Achievable Throughput Comparison of Sensing-Based and Interference-Constrained Transmissions in Cognitive Radio Networks

Gosan Noh and Daesik Hong
Yonsei University
Korea

1. Introduction

Cognitive radio has been introduced in order to solve the spectrum scarcity problem (Haykin 2005). Although having limited radio resources, we need lots of spectrum to deploy newly developed wireless applications. Meanwhile, a large portion of allocated spectrum is identified as unused by an actual radio spectrum measurement. Thus, a new access scheme which allows spectrum sharing between different wireless systems referred as dynamic spectrum access is required (Zhao & Sadler 2007). Dynamic spectrum access is based on cognitive radio technology which enables learning from and adapting to the external radio environment.

As a way of spectrum sharing between licensed and unlicensed users, spectrum overlay approach is considered. In spectrum overlay networks, a primary network has a license for the exclusive use of the allocated spectrum. In contrast, a secondary network has lower access priority. While the primary users access the licensed spectrum wherever and whenever they want, the secondary users access the spectrum on condition that the transmission of the primary network is sufficiently protected, i.e., the interference to the primary network should be less than a predefined threshold.

There are two ways for satisfying the protection condition: Sensing-based and interference-constrained transmissions. In sensing-based transmission, as a means of avoiding interference, the secondary users sense the spectrum before they start transmission (Liang et al. 2007; Kim et al.). Only if the secondary users detect the white space, they can access the spectrum. Even during the transmission, if the primary user uses the spectrum, the secondary user has to stop transmission. In interference-constrained transmission, on the contrary, the secondary users are allowed to transmit during the primary user transmission (Gastpar 2007). However, the transmit power should be adjusted not to interfere the primary user transmission.

In this chapter, we compare the two transmission schemes in terms of achievable throughput of the secondary user and provide a criterion for the transmission mode selection of sensing-based transmission and interference-constrained transmission.

The rest of this chapter is organized as follows. Section 2 presents the system model for the sensing-based and interference-constrained transmissions. Throughput analyses for both of the schemes are followed in Section 3. The simulation results are shown in Section 4. In Section 5, the conclusion is drawn.

2. System Model

A coexistence scenario of spectrum overlay between primary and secondary networks is depicted in Fig. 1. Primary and secondary networks are deployed in the overlapping regions and use the same frequency band. In Fig. 1, there are pairs of transmitter and receiver for the primary and secondary networks. We define channel gains between each pair of transmitter and receiver as e (from the primary transmitter to the primary receiver) and g (from the secondary transmitter to the secondary receiver). We also define the channel gains representing the interference between primary and secondary networks as f (from the secondary transmitter to the primary receiver) and h (from the primary transmitter to the secondary receiver).

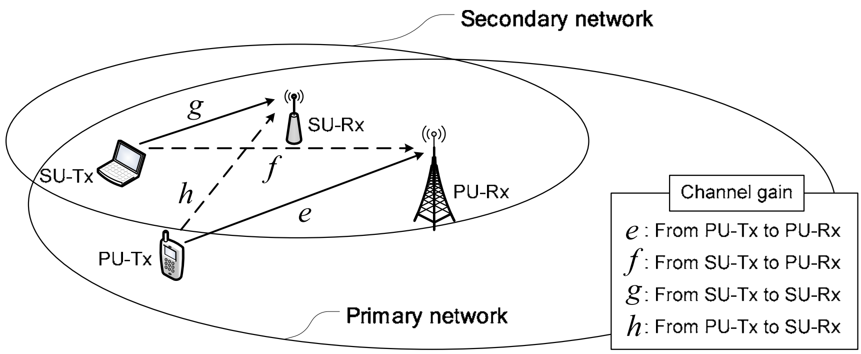

Fig. 1. A coexistence scenario of primary and secondary networks. Primary and secondary networks are over-deployed and interfere with each other.

The basic concept of spectrum overlay approach is to unlock licensed spectrum to secondary users. Secondary users can access the licensed spectrum on condition that their interference to primary users is limited. Possible solutions for this problem are sensing-based transmission and interference-constrained transmission. The difference of two schemes is based on the support for the simultaneous transmission.

In sensing-based transmission, the secondary user should sense the existence of the primary user in the licensed spectrum before transmission. Through the transmission, whenever the primary user accesses the licensed spectrum, the secondary user is required to stop transmitting and vacate the spectrum. Each secondary user frame is divided into a sensing slot and a data transmission slot. The time length that the secondary user senses the spectrum is sensing duration n_D and the time length between the consecutive sensing durations is sensing period n_P (Noh 2008).

In interference-constrained transmission, the secondary user can access while the primary user uses the spectrum. However, the power of the secondary user should be lessen so as to the QoS of the primary user is guaranteed. Without loss of generality, we employ a restriction that the interference power of the secondary transmitter measured at the primary receiver should be lower than a predetermined threshold.

3. Throughput Analysis

In this section, the achievable throughput of the secondary user by means of both sensing-based and interference-constrained transmission is presented and then compared in terms of location of terminals and the acceptable power level of the primary user.

3.1 Sensing-Based Transmission

The first thing to derive the secondary user throughput based on sensing-based transmission is evaluating the sensing accuracy. During the sensing duration, $r(n)$ denotes the primary user signal received by the secondary user. Then, the detection problem can be written as

$$\begin{aligned} \mathcal{H}_0 &: r(n) = w(n) \\ \mathcal{H}_1 &: r(n) = p(n) + w(n) \end{aligned} \tag{1}$$

for $n = 0, \dots, n_D - 1$. $\mathcal{H}_0$ denotes the noise only hypothesis and $\mathcal{H}_1$ denotes the primary user signal plus noise hypothesis. $p(n)$ is the primary user signal and $w(n)$ is the noise (Liang et al. 2007). The primary user signal $p(n)$ is assumed to be a zero-mean, complex-valued, circularly symmetric, white Gaussian random process with a variance σ_p^2. The complex-valued, circularly symmetric AWGN $w(n)$ with a variance σ_w^2 is independent of the primary user signal.

In order to detect the existence of a random signal such as p(n), an energy detector is applicable (Kay 1998). The decision rule is written as

$$T = \sum_{n=0}^{n_D-1} |r(n)|^2 \underset{\mathcal{H}_0}{\overset{\mathcal{H}_1}{\gtrless}} \eta \tag{2}$$

where T is the test statistic and η is the threshold.

Two probabilities are defined in conjunction with the detection procedure: false alarm probability and detection probability. False alarm probability P_{FA} is the probability to decide $\mathcal{H}_1$ but $\mathcal{H}_0$ is true. Detection probability P_D is the probability to decide $\mathcal{H}_1$ and it is true.

False alarm probability P_{FA} is given by

$$P_{FA} = \Pr\{T > \eta; \mathcal{H}_0\} = Q\left(\frac{\eta}{2\sqrt{n_D}\sigma_w^2} - \sqrt{n_D}\right) \tag{3}$$

where $Q(\cdot)$ is the right-tail probability for the Gaussian random variable (Kay 1998). Detection probability P_D is also given by

$$P_D = \Pr\{T > \eta; \mathcal{H}_1\} = Q\left(\frac{\sigma_w^2}{\sigma_p^2 + \sigma_w^2}\left(Q^{-1}(P_{FA}) - \frac{\sqrt{n_D}\sigma_p^2}{\sigma_w^2}\right)\right) \tag{4}$$

By rearranging (3) and (4) and canceling η, we have following relations:

$$P_{FA} = Q\left(\sqrt{n_D}\gamma_p + (1+\gamma_p)Q^{-1}(P_D)\right) \tag{5}$$

$$P_D = Q\left(\frac{1}{1+\gamma_p}\left(Q^{-1}(P_{FA}) - \sqrt{n_D}\gamma_p\right)\right) \tag{6}$$

where γ_p represents the signal-to-noise ratio (SNR) of the primary user, i.e., $\gamma_p = \sigma_p^2 / \sigma_w^2$. There is a tradeoff relationship between the false alarm probability and the detection probability. Lower false alarm probability gives the secondary user more chances to access the channel and higher detection probability guarantees the transmission of the primary user more strongly. However, realizing both the two goals are impossible. Hence, by using the tradeoff relationship above, the secondary user throughput can be derived. The secondary user succeeds in transmitting its data when there is no false alarm, where no false alarm means the primary user does not use the spectrum and the secondary user knows this information (Liang et al. 2007). The secondary user throughput of the sensing-based transmission is given by

$$C_{SB} = P_{idle}\frac{n_P - n_D}{n_P}\left(1 - P_{FA}\right)C_0 \tag{7}$$

such that $(1-P_D)|f|^2 P_s^{\max} \le \lambda$, where λ is the interference threshold at the primary receiver. This constraint means that the expected interference from the secondary transmitter experienced at the primary receiver should be lower than a predetermined threshold. This constraint is required to protect the transmission of the primary user.

However, in practical situations, we set as $(1-P_D)|f|^2 P_s^{\max} = \lambda$ so as to maximize the secondary user throughput. The reason comes from the fact that the monotonic increase of the detection probability (6). Thus we set the detection probability as $P_D = 1-\lambda/|f|^2 P_s^{\max}$. P_{idle} is the probability that the primary user does not uses the spectrum, which is given as: $P_{idle} = \mu/(\lambda+\mu)$. $(n_P - n_D)/n_P$ represents the ratio of the transmission time to the total time. C_0 denotes the capacity of the secondary user without any interference. C_0 is given by

$$C_0 = \log_2(1+\gamma_s) \tag{8}$$

where γ_s is the SNR of the secondary user.

3.2 Interference-Constrained Transmission

The secondary user throughput based on interference-constrained transmission is presented. Interference-constrained transmission allows the secondary user simultaneous transmission with the primary user. In this case, however, the primary user transmission also should be protected by means of power control of the secondary user. If the interference of the secondary user experienced by the primary receiver is strong, the power of the secondary transmitter should be lessened. Thus, the secondary user power is controlled so as to its interference at the primary receiver is lower than a predetermined threshold, i.e., $|f|^2 P_s \le \lambda$ (Gastpar 2007). P_s is the transmit power of the secondary user. Hence, the secondary user throughput of the interference-constrained transmission is given by

$$C_{\mathrm{IC}} = \log_2\left(1+\frac{|g|^2 P_s}{|h|^2 \sigma_p^2 + \sigma_w^2}\right) \tag{9}$$

such that $|f|^2 P_s \le \lambda$.

In order to maximize the secondary user throughput, the optimal strategy is that the interference power of the secondary user meets the threshold, i.e., $|f|^2 P_s = \lambda$. By this principle, the throughput (9) is rewritten as

$$C_{\mathrm{IC}} = \log_2\left(1+\frac{|g|^2 \lambda/|f|^2}{|h|^2 \sigma_p^2 + \sigma_w^2}\right) \tag{10}$$

Notice that there is an interference term in (10) which is comes from the primary transmitter and degrades the secondary user throughput.

Parameter	Value
λ	0.2 kpkts/s
μ	0.6 kpkts/s
n_D	30 samples
n_P	300 samples
W	1 MHz

Table 1. Common simulation parameters.

4. Simulation Results

In this section, the throughput performances of both the sensing-based and interference-constrained transmissions are evaluated by computer simulations. In a primary network, we assume that there is a primary transmitter and a primary receiver. Similarly, in a secondary network, there is a secondary transmitter and a secondary receiver.

We assume a cellular scenario where the primary network and the secondary network are over-deployed. Thus, we are interested in the distances between two terminals and base stations. The distance from the secondary transmitter to the primary receiver is denoted by l_f. l_f affects of the interference from the secondary user to the primary user. The distance from the secondary transmitter to the secondary receiver is denoted by l_g. l_g determines the signal quality of the secondary user. The distance from the primary transmitter to the secondary receiver is denoted by l_h. l_h affects of the interference from the primary user to the secondary user.

We consider the path loss and short-term fading as a channel model. Path loss exponent is assumed to be 4. In addition, Rayleigh block fading is assumed, where each of channel gain is circularly symmetric complex-Gaussian random variable. Hence, the channel gain f is decomposed into the path loss component and the Rayleigh fading component, i.e., $f = (l_f / l_0)^{-\alpha/2} \hat{f}$, where l_0 denotes a unit distance and $\hat{f}$ denotes a zero mean complex-Gaussian random variable or unit variance. Similarly, g and h are also decomposed into $g = (l_g / l_0)^{-\alpha/2} \hat{g}$ and $h = (l_h / l_0)^{-\alpha/2} \hat{h}$, respectively.

The primary user follows Markovian traffic, with arrival rate $\lambda = 0.2$ kpkts/s and service rate $\mu = 0.6$ kpkts/s. Thus, the time portion that the primary user is in idle state is given as $P_{idle} = 0.75$. For sensing-based transmission, we assumed an energy detector with the sensing duration $n_D = 30$ samples and the sensing period $n_P = 300$ samples. The system bandwidth is given by $W = 1$ MHz. We assume a full-traffic model, where the secondary user always has traffic to transmit. These common parameters are summarized in Table 1.

Under the sensing-based transmission, the secondary user throughput as a function of the SNR of the primary user is depicted in Fig. 2. It is observed that the secondary user throughput increases with the increase with the SNR of the primary user. As the SNR increases, the energy detection becomes more accurate and enhances the throughput of sensing-based transmission. In addition, The secondary user throughput increases with λ. With higher λ, the interference limit of the primary user is relaxed, the secondary user can transmit with higher power, and the throughput is enhanced.

Oppositely, under the interference-constrained transmission, the secondary user throughput as a function of the SNR of the primary user is shown in Fig. 3. Notice that the secondary user throughput decreases with the increase with the SNR of the primary user. Differently from the sensing-based transmission, as the SNR of the primary user increases, the interference from the primary transmitter greatly degrades the secondary user throughput as in (10). Similar to that of the sensing-based transmission, it is observed that the secondary user throughput increases with λ.

We then compare the throughput performance of the sensing-based transmission with the interference-constrained transmission in Fig. 4, Fig. 5, and Fig. 6.

Fig. 4 depicts the secondary user throughput of both the sensing-based and the interference-constrained transmission as a function of the interference threshold of the primary receiver. The secondary user throughput increases with the increase of λ in both schemes. However, there is a crossing point at about $\lambda = 0.05$. In low λ region, the sensing-based transmission achieves higher throughput, but in the high λ region, the interference-constrained transmission outperforms the other.

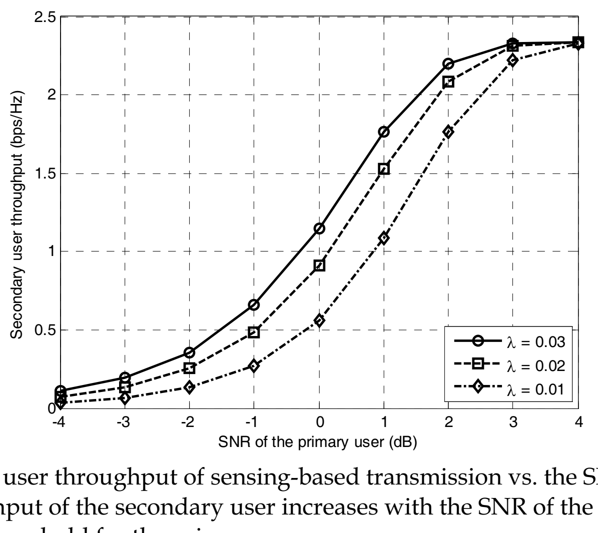

Fig. 2. Secondary user throughput of sensing-based transmission vs. the SNR of the primary user. The throughput of the secondary user increases with the SNR of the primary user and the interference threshold for the primary user.

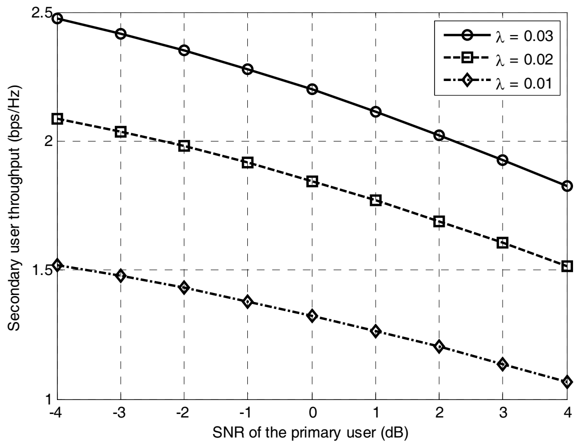

Fig. 3. Secondary user throughput of interference-constrained transmission vs. the SNR of the primary user. The throughput of the secondary user decreases with the SNR of the primary user but increases with the interference threshold for the primary user.

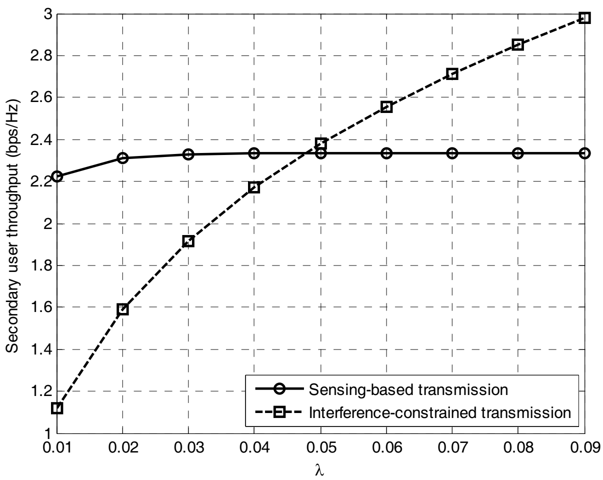

Fig. 4. Throughput comparison of the sensing-based and interference-constrained transmissions vs. the interference threshold of the primary receiver. The throughput of the sensing-based scheme is saturated as the threshold gets higher without saturation.

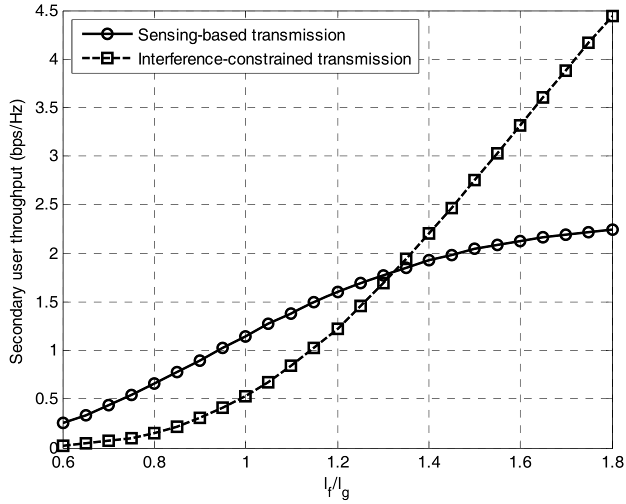

Fig. 5. Throughput comparison of the sensing-based and interference-constrained transmissions vs. the distance ratio l_f/l_g . The throughput is saturated in the sensing-based scheme while the throughput is sharply increasing in the interference-constrained scheme.

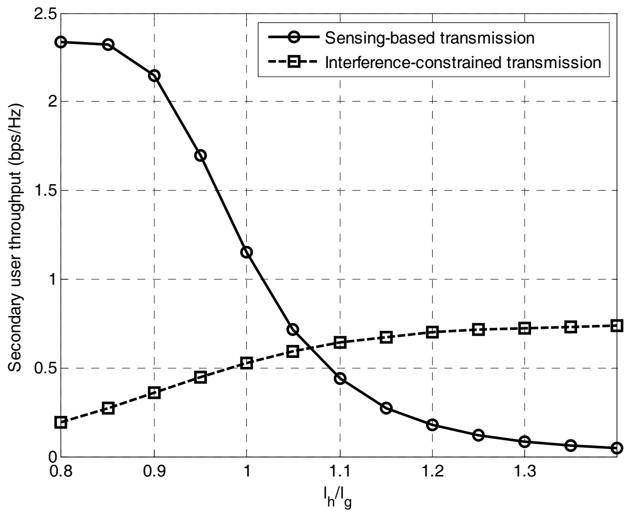

Fig. 6. Throughput comparison of the sensing-based and interference-constrained transmissions vs. the distance ratio l_h/l_g . The throughput by the sensing-based scheme decreases while that by the interference-constrained scheme increases.

Fig. 5 shows the secondary user throughput as a function of the distance ratio l_f / l_g . As l_f / l_g increases, the primary receiver becomes farther from the secondary transmitter. Then, the spectrum opportunity of the secondary user increases and the throughput is also increased. However, the throughput is saturated in the sensing-based scheme while the throughput is sharply increasing in the interference-constrained scheme. Thus, the effect of the interference threshold is more sensitive to the interference-constrained transmission.

Fig. 6 shows the secondary user throughput as a function of the distance ratio l_h / l_g . Notice that as l_h / l_g increases, the throughput by the sensing-based scheme decreases while that by the interference-constrained scheme increases. If the primary transmitter goes farther from the secondary receiver, it becomes difficult to sense the primary user and the throughput degrades in the sensing-based scheme but the interference decreases and the throughput is enhanced in the interference-constrained scheme.

7. Conclusion

We have discussed the achievable throughput of both the sensing-based and interference-constrained transmission in cognitive radio networks. The derivations of both schemes are presented and their throughput performances have been compared in various environments via computer simulations. In conclusion, the sensing-based scheme is advantageous when the interference threshold is tight and the primary and secondary users are relatively close. Oppositely, the interference-constrained scheme is better when the interference threshold is loose and the primary transmitter and receiver are located far from the secondary user.

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Cognitive radio is a hot research area for future wireless communications in the recent years. In order to increase the spectrum utilization, cognitive radio makes it possible for unlicensed users to access the spectrum unoccupied by licensed users. Cognitive radio let the equipments more intelligent to communicate with each other in a spectrum-aware manner and provide a new approach for the co-existence of multiple wireless systems. The goal of this book is to provide highlights of the current research topics in the field of cognitive radio systems. The book consists of 17 chapters, addressing various problems in cognitive radio systems.