Sensing for Opportunistic Spectrum Access in Cognitive Radio: Exploitation of the Time to the Dead-Line

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***Abstract*—This paper investigates some sensing strategies for a secondary user which has to stop its transmissions within a fixed time when a primary user begins to transmit. Instead of stopping the transmission as soon as a primary user is detected, the fixed time given by the regulation to leave the medium can be exploited until its dead-line by the secondary user. For this purpose, an appropriate sensing strategy has to be used. We show in this paper how to exploit this time to the dead-line. In order to do so, the parameters to tune will be the length and the periodicity and the number of quiet periods used by the secondary user in order to perform sensing. The constraints are to meet a probability of false alarm and of detection for a given sensibility level (in dB). We will show how the channel use of the secondary user may benefit of the exploitation of transmission until the dead-line.**

I. INTRODUCTION

One of the first applications of the cognitive radio concept concerns the use of the temporary unused TV spectrum by secondary user (thus, the primary user is the TV in the VHF/UHF bands). This idea began to take a concrete form with the FCC notice of proposed rulemaking ”Facilitating opportunities for flexible, efficient, and reliable spectrum use employing cognitive radio technologies” published in 2003 [2] and the creation of the 802.22 standardization group which aims at developing a standard for a cognitive radio-based PHY/MAC/air-interface for use by license-exempt devices on a non-interfering basis in spectrum that is allocated to the TV Broadcast Service. In this system, the secondary user senses periodically (quasi-continuously) the channel and uses it if no primary user is detected. In order to protect the primary user an elevated probability of detection is required. Of course such a system does not deploy all the concept of cognitive radio, however it is a first primitive but also concrete form of CR. In this context, we investigate variants in the sensing strategy, taking into account some essential parameters of the systems described in 802.22 . The required performance of the sensing is that a primary user should be detected within the two first seconds of the beginning of its transmission within a given sensibility. Those 2 seconds is what we will call the time to the deadline. We see how to tune the parameters to meet the requirement and show how to exploit the time to the deadline to choose a sensing strategy. The system parameters that we take into consideration are described in section II. In section III we explain how we can tune the parameters in various basic sensing strategies, and especially we look at the impact on the quiet period length. Finally we show in section IV how the time to the dead line can be used and we evaluate the result on the throughput or channel use of the secondary user.

II. DESCRIPTION OF THE SYSTEM PARAMETERS

In the sensing for opportunistic spectrum access described in 802.22 [4], the time is divided in successive frames of 10ms, which corresponds in the discrete time model of this paper to 60000 samples (considering the sampling frequency adapted to the used bands). Those frames may contain data and/or a quiet period used to sense the channel. The sensing is made to ensure that no primary user is present so that the secondary user can transmit. The quiet periods repeat with a periodicity in time, we can change this periodicity and the length of the quiet period in order to adjust the performance of the sensing. The required performance of the sensing is that a primary user should be detected within the two first seconds of the beginning of its transmission with a sensibility of -15dB (ratio of the primary signal power on noise power) or a sensibility of -20dB. Those 2 seconds is what we will call the time to the deadline. This detection has to be performed with a probability of detection of 0.9. The probability of false alarm is usually set to 0.1.

At that point, various strategies can be considered for the repartition of the quiet periods in time. We can imagine one quiet period each 2 seconds, or many quiet periods in 2 seconds, the decision about the detection being made by collecting the information from the various quiet periods. We consider that at the most, the number of quiet periods in 2 sec would be 200, i.e. one quiet period for each frame of 10ms.

For a given periodicity of the quiet periods we call M the maximal number of quiet periods that can fall in 2 seconds.We call L the length (in number of samples) between the beginning of two quiet periods (i.e. the Quiet Periods periodicity). L is the length of what we call a meta-frame (see figures 1,2 and 3). $nslot$ is the name given to the length (number of samples) of a quiet period.

So, for a given L, the number of quiet periods arising in 2 seconds is M (maximum number of quiet periods in 2 seconds) or $M-1$: it depends on the starting point of the 2 seconds (see figure 4,5).

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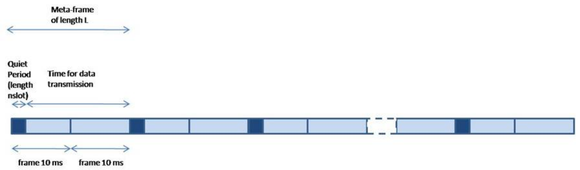

Fig. 1. Example where there is one Quiet Period every 2 frames of 10 ms. So the maximal number of Quiet Periods in 2s is M=100 in that case.

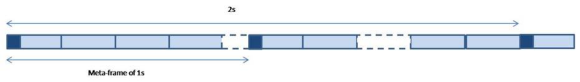

Fig. 2. Example where there is one Quiet Period every second. In that case M=2.

III. TUNING THE SYSTEM PARAMETERS

The first basic parameter that one has to tune is the length (number of samples) of a Quiet Period necessary to obtain the required performance (Pd=0.9, Pfa=0.1), taking into account that due to the random arrival of a primary user, some of the samples involved in the decision may be unaffected by the signal. We will investigate the Quiet Period length in different configurations and strategies.

We consider that the detection is performed through an energy detector which takes into account the various quiet periods that can be affected by the primary user signal. So, we collect the samples of R successive quiet periods, compute the total energy (sum of those squared samples, denoted Y), compare to a threshold and decide about the presence of a primary user or not. The common model used is that the primary user is like an additional Gaussian noise of power σ_p (other models can be used without loss of generality [1]). Through the use of the central limit theorem, Y can be modeled as a Gaussian random variable and the probabilities P_d and P_f can be expressed analytically.

We consider here two configurations:

-Configuration 1: there are 2 seconds between the beginning of a quiet period and the end of the M^{th} successive quiet period (figure 6).

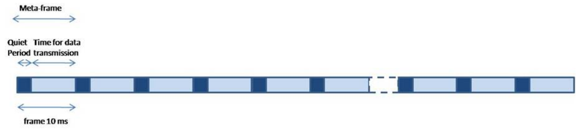

Fig. 3. Example where there is one Quiet Period per frame of 10 ms. In that case M=200.

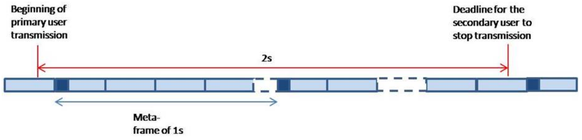

Fig. 4. In this figure the length of a meta-frame is 1s. The number of Quiet Period in the time to the deadline is 2 (equal to M).

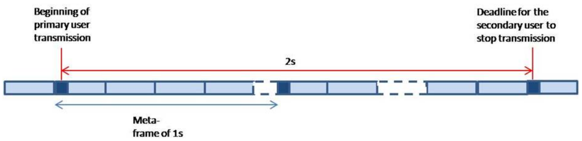

Fig. 5. In this figure the length of a meta-frame is 1s. But the number of full Quiet Period in the time to the deadline is 1 (equal to M-1). The first Quiet Period is only partially affected by the signal so if it is considered for the decision, some of the samples will be constituted only of noise (note also that the last Quiet Period can not be considered for decision because its end is beyond the deadline)

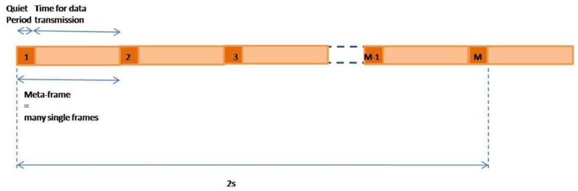

Fig. 6. Configuration 1

-Configuration 2: there are 2 seconds between the beginning of a quiet period and the beginning of the $(M+1)^{th}$ successive quiet period (figure 7).

So, in whatever 2 seconds period, the maximal possible number of full quiet period is M, but the number of full quiet period can also be smaller if the beginning of the 2 seconds is not at the beginning of a Meta-frame. In configuration 1 there will be more often only $M-1$ full Quiet Period in 2s than in configuration 2.

Also we consider two strategies which can be applied in each configuration.

-Strategy A: the decision about the presence of a primary user is done by collecting the samples of M Quiet Periods. (so in the 2 seconds to the deadline there might be M Quiet Periods fully affected by the signal, or only $M-1$ fully affected while the remaining one is partially or not affected (see figure 5), depending on the starting time for the 2 seconds).

-Strategy B: the decision about the presence of a primary user is done collecting the samples of $M-1$ Quiet Periods. (so, when there is a primary user, in the 2 seconds to the deadline there is always $M-1$ Quiet Periods fully affected by the signal)

In strategy A, the fact that some samples used for the decision may be impacted by the signal while some other not, has to be taken into account in the performance expression. As

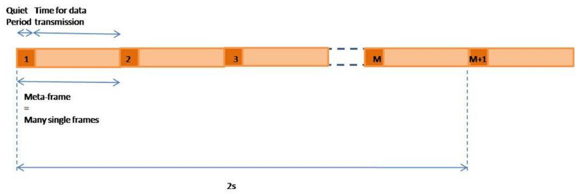

Fig. 7. Configuration 2

a first step, for a decision based on the observation of $N+K$ samples affected by a noise where N of those samples may be also affected by a signal, we can express the P_d and P_{fa} as:

$$P_{fa} = Q(\frac{\gamma/\sigma_w^2 - (N+K)}{\sqrt{2(N+K)}}) \tag{1}$$

$$P_d = Q(\frac{\gamma - \left[(N+K)\sigma_w^2 + N\sigma_s^2\right]}{\sqrt{2N(\sigma_w^2+\sigma_s^2)^2 + 2K\sigma_w^4)}}) \tag{2}$$

Where γ is the threshold, σ_w^2 is the variance of the noise and σ_s^2 is the variance of the signal samples.

Taking into account the fact that the primary user can start its transmission equiprobably in any instant of a frame, the probability of detection during the first 2 seconds of the transmission can be written as $P_{d,1}$ for the configuration 1 and $P_{d,2}$ for the configuration 2, see equations 3 and 4.

The P_d is expressed as a function of P_{fa} (which will be set to 0.1), the length of a Quiet Period $nslot$, the total number of samples considered for the decision $N_{tot,A} = M * nslot$, and L the length of a meta-frame (in configuration 2, L is the number of samples in 2s divided by M, while in configuration 1 L is the number of samples in 2s minus $nslot$ divided by M). In strategy B, the $M-1$ Quiet Periods used to detect the primary user are always fully included in the 2 seconds to the deadline, so all the samples are affected by the signal. So, the probability of detection is expressed as:

$$P_{d,B} = Q\left(\frac{Q^{-1}(P_{fa} * \sqrt{2 * N_{tot}} - (N_{tot}) * SNR}{\sqrt{2 * (N_{tot}) * (1+SNR)^2}}\right)$$

with $N_{tot,B} = (M-1) * nslot$.

And the total number of samples necessary in strategy B to obtain the required performance is:

$$N_{tot,B} = 2\left[\left(Q^{-1}(P_{fa}) - Q^{-1}(P_d)\right)SNR^{-1} - Q^{-1}(P_d)\right]^2$$

In strategy A the analytical expression of the number of samples is more difficult to recover, so we have obtained the numerical values by dichotomies using the expressions $P_{d,1}$ and $P_{d,2}$.

In strategy A, some samples used in the detection may be not affected by the signal, so they impair the detection, it is why the total number of samples required is major to the total number of samples required in strategy B. However, in strategy A the total number of samples is split over more Quiet Periods (M, versus $M-1$ in strategy B), so it is possible for the number of samples per Quiet Period to be less in strategy A.

Based on the expression linking the probability P_d (which has to be 0.9), P_{fa} (0.1) and the number of samples, we have performed the computation of the number of samples required for the detection in strategy A and B and configurations 1 and 2 for the two extreme cases: $M = 200$ and $M = 2$. Those results are given in the tables of figures 8 and 9.

SNR=-15dB	M=2		M=200	
	Ntotal (number of samples used in the detection)	*nslot* (length of a quiet period, i.e. number of sample per Quiet Period)	*Ntotal* (number of samples used in the detection)	*nslot* (length of a quiet period, i.e. number of sample per Quiet Period)
Strategy A	53350	**26675**	13693	**69** (68,46)
Strategy B	13558	**13558**	13558	**69** (68,13)

Fig. 8. Number of samples needed for the detection in configuration 1 with SNR=-15dB

SNR=-20dB	M=2		M=200	
	Ntotal (number of samples used in the detection)	*nslot* (length of a quiet period, i.e. number of sample per Quiet Period)	*Ntotal* (number of samples used in the detection)	*nslot* (length of a quiet period, i.e. number of sample per Quiet Period)
Strategy A	523930	**261965**	134030	**671**
Strategy B	132710	**132710**	132710	**667**

Fig. 9. Number of samples needed for the detection in configuration 1 with SNR=-20dB

It is obvious that in Configuration 1 strategy B is better as it reduces the length of the Quiet Period: it is better to perform the decision considering $(M-1)$ Quiet Periods. However configuration 2 is more natural and it is the one which deserves major attention.

This analysis allows us to see which strategy minimizes the length of a Quiet Period. In configuration 2 (the most common), strategy A minimizes the Quiet Period length cf. figure 10. However, in order to see the advantage of one strategy over another one, one has to look at the resulting throughput. This is discussed in the following section where the use of the time to the dead line has an impact on the result.

IV. EXPLOITATION OF THE TIME TO THE DEAD-LINE

We investigate here the impact of the chosen strategy on the channel use of the secondary user (also called normalized achievable throughput in some papers [1]).

We have seen that strategy B results in a larger length of the quiet period, so the time allowed for data is smaller. However we can identify an advantage in strategy B: as the detection is performed sooner, when a primary user is detected, there is a remaining time to the deadline that can still be exploited by the secondary user, while in strategy A when a primary user is detected there is no way to know if the time to the deadline is over or not so the communication has to stop right at that moment. The systematic use of the time to the deadline in strategy B allows to increase the throughput. It may result in

SNR=-20dB	M=2		M=200	
	Ntotal (number of samples used in the detection)	nslot (length of a quiet period, i.e. number of sample per Quiet Period)	Ntotal (number of samples used in the detection)	nslot (length of a quiet period, i.e. number of sample per Quiet Period)
Strategy A	133840	**66920**	132710	**664**
Strategy B	132710	**132710**	132710	**667**

Fig. 10. Number of samples needed for the detection in configuration 2

$$P_{d,1} = \sum_{i=0}^{nslot-1} \frac{1}{L} Q\left(\frac{Q^{-1}(P_{fa} * \sqrt{2 * N_{tot}} - (N_{tot} - i) * SNR}{\sqrt{2 * (N_{tot} - i) * (1 + SNR)^2 + 2 * i}}\right) + \frac{L - nslot}{L} * Q\left(\frac{Q^{-1}(P_{fa} * \sqrt{2 * N_{tot}} - (N_{tot} - nslot) * SNR}{\sqrt{2 * (N_{tot} - nslot) * (1 + SNR)^2 + 2 * nslot}}\right) \quad (3)$$

$$P_{d,2} = \sum_{i=0}^{nslot-1} \frac{1}{L} Q\left(\frac{Q^{-1}(P_{fa} * \sqrt{2 * N_{tot}} - (N_{tot} - i) * SNR}{\sqrt{2 * (N_{tot} - i) * (1 + SNR)^2 + 2 * i}}\right) + \frac{L - nslot}{L} * Q\left(\frac{Q^{-1}(P_{fa} * \sqrt{2 * N_{tot}} - (N_{tot}) * SNR}{\sqrt{2 * (N_{tot}) * (1 + SNR)^2}}\right) \quad (4)$$

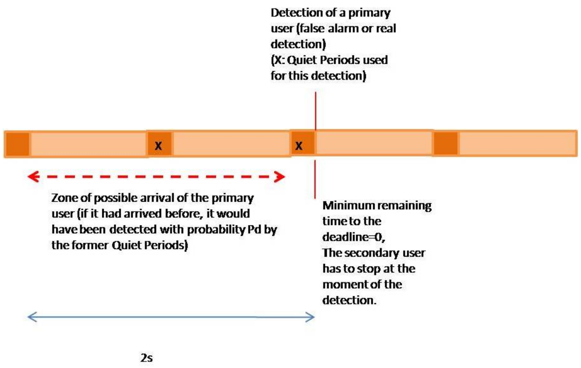

Fig. 11. Strategy A: no remaining time to the deadline is exploitable when a detection is done

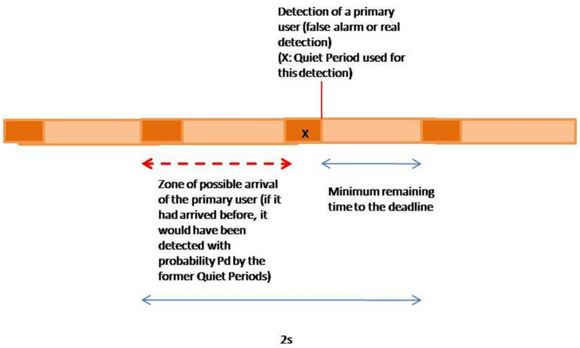

Fig. 12. Strategy B: there is a remaining time to the deadline when a detection is done

a better throughput in strategy B versus strategy A, even if the Quiet Periods are longer.

In order to evaluate the throughput differences due to the use of the remaining time to the deadline, we will consider without loss of generality the case M=2 and configuration 2.

The concept of remaining time is explained with the figures 11 and 12.

Figure 11 shows that in strategy A, when a primary user has been detected, there is no way to know if its transmission did begin two seconds ago or later, so the communication of the secondary user has to stop.

Figure 12 shows that in strategy B, when a primary user has been detected, it must have begun to transmit at maximum (M-1)*L samples ago (i.e. 1 second ago in the case M=2, configuration 2), otherwise it would already have been detected by the former Quiet Period with the required probability of detection. So there are still L samples to the dead line and they can be used for the transmission by secondary user.

The exploitation of the remaining time to the deadline is of particular interest when no primary user is present. In that case a false alarm makes the secondary stop. More particularly when a detection is done (real detection or false alarm, as they are undistinguishable by the secondary user), it is required by the 802.22 standard to stop the secondary transmission for 10 minutes. Taking into account this parameter, we have evaluated the throughput of the secondary user when no primary user is present so when only the false alarms reduce the data transmission.

In strategy A, at the end of each Quiet Period a decision is taken (based on the samples of the M last Quiet Periods) whether a primary user is present or not. So it continues to transmit with probability (1-Pfa) an amount of (L-nslot) data samples in a total time of L samples, or it stops the transmission for 10 minutes with probability Pfa. Consequently, after some simple computation and by using ergodicity, we can express the channel use ρ as:

$$\rho_A = \frac{(1 - P_{fa})(L - nslot_A)}{(1 - P_{fa})L + P_{fa}(nslot_A + N_{10min})} \quad (5)$$

While in strategy B, the secondary continues to transmit with probability (1-Pfa) an amount of L-nslot data samples in a total time of L samples (so there is less data than in strategy A because nslot is larger) but with probability Pfa it transmits L-nslot data samples in the time remaining to the deadline before stopping for 10 minutes. We can express the channel use as:

$$\rho_B = \frac{(1 - P_{fa})(L - nslot_B) + P_{fa}(L - nslot_B)}{(1 - P_{fa})L + P_{fa}(nslot_B + N_{10min})} \quad (6)$$

The channel-use ratio ρ_B/ρ_A has been evaluated for a sensibility level of $-20dB$ (the corresponding values for the parameters are given in figure 10). In this case $\rho_B/\rho_A = 9.8\%$. So, the evaluation of those channel uses makes appear a gain of 9.8% in strategy B while its quiet periods are longer. The above analytical expressions (5) and (6) have been derived assuming independency between the decisions after each quiet period. This assumption helps in giving a simple closed form of the channel use but is not strictly true, it is an approximation. So we have also evaluated the channel use through simulations where the decision dependency on the samples of former quiet periods is kept. The results of the simulation make appear a gain of 7.4% in the channel use of strategy B. The simulation results are in agreement with the results of the simplified analytical expression (5) and (6): it shows the improvement of channel use in strategy B while its quiet periods are longer. Thus, paradoxically, while strategy B reduces the time allocated for data in a frame, it increases the channel use thanks to the possible exploitation of the remaining time to the deadline.

V. CONCLUSION

We have seen here two sensing strategies. Under the same constraints of false alarm and detection probability, the first strategy gives the maximum channel use to the secondary user under the condition that in both strategies the secondary user stops its transmission as soon as a primary user is detected. However, if the secondary user takes the liberty to transmit even after the detection of a primary user (or a false alarm) but within the time to the dead line given by the regulation, the second strategy provides a better channel use to the secondary user. This improvement of the channel use takes place especially in the absence of primary user, when the secondary user is stopped only by false alarms.

REFERENCES

[1] Y.C. Liang, Y.H. Zeng, E. Peh, A. T. Hoang, ”Sensing-Throughput Tradeoff for Cognitive Radio Networks”, IEEE Transactions on Wireless Communications, vol. 7, number 4, Apr. 2008.

[2] Federal Communications Commission, ”Facilitating opportunities for flexible, efficient, and reliable spectrum use employing cognitive radio technologies, notice of proposed rule making and order, FCC 03-322,” Dec. 2003.

[3] A. Ghasemi, E.S. Sousa, ”Optimization of spectrum sensing for opportunistic spectrum access in cognitive radio networks”, in Proc. IEEE CCNC 2007.

[4] C.R.Stevenson, C.Cordeiro, E.Sofer, G.Chouinard ”‘Functional Requirements for the 802.22 WRAN Standard”’ IEEE 802.22, November 2006.