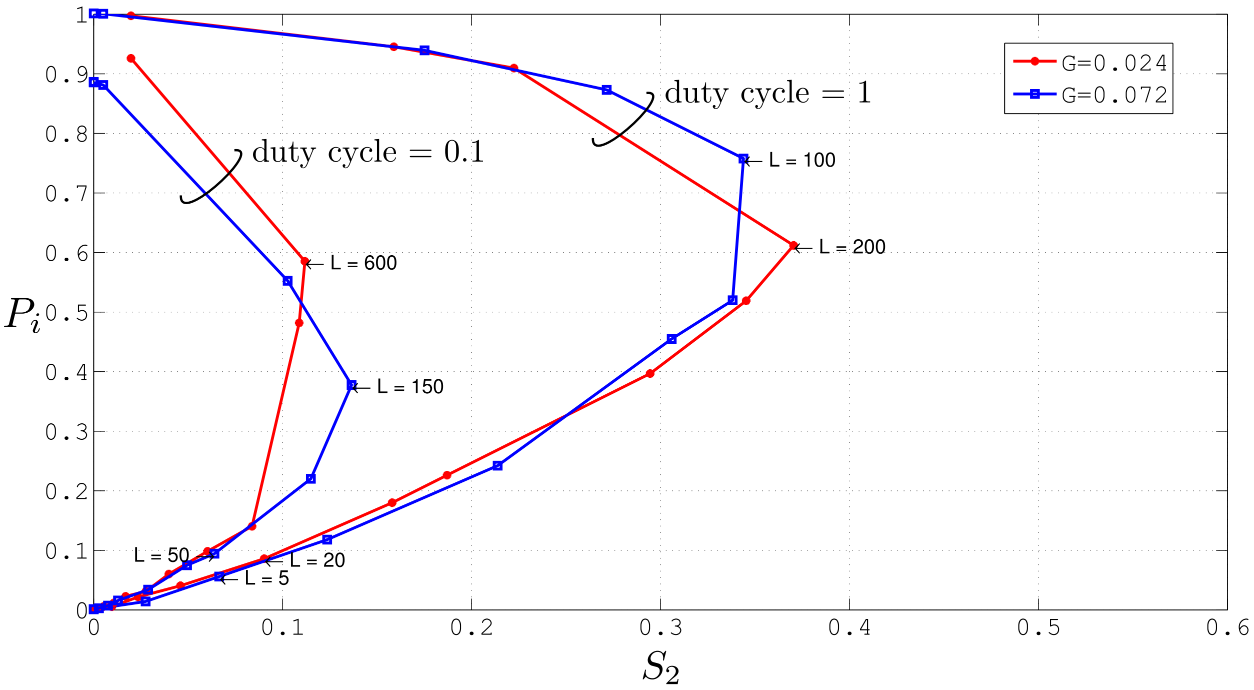


Fig. 13. P_i as a function of S_2, parameterized with respect to L, for various values of G and of the duty cycle.

This metric is directly related to the performance degradation of the primary network caused by the activity of the secondary network.

- The throughput of the secondary network is defined as

$$S_2 = \frac{N_s L}{\sum_i T_i} \tag{8}$$

where N_s is the number of successful secondary transmissions (i.e., without interference with the primary network) and T_i is the duration of the i-th idle period.

In Fig. 13, P_i is shown as a function of S_2, for various values of G and of the *duty cycle*. The curves, parameterized with respect to L, show clearly the trade-off between the performance of primary and secondary networks. In Fig. 13, a few value of L of interest are indicated. For example, in order to have $P_i < 0.1$ with $G = 0.024$, the secondary network should transmit for $L = 20$ minislots, with a corresponding secondary throughput $S_2 = 0.1$.

VI. CONCLUSIONS

In this book chapter, we have considered the co-existence of a primary IEEE 802.15.4 WSN with a secondary WSN. The goal of the latter WSN is to transmit in the inactivity periods of the former WSN. First, we have proposed a rigorous DTMC-based queuing model of a single-hop IEEE 802.15.4 WSN (considering a mini-slotted approach to discretize the original continous time M/G/1/N WSN queue). On the basis of this model, we have derived the exact distribution of the idle times of the primary IEEE 802.15.4 WSN. Since these idle times can be accurately approximated as geometric, owing to the memoryless property of the geometric distribution the best transmission strategy for the secondary WSN simply requires to estimate the average per-node traffic load of the primary network, together with its number of nodes. Our results show clear that there exists a trade-off between the throughput achievable in the secondary WSN and the probability of interference of the same WSN with the primary WSN.

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