Optimizing the Number of Samples for Multi-Channel Spectrum Sensing

Saud Althunibat, Tung Manh Vuong and Fabrizio Granelli

University of Trento, DISI, Trento, Italy
althunibat@disi.unitn.it, manhtung.vuong@studenti.unitn.it, granelli@disi.unitn.it

***Abstract*—Spectrum sensing in cognitive radio technology consumes a significant amount of time and energy resources. Thus, it has a direct effect on the achievable throughput and consumed energy. In case of multi-channel systems, the problem becomes more affective since both the resources expenditure and the performance influence of spectrum sensing increase. Considering energy detection as the spectrum sensing method, a number of energy samples should be collected from each channel. Unlike the conventional scheme, the number of samples collected from each channel should be different due to the variant channel conditions. In this paper, the number of samples collected from each channel is optimized based on different setups, namely, throughput maximization setup, interference minimization setup, ans sensing energy minimization setup.**

I. Introduction

In the light of the increasing demand on limited spectrum resources, cognitive radio (CR) has been proposed as a smart solution for spectrum shortage problem. CR enables an efficient usage of the licensed spectrum bands, where it gives unlicensed users, also called cognitive users (CUs), the capability to exploit the temporally-unused portions of the licensed spectrum [1].

The initial necessary process of a cognitive transmission is called spectrum sensing [2]. Spectrum sensing aims at identifying the instantaneous spectrum status in order to use the unoccupied portions. It is greatly important to perfectly perform spectrum sensing as it guarantees an efficient resources utilization and avoids collisions with the licensed users. Thus, strict constraints on detection accuracy are set in CR standards [3].

Spectrum sensing in multi-channel systems spends a significant portion of time and energy resources due to the large number of sensed channels [4]. Thus, many works in the literature have investigated this problem, where some energy-efficient CSS schemes have been proposed. For example, in [5], the CUs are divided into non-disjoint subsets such that only one subset senses the spectrum while the other subsets enter a low power mode. The energy minimization problem is formulated as a network lifetime maximization problem with constraints on the detection accuracy. Another algorithm for user selection is proposed in [6], where the user subset that has the lowest cost function and guarantees the desired detection accuracy is selected. The cost function is related to the system energy consumption. A distributed approach for selecting the participating CUs is proposed in [7], where the expected energy consumption is calculated by each CU prior to the beginning of the CSS process: if it is lower than a given threshold, the corresponding CU will participate; otherwise, it will not participate. The multi-channel spectrum sensing problem is formulated as a coalition formation game in [8]. A utility function of each coalition takes into account both the sensing accuracy and energy efficiency, and a distributed algorithm is proposed to find the optimal partition that maximizes the aggregate utility of all the coalitions in the system.

Spectrum sensing can be performed by several methods such as energy detection, matched-filter-based sensing, and wavelet-based sensing [9]. The most popular method is energy detection due to its simplicity and good performance in case of no prior information about the licensed signal is available [9]. In energy detection, a number of energy measurements are taken from the spectrum. Each measurement is called sample. The average of the collected samples is then compared to a predefined threshold in order to decide if the channel is used or not. Intuitively, increasing the number of collected samples from a specific channel will improve the decision reliability. However, it requires a longer sensing time and more energy consumption accordingly. Also, in case of multi-channel systems, the possible total number of samples should be proportionally distributed among channels. This is due to the fact that different channels experience different conditions and characteristics.

In this work, the number of samples collected from each channel is optimized based on different setups with different constraints. The considered setups include : (i) throughput maximization setup with a constraint on the total number of samples, (ii) interference minimization setup with a constraint on the total number of samples, and (iii) sensing energy minimization setup with a constraint on the average achievable throughput. In each setup, an approximated formula for the optimal number of samples is given. Simulation results show a significant improvement in the performance compared to the equal distribution of the samples among channels.

The rest of the paper is organized as follows. Section II describes the system model. The different considered setups for optimizing the number of samples are discussed in Section III. Evaluation and simulation results are explored in Section IV, and the conclusions are drawn in Section V

II. System Model

Consider a single CU that tries to exploit the unused channels of a licensed spectrum. The licensed spectrum is divided into L identical channels. For any channel, the probability that it is occupied/not occupied by a licensed user is denoted by P_1 and P_0, respectively. Aiming at identifying the unoccupied channels and protecting the licensed users, the CU should sense the spectrum before using it. The adopted sensing method in this work is energy detection [9]. In energy detection, the CU measures the contained energy in each channel for a specific time. Assume the total time dedicated for sensing all channels, called sensing time, is denoted by T_s.

While sensing a specific channel, a number of samples (energy measurements) is collected by the CU. The spectrum decision (*busy* or *free*) is taken by comparing the average of

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the collected samples (A_i) from a channel to a predefined threshold called detection threshold (λ). The decision is *busy*, if the samples' average is larger than the detection threshold. Otherwise, the CU will identify the corresponding channel as free, and consequently, use it. Mathematically, the spectrum decision of the i^{th} channel (d_i) is expressed as follows

$$d_i = \begin{cases} busy, & \text{if } A_i \geq \lambda, \\ free, & \text{if } A_i < \lambda. \end{cases} \tag{1}$$

The reliability of the made decision is evaluated by two indicators, namely, detection probability (P_{di}) and false-alarm probability (P_{fi}). Detection probability of the i^{th} channel represents the probability of identifying the i^{th} channel as *busy* given that it is actually occupied. On the other hand, false-alarm probability of the i^{th} channel represents the probability of identifying the i^{th} channel as *busy* given that it is actually unoccupied. Considering AWGN channels, both P_{di} and P_{fi}, can be respectively expressed as follows [10]

$$P_{di} = Q\bigg(\frac{\lambda - \sigma_i^2 - \delta_i^2}{(\sigma_i^2 + \delta_i^2)/\sqrt{S_i}}\bigg) \tag{2}$$

$$P_{fi} = Q\bigg(\frac{\lambda - \sigma_i^2}{\sigma_i^2/\sqrt{S_i}}\bigg) \tag{3}$$

where S_i is the number of samples collected from the i^{th} channel, σ_i^2 is the noise variance and δ_i^2 is the variance of the transmitted signal of the licensed user. The function $Q(.)$ is given as follows [11]

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty exp(\frac{-t^2}{2})\, dt \tag{4}$$

According to the interweave CR model [12] adopted in this paper, the CU will use only the channel that has been identified as *free*. Thus, the average achievable throughput in terms of the amount of successfully delivered data can be given as follows:

$$D = \sum_{i=1}^{L} RT_t P_0 (1 - P_{fi}) \tag{5}$$

where R is the transmission data rate and T_t is the transmission time. Notice that we assume the transmitted data will be successfully delivered only if the channel is actually unoccupied and identified as *free* [13].

Likewise, the consumed energy in spectrum sensing is given as follows:

$$E_s = \sum_{i=1}^{L} \frac{S_i}{f_s} P_s \tag{6}$$

where f_s is the sampling frequency and P_s is the sensing power. Notice that the factor ($\frac{S_i}{f_s}$) is equal the sensing time of the i^{th} channel.

Another important performance indicator is the resultant interference at the licensed users side. The average interference energy can be expressed as follows:

$$I = \sum_{i=1}^{L} P_t T_t P_1 (1 - P_{di}) \tag{7}$$

where P_t is the transmit power.

III. Optimizing the Number of Samples per Channel

In the conventional spectrum sensing, the total number of samples (or the total sensing time) is equally divided among channels. However, such an approach might not attain the best achievable performance of the spectrum sensing process either in terms of detection accuracy or resource efficiency. Thus, there should be an optimal distribution of the samples among channels such that a specific performance metric is optimized. In this section we optimize the number of collected samples from each channel based on two different setups. The considered setups are throughput maximization and energy minimization. However, in each setup, a constraint on the other metrics is considered in order to achieve balance between the two setups.

A. Throughput Maximization Setup

Throughput is the main metric to describe any wireless transmission. Thus, throughput maximization has been set as an objective of many proposed algorithms in different topics in communications. As for multi-channel CR, in this subsection, we optimize the number of samples collected per channel for throughput maximization. However, due to the limited time resources, maximizing throughput should not yield in a sensing time that exceeds the available time resources for sensing. Therefore, a constraint that keeps the total number of samples under an upper bound should be taken into account.

Using (5), throughput maximizing problem by optimizing the number of samples per channel can be formulated as follows

$$\max_{S_i} \sum_{i=1}^{L} P_0 RT_t (1 - P_{fi}) \tag{8}$$

subject to

$$\sum_{i=1}^{L} S_i \leq S_T \tag{9}$$

Notice that the through maximization problem given in (8) is equivalent to a minimization problem of the false-alarm probability. Similarly, the constraint on the total number samples acts as a constraint on the energy consumed in spectrum sensing.

Aiming at solving the maximization problem, we use the method of Lagrange multipliers. To this end, the Lagrange function ($f(Si, \gamma)$) is defined as follows

$$f(Si, \gamma) = \sum_{i=1}^{L} P_0 RT_t (1 - P_{fi}) - \gamma \bigg(\sum_{i=1}^{L} S_i - S_T \bigg) \tag{10}$$

where $gamma$ is termed as Lagrange multiplier. Consequently, the optimal solution is derived by equalizing the first derivative of the Lagrange function to zero. The first derivative of the Lagrange function with respect to S_i is derived as follows

$$\begin{aligned} \frac{\partial f(Si,\gamma)}{\partial S_i} &= \frac{\partial}{\partial S_i} \bigg(\sum_{i=1}^{L} P_0 RT_t (1 - P_{fi}) + \gamma \bigg(\sum_{i=1}^{L} S_i - S_T \bigg) \bigg) \\ &= -P_0\, R\, T_t\, \frac{\partial P_{fi}}{\partial S_i} - \gamma \end{aligned} \tag{11}$$

Now, using the Leibenz-Integral rule, $\frac{\partial P_{fi}}{\partial S_i}$, which appears in (11), can be found as follows

$$\frac{\partial P_{fi}}{\partial S_i} = \frac{\partial}{\partial S_i}\Bigg(\frac{1}{\sqrt{2\pi}}\int_{\frac{\lambda-\sigma_i^2}{\sigma_i^2/\sqrt{S_i}}}^{\infty} exp(\frac{-t^2}{2})\cdot dt\Bigg)$$

$$= \frac{-1}{\sqrt{2\pi}}\cdot\frac{\lambda-\sigma_i^2}{\sigma_i^2}\cdot\frac{1}{2\sqrt{S_i}}\cdot exp\Bigg(\frac{-(\frac{\lambda-\sigma_i^2}{\sigma_i^2})^2}{2}S_i\Bigg) \quad (12)$$

By substituting (12) into (11)

$$\frac{\partial f(Si,\gamma)}{\partial S_i} = \frac{P_0\,RT_t}{\sqrt{2\pi}}\cdot\frac{\lambda-\sigma_i^2}{\sigma_i^2}\cdot\frac{1}{2\sqrt{S_i}}\cdot exp\Bigg(\frac{-(\frac{\lambda-\sigma_i^2}{\sigma_i^2})^2}{2}S_i\Bigg)-\gamma \quad (13)$$

As stated earlier, the optimal value of S_i can be found by setting the value of $\frac{\partial f(Si,\gamma)}{\partial S_i}$ to zero, as follows

$$\frac{P_0\,RT_t}{\sqrt{2\pi}}\cdot\frac{\lambda-\sigma_i^2}{\sigma_i^2}\cdot\frac{1}{2\sqrt{S_i}}\cdot exp\Bigg(\frac{-(\frac{\lambda-\sigma_i^2}{\sigma_i^2})^2}{2}S_i\Bigg)-\gamma = 0 \quad (14)$$

which can be rewritten as follows

$$S_i^* = \begin{cases}\Bigg(\frac{\lambda-\sigma_i^2}{\sigma_i^2}\cdot\frac{P_0\,RT_t}{2\sqrt{2\pi}\,\gamma}\Bigg)^2\cdot exp\Bigg(-\big(\frac{\lambda-\sigma_i^2}{\sigma_i^2}\big)^2 S_i^*\Bigg), & \text{if } \sigma_i^2 \leq \lambda,\\ 0, & \text{if } \sigma_i^2 > \lambda.\end{cases} \quad (15)$$

However, the solution in (15) does not represent a closed form expression of the optimal S_i^* since it still appears in both sides. On the other hand, it cannot be further analytically simplified. Therefore, an approximation should be presented.

The presented approximation is based on the well-known limit of the exponential function

$$exp(x) = \lim_{n\to+\infty}\big(1+\frac{x}{n}\big)^n \quad (16)$$

Consequently, if we consider n is a very large number, the exponential function can be approximated as follows

$$exp(x) \approx \big(1+\frac{x}{n}\big)^n \text{ for a very large } n \quad (17)$$

Now, by applying this to the exponential function in (15), it can be rewritten as follows

$$S_i^* \approx \Bigg(\frac{\lambda-\sigma_i^2}{\sigma_i^2}\cdot\frac{P_0\,RT_t}{2\sqrt{2\pi}\,\gamma}\Bigg)^2\cdot\Bigg(1-\frac{(\frac{\lambda-\sigma_i^2}{\sigma_i^2})^2}{n}S_i^*\Bigg)^n \quad (18)$$

By taking the n^{th} root for both sides, (18) can be expressed as follows

$$S_i^{*\frac{1}{n}} \approx \Bigg(\frac{\lambda-\sigma_i^2}{\sigma_i^2}\cdot\frac{P_0\,RT_t}{2\sqrt{2\pi}\,\gamma}\Bigg)^{\frac{2}{n}}\cdot\Bigg(1-\frac{(\frac{\lambda-\sigma_i^2}{\sigma_i^2})^2}{n}S_i^*\Bigg) \quad (19)$$

For a very large n, $S_i^{*\frac{1}{n}} \approx 1$. Therefore, (19) can be further simplified as follows

$$S_i^* \approx \begin{cases}\frac{n}{(\frac{\lambda-\sigma_i^2}{\sigma_i^2})^2}\cdot\Bigg(1-\Bigg(\frac{\lambda-\sigma_i^2}{\sigma_i^2}\cdot\frac{P_0\,RT_t}{2\sqrt{2\pi}\,\gamma}\Bigg)^{\frac{-2}{n}}\Bigg), & \text{if } \sigma_i^2 \leq \lambda,\\ 0, & \text{if } \sigma_i^2 > \lambda.\end{cases} \quad (20)$$

The equation above represents an approximated expression of the optimal number of samples for the i^{th} channel that maximizes the achievable throughput of the CU. It is worth mentioning that the accuracy of the approximation increases as n increases, which will be verified in the evaluation section.

B. Interference Minimization Setup

Due to channel conditions including shadowing and multipath fading, there is a probability that the made decision is wrong. The wrong decision can be either a false-alarm or a missed-detection. While the former degrades the efficient utilization of the available spectrum (achievable throughput of the CU), the latter increases the interference at the licensed users. In the previous subsection, the distribution of samples among channels has been optimized to increase the achievable throughput (by decreasing the false-alarm probability), while minimizing the resultant interference is set as objective of optimizing the number of samples for each channel in the following.

Using (7), and similar to (8) and (9), interference minimization problem with a constraint on the total number of samples can be formulated as follows

$$\min_{S_i}\sum_{i=1}^{L} P_1 P_t T_t(1-P_{di}) \quad (21)$$

subject to

$$\sum_{i=1}^{L} S_i \leq S_T \quad (22)$$

Using Lagrange method, (25) can be solved by the same procedure followed previously to solve (8). After some mathematical processes, the simplest solution can be expressed as follows

$$S_i^* = \begin{cases}\Bigg(\frac{\lambda-(\sigma_i^2+\delta_i^2)}{\sigma_i^2+\delta_i^2}\cdot\frac{P_1\,P_t\,T_t}{2\sqrt{2\pi}\,\gamma}\Bigg)^2 exp\Bigg(-\big(\frac{\lambda-(\sigma_i^2+\delta_i^2)}{\sigma_i^2+\delta_i^2}\big)^2 S_i^*\Bigg), & \text{if } \sigma_i^2+\delta_i^2 \geq \lambda,\\ 0, & \text{if } \sigma_i^2+\delta_i^2 < \lambda.\end{cases} \quad (23)$$

Similar to the solution given in (15), the formula obtained in (23) is not a closed form expression and cannot be obtained even numerically since γ is unknown. Thus, an approximation is required. Following the same approximations performed in (16)-(20), an approximated formula for the optimal number of samples of the i^{th} channel that minimizes the resultant interference can be given as follows:

$$S_i^* \approx \begin{cases}\frac{n}{(\frac{\lambda-(\sigma_i^2+\delta^2)}{\sigma_i^2+\delta^2})^2}\Bigg(1-\Bigg(\frac{\lambda-(\sigma_i^2+\delta^2)}{\sigma_i^2+\delta^2}\cdot\frac{P_1\,P_t\,T_t}{2\sqrt{2\pi}\,\gamma}\Bigg)^{\frac{-2}{n}}\Bigg), & \text{if } \sigma_i^2+\delta_i^2 \geq \lambda,\\ 0, & \text{if } \sigma_i^2+\delta_i^2 < \lambda.\end{cases} \quad (24)$$

C. Energy Minimization Setup

Energy consumption represents a main concern for mobile users, and it has gained an increasing attention recently. This is due to the fact that mobile terminals are usually equipped by a limited energy resources. In this subsection, we optimize the number of samples per channel for energy minimization objective in a multi-channel CR system. In order to avoid the negative effect on the achievable throughput, a lower bound of the achievable throughput is kept.

energy minimization problem can be formulated as follows

$$\min_{S_i}\sum_{i=1}^{L}\frac{S_i}{f_s}P_s \quad (25)$$

subject to

$$\sum_{i=1}^{L} P_0 RT_t(1-P_{fi}) \geq D_T \quad (26)$$

From (25) and (26), it is clear that energy minimization problem is equivalent to minimizing the total number of samples, while the lower bound on throughput represents an upper bound on the false-alarm probability.

Also, by using Lagrange multiplier method, the optimal solution can be found by solving the following equation

$$\frac{P_s}{f_s} + \gamma \frac{P_0 \, R \, T_t}{\sqrt{2\pi}} \cdot \frac{\lambda - \sigma_i^2}{\sigma_i^2} \cdot \frac{1}{2\sqrt{S_i}} \cdot exp\left(\frac{-(\frac{\lambda-\sigma_i^2}{\sigma_i^2})^2}{2} S_i \right) = 0 \tag{27}$$

$$S_i^* = \begin{cases} \left(\frac{\lambda-\sigma_i^2}{\sigma_i^2} \cdot \frac{f_s}{P_s} \cdot \gamma \frac{P_0 \, R \, T_t}{2\sqrt{2\pi}} \right)^2 exp\left(-\,(\frac{\lambda-\sigma_i^2}{\sigma_i^2})^2 S_i \right), & \text{if } \sigma_i^2 \leq \lambda, \\ 0, & \text{if } \sigma_i^2 > \lambda. \end{cases} \tag{28}$$

Similarly, the approximation in (16) can be used to obtain an approximated closed form expression of the optimal number of samples for the i^{th} channel, as follows

$$S_i^* \approx \begin{cases} \frac{n}{(\frac{\lambda-\sigma_i^2}{\sigma_i^2})^2} \cdot \left(1 - \left(\frac{\lambda-\sigma_i^2}{\sigma_i^2} \cdot \frac{f_s}{P_s} \cdot \gamma \frac{P_0 \, R \, T_t}{2\sqrt{2\pi}} \right)^{\frac{-2}{n}} \right), & \text{if } \sigma_i^2 \leq \lambda, \\ 0, & \text{if } \sigma_i^2 > \lambda. \end{cases} \tag{29}$$

IV. Evaluation and Discussion

In order to explore the performance of the proposed solutions, let us consider a licensed spectrum of $L = 3$ channels. For any of the channels, the probability of being occupied is $P_1 = 0.5$. The other simulation parameters required to compute throughput and energy consumption are listed in Table I. The results of each optimization setup are compared to the conventional scheme. In the conventional scheme, the total number of samples is equally distributed among channels.

Table I: Simulation Parameters

Parameter	Value	Parameter	Value
T_t	$0.05\,ms$	P_s	$10\,mW$
P_t	$100\,mW$	F_s	$0.1\,MHz$
λ	1	R	$100K\,bps$

A. *Throughput Maximization Setup*

In this setup, we consider that the total time dedicated for sensing all channels is equal to $1\,ms$. The variance of the licensed signal is assumed identical among channels and equals to $\delta_i = 0.1$. During simulation, the noise variances of the first and the second channels are assumed fixed, while the noise variance over the third channel is left variable, as indicated below each figure.

Fig. 1 shows the optimal number of the collected samples from each channel in order to maximize the achievable throughput versus the noise variance over the third channel. The shown curves clearly give three observations. The first observation is that the optimal number of samples for a specific channel depends not only on the noise variance of the corresponding channel, but also on the noise variances of the other channels. Also, it can be observed that once the noise variance of a channel exceeds the detection threshold (λ), the optimal number of samples is zero. This can be justified because if $\sigma^2 > \lambda$, the resultant false alarm probability of the corresponding channel is very high (> 0.5) whatever the number of samples. Thus, it is optimum not to sense it in order to maximize the achievable throughput. The third observation is that the order of the optimal number of channels is equivalent to the order of the noise variances, where the channel with worst conditions (high value of σ^2) should have the the longest sensing time (largest number of samples).

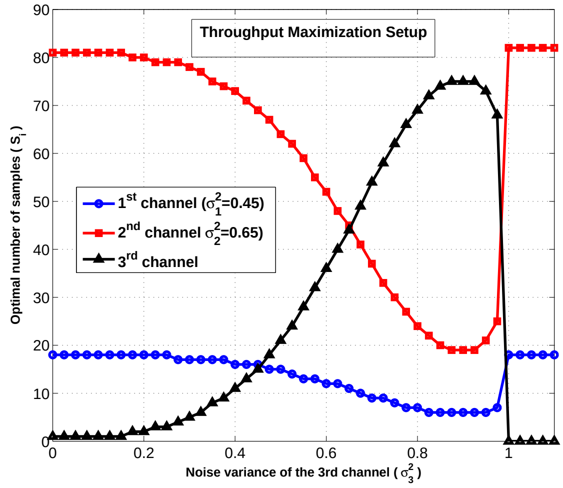

Fig. 1. *The optimal number of the samples from each channel versus the noise variance over the third channel based on throughput maximization setup.* ($\sigma_1^2 = 0.45, \sigma_2^2 = 0.65$)

Fig. 2 plots the average achievable throughput versus the noise variance of the third channel. The conventional approach of distributing the number of samples is considered as a baseline for comparison. The conventional approach implies that the total number of samples is equally divided among channels regardless of their conditions. The results in Fig. 2 show that optimizing the number of samples can increase the achievable throughput especially if one (or more) of the channels has a strong noise signal. The achievable throughput using the derived approximation for the optimal number of samples is also shown in order to verify its accuracy.

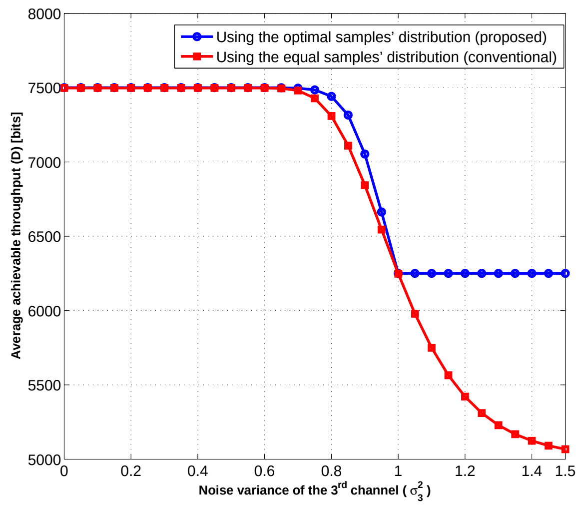

Fig. 2. *The average achievable throughput versus the noise variance of the third channel based on the conventional approach and the proposed throughput maximization setup.* ($\sigma_1^2 = 0.45, \sigma_2^2 = 0.65$).

B. *Interference Minimization Setup*

Similar to the previous setup, in this setup, we consider that the total time dedicated for sensing all channels is equal to $1\,ms$. The variance of the licensed signal is assumed identical among channels and equals to $\delta_i = 0.1$. During simulation, the sum of the variances of the licensed signal and noise signal of the first and the second channels are assumed fixed, while it is left variable for the third channel, as indicated below each figure.

Based on the interference minimization setup, the optimal number of samples for each channel versus the sum of the variances of the licensed signal and noise signal of the third channel is explored in Fig. 3. As long as the variances' sum $(\sigma_3^2 + \delta_3^2)$ is less than the detection threshold (λ), the optimal number of samples is zero. This means that there is no need to sense the third when $\sigma_3^2 + \delta_3^2 < \lambda$ since the resultant interference is high (high missed-detection probability) whatever the number of samples.

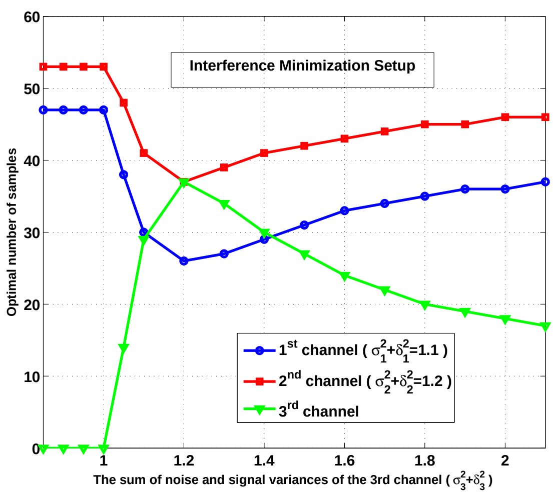

Fig. 3. *The optimal number of the samples from each channel versus the sum of the noise variance and the signal variance over the third channel based on interference minimization setup.* $(\sigma_1^2 + \delta_1^2 = 1.1, \sigma_2^2 + \delta_2^2 = 1.2)$.

Fig. 4 shows the resultant interference energy versus the sum of the variances of the licensed signal and noise signal of the third channel. The results prove the reduction in the interference that can be attained using the optimal number of samples especially if one (or more) of the channels has a small sum of the variances of the licensed signal and noise signal.

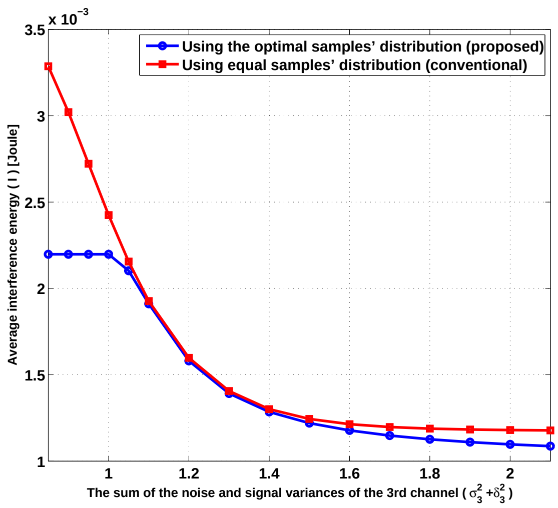

Fig. 4. *The average induced interference energy versus the sum of the noise variance and the signal variance over the third channel in the conventional approach and the proposed interference minimization setup.* $(\sigma_1^2 + \delta_1^2 = 1.1, \sigma_2^2 + \delta_2^2 = 1.2)$.

C. Sensing Energy Minimization Setup

As described earlier, minimizing the sensing energy is equivalent to minimizing the total number of samples for the three channels. In this setup, the constrain on the average total achievable throughput is set to $3.375\,Kbps$, which is equivalent to the average sum of the false-alarm probabilities for the three channel that is equal to 0.55.

Fig. 5 shows the optimal number of samples for each channel versus the noise variance of the third channel based on sensing energy minimization setup. The results confirm what is concluded from Fig. 1: the channel whose noise variance exceeds λ should not be sensed. Notice that at low values of σ_3^2, low false alarm probability can be attained by a low number of samples, while as σ_3^2 increases, more samples should be collected.

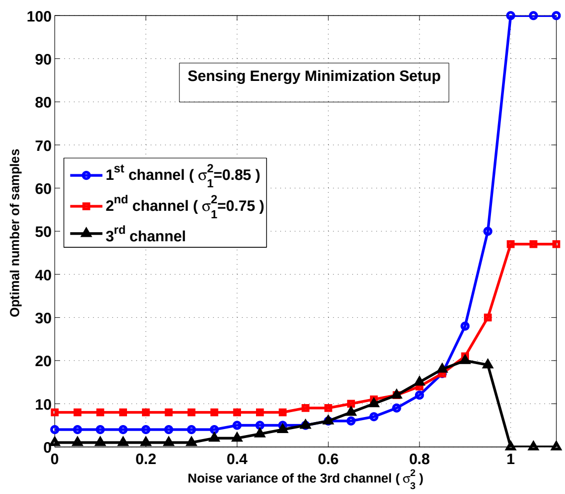

Fig. 5. *The optimal number of the samples from each channel versus the noise variance over the third channel based on sensing energy minimization setup.* $(\sigma_1^2 = 0.85, \sigma_2^2 = 0.75)$

The consumed energy in spectrum sensing is shown in Fig. 6 versus the noise variance of the third channel for both the optimal distribution and the conventional distribution of the samples. A huge reduction can be achieved in the sensing energy if the optimal distribution is used instead of the equal distribution of samples among channels.

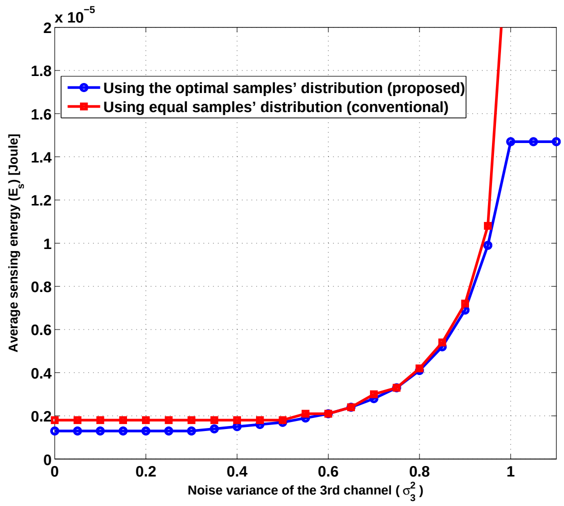

Fig. 6. *The average consumed energy in spectrum sensing versus the noise variance of the third channel based in the conventional approach and the proposed sensing energy minimization setup.* $(\sigma_1^2 = 0.85, \sigma_2^2 = 0.75)$.

V. Conclusions

Optimizing the number of samples of each channel is investigated in this paper for multi-channel spectrum sensing.

Different setups have been considered, namely, throughput maximization, interference minimization and energy consumption minimization. Results show that, for throughput maximization or energy minimization objectives, the channel that has a noise variance higher than the detection threshold should not be sensed. Also, the channel whose sum of noise and licensed signals is less than the detection threshold should not be sensed if the interference minimization is the main objective. Moreover, an approximation of the optimal number of samples for each channel is presented.

REFERENCES

[1] J.Mitola and G.Q.Maguire,"Cognitive radio: Making software radios more personal", *IEEE Personal Communications*, vol. 6, no. 4, pp. 13-18, 1999.

[2] A. Ghasemi and E.S. Sousa, "Spectrum sensing in cognitive radio networks: requirements, challenges and design trade-offs", *IEEE Communications Magazine,* vol. 46, no. 4, 2008, pp. 32-39.

[3] F. Granelli, et al. "Standardization and research in cognitive and dynamic spectrum access networks: IEEE SCC41 efforts and other activities", *Communications Magazine, IEEE*, 48.1 (2010): 71-79.

[4] A. Mesodiakaki, et al. "Energy efficiency analysis of secondary networks in cognitive radio systems." *Communications (ICC), 2013 IEEE International Conference on. IEEE,* 2013.

[5] Cheng, Peng, Ruilong Deng, and Jiming Chen. "Energy-efficient cooperative spectrum sensing in sensor-aided cognitive radio networks, *IEEE Wireless Communications,* 19.6 (2012): 100-105.

[6] Najimi, M., et al., "A Novel Sensing Nodes and Decision Node Selection Method for Energy Efficiency of Cooperative Spectrum Sensing in Cognitive Sensor Networks, *IEEE Sensors Journal,* vol.13, no.5, pp.1610,1621, May 2013.

[7] S. Althunibat et al. "Energy-Efficient Partial-Cooperative Spectrum Sensing in Cognitive Radio over Fading Channels, *IEEE VTC-Spring,* 2013.

[8] H. Xiaolei, et al. "A coalition formation game for energy-efficient cooperative spectrum sensing in cognitive radio networks with multiple channels." *Global Telecommunications Conference (GLOBECOM 2011), IEEE*, 2011

[9] T. Yucek, and H. Arslan, "A survey of spectrum sensing algorithms for cognitive radio applications." *Communications Surveys & Tutorials, IEEE,* 11.1 (2009): 116-130.

[10] F. Digham, M.S. Alouini, and M.K. Simon, "On the energy detection of unknown signals over fading channels," *IEEE Transactions on Communications*, 55.1 (2007): 21-24.

[11] A. H. Nuttall, "Some integrals involving the Q_M function", *IEEE Transactions on Information Theory*, vol. 21, no. 1, pp. 9596, January 1975.

[12] J. Mitola, "Cognitive radio for flexible mobile multimedia communications", *999 IEEE International Workshop on Mobile Multimedia Communications (MoMuC'99)*, 1999.

[13] S. Althunibat and F. Granelli, "Novel Energy-Efficient Reporting Scheme for Spectrum Sensing Results in Cognitive Radio", *IEEE ICC*, Budapest-Hungary, June- 2013.