# A NON-PERIODIC SENSING STRATEGY FOR IMPROVED THROUGHPUT IN COGNITIVE RADIO NETWORKS

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## ABSTRACT

This paper deals with a smart sensing strategy in an overlay cognitive radio network, to effectively exploit secondary-user (SU) transmitting opportunities, while preserving primary-user (PU) interference. Specifically, we consider a non-periodic sensing policy characterized by different transmitting and silence periods, and we derive closed-form expressions for the average SU throughput and interference in AWGN and fading channels, assuming a Poisson alternating renewal process for the PU traffic. Our analysis, confirmed by computer simulations, shows that the proposed strategy can increase the throughput with respect to a classical periodic sensing policy. Furthermore, optimal transmitting and silence periods can be identified for a given sensing time, trading off throughput for PU interference.

***Index Terms*** **—** Cognitive radio networks, spectrum sensing, throughput.

## 1. INTRODUCTION

Secondary cognitive radio (CR) networks try to opportunistically exploit frequency bands underutilized by primary users (PUs) of legacy networks [1]. In this view, spectrum sensing [2] [3] is typically employed by secondary users (SUs) to possibly identify the resources that are temporarily unused by primary users (PUs), followed by either transmission periods or silence periods, if the PUs are detected as inactive or active, respectively.

Most of the CR techniques in the literature, such as [4]-[10], consider a strictly periodic sensing (PS) strategy, where each sensing interval $\tau$ is followed by a transmission interval $T_{\text{TX}}$, or by a waiting interval $T_{\text{W}}$, with the same fixed duration $T_{\text{TX}} = T_{\text{W}}$. Although this choice may simplify the sensing procedure and make uniform the sensing costs over time, it is obviously suboptimal. Indeed, to maximally exploit the PU absence and maximize the SU opportunistic capacity, every time the SU detects a PU signal, the SU would be interested to immediately re-sense the channel (e.g., $T_{\text{W}}$ as small as possible) in order to immediately realize when the PU becomes inactive. Conversely, the SU would be interested to make $T_{\text{TX}} >> \tau$ in order to reduce the capacity loss induced by sensing.

Assuming a common model for the PU activity (Poisson birth-death process) [4]-[9], we derived in [10] analytical expressions of the SU throughput and interference for a PS strategy, establishing the optimal period $T_{\text{TX}} + \tau = T_{\text{W}} + \tau$ under a constraint on the average collision duration between SU and PU signals. Indeed, a PS strategy that maximizes the SU throughput by increasing the transmission duration $T_{\text{TX}}$, also produces unacceptable interference to the PU, since, for longer $T_{\text{TX}}$ durations, it is more likely that the PU reactivates during the SU transmission.

Aiming at interference-constrained throughput maximization, this paper proposes and analyzes a simple approach based on non-periodic sensing (N-PS). The key idea is to allocate silence durations $T_{\text{W}}$ that can be different from transmission durations $T_{\text{TX}}$, thereby generalizing and improving the throughput maximization approach of PS policies [4]-[10]. Although this idea is quite intuitive, to the best of the authors knowledge, this simple N-PS policy has not attracted much consideration at the physical (PHY) layer of CRs so far, while it is known as persistent sensing when $T_{\text{W}} = 0$ at the medium access control (MAC) layer [11]. It should be noted that other papers have proposed N-PS in order to reduce the cost of sensing, by adapting the sensing epochs to the PU traffic [12]-[14]; differently, we focus on throughput maximization. Besides, more sophisticated N-PS approaches have jointly considered sensing at the PHY layer and multiple-SUs scheduling at the MAC layer, possibly including feedback information [15] [16]: however, this scenario is out of the scope of this paper.

This paper leverages on an analytical framework based on reward renewal process theory [17]-[19]. This way, it is possible to exactly compute the SU throughput and the generated interference, and to establish the non-obvious allocation policy for $T_{\text{TX}}$ and $T_{\text{W}}$ that maximizes the SU throughput under a prescribed interference constraint and a fixed sensing interval $\tau$. The correctness of the analytical findings is also confirmed by simulation results, both in AWGN and Rayleigh fading channels.

## 2. SYSTEM MODEL

We consider an overlay CR network where an SU first performs spectrum sensing over a given frequency band, in order to decide about the presence of a PU signal, and then, in the same band, either transmits data or stays in silence, depending on the sensing decision. We assume an N-PS strategy where, in case of silence, the sensing operation is repeated after $T_1 = T_{\text{W}} + \tau$ seconds, whereas, in case of data transmission, the sensing operation is repeated after $T_2 = T_{\text{TX}} + \tau$ seconds, as shown in Fig. 1.

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### 2.1. PU Signal Model

For what concerns the PU activity, we assume that the PU signal switches between the busy (ON) state and the idle (OFF) state. We assume that the durations of the ON (OFF) states are exponentially distributed with mean $\beta_1$ ($\beta_0$), leading to a Poisson birth-death process. We define $p_\alpha = \mathrm{P}\{H_\alpha\} = \beta_\alpha / (\beta_0 + \beta_1)$, i.e., the probability that the PU signal is present (absent) when $\alpha = 1$ (when $\alpha = 0$). In addition, aiming at OFDM-based licensed communications, we model the PU signal as a complex Gaussian process.

### 2.2. SU Sensing Phase

For spectrum sensing purposes, the SU makes use of an energy detector (ED) with sampling frequency $f_\mathrm{S}$ and number of samples $M = \lfloor f_\mathrm{S}\tau \rfloor$. We assume that the sensing duration $\tau$ is fixed, and sufficiently short, so that the PU signal can be well approximated as either ON or OFF during the whole sensing stage. The signal received by the ED of the SU is modeled as $\mathbf{y}_\mathrm{ED} = \alpha\mathbf{x}_\mathrm{ED} + \mathbf{n}_\mathrm{ED}$, where $\alpha \in \{0,1\}$ represents the $H_\alpha$ hypothesis, $\mathbf{x}_\mathrm{ED}$ is the PU signal, Gaussian with zero mean and covariance $\sigma_\mathrm{x}^2\mathbf{I}_N$, and $\mathbf{n}_\mathrm{ED}$ is a complex AWGN with zero mean and covariance $\sigma_\mathrm{n}^2\mathbf{I}_N$. After the sensing interval $\tau$, $\Lambda(\mathbf{y}_\mathrm{ED}) = \|\mathbf{y}_\mathrm{ED}\|^2$ is compared with a threshold $\lambda$: the probability of false alarm is expressed by $P_\mathrm{FA} = \mathrm{P}\{\hat{H}_1 | H_0\} = \mathrm{P}\{\Lambda(\mathbf{y}) > \lambda | H_0\} = 1 - F_{2M}(2\lambda/\sigma_\mathrm{n}^2)$, and the probability of detection is $P_\mathrm{D} = \mathrm{P}\{\hat{H}_1 | H_1\} = \mathrm{P}\{\Lambda(\mathbf{y}) > \lambda | H_1\} = 1 - F_{2M}(2\lambda/[(1+\gamma_\mathrm{P})\sigma_\mathrm{n}^2])$, where $F_{2M}(\cdot)$ is the cumulative distribution function of a chi-squared random variable with $2M$ degrees of freedom, and $\gamma_\mathrm{P} = \sigma_\mathrm{x}^2/\sigma_\mathrm{n}^2$ is the primary signal-to-noise ratio (SNR) [2] [3] [20]. After the sensing phase, with probability $\mathrm{P}\{\hat{H}_1\} = P_\mathrm{FA}p_0 + P_\mathrm{D}p_1$ the SU waits in silence for a duration $T_\mathrm{W} = T_1 - \tau$, and with probability $\mathrm{P}\{\hat{H}_0\} = 1 - \mathrm{P}\{\hat{H}_1\}$ the SU transmits data for a duration $T_\mathrm{TX} = T_2 - \tau$.

### 2.3. SU Transmission: Throughput and Interference

During the transmission phase of duration $T_\mathrm{TX} = T_2 - \tau$, the SU received signal can be modeled as

$$y_\mathrm{SU}(t) = h s_\mathrm{SU}(t) + a(t) i_\mathrm{PU}(t) + n_\mathrm{SU}(t), \qquad (1)$$

where $h$ is the channel coefficient, assumed constant during the transmission interval $T_\mathrm{TX}$, with $\mathrm{E}\{|h|^2\} = 1$, $s_\mathrm{SU}(t)$ is the SU transmitted data, with zero mean and variance $\sigma_\mathrm{s}^2$, $a(t)$ is the activity of the PU, equal to 0 when the PU signal is absent and to 1 when present, $i_\mathrm{PU}(t)$ is the PU signal, assumed Gaussian with zero mean and variance $\sigma_\mathrm{i}^2$, and $n_\mathrm{SU}(t)$ is a complex AWGN with zero mean and variance $\sigma_\mathrm{n}^2$. We define the secondary SNR as $\gamma_\mathrm{S} = \sigma_\mathrm{s}^2/\sigma_\mathrm{n}^2$, and the instantaneous conditional signal-to-interference-plus-noise ratio (SINR) at the SU receiver as

$$\gamma(|h|^2, t) = \frac{|h|^2\,\sigma_\mathrm{s}^2}{\sigma_\mathrm{n}^2 + a(t)\sigma_\mathrm{i}^2} = \frac{|h|^2\,\gamma_\mathrm{S}}{1 + a(t)\gamma_\mathrm{P}}, \qquad (2)$$

whose statistical average over the probability density function of the fading gain is expressed by

$$\bar{\gamma}(t) = \int_0^{+\infty} \gamma(|h|^2, t) f_{|h|^2}(|h|^2)\, d|h|^2 = \frac{\gamma_\mathrm{S}}{1 + a(t)\gamma_\mathrm{P}}. \qquad (3)$$

The throughput achievable by the SU at time $t$, assuming constant-power transmissions, can be expressed as [21]

$$C(t) = \int_0^{+\infty} \log_2\left(1 + \gamma(|h|^2, t)\right) f_{|h|^2}(|h|^2)\, d|h|^2, \qquad (4)$$

which is a function of $\bar{\gamma}(t)$. In AWGN, (4) leads to $C(t) = \log_2\left(1 + \bar{\gamma}(t)\right)$, whereas, in Rayleigh fading channels, (4) yields $C(t) = e^{1/\bar{\gamma}(t)} E_1(1/\bar{\gamma}(t)) \log_2 e$, where $E_1(\cdot)$ is the exponential-integral function of first order [21]. Therefore, when the PU is absent, the throughput can be calculated as $C_0 = [C(t)]\big|_{a(t)=0}$, which is a function of $\bar{\gamma}(t) = \gamma_\mathrm{s}$, whereas, when the PU is present, the throughput can be obtained as $C_1 = [C(t)]\big|_{a(t)=1}$, which is a function of $\bar{\gamma}(t) = \gamma_\mathrm{s}/(1+\gamma_\mathrm{p})$.

When the SU transmits, a collision with the PU signal may happen. In order to warranty the licensed PU transmission, a constraint on the interference seen by the PU is necessary. As indicator for the interference seen by the PU, we use the collision duration ratio (CDR) [10], which is the total duration of the collision events normalized by the observation time. Our aim is to maximize the average SU throughput as a function of the transmission duration $T_\mathrm{TX} = T_2 - \tau$ and of the silence duration $T_\mathrm{W} = T_1 - \tau$, for a fixed sensing interval $\tau$, with a constraint on the CDR, i.e., on the average time where the SU interferes with the PU. The average SU throughput, as well as the associated average CDR, can be computed by exploiting the reward renewal process theory, as detailed in the following section.

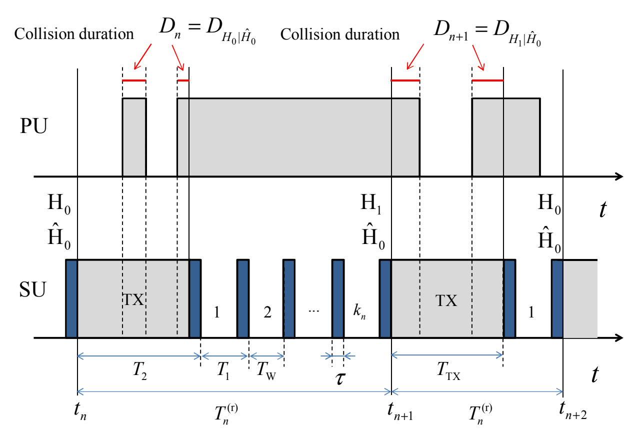


Fig. 1. Example of PU and SU activity versus time.

## 3. RENEWAL THEORY

The activity of the SU is characterized by a process that, according to the sensing outcome, randomly alternates among transmission and waiting states, as shown in Fig. 1. Thus, the SU activity can be modeled as an alternate renewal process [18] [19], where the renewal event at time $t_n$ is a transmission, and the inter-renewal time $T_n^{(\mathrm{r})} = t_{n+1} - t_n$ between two transmissions of the SU is

$$T_n^{(\mathrm{r})} = T_2 + k_n T_1. \qquad (5)$$

$\{T_n^{(\mathrm{r})}\}_{n=0,\ldots,\infty}$ is a succession of i.i.d. random variables generated by the random integer number $k_n \in [0,\infty)$ of SU silence states (e.g., $\hat{H}_1$ ) that may occur between two SU transmission phases (e.g., $\hat{H}_0$ ), as clarified by Fig. 1. If $r_n$ is any reward (utility or cost) associated with the $n$ th renewal interval, and $N(t)$ is the number of renewal events at time $t$, the time-averaged reward can be computed by the knowledge of its expected value during a single renewal time, as expressed by [18] [19]

$$\lim_{t\to\infty} \frac{1}{t}\sum_{n=0}^{N(t)} r_n = \frac{\mathrm{E}\{r_n\}}{\mathrm{E}\{T_n^{(\mathrm{r})}\}} . \tag{6}$$

For instance, to quantify the amount of interference generated to the PU, we may consider as a reward (cost) the duration $D_n$ of the collision between PU and SU during the $n$ th renewal cycle. Obviously, in order to have a collision, both PU and SU should transmit. Thus, at the end of the sensing interval $\tau$, the SU should have decided that the PU was silent (i.e., $\hat{H}_0$), and the PU has to reactivate (or stay active), possibly also several times, during the successive SU transmission time $T_{\mathrm{TX}} = T_2 - \tau$. Note that, from Fig. 1, there are two different scenarios: the PU was either silent (i.e., $H_0$, and the ED decided correctly) or active (i.e., $H_1$, and the ED missed the detection) during sensing. Consequently, by conditional probability, it is possible to conclude that

$$\mathrm{E}\{D_n\} = P_{H_0|\hat{H}_0}\mathrm{E}\{D_{H_0|\hat{H}_0}\} + P_{H_1|\hat{H}_0}\mathrm{E}\{D_{H_1|\hat{H}_0}\} , \tag{7}$$

where $P_{H_\alpha|\hat{H}_0}$ is the conditional probability that the PU was in $H_\alpha$ if the SU has decided for $\hat{H}_0$, and $D_{H_\alpha|\hat{H}_0}$ represents the total duration of the PU activity (possibly by multiple reactivations) during the SU transmission time $T_2 - \tau$, assuming that the PU was silent ( $\alpha = 0$ ) or not ( $\alpha = 1$ ) during the ED sensing interval. Observing that also the PU activity can be modeled as an alternate renewal process, with exponential distribution, it is possible to exploit classical results of availability theory [17] to establish the time activity ratio of the PU during an interval time $T_2 - \tau$. This is summarized by the conditional CDRs, expressed by [10]

$$\begin{aligned} \rho_{H_0|\hat{H}_0}(T_2-\tau) &= \frac{\mathrm{E}\{D_{H_0|\hat{H}_0}\}}{T_2-\tau} = p_1 G_\beta(T_2-\tau), \\ \rho_{H_1|\hat{H}_0}(T_2-\tau) &= \frac{\mathrm{E}\{D_{H_1|\hat{H}_0}\}}{T_2-\tau} = 1 - p_0 G_\beta(T_2-\tau), \end{aligned} \tag{8}$$

where $G_\beta(t) = 1-(1-e^{-\beta t})/(\beta t)$ is a monotone increasing function with respect to $t$, and $\beta = (\beta_0+\beta_1)/(\beta_0\beta_1)$. Note that the CDRs in (8), which represent the average PU activity during the SU transmission, are different if the PU was silent ( $\alpha = 0$ ) or active ( $\alpha = 1$ ) during the sensing stage.

In the $n$ th renewal interval, the number of SU silent periods is $k_n$, which means that the SU takes a decision $\hat{H}_0$ after the first sensing period and successively takes $k_n$ (independent) decisions $\hat{H}_1$. Thus, we can calculate the probability $\mathrm{P}\{k_n = k\} = (1-\mathrm{P}\{\hat{H}_1\})(\mathrm{P}\{\hat{H}_1\})^k$, and

$$\mathrm{E}\{T_n^{(\mathrm{r})}\} = T_2 + \mathrm{E}\{k_n\}T_1 = \frac{\mathrm{P}\{\hat{H}_0\}T_2 + \mathrm{P}\{\hat{H}_1\}T_1}{\mathrm{P}\{\hat{H}_0\}} . \tag{9}$$

By means of (6), we define the CDR $\rho_{\mathrm{I}} = \mathrm{E}\{D_n\}/\mathrm{E}\{T_n^{(\mathrm{r})}\}$, i.e., the fraction of time affected by collision (interference). By (7)-(9) and the Bayes rules $P_{H_0|\hat{H}_0}\mathrm{P}\{\hat{H}_0\} = (1-P_{\mathrm{FA}})p_0$ and $P_{H_1|\hat{H}_0}\mathrm{P}\{\hat{H}_0\} = (1-P_{\mathrm{D}})p_1$, we get the interference

$$\rho_{\mathrm{I}}(T_1,T_2) = \frac{p_1(1-P_{\mathrm{D}}) + p_0 p_1 (P_{\mathrm{D}} - P_{\mathrm{FA}}) G_\beta(T_2-\tau)}{\mathrm{P}\{\hat{H}_0\}T_2 + \mathrm{P}\{\hat{H}_1\}T_1}(T_2-\tau) . \tag{10}$$

Note that $\rho_{\mathrm{I}}(T_2,T_2)$ is exactly the CDR obtained in [10].

Similarly, now we consider as a reward (utility) the opportunistic capacity of the SU during the $n$ th renewal interval, expressed by

$$C_n = \int_{t_n}^{t_n+T_2-\tau} C(t)dt = C_0(T_2-\tau-D_n) + C_1 D_n . \tag{11}$$

Therefore, we obtain

$$\begin{aligned} \mathrm{E}\{C_n\} &= C_0(T_2-\tau) + (C_1-C_0)\mathrm{E}\{D_n\} = \{C_0 + (C_1 - C_0) \\ &\times \left[P_{H_0|\hat{H}_0}\rho_{H_0|\hat{H}_0}(T_2-\tau) + P_{H_1|\hat{H}_0}\rho_{H_1|\hat{H}_0}(T_2-\tau)\right]\}(T_2-\tau). \end{aligned}$$

By means of (6), we define the average throughput as $R = \mathrm{E}\{C_n\}/\mathrm{E}\{T_n^{(\mathrm{r})}\}$, and by (8) (9) we obtain the throughput

$$R(T_1,T_2) = \frac{K_0 - p_0 p_1 (P_{\mathrm{D}} - P_{\mathrm{FA}})(C_0 - C_1) G_\beta(T_2-\tau)}{\mathrm{P}\{\hat{H}_0\}T_2 + \mathrm{P}\{\hat{H}_1\}T_1}(T_2-\tau), \tag{12}$$

where $K_0 = p_0(1-P_{\mathrm{FA}})C_0 + p_1(1-P_{\mathrm{D}})C_1 > 0$.

## 4. THROUGHPUT MAXIMIZATION

Intuition suggests that, in order to maximize the throughput, the SU should avoid silent periods by using the minimum $T_1^* = T_{\mathrm{W}}^* + \tau = \tau$ (persistent sensing), and use the maximum transmission time allowed by the protocol. However, this way, also the CDR (interference) would be maximized. For any meaningful detector (i.e., with $P_{\mathrm{D}} > P_{\mathrm{FA}}$), this is confirmed by (12) and (10), which monotonically increase with $T_2$ and decrease with $T_1$. However, to warranty a certain (low) level of CDR (interference) $\rho_{\mathrm{I}} = \bar{\rho}_{\mathrm{I}}$, by (10) we introduce a constraint on the admissible values of $T_1$ and $T_2$. Specifically, for any $T_2$ we must choose $T_1$ according to

$$T_1 = g_{\mathrm{c}}(T_2) = \frac{1}{\mathrm{P}\{\hat{H}_1\}}\left[A(T_2) - \mathrm{P}\{\hat{H}_0\}T_2\right], \tag{13}$$

where $A(T_2) = \frac{p_1}{\bar{\rho}_{\mathrm{I}}}\left[(1-P_{\mathrm{D}}) + p_0(P_{\mathrm{D}} - P_{\mathrm{FA}})G_\beta(T_2-\tau)\right](T_2-\tau)$ is a monotonically increasing function. We observe that the couple $(T_2,T_1)$ satisfying (13) is obtained by the intersection of the monotonically increasing function $A(T_2)$ with a family (indexed by $T_1$) of parallel straight lines in the $(T_2,T_1)$ Cartesian plane, representing the average sensing period $T_{\mathrm{s}}$, as expressed by

$$T_{\mathrm{s}} = \mathrm{P}\{\hat{H}_0\}T_2 + \mathrm{P}\{\hat{H}_1\}T_1 = A(T_2) . \tag{14}$$

Although we omit the details, it can be proved that the constraint equation (14) [i.e., (13)] always admits a unique solution $(T_2,T_1)$ for $T_2 \geq g_{\mathrm{c}}^{-1}(\tau)$, because $g_{\mathrm{c}}(\cdot)$ is monotonically increasing, as well as its inverse $g_{\mathrm{c}}^{-1}(\cdot)$. This means that, to maintain a prescribed level of interference ratio, it is necessary to simultaneously increase (or decrease) both $T_2$ and $T_1$, by $T_1 = g_{\mathrm{c}}(T_2)$. It can be proved also that $g_{\mathrm{c}}(\cdot)$ is convex: therefore, a PS policy with $T_2 = T_1 = T_{\mathrm{s}}$ in (14), and with the same amount of interference $\bar{\rho}_{\mathrm{I}}$ of N-PS, is always characterized by a greater $T_2$ than for N-PS, for any sensing interval $\tau$. This leads to lower throughput than for N-PS, as clarified in the following. Indeed, by substituting (14) in (12), we obtain that the interference-constrained throughput maximization becomes

$$T_2^* = \arg\max_{T_2} \left[ R\left(g_c\left(T_2\right), T_2\right) \right], \text{ s.t. } \begin{array}{l} T_2 \geq g_c^{-1}(\tau) \geq \tau, \\ T_1 \geq \tau, \end{array} \quad (15)$$

which, by some basic algebra, yields

$$R\left(g_c\left(T_2\right), T_2\right) = \frac{p_1}{\bar{\rho}_I} \frac{K_0 - p_0 p_1 \left(P_D - P_{FA}\right)\left(C_0 - C_1\right) G_\beta\left(T_2 - \tau\right)}{\left(1 - P_D\right) + p_0\left(P_D - P_{FA}\right) G_\beta\left(T_2 - \tau\right)}. \quad (16)$$

The rate (16) is monotonically decreasing with respect to $G_\beta\left(T_2 - \tau\right)$, which increases monotonically with $T_2$. Thus, the interference-constrained throughput, differently from the unconstrained case (12), monotonically decreases for increasing $T_2$, and the solution of (15) is given by

$$T_1^* = \tau, \quad T_2^* = g_c^{-1}(\tau). \quad (17)$$

The solution (17) corresponds to persistent sensing $T_W = 0$, as in the unconstrained case, and yields the minimum transmission time $T_{TX} = T_2 - \tau$ that satisfies (13) [i.e., (14)] with a non-negative $T_W = T_1 - \tau$, i.e., $T_1 \geq \tau$.

Energy-efficient spectrum sensing, such as [22] [23], mostly depends on the average sensing period $T_s$. In this view, (14) unveils that, for any interference constraint $\bar{\rho}_I$, there exists a unique average sensing period $T_s$ that maximizes the throughput. Conversely, for a constrained energy efficiency, i.e., a constrained sensing period $T_s$, there exists a unique (throughput-suboptimal) solution $T_2 = A^{-1}(T_s)$.

## 5. VALIDATION BY SIMULATIONS

We consider a case study with moderate PU load, where $\beta_0 = 700$ ms and $\beta_1 = 300$ ms, so that $\mathrm{P}\{H_1\} = 0.3$. We assume $\gamma_P = 3$ dB and $\gamma_S = 5$ dB, and fix $f_S = 100$ kHz, $\tau = 1$ ms, and $\lambda$ such that $P_D = 0.9$. We assume SU transmissions in AWGN or Rayleigh fading. Our aim is to quantify the throughput increase of our N-PS strategy with respect to PS [10], which corresponds to $T_2 = T_1$.

Fig. 2 compares the throughput $R(g_c(T_2), T_2)$ in (16) of the proposed N-PS strategy, for an interference constraint $\bar{\rho}_I = 0.05$, with the throughput $R(T_2, T_2)$ of the PS policy, which does not constrain the interference. Clearly, both theoretical analysis and simulations illustrate that the constrained throughput (16) increases when $T_2$ is reduced, up to the optimal value $T_2^* \approx 21$ ms, which corresponds to the minimum value $T_1^* = \tau = 1$ ms, i.e., persistent sensing with $T_W = 0$. Noteworthy, the N-PS throughput in $T_2^*$ is significantly greater than the maximum throughput granted by PS, both in AWGN and Rayleigh fading. Moreover, Fig. 2 and Fig. 3 show that, for increasing suboptimal values $T_2 > T_2^*$, the PS strategy may have greater SU throughput, but generates uncontrolled (increasing) interference to the PU; conversely, in the N-PS policy, the interference is constrained by design. Fig. 4 confirms that the constraint function $T_1 = g_c(T_2)$ in (13) is convex and increasing: for any interference level, there exists a couple $(T_2, T_1)$ where the two policies coincide ($T_2 = T_1 \approx 51$ ms when $\bar{\rho}_I = 0.05$).


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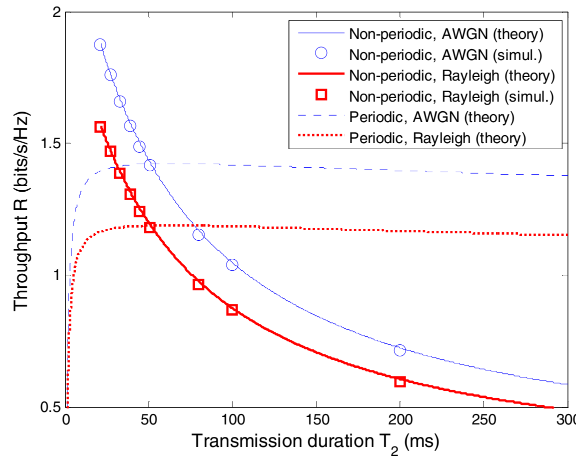

Fig. 2. Throughput versus the SU transmission duration.

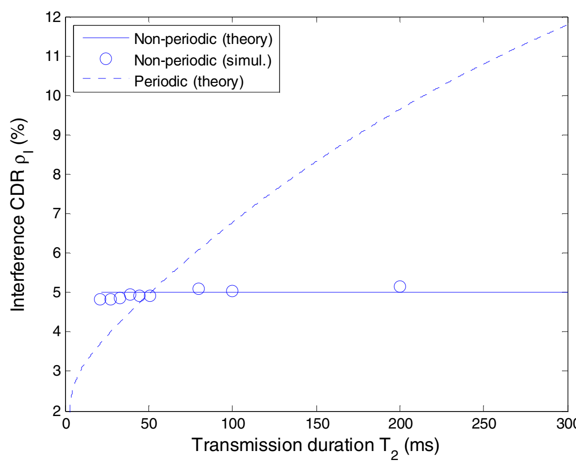

Fig. 3. CDR (interference) versus the SU transmission duration.

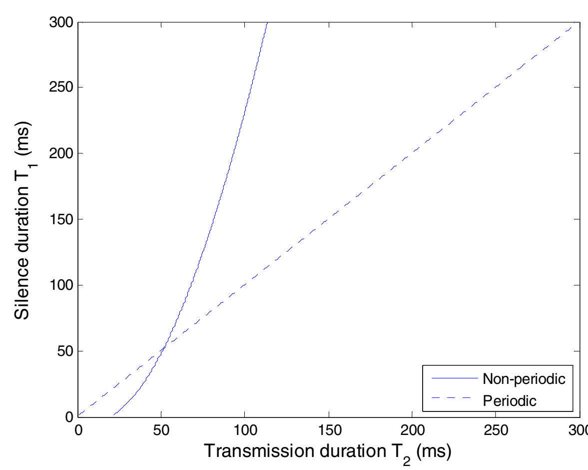

Fig. 4. SU silence duration versus the SU transmission duration.

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