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# Throughput maximization with reduced data loss rate in cognitive radio network

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**Abstract** In this paper, we have investigated a technique to eliminate the sensing-throughput trade-off of the conventional method in the cognitive radio network. First, we have discussed the sensing—throughput trade-off caused by the conventional method in the cognitive radio network and then proposes a frame structure for eliminating such an issue which is presented in the conventional approach. However, the proposed method has a drawback, which is solved by the enhancement in the frame structure. We have numerically simulated and compared the throughput of cognitive users for both (conventional and propose) methods. The frame structure enhancement technique decreases the probability of frame collision between the primary and secondary users (SUs) and reduces the data rate loss.

**Keywords** Cognitive radio · False-alarm · Probability of detection · Throughput · Data rate · Wireless network

## 1 Introduction

As the wireless communication systems are making the transition from wireless telephony to interactive internet data and multimedia type applications, the demand of higher data rate transmission is increasing tremendously. To accommodate the demand of channel capacity and data rates within the limited bandwidth availability, is a very challenging task and require innovative technologies which offer new ways of exploiting the available radio spectrum. Cognitive radio offers a solution for the spectral crowding problem by introducing the opportunistic usage of the frequency bands which are not heavily occupied by the licensed users [6, 12]. The wireless networks have been characterized by a fixed spectrum allocation policy, where governmental agencies assign the spectrum to license holders on a long-term basis for the large geographical regions [23]. However, according to the measurements made by the Federal Communications Commission (FCC), large portion of the assigned spectrum is used sporadically leading the fact that fixed spectrum allocation policy has resulted in several bands being severely underutilized both in the temporal and spatial manner [4], which motivates the invention of cognitive radio network. The cognitive radio proposes secondary access to the already-licensed spectrum as a means to mitigate the spectrum scarcity [3]. However, this spectrum sharing should be carried out in a controlled fashion so that the primary licensee's operation in the band is not compromised. [18, 19, 21] discusses the spectrum sharing for OFDM SUs. Therefore, the SUs trying to access the licensed spectrum should consider the impact of their transmission on the reception quality of the primary licensee. The secondary access does not affect primary user (PU) operation as long as the total interference power at the primary receiver remains below a certain threshold. For a wireless receiver, any signal other than the signal originally destined to be received by that receiver is considered as interference [13, 18]. One of the main difficulties to allocating resources in the cognitive radio (CR) systems is the interference power generated by its users at the PU receiver should not exceed the predefined threshold [21]. Two main approaches have been developed for the cognitive radio so far, to access the licensed spectrum by cognitive user: (1) the opportunistic spectrum

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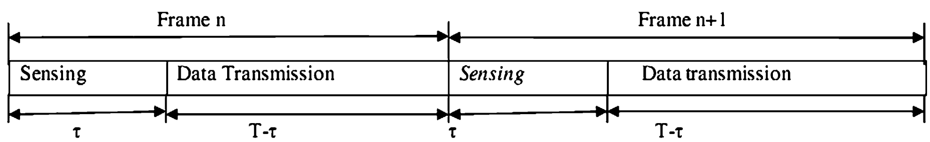


**Fig. 1** Frame structure of the conventional sensing-based spectrum sharing approach for cognitive radio networks

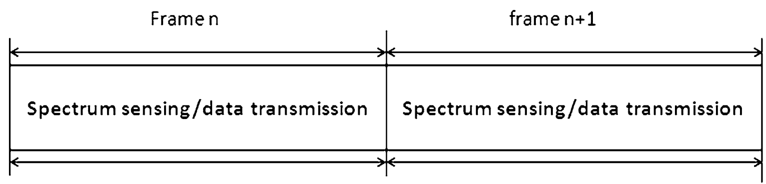


**Fig. 2** Frame structure of the proposed approach

access (OSA), according to which a SU can access a frequency band only when it is detected to be idle [22], and (2) the spectrum sharing (SS) based on which the SUs under the condition of protecting the PUs from harmful interference [5].

Recently, a hybrid approach has been proposed with aiming to increase the throughput of the aforementioned schemes, in which the SUs first sense the status (active/idle) of a frequency band (similar to OSA) and then adapt their transmit power based on the decision made by spectrum sensing [8] to avoid the harmful interference with the PU as similar to SS [9]. The potential parameters related to the spectrum sensing are: (1) false-alarm probability and (2) detection probability. The false-alarm specifies that SU falsely detect the PU transmission in the sensing band, however the actual licensed user is not transmitting. Therefore, lower the false-alarm probability provides more opportunities for the cognitive radio users to reuse the spectrum band and results higher achievable throughput [15]. On the other hand, higher detection probability provides better PU transmission protection. A SU that employs a scheme in which first sensing and then transmission is performed as shown in Fig. 1, which depicts that the SU ceases data transmission at the beginning of each frame, first performs the spectrum sensing for $\tau$ units of time and then data transmission for remaining frame duration that is for $(T - \tau)$. However, there is a potential problem in this scheme which is so called sensing-throughput trade-off [10, 11]. However, it is well known from the classical detection theory [7, 14] that an increase in the sensing time results higher probability of detection and lower probability of false-alarm, which decreases the data transmission time and hence throughput of the cognitive radio user. Apart from the sensing-throughput trade-off, there are other problems such as: (a) low probability of detection or (b) unpredictable PU transmission during the transmission time of SU.

In order to avoid the sensing-throughput trade-off and maximize the throughput of spectrum sharing cognitive radio networks, an approach is proposed in [17]. Frame structure for this approach is shown in Fig. 2, in which both the spectrum sensing and data transmission is performed at the same time and for whole frame duration that increases both the sensing time and data transmission time. This enhancement in the sensing time provides better performance in the form of decrease in the false-alarm as well as increase in the detection probability. Consequently, we achieve significant enhancement in the throughput of cognitive radio user. This approach determines the action of cognitive radio network in the next frame which is based on the sensing decision of the previous frame. The SU adapt their transmit power in the next frame and transmits with lower power if the sensing result of the previous frame shows that the PU is transmitting whereas transmits with higher power if the PU is not transmitting. Hence, the harmful interference to the PUs can be avoided. In Fig. 2, the sensing has been performed during the frame $n$, is utilised for data transmission in frame $(n + 1)$. The SU during frame $(n+1)$ transmits data with high power in case if sensing during the frame $n$ shows idle PU and vice-versa. However, a potential problem arises if during the transmission time of SU that is suppose during frame $(n + 1)$, the PU becomes active from the previous frame's (frame $n$) idle state but SU is not aware to this fact because current frame's (frame $n+1$) sensing results are not present, due to this SU transmits with high power based on the sensing decision of frame $n$, which results collision of the SU's frame $(n + 1)$ with the PU's frame and all the data carried in a collided frame will be lost. This problem has been until discussed only for case where sensing and transmission is performed alternatively [20]. In this paper, we have emphasized on this problem. This paper has been organised as follows. Section 2 describes the system model of the cognitive user and problem formulation. A novel approach for the SU's data transmission has been proposed with the frame structure for data transmission. In Sect. 3, throughput for the proposed scheme has been discussed. Section 4, shows the numerically simulated results. Finally, Sect. 5 concludes the paper.

## 2 System model and problem formulation

Cognitive radio system in which the spectrum sensing and data transmission is performed simultaneously worked as

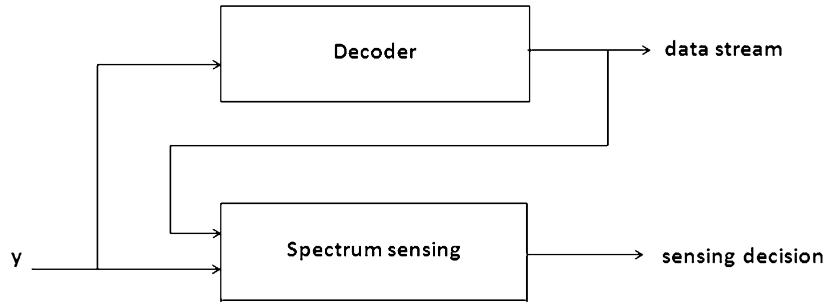


**Fig. 3** Receiver structure for the cognitive user for frame structure as shown in Fig. 2

follow. We have considered a cognitive radio network in which a centralized controller is utilized, for example base station, which collects information about spectrum bands from SUs [1, 2] and uses that information to allocate an appropriate spectrum band to a SU such that the channel requirement of the SU is satisfied. Further, the SU performs an initial spectrum sensing on the allocated spectrum band to determine the status of frequency band. Based on the sensing result, the SU communicate using the higher transmit power if the sensing result detect that at that time PU is not transmitting on that spectrum band and lower transmit power if PU is transmitting. The secondary receiver decodes the signal sent by the secondary transmitter, strips it away from the received signal and uses the remaining signal to perform spectrum sensing in order to determine the action of the cognitive radio network in the next frame. At the end of the frame, if the status of the PUs has changed after the initial spectrum sensing was performed, the SUs will adapt their transmit power (from higher to lower or vice-versa) based on the sensing decision to avoid causing the harmful interference to the PUs.

### 2.1 Cognitive receiver structure

The cognitive radio receiver structure for the SU in which spectrum sensing and data transmission is performed simultaneously is shown in Fig. 3. The received signal at the SU is given by [17]:

$$y = \theta s_p + h_s x_s + w(t) \tag{1}$$

where $\theta$ denotes the actual status of the frequency band ($\theta = 1$ if the band is active and $\theta = 0$ when it is idle) and $s_p$ denotes the received signal from the PU in that frequency band. $h_s$ denotes the channel gain between the secondary transmitter and the secondary receiver, $x_s$ represents the signal from the secondary transmitter and $w(t)$ denotes the additive white Gaussian noise (AWGN). The received signal is initially passed through the decoder as shown in Fig. 3, which decode the signal form secondary transmitter. The signal from the secondary transmitter is cancelled out from the aggregate received signal $y$ as given by Eq. (1), whereas the remaining signal, which is given by:

$$\tilde{y} = \theta s_p + w(t) \tag{2}$$

This signal is used for the spectrum sensing. This is the signal that secondary receiver would receive if secondary transmitter ceases transmission.

### 2.2 Frame structure

In the frame structure as shown in the Fig. 2, the sensing and data transmission is performed simultaneously for whole frame duration $T$, so that throughput is maximized for frame structure of Fig. 2 as compared to the conventional frame structure as shown in Fig. 1. Frame structure as shown in Fig. 2 has following advantage:

(1) It enables the detection of very weak signals from the PUs, the detection of which under frame structure of Fig. 1 would significantly reduce the data transmission time because detection of very weak signals from PUs requires large sensing time,
(2) It leads to an improved detection probability, thus better protection of the PUs from harmful interference,
(3) It results to decrease the false-alarm probability, which enables a better use of the available unused spectrum,
(4) The computation of the optimal sensing time is no longer an issue, since it is maximized and equal to frame duration, and
(5) The continuous spectrum sensing can be achieved under the proposed cognitive radio system, which ensures better protection of the primary networks.

Apart from the aforementioned advantages of the frame structure as shown in Fig. 2, there is a problem of this frame structure because sensing results of previous frame is used by next frame to transmit data at lower or higher power. So in that case, if during the transmission in a frame, PU changes state (for example, if $\theta$ changes from 0 to 1), the SU's frame collide with the PU's data, because same frame's sensing results are not used in the same frame to adapt SU's power to avoid collision and all the data carried in collided frame will be lost. To reduce the data loss due to collision, we have proposed a (Fig. 4) novel frame structure, which is

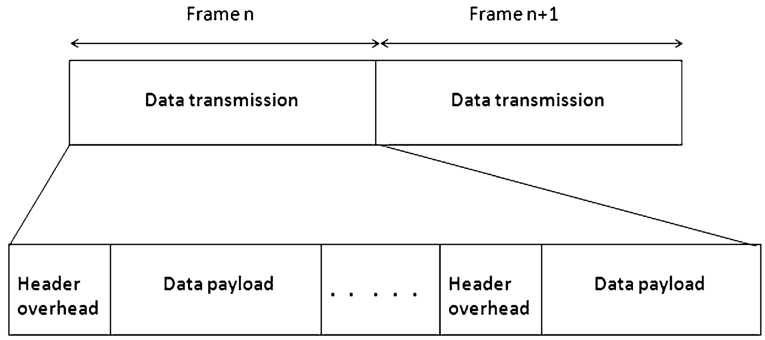


**Fig. 4** Frame structure for the proposed scheme

modified form of Fig. 2. In this modified frame structure, instead of sending one long block of data in the each frame as shown in Fig. 2, we send two or more shorter blocks of data in the transmission time of each frame as shown in Fig. 4. In the proposed scheme, the sensing and transmission is performed simultaneously as in Fig. 2. In this scheme, in the transmission time of the frame, there is two or more header overhead and data payload as shown in Fig. 4. Thus in each frame, we send sequence of header overhead block followed by data payload block. The header overhead includes fixed-length transmission control information and the data payload includes data which has to send. Now, if during the transmission in a frame, PU changes from idle to active ($\theta$ changes from 0 to 1), only the data carried in the collided data payload block of that frame will be lost and rest of the data payload blocks of the same frame will be protected from being lost. So shorter the data payload block, more data is successfully sent. In this proposed method, header overhead consists of flag bit. This flag bit uses the sensing result of the same frame that is calculated up till that time, which removes the shortcoming of Fig. 2 because previous frame's sensing results is applied to current frame. However, in Fig. 4 frame's structure the same frame's sensing decision is used in the same frame. The flag bit is set if the sensing results are different from the previous frame's sensing result, then SU adapts its transmission power from high-to-low and vice-versa. Thus, this method is an efficient method for cognitive user's data transmission as compared to the conventional data transmission method.

## 3 Throghput

For conventional scheme, the throughput is given by the expression [16]:

$$\frac{T-\tau}{T}\left[P(H_1)(1-P_d)\log_2\left(1+\frac{SNR_s}{1+SNR_p}\right) + P(H_0)(1-P_f)\log_2(1+SNR_s)\right] \tag{3}$$

Equation (3) is for the frame structure of Fig. 1. There are two probabilities of interest, which are used for the spectrum sensing: (1) probability of detection ($P_d$), which defines under hypothesis $H_1$, the probability of the algorithm correctly detecting the presence of primary signal, and (2) probability of false-alarm ($P_f$), which defines under hypothesis $H_0$, the probability of the algorithm falsely declaring the presence of the PU's signal. From the PU's perspective, if the probability of detection is high, the received protection is better. From the SU's perspective, however, if the probability of false-alarm is low, there are more chances from which the SUs can use the frequency bands when they are available. Obviously, for a good detection algorithm, the probability of detection should be as high as possible while the probability of false-alarm should be as low as possible. $P(H_0)$ and $P(H_1)$ are the probability that frequency band is idle and active, respectively. $SNR_s$ is signal-to-noise ratio of the secondary link that is signal-to-noise ratio from secondary transmitter to secondary receiver. $SNR_p$ is the signal-to-noise ratio of the PU received at the receiver of the secondary transmission link. Frame structure for Eq. (3) disrupts the continuous communication in the spectrum sharing cognitive radio network and decreases throughput by factor of ($\frac{T-\tau}{T}$). When the SU is sensing the spectrum of the PU in a cognitive radio network, there are two hypotheses for the received signal $y(t)$: PU is absent or present, that is denoted by $H_0$ and $H_1$, respectively.

$$y(t) = \begin{cases} h\, s(t) + w(t) & H_1 \\ w(t) & H_0 \end{cases}$$

where $h$ is the channel gain, $w(t)$ is the additive white Gaussian noise with mean zero and variance $E[|w(t)|^2] = \sigma_w^2$, $s(t)$ is the signal of PUs, which is assumed to be random process with mean zero and variance $E[|s(t)|^2] = \sigma_s^2$. $w(t)$ and $s(t)$ are assumed to be mutually independent. $\overline{P_d}$, is the target probability of detection for which the PUs are defined as being sufficiently protected. The probability of false-alarm is related to the target detection probability as follows [10]:

$$P_f = Q\left(\sqrt{2\gamma+1}\,Q^{-1}(\overline{P_d}) + \sqrt{\tau f_s}\gamma\right) \tag{4}$$

On the other hand, for a target probability of false-alarm $\overline{P_f}$, the detection probability is given by [10]:

$$P_d = Q\left(\frac{1}{\sqrt{2\gamma+1}}\left(Q^{-1}(\overline{P_f}) - \sqrt{\tau f_s}\gamma\right)\right) \tag{5}$$

In Eqs. (4) and (5), $\gamma$ is the signal-to-noise ratio of the PU's signal at the secondary detector, $f_s$ is the sampling frequency. $N$ is the number of samples used for the spectrum sensing by SU where $N = \tau f_s$. Energy detection is the most popular spectrum sensing technique and its test statistics for received signal $y$ is given as follows:

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

Here $T(y)$ is a random variable whose value determines the presence and absence of PU by cognitive user's sensor. $Q$ is the complementary unit Gaussian distribution function and defined as [20]:

$$Q(x) = \int_x^{\infty} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{u^2}{2}\right) du \tag{6}$$

$$Q^{-1}(x) = 1 - Q(x) \tag{7}$$

also

$$P(H_0) = 1 - P(H_1) \tag{8}$$

For the proposed approach in which sensing and transmission is performed simultaneously, the expression for the throughput is given by:

$$P(H_1)(1-P_d)\log_2\left(1+\frac{SNR_s}{1+SNR_p}\right) + P(H_0)(1-P_f)\log_2(1+SNR_s) \tag{9}$$

From Eq. (9), it is clear that throughput is not decreased by amount $(\frac{T-\tau}{T})$ as in the conventional approach because the sensing and transmission is performed simultaneously. Thus by comparing Eqs. (3) and (9), it is clear that throughput for frame structure of Fig. 2 and Fig. 3 is more than that of Fig. 1.

## 4 Simulation results

In this section, we have presented the simulation results of the proposed frame structure and have compared with that of the conventional method. In the simulation, the frame duration is set to $T = 100$ ms and the probability for the active frequency band is $P(H_1) = 0.2$, then from Eq. (8), $P(H_0) = 0.8$. The received SNR from the secondary transmitter is $SNR_s = 20$ dB, whereas the bandwidth of the channel and the sampling frequency $f_s$ are assumed to be 6 MHz. Then, we numerically simulated the throughput of the SUs for the conventional and proposed frame structure by taking different SNR from the PU.

From Fig. 4 of [16], we have compared the results for conventional and proposed approach for low SNR region. In Fig. 5, the throughput (bits/second) of the SUs versus sensing time (ms) is plotted for several values of the SNR from the PUs and the target probability of detection for this curve is ($\overline{P}_d = 99.99$ %). Figure 5 reveals that the throughput for proposed approach is much more than that for conventional approach and it is also observed that the throughput of cognitive user for higher values of the PU's SNR is much less than that of low values of the SNR. Figure 6 shows the throughput versus $P(H_0)$ that is the probability for which the frequency band is idle for chosen target probability of detection as in Fig. 5 and it is clear that as probability of the frequency band being idle increases, the throughput of the SUs increases and it is more for the proposed approach as compared to conventional approach.

Figure 7 shows the variation of throughput of the SUs with the target probability of detection for conventional and proposed approaches and it is observed that as the target probability of detection increases, the throughput of cognitive users decreases and reaches zero when the target probability of detection is unity for the conventional approach, but for the proposed approach, the throughput is significantly enhanced and is non-zero. Thus in the proposed approach, we have obtained high protection against interference for PU and significantly enhanced throughput of the cognitive users, simultaneously. Hence from Fig. 7 it is clear that proposed approach provides better protection against interference to the PU.

## 5 Conclusion

This article deals with the throughput maximization in the cognitive radio network along with reduced data rate loss. We have compared numerically simulated results of the throughput of the cognitive users for the proposed approach (sensing and transmission is performed simultaneously) with that of the conventional approach (sensing and transmission is performed alternatively). The simulation results reveal that the significant improvements in the throughput of the SUs have been achieved for proposed approach than that of the conventional approach. However, the proposed method has a drawback that is solved by an enhancement in the frame structure. Moreover, the frame structure enhancement also decreases the probability of frame collision between the primary and SUs. Thus, the data loss rate has been minimized by dividing the transmission time into small segments, which consist of the header overhead and data payload. It means that the PUs are adequately protected

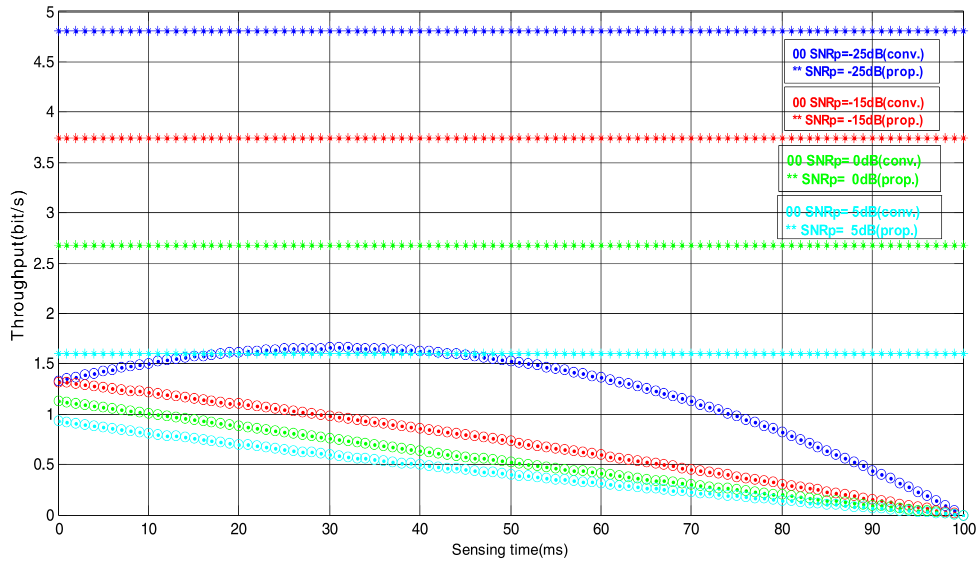


**Fig. 5** Throughput (bits/second) of the secondary users versus sensing time (ms) for several values of the SNR from the PU

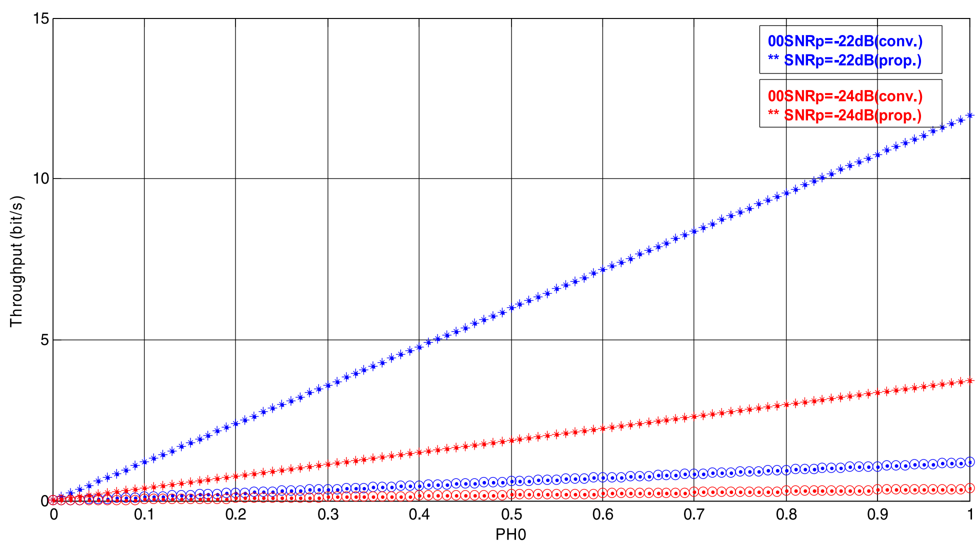


**Fig. 6** Throughput (bits/second) of the SUs versus probability of the PU being idle, $P(H_0)$ for several values the SNR from the primary user

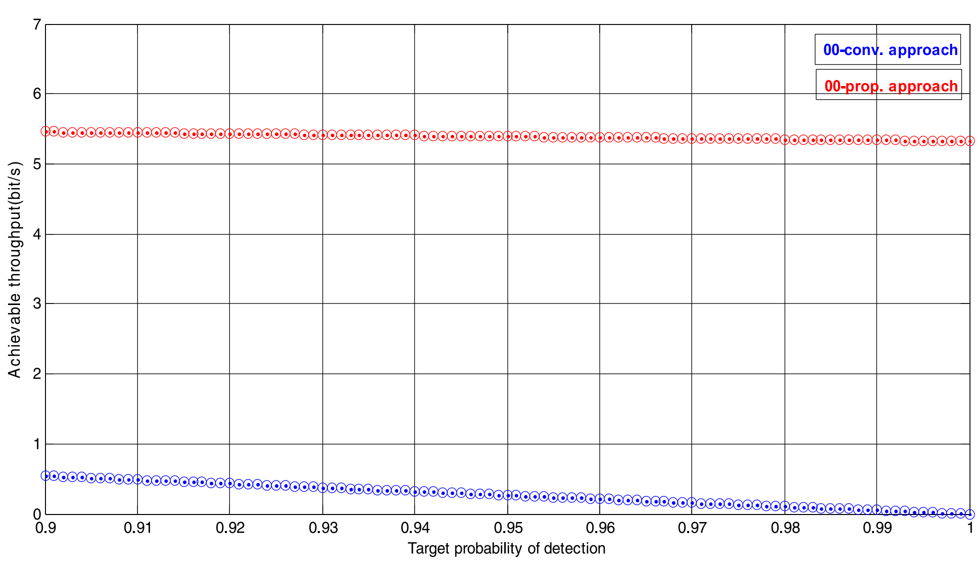


**Fig. 7** Throughput (bits/second) of the SUs versus target probability of detection for $SNR_p = -22$ dB

against the harmful interference produced by the SUs in the same frequency band.

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