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Interference Aware Optimisation of Throughput in Cognitive Radio System

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ABSTRACT

In the cognitive radio (CR) system where spectrum sensing and data transmissions are performed simultaneously, the proper selection of frame duration (τ) is of utmost importance. Small τ leads to an increased false alarm probability while large value of it delays implementation of sensing decision of the current frame to the next. The former case decreases the achievable throughput of the CR user while latter one may disturb the licensed user communication. Under the constraints of maintaining a target detection probability of $\overline{P_d}$, this paper attempts to design a frame duration τ where achieved throughput of the CR system is maximised. To do so, an analysis of achievable throughput with τ was performed which reveals that, initially, with the increase in τ, the achievable throughput increases sharply, but after its certain value, the increments are negligible and achievable throughput appears to maintain a constant value. The performed analysis shows that, it is not possible to perfectly optimize τ, however, a close optimisation can still be performed which can maximise the achievable throughput. From the realistic point of view, the CR system is further modelled under uncertain noise conditions. The achieved simulation results well justify the presented analysis.

Keywords: Cognitive radio, energy detection, sensing time, interference, achievable throughput

1. INTRODUCTION

The transitions in the communication from the wireless telephony to the dynamic internet services and multimedia services have raised the demand for high data rates. It is challenging to accommodate such a high data rate services and larger number of wireless communication devices within the limited availability of the spectrum. The fixed spectrum allocation policies have further increased the spectrum scarcity problem to its peak. With the measurements performed by the Federal Communications Commission (FCC), it has been revealed that the licensed spectrum is unoccupied for most of the time[1]. This fact motivates the re-use of under utilised portion of the licensed spectrum through the concept of cognitive radios (CRs). In the CR environment, the licensed and unlicensed users are often called as primary user (PU) and secondary user (SU), respectively. The CR allows SU to temporarily share the underutilised portion of the licensed spectrum which is not being used by the PU, but this sharing of spectrum must be executed in a manner which can assure sufficient protection required by the PUs[2-3]

There are two main approaches for spectrum sharing. (i) Overlay approach, under this approach SU accesses the licensed spectrum only when it is sensed to be idle[4], (ii) the underlay approach, it allows SU to share the licensed spectrum with the PU independent of its status (active/idle), but the transmissions are to be performed at such a low power that these do not interfere any ongoing communication of the PU. A mathematical analysis has been performed to study and define the fundamental limits of CR under the underlay scheme[5]. Authors formulated the sensing-throughput tradeoff[6] present in the CR system and then optimised the same. An intelligent cooperation of PU is used to improve the achievable throughput of the CR system[8-9]. The CR system based on the overlay approach generally communicates using the conventional frame structure in which spectrum sensing (SS) and data transmissions (DT) are performed in the alternate slots, within the same frame duration[6-7]. The SU based on conventional frame structure (in Fig. 1) ceases its DT at the start of each frame and performs SS for τ units of time. If the sensing decision is obtained to be idle, it resumes its DT (on the same channel) for the next $(T-\tau)$ units before the start of next frame, otherwise a search to find a next idle channel is initiated.

The CR system working under the conventional frame structure deals with an inherent problem of tradeoff between the SS and DT durations[6-7]. Large SS duration results in an improved protection of the PU but degrades the achievable throughput of the SU, while for the reverse case; the small SS duration improves achievable throughput of SU on one hand but degrades protection of PU on the other hand[10]. To overcome this sensing-throughput tradeoff problem, the authors have proposed a novel[10-12] CR system, the novel frame and receiver structures for the same have been shown in Figs. 2 and 3, respectively. The SU under the use of proposed frame and receiver structure is capable to perform the tasks of SS and DT simultaneously, so, improves the CR throughput while overcoming the existing sensing-throughput tradeoff problem.

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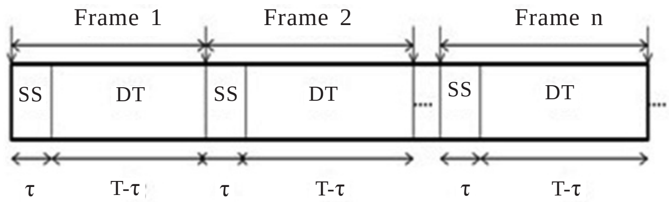

Figure 1. The conventional frame structure.

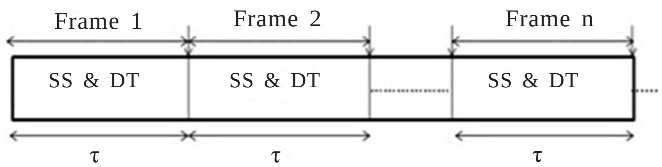

Figure 2. Frame structure for the proposed cognitive radio system[10-12], SS and DT are spectrum sensing and data transmission time, respectively.

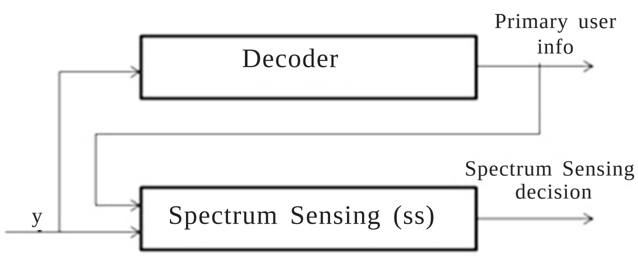

Figure 3. The decoder structure of the proposed CR system[10-12].

The SU under the novel approach does not only possess high sensing efficiency, but also improve its achievable throughput, so, sets a milestone towards an efficient CR system.

The novel CR system implements the SS decision of the previous frame ((n-1)th) to the ongoing (n^{th}). Therefore, in the case of large frame duration, if any PU gets activated during the n^{th} frame, there is no effective method to abort the ongoing communication of SU in between (due to delay in implementation of sensing decision from the (n-1)th frame to the n^{th}), which results in a collision to n^{th} frame of SU with the ongoing PU frame. This collision leads to an accidental loss of data of both the collided frames. In such a case, CR breaks the spectrum usage policies and disturbs an ongoing PU communication, which is a very serious problem to deal with. Authors attempted to solve this problem by proposing another frame structure[11] where instead of transmitting one long block of data (or packet) within a given frame duration[10-12], more than one block of short length can be transmitted, or in other words, the frame of small duration is used. The advantage of the proposed frame structure is to enable SU to implement its SS decision as quickly as possible, possibly within the ongoing frame duration. However, its disadvantage is that it is not clear about the frame duration or how many blocks of data that should be sent within a given τ, this makes CR operation doubtful. On one hand, a small τ degrades the achievable throughput and may even fail to give a valid sensing decision (due to lack of required number of samples), however, on the other hand, a large value of it unnecessarily induces a delay in implementing the sensing decision of current frame to the next, this undesirably can interfere an ongoing communication of the PU. So, it becomes necessary to find an optimal frame duration where achievable throughput of the CR system is maximised, and this paper attempts to do so.

This paper first formulates the optimisation problem and then performs an analysis which reveals that, it is not possible to perfectly optimize τ, however, a close optimisation can still be performed which maximise the achievable throughput of the SU. As an example, for different SNR_p values of -20 dB, -21 dB, and -22 dB, the closely optimised values of τ (where maximum throughput of ≈ 4.6609 bits/s/Hz is obtained) are obtained to be 102.8 ms, 162.6 ms, and 199.8 ms, respectively (as depicted through Fig. 6).

To study its robustness, the CR system was further analysed under the uncertain noise conditions. The analysis showed that, there exists a SNR wall beyond which an energy detector fails to give a valid sensing decision, no matter for how long sensing was performed. As an example, at a noise uncertainty factor of 1dB, the achieved SNR wall is -3.3292 dB, which means that: at an uncertainty factor of 1dB, the energy detector may fail to provide valid sensing results for a SNR below -3.3292 dB.

2. SYSTEM MODEL

According to the energy detection-based spectrum sensing scheme, the status (active/idle) of the PU on a frequency band of interest is represented by the following hypothesis H_1 and H_0 as follows:

$$H_1 : y(n) = s(n) + u(n) \tag{1}$$

$$H_0 : y(n) = u(n) \tag{2}$$

where $u(n)$ and $s(n)$ denotes the noise and the PU signal, and both are considered to be independent and identically distributed (iid) random variables with zero mean and variances of σ_u^2 and σ_p^2, respectively. $y(n)$, represents the signal received by the sensing node.

The test static for the energy detection scheme can be written as

$$\xi(y) = \frac{1}{N}\sum_{n=1}^{N}\left|y(n)\right|^2 \tag{3}$$

where, $N = \tau f_s$.N is the total number of samples collected at the sensing node, τ is the frame duration (or sensing time) as shown in Fig. 2 and f_s is the sampling frequency of the received signal. Under a reference threshold ε, the probability of detection P_d and false alarm P_{fa} can be written as

$$P_d = \Pr\left(\xi(y) \succ \varepsilon / H_1\right) = \int_{\varepsilon}^{\infty} \mathrm{P}_1(x)dx \tag{4}$$

$$P_{fa} = \Pr\left(\xi(y) \succ \varepsilon / H_0\right) = \int_{\varepsilon}^{\infty} \mathrm{P}_0(x)dx \tag{5}$$

where, $p_1(x)$ and $p_0(x)$ are the probability density function (PDF) for the test static $\xi(y)$ considered under the hypothesis H_1 and H_0, respectively.

For a circularly symmetric complex Gaussian (CSCG) primary signal and noise case, the probability of detection P_d and false alarm can be written as[6,10,11]

$$P_d(\tau) = Q\left(\left(\frac{\varepsilon}{\sigma_u^2} - \gamma - 1\right)\sqrt{\frac{\tau f_s}{2\gamma + 1}}\right) \quad (6)$$

$$P_{fa}(\tau) = Q\left(\left(\frac{\varepsilon}{\sigma_u^2} - 1\right)\sqrt{\tau f_s}\right) \quad (7)$$

where $Q(.)$ is the complementary distribution function of the standard Gaussian signal and can be written as[13]

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^t \exp\left(-\frac{t^2}{2}\right)dt \quad (8)$$

and γ denotes SNR of the primary signal received at the sensing node and can be written as

$$\gamma = \frac{P_P}{\sigma_u^2} = \frac{\sigma_P^2}{\sigma_u^2} \quad (9)$$

$P_p\left(= \sigma_P^2\right)$ denotes power of the primary signal received at the sensing node. High value of P_d assures better protection to the PU, while low value of P_{fa} is needed to improve the throughput of SU. So, for an efficient CR system, the values of P_d and P_{fa} are high and low, respectively. The performance of energy detector depends mainly on the threshold chosen, so from the PU point of view, to assure sufficient protection to the PU, the threshold can be computed under the constraint of maintaining a target detection probability of $\overline{P_d}$. Under $\overline{P_d}$, the P_{fa} can be represented as

$$P_{fa}(\tau) = Q\left(\sqrt{2\gamma + 1}Q^{-1}\left(\overline{P_d}\right) + \sqrt{\tau f_s}\gamma\right) \quad (10)$$

3. ANALYSIS OF THROUGHPUT WITH THE FRAME DURATION

Let R_0 and R_1 denote the transmission rate of the CR system under the conditions when the PU is idle and active, respectively, and can be represented as

$$R_0 = \log_2\left(1 + SNR_s\right) = \log_2\left(1 + \frac{P_s}{\sigma_u^2}\right) \quad (11)$$

$$R_1 = \log_2\left(1 + \frac{SNR_s}{1 + SNR_p}\right) = \log_2\left(1 + \frac{P_s}{P_p + \sigma_u^2}\right) \quad (12)$$

where SNR_s and SNR_p denotes SNR of secondary and primary user received at the sensing node.

Let us define, for a given frequency band of interest, $P(H_0)$ and $P(H_1)$ are denoting the idle and active status of the PU, respectively. Using the novel frame structure of Fig. 2, the throughput C_0 and C_1 corresponding to the transmission rates of R_0 and R_1 can be written as

$$C_0(\tau) = R_0\left(1 - P_{fa}(\tau)\right)P(H_0) \quad (13)$$

$$C_1(\tau) = R_1\left(1 - P_d(\tau)\right)P(H_1) \quad (14)$$

So, from Eqns (13) and (14), the average achievable throughput of the CR network can be written as

$$C(\tau) = C_0(\tau) + C_1(\tau) \quad (15)$$

The objective of CR is to maximise its achievable throughput under the constraint of providing sufficient protection to the PU, and can mathematically be represented as

$$\max_\tau C(\tau) = C_0(\tau) + C_1(\tau) \quad (16)$$

such that

$$P_d(\tau) \geq \overline{P_d} \quad (17)$$

The Eqn (17) shows that, $\overline{P_d}$ is the minimum P_d required to provide sufficient protection to the PUs.

Assuming $\alpha = \sqrt{2\gamma + 1}Q^{-1}\left(\overline{P_d}\right)$, the Eqn in (10) can be re-written as

$$P_{fa}(\tau) = Q\left(\alpha + \sqrt{\tau f_s}\gamma\right) \quad (18)$$

Now, from Eqn (18), the average achievable throughput in Eqn (15) can be written as

$$C(\tau) = R_0\left(1 - Q\left(\alpha + \sqrt{\tau f_s}\gamma\right)\right)P(H_0) + R_1\left(1 - \overline{P_d}\right)P(H_1) \quad (19)$$

Now, differentiating Eqn (19) with respect to τ, we gets

$$C'(\tau) = R_0 P(H_0)\frac{\gamma\sqrt{f_s}}{2\sqrt{2\pi\tau}}\exp\left(-\left(\alpha + \sqrt{\tau f_s}\gamma\right)^2 \Big/ 2\right) \quad (20)$$

As it is already known that the value of τ at which $C(\tau)$ is maximised is nothing but it is that value from the range $(0, \infty)$ where $C'(\tau)$ in Eqn (20) becomes zero.
or indirectly,

$$C'_{\tau \to \tau^*}(\tau) = 0 \quad (21)$$

But it is evident from Eqn (20) that there is no value of τ^* where $C'(\tau)$ is exactly zero. This shows that the exact optimum solution of Eqn (16) cannot be obtained.

However, by analysing the behaviour of $C'(\tau)$ with various values from the range $(0, \infty)$ it was found that $C'(\tau)$ is decreasing in τ (as shown in Fig. 4) and after a certain value of τ (i.e. τ^*), it closely approaches to zero. This further shows that even no exact optimisation is possible for frame duration τ, a close optimisation can still be performed for those values of τ which satisfy the Eqn (22) as follows

$$C'_{\tau \to \tau^*}(\tau) \approx 0 \quad (22)$$

4. COGNITIVE RADIO UNDER THE NOISE UNCERTAINTY

From Eqns (6) and (7), the value of P_d under target $\overline{P_{fa}}$ can be written as

$$P_d = Q\left(\frac{1}{\sqrt{2\gamma + 1}}\left(Q^{-1}\left(\overline{P_{fa}}\right) - \gamma\sqrt{\tau f_s}\right)\right) \quad (23)$$

So, under the target P_d and P_{fa} (i.e. $\overline{P_d}$ and $\overline{P_{fa}}$) values, the minimum number of samples $(N = \tau f_s)$ required to achieve this target can be expressed using Eqns (10) and (23), as follows

$$N_{\min} = \frac{1}{\gamma^2}\left[Q^{-1}\left(\overline{P_{fa}}\right) - Q^{-1}\left(\overline{P_d}\right)\sqrt{2\gamma + 1}\right]^2 \quad (24)$$

The Eqn (24) shows that under the known value of signal power σ_n^2, the primary signal can be detected at arbitrary low value of SNR by simply increasing the number of samples N (or indirectly, by increasing the frame duration/sensing time, Fig. 2).

Now, considering the case of noise uncertainty, the noise distribution can be modelled through an interval

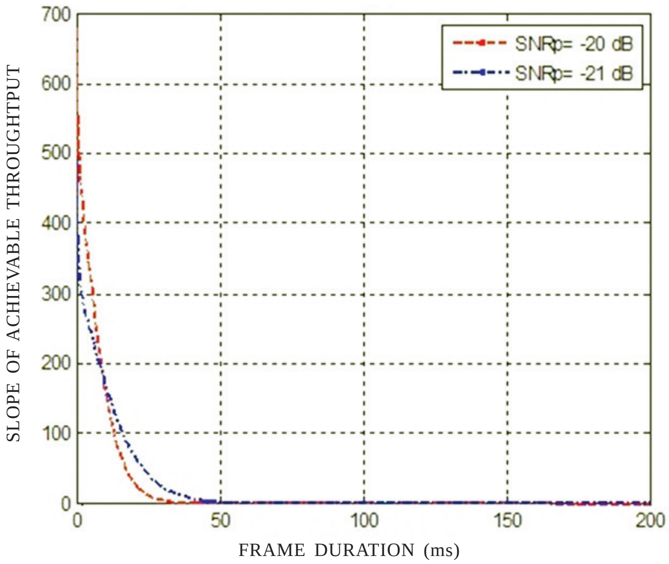

Figure 4. Variation of slope of achievable throughput with τ.

$\sigma_u^2 \in \left[\frac{1}{\theta}\sigma_u^2, \theta\sigma_u^2\right]$, where σ_u^2 is the assumed noise variance whose uncertainty size can be represented by $\theta > 1$.

Under uncertain noise conditions, the marginal detection ($P_{d,u}$) and false alarm ($P_{fa,u}$) probabilities can further be written as

$$P_{d,u} = \min_{\sigma_u^2 \in \left[\frac{1}{\theta}\sigma_u^2, \theta\sigma_u^2\right]} Q\left(\left(\frac{\varepsilon}{\frac{1}{\theta}\sigma_u^2} - \gamma_u - 1\right)\sqrt{\frac{\tau f_s}{2\gamma_u + 1}}\right) \quad (25)$$

$$P_{fa,u} = \max_{\sigma_u^2 \in \left[\frac{1}{\theta}\sigma_u^2, \theta\sigma_u^2\right]} Q\left(\left(\frac{\varepsilon}{\theta\sigma_u^2} - 1\right)\sqrt{\tau f_s}\right) \quad (26)$$

where γ_u is the SNR under the noise uncertainty condition and can be represented as

$$\gamma_u = \frac{P_P}{\left(\frac{1}{\theta}\sigma_u^2\right)} = \gamma \cdot \theta \quad (27)$$

Now, assuming the target detection and false alarm probabilities as $\overline{P_{d,u}}$ and $\overline{P_{fa,u}}$, and eliminating ε from Eqns (25) and (26) gives

$$N = \frac{1}{\gamma_u^2}\left[\frac{Q^{-1}\left(\overline{P_{fa,u}}\right)\theta - \frac{1}{\theta}Q^{-1}\left(\overline{P_{d,u}}\right)\sqrt{2\gamma+1}}{\gamma - \left(\theta - \frac{1}{\theta}\right)}\right]^2 \quad (28)$$

For low γ values, approximating $2\gamma + 1 \approx 1$, Eqn (28) can be re-written as

$$N \approx \frac{1}{\gamma_u^2}\left[\frac{Q^{-1}\left(\overline{P_{fa,u}}\right)\theta - \frac{1}{\theta}Q^{-1}\left(\overline{P_{d,u}}\right)}{\gamma - \left(\theta - \frac{1}{\theta}\right)}\right]^2 \quad (29)$$

From Eqn (29), equating the denominator to zero, the SNR wall can be written as

$$SNR_{wall} = \frac{\theta^2 - 1}{\theta} \quad (30)$$

The SNR wall tells that as the value of received signal power becomes less than the noise uncertainty (as given in Eqn (31)), the energy detector fails to detect the PU signal robustly.

$$P_P \le \left(\frac{\theta^2 - 1}{\theta}\right) \cdot \sigma_u^2 \quad (31)$$

5. SIMULATION RESULTS

The probability with which the frequency band of interest is idle is assumed to be $P(H_0)$=0.7, $\overline{P_d}$ =0.9999, $SNRs$=20dB, the sampling frequency f_s and the bandwidth of PU are considered to be 6 MHZ. The noise is considered to be zero-mean CSCG process.

Figure 4 illustrates the variations of $C'(\tau)$ with τ. It is illustrated that the value of τ for which $C'(\tau)$ approaches to zero, shows approximated maximum value of $C(\tau)$. The indicated point in Figs. 6, 7 and 8 depicts the same thing.

The graph in Fig. 5 compares the achievable throughput of the proposed CR system with the conventional CR system[7] based on the frame structure of Fig. 1 and the un-optimised CR system[10, 12] based on the frame structure of Fig. 2. It is evident that the CR system with its optimised frame duration achieves high throughput than both, the conventional[7] and the un-optimised[10,12] CR systems. The plots indicated with 'CR without optimisation in[10,12]' and 'CR with optimised frame duration' maintain constant value of their throughput with the frame duration τ. The constant curves indicate that the CR system operating under the frame structure of Fig. 2 is capable to perform the tasks of spectrum sensing and data transmissions simultaneously, or in other words, it is free from any sensing-throughput tradeoff[10-12].

Figure 6 plots achievable throughput of the CR system under various values of frame duration. Indicated points show the existence of optimal frame duration τ^*. Below τ^*, the P_{fa} increases which reduces the throughput of CR system, and above it, the throughput remains constant till channel stands idle. But, as the channel gets busy, the throughput of the CR system reduces quickly, as shown in Fig. 7. It is also revealed

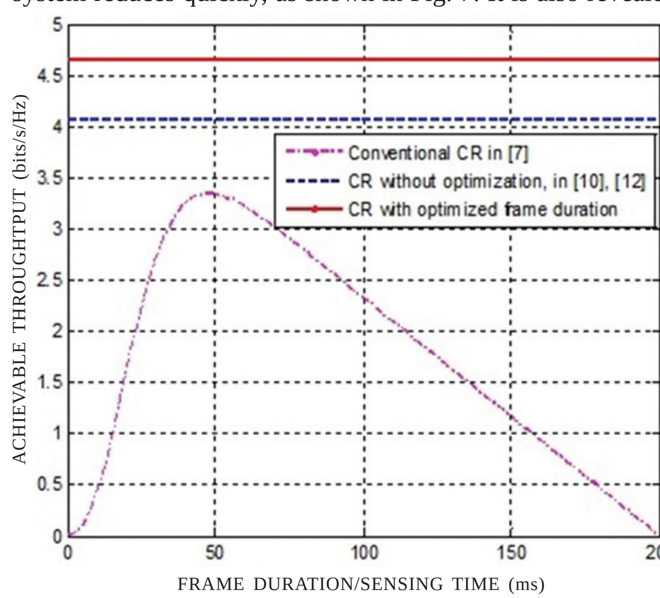

Figure 5. Variation of achieved throughput with the frame duration. Assumed SNR_p = -20 dB.

that: as the SNR_p increases, the achievable throughput increases and the value of τ^* decreases. This shows that under the low SNR regime, large frame duration is needed to improve the sensing performance.

Figure 8 was analysed under various values of $\overline{P_d}$, the indicators indicate the value of τ at which achievable throughput is maximised. It is shown that high value of $\overline{P_d}$ reduces the chances for licensed spectrum utilisation, which in return degrades the throughput of CR system. Also, under high $\overline{P_d}$, to maintain the throughput value to its maximum, τ^* is increased.

The graph in Fig. 9 plots the total error rate T_e as a function of frame duration. It is illustrated that at frame duration τ^*, T_e is minimised (close to zero). It is also shown that the increase in SNR improves the sensing performance, which further results in reduced T_e.

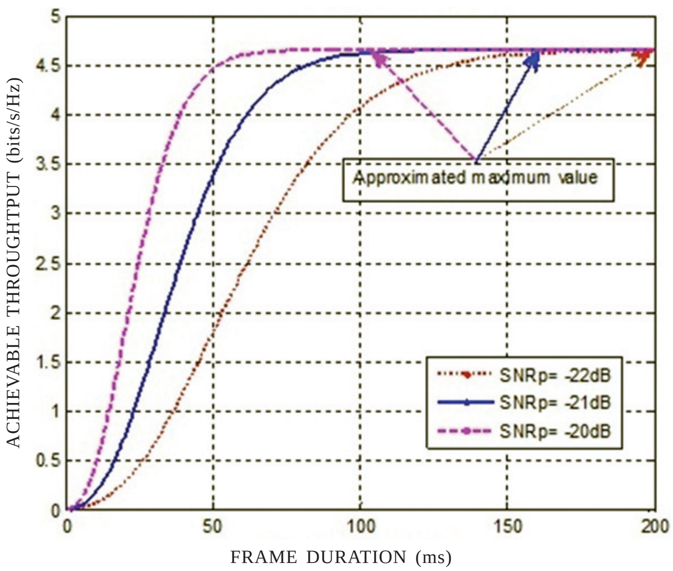

Figure 6. Achievable throughput under various values of SNR_p.

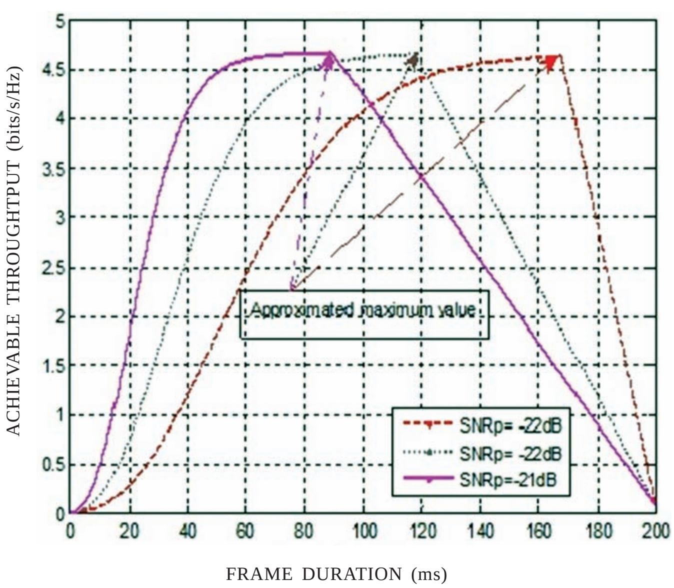

Figure 7. Achievable throughput under various values of SNR_p. It is assumed that, after time τ^*, the PU gets activated with the probability $P(H_1)$= 0.3 to 0.99.

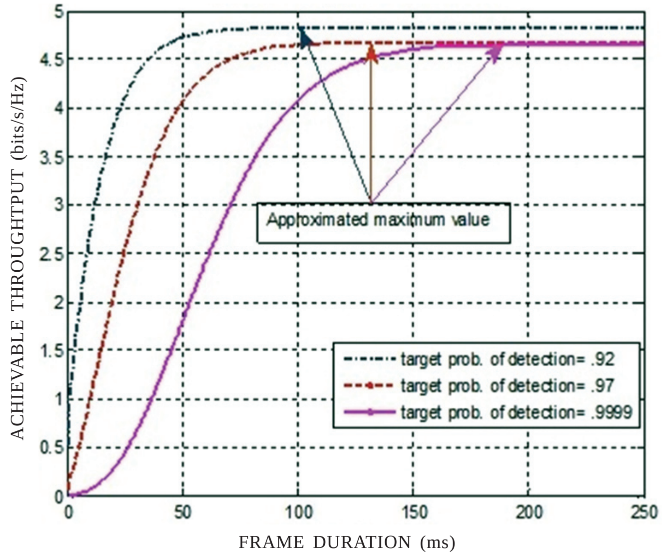

Figure 8. Achievable throughput under various values of P_d.

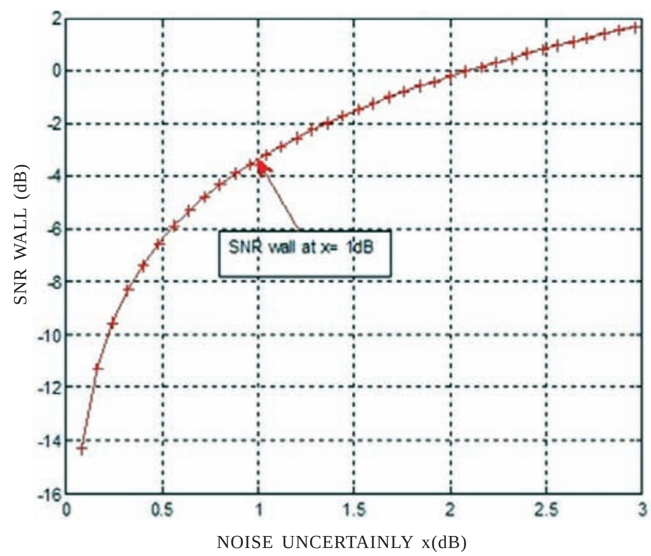

Figure 9. Total error rate (T_e) *vs* frame duration.

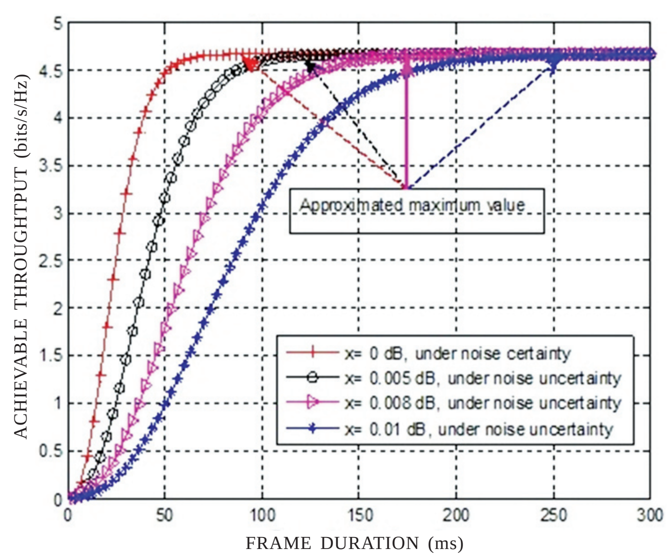

Figure 10. Analysis of SNR wall with the noise uncertainty factor *x*.

The graph in Fig. 10 shows variations to the SNR wall with the noise uncertainty factor *x*. It is shown that: with the increase in value of *x*, the SNR wall increases, which further increases the barrier on the detection performance. As illustrated in Section 1, due to SNR wall, the CR may not provide valid sensing results, no matter for how long sensing was performed.

Figure 11 plots achievable throughput under the uncertain noise conditions. It is shown that the uncertainty factor *x* imposes a limit on the performance of CR system. As the uncertainty factor *x* increases, the achievable throughput decreases, however, under a given value of *x*, there exists an optimum frame duration τ^* where achieved throughput of the CR system is maximised (shown through the arrows).

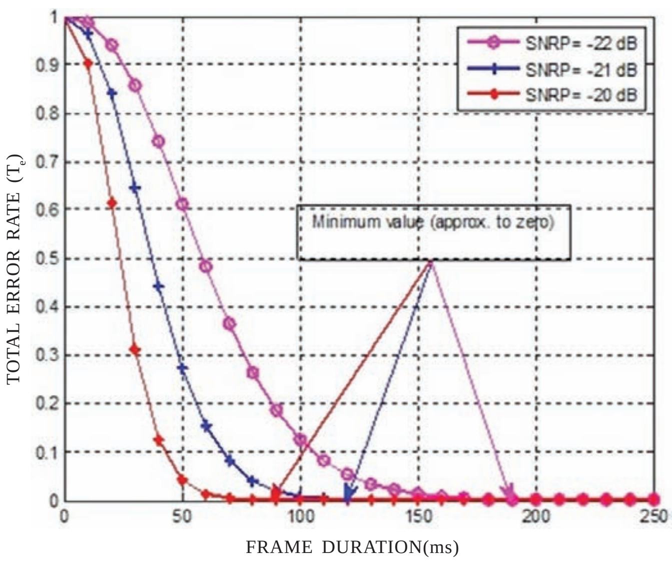

Figure 11. Achievable throughput under uncertain noise conditions.

6. CONCLUSION

The authors have studies and analyses the achievable throughput of the cognitive radio system with frame duration τ. This article attempts to find the optimum frame duration τ^*, where achievable throughput of the CR system is maximised. Through the analysis performed it is revealed that the perfect optimisation is not possible, however, a close optimisation can still be achieved, and the authors did the same. The performed optimisation maximises the achievable throughput of the CR system while assuring sufficient protection to the licensed users. The cognitive radio was further studied and analysed under the uncertain noise conditions where it was shown that there exists a SNR wall beyond which an energy detector fails to promise valid sensing results. The presented simulation results well justify the performed analysis. In future, we plan to improve robustness of the cognitive radio system under the uncertain noise conditions.

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Mr Gaurav Verma received his B.Tech (Elect. Comm. Engg.) from National Institute of Technology Raipur, in 2010 and M.Tech (Communication Systems) from National Institute of Techhnology Tiruchirappalli, in 2012. Currently pursuing his PhD from National Institute of Technology Kurukshetra. Presently working as Assistant Professor in the Department of Electronics and Communication Engineering, National Institute of Technology Kurukshetra, India. His Research interests include:Cognitive Radio, wireless networking, wireless communications and next generation of communication systems.

In the current study Gaurav Verma investigated the problem of optimum frame duration for the CR system operating under the frame structure of Fig. 2. Formulated the optimisation problem of equation (16) and performed the optimisation. Obtained and drawn the simulation results.

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In the current study O.P. Sahu analysed the proposed CR system under the uncertain noise conditions. Formulated the SNR wall for the proposed CR system.