A Novel Definition of Spectrum Holes for Improved Spectrum Utilization Efficiency

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Abstract

Improving spectrum utilization efficiency is a fundamental goal of dynamic spectrum access technology. The definition of spectrum holes determines how to detect and exploit them. Current definitions of spectrum holes are ineffective in exploiting spatial-temporal spectrum holes. In this paper, a novel definition of spectrum holes is proposed, in which **throughput loss** indicates the impact of secondary users on primary users. The definition specifies spectrum holes, unifies the impact of secondary users on primary users and is effective exploiting spatial-temporal spectrum holes. Theoretical analysis and numerical simulations show that the new definition proposed in this paper significantly improves the spectrum utilization efficiency.

1. Introduction

Radio frequency spectrum is a precious resource for wireless communication systems. With the rapid development of wireless communication services, there is an increasing demand for spectrum. Existing static spectrum allocations policies have resulted in the low utilization of spectrum[1-4]. The dynamic spectrum access (DSA) policy is proposed as an alternative to efficiently use radio spectrum[5-8]. In DSA, portions of the spectrum are allocated to one or more users, known as primary users (PUs). Spectrum use is not exclusively granted to these users, although they have a higher priority. Other users, referred to as secondary users (SUs), can also access the allocated spectrum, provided the PUs are properly protected. By doing so, the radio spectrum is reused opportunistically, thereby significantly improving the spectrum utilization[5-8].

Cognitive radio (CR) technology is an important means to realize DSA. Users with cognitive functions can sense the spectrum environment using intelligent means. They can automatically search and use available spectrum, thereby realizing authorized spectrum sharing[5-8]. In[9], a spectrum hole is defined as a (time, location, frequency-band)-tuple that a secondary user can use, while maintaining interference with all primary systems within an acceptable level.

In order to reuse the spectrum, a secondary user must be able to reliably identify a spectrum hole. In the above definition of a spectrum hole, the key factor is the impact of SUs on PUs. For a temporal spectrum hole, the impact refers to the probability when PUs and SUs simultaneously use the same spectrum. This has been referred to as the collision probability[10]. The collision probability ignores the position relationship between SUs and PUs, which is essential for exploiting spatial spectrum opportunities. For a spatial spectrum hole, this impact refers to power which is received by primary receiver from secondary transmitters, referred to as interference [11-13]. It alternately refers to the outage probability of the primary receiver, which is a function of the interference. The interference and the outage probability only reflect the intensity of the interfering signal. They does not reflect the duration of the interference. It also cannot fully reflect the impact of SUs on PUs. In [14], the Bayesian risk function was minimized by selecting the sensing threshold. This was a tradeoff between the risk of collision probability and secondary users losing communication opportunity.This tradeoff exploited both the temporal and spatial spectrum opportunity, and greatly improved the spectrum utilization. However, it lacks a theoretical basis. In [15], a three-region scheme for space-time spectrum sensing and access was designed with one primary transmitter at the center. This includes the black, grey, and white region. However, the authors have not jointly considered the interference and collision probability, as above, which doesn't fully reflect the impact of SUs on PUs.

In this paper, the average throughput loss percentage (hereafter referred to as throughput loss) of the PUs reflects the impact of SUs on PUs. The throughput loss is a comprehensive indicator, which contains the collision probability and intensity of interference. It unifies the impact of SUs on PUs in the spatial-temporal spectrum holes. Considering the throughput loss improves the spectrum utilization .In addition, the throughput loss is more intuitive, compared to Bayesian risk criteria. In this paper we design networks and channel models. Through theoretical analysis and numerical simulations, it is shown that the throughput loss is a more effective impact indicator than conventional indicators (e.g., collision probability, interference, and Bayesian risk) in terms of spectrum utilization.

The remainder of this paper is organized as follows. In section 2, we propose the spectrum holes definition with throughput loss as an impact indicator. In section 3, we introduce the networks and channel models to verify the definition. In section 4, we derive the optimal scheme of spectrum hole utilization in the models. In section 5, this definition is compared to conventional definitions of spectrum holes. In section 6, the numerical simulations and analysis are presented. In section 7, we conclude this research.

2. Spectrum Holes Definition

The definition of spectrum holes determines how to detect and exploit them. In this definition, the impact of SUs on PUs is a key factor. Conventional definitions of spectrum holes have many shortcomings. In this section, we first define spectrum holes with throughput loss as an impact indicator.

The average throughput loss percentage of PUs indicates the impact of SUs on PUs as

$$k = \frac{T_p^{\max} - T_p^{ave}}{T_p^{\max}} ? \ 100\% \tag{1}$$

where $T_p^{\max}$ is the maximum average throughput of PUs and T_p^{ave} is the average throughput of PUs. This can be predicted through channel models, provided a secondary transmitter (ST) is used.

The proposed definition of a spectrum holes is as follows:

Definition: a spectrum hole is defined as a (time, location, frequency-band)-tuple that a secondary user can use, while maintaining the throughput loss to all primary users in the specified frequency band within an acceptable level.

Choosing a suitable value for k is important. In a practical system, PUs cannot always work at the maximum average throughput. There is spare throughput against all kinds of interference. We choose a suitable value for k to guarantee QoS of the PUs and make the SUs attain the maximum throughput.

3. Network and Channel Models

3.1 Networks Model

As shown in **Fig. 1**, we consider a network model consisting of a pair of fixed PUs (including a primary transmitter (PT) and a primary receiver (PR)) and a pair of SUs (including a secondary transmitter (ST) and a secondary receiver (SR)). The SUs opportunistically exploit a spectrum band licensed to the PUs. Assume that the PUs are rate-adaptive digital communication systems, and occupy the spectrum band with a probability q.

In **Fig. 1**, PT is located in the origin of coordinates. The coordinates of PR, ST, and SR are labeled in the respective brackets. The angle between the communication direction from ST to SR and the X-axis is f. The angle between the communication direction from PT to PR and the X-axis is q. r is the distance from PT to ST. r_p and r_s denote the communication distance of the PUs and SUs, respectively. d_{ps} denotes the distance from PT to SR. d_{sp} denotes the distance from ST to PR.

$$d_{ps} = \sqrt{r^2 + r_s^2 + 2rr_s \cos f} \tag{2}$$

$$d_{sp} = \sqrt{r^2 + r_p^2 - 2rr_p \cos q} \tag{3}$$

In **Fig. 1**, the circles with radius d are the protected regions. Any active transmitter cannot be inside this region, to exclude the possibility that the receive signal and interference power reaches infinity. It's worth noting that the protected region of ST is used to exclude the possibility that the sensing receive power reaches infinity.
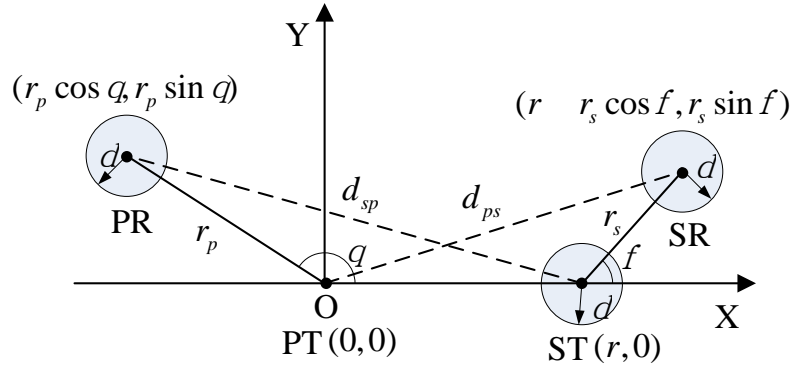

Fig. 1. Network model

3.2 Channel Model

Consider a wireless channel model with both large-scale path loss and small-scale fading. Free-space path loss, h_{PL}, models the average power changing with distance. Rayleigh fading h_{FD} is adopted for small-scale variation. The channel model between any Tx-Rx pair can then be written as follows:

$$h = h_{PL} ? h_{FD} \tag{4}$$

where $h_{FD} \sim \mathcal{CN}(0,1)$ is a complex circular Gaussian random variable with independent real and imaginary parts with equal variance; and

$$h_{PL} = \frac{A}{r^{a/2}} \tag{5}$$

where A is a constant dependent upon the frequency and transmitter/receiver antenna gain, r is the distance between the Tx-Rx pair, and a is the path loss exponent. Without loss of generality, we normalize $A = 1$ for simplicity and consider $a \geq 2$, which is typical in practical applications.

3.3 Signal and Sensing Models

To sense the primary transmission, ST must perform a hypothesis test between the following two hypotheses: $\mathcal{H}_0$ (primary signal absent) and $\mathcal{H}_1$ (primary signal present). This test is conducted as follows:

$$y(i) = \begin{cases} w(i) & : \mathcal{H}_0 \\ x(i) + w(i) & : \mathcal{H}_1 \end{cases} \quad (i = 1, 2, \cdots, N) \tag{6}$$

where N is the number of samples, $y(i)$ is the received samples at ST, $x(i) \sim \mathcal{CN}(0, s_x^2)$ is the signal received at ST from PT after path loss and fading, and $w(i)$ is assumed to be a circularly-symmetric complex Gaussian random variable with mean zero and one-sided power

spectral density s_w^2 , namely, $w(i) \square \ CN(0, s_w^2)$. Based on the channel model in (4), $s_x^2 = P_p h_{PL}^2 d$ where P_p is transmit power of PT. The primary signal $x(i)$ is independent of the noise $w(i)$.

The decision statistic is $Y = \frac{1}{N} \overset{N}{\underset{i=1}{\mathring{a}}} |y(i)|^2$. The probabilities of miss detection $p_m = \Pr \{\mathcal{H}_0 / \mathcal{H}_1\}$ and false alarm $p_f = \Pr \{\mathcal{H}_1 / \mathcal{H}_0\}$ are [16]:

$$p_m(e, N) = Q\left((g + 1 - \tfrac{e}{s_w^2})\sqrt{\tfrac{N}{2g+1}}\right) \tag{7}$$

$$p_f(e, N) = Q\left((\tfrac{e}{s_w^2} - 1)\sqrt{N}\right) \tag{8}$$

where g is the signal to noise ratio (SNR) at ST, $g = P_p r^{-a} s_w^{-2}$ in the above channel model, and e is the decision threshold. $Q(x) = \frac{1}{2p} \overset{¥}{\underset{x}{\mathring{O}}} \exp(-\tfrac{t^2}{2})dt$ is the tail probability of the standard normal distribution.

4. Optimization of Spatial-Temporal Spectrum

4.1 Channel States

In DSA, for a temporal spectrum hole, SUs cannot simultaneously operate in the same channel with the PUs. Collision between the SUs and PUs may only occur due to sensing errors. But for a spatial-temporal spectrum hole, we allow for it if the distance from PR is far enough. So, we model the spectrum access process as a four-state process, where state 0 means no user operates in the channel. State 1 means the PUs operate in the channel. State 2 means the SUs operate in the channel. State 3 means both the PUs and the SUs operate in the channel. The channel state set is $S \square \{0, 1, 2, 3\}$. It is assumed that PUs occupy the spectrum band with a probability q and SUs opportunistically occupy it. The probability in every channel state is, respectively:

$$\mathrm{P}_0 = (1 - q)p_f \tag{9}$$

$$\mathrm{P}_1 = q(1 - p_m) \tag{10}$$

$$\mathrm{P}_2 = (1 - q)(1 - p_f) \tag{11}$$

$$\mathrm{P}_3 = q p_m \tag{12}$$

4.2 Throughput Achieved in Every Channel State

In the system models described above, we assume the bandwidth is 1Hz. As the network model only consists of a pair of PUs and SUs, we replace the throughput with channel capacity [17]. The throughput of the PUs achieved in state1 is

$$R_1^p = \log_2 \left(1 + \frac{P_p r_p^{-a}}{s_w^2} \right) \tag{13}$$

The throughput of the SUs achieved in state2 is

$$R_2^s = \log_2\left(1 + \frac{P_s r_s^{-a}}{s_w^2}\right) \tag{14}$$

where s_w^2 is power of the additive white Gaussian noise (AWGN), P_p is the transmission power for the PUs, and P_s is the transmission power for the SUs.

We assume that the SUs and PUs can vary their data rate through a combination of adaptive modulation and coding. This allows the transmitter and receiver to employ the most reliable communication at the highest rate permitted, given the signal-to-interference-plus-noise ratio (SINR).We assume that they use random Gaussian codebooks. As a result, their transmitted signals can be treated as white Gaussian processes. The transmission of other users is treated as Gaussian noise. The maximal rate of users when the secondary user and the primary user share the spectrum can be represented as follows:

The throughput of the SUs achieved in state3 is

$$R_3^s = \log_2\left(1 + \frac{P_s r_s^{-a}}{s_w^2 + P_p d_{ps}^{-a}}\right) \tag{15}$$

The throughput of the PUs achieved in state3 is

$$R_3^p = \log_2\left(1 + \frac{P_p r_p^{-a}}{s_w^2 + P_s d_{sp}^{-a}}\right) \tag{16}$$

4.3 Optimization of Spatial-Temporal Spectrum for Proposed Definition

The average throughput of the SUs is

$$T_s = P_2 R_2^s + P_3 R_3^s = (1-q)(1-p_f)R_2^s + qp_m R_3^s \tag{17}$$

The average throughput of the PUs is

$$T_p^{ave} = P_1 R_1^p + P_3 R_3^p = qR_1^p - qp_m(R_1^p - R_3^p) \tag{18}$$

The maximum average throughput of the PUs is $T_p^{\max} = qR_1^p$.

Maximizing the available spatial-temporal spectrum opportunity using the spectrum holes definition in this paper can be formulized as follows:

$$\text{OP1:} \max_{p_f}\left((1-q)(1-p_f)R_2^s + qp_m R_3^s\right) \tag{19}$$

$$\text{Subject to: } qR_1^p - qp_m(R_1^p - R_3^p) ? (1 \quad k)qR_1^p \tag{20}$$

where $0 \# k \quad 1$ is a scaling factor that denotes the maximum average throughput loss ratio that is acceptable for PUs due to interference of the SUs. We first introduce the following proposition to solve this problem:

Proposition1: p_f is a decreasing function of p_m.

Proof: According to (7) and (8), we can obtain:

$$\frac{dp_f}{de} = -\frac{\sqrt{N}}{2ps_w^2}e^{-\frac{N(e-s_w^2)^2}{2s_w^4}} \tag{21}$$

$$\frac{dp_m}{de} = \frac{\sqrt{N(2g+1)}}{2p(2g+1)s_w^2} e^{-\frac{N(e-s_w^2-gs_w^2)^2}{2(2g+1)s_w^4}}$$ (22)

So,

$$\frac{dp_f}{dp_m} = \frac{dp_f}{de}?\frac{de}{dp_m} \quad 0$$ (23)

Therefore p_f is a decreasing function of p_m. Proposition 1 is proved.

The objective function in equation (19) is a decreasing function of p_f.

We can obtain from the constraint condition (20):

$$p_m ? kR_1^p \left(R_1^p \quad R_3^p\right)^{-1} = p_m^*$$ (24)

where p_m^* denotes the optimal miss detection probability. Because p_m is a decreasing function of p_f, the optimal false alarm probability is:

$$p_f^* = Q\left\{ \frac{殞}{譈} - \sqrt{\frac{2g+1}{N}} Q^{-1}\left(p_m^*\right) \sqrt{N} \right\}$$ (25)

It is worth noting that $kR_1^p \left(R_1^p - R_3^p\right)^{-1} > 1$ can occur when r is large enough. However, miss detection probability is not greater than 1. In this case, we order $p_m^* = 1$ and $p_f^* = 0$ to maximize the SUs throughput.

The maximum average throughput of the SUs is:

$$(1-q)(1-p_f^*)R_2^s + qp_m^*R_3^s$$ (26)

5. Comparison of the Proposed and Conventional Definitions

As stated in the introduction, the interference only reflects the intensity of the interfering signal. It does not reflect the duration of the interference signal. So, it cannot fully reflect the impact of SUs on PUs. We only consider the definition based on the collision probability constraint and the Bayesian risk in this section.

5.1 Comparison to the Collision Probability Constraint

We maximize the available spatial-temporal spectrum using the spectrum holes definition as follows [10]:

$$\text{OP2: } \max_{p_f}\left((1-q)(1-p_f)R_2^s + qp_mR_3^s\right)$$ (27)

$$\text{Subject to: } p_m £ \bar{p}_m$$ (28)

where $\bar{p}_m$ is the minimum miss detection probability. The inequality (28) constrains the collision probability between the PUs and the SUs. We easily obtain the optimal false alarm probability to maximize the SUs throughput as follows:

$$\bar{p}_f = Q\left\{ \frac{殞}{譈} - \sqrt{\frac{2g+1}{N}} Q^{-1}\left(\bar{p}_m\right) \sqrt{N} \right\}$$ (29)

The maximum average throughput of the SUs is:

$$(1-q)(1-\bar{p}_f)R_2^s + q\bar{p}_mR_3^s$$ (30)

In this case, the maximum value of k is:

$$k_m = \bar{p}_m (R_1^p - R_{3\min}^p) / R_1^p \tag{31}$$

where $R_{3\min}^p$ is the minimum value of R_3^p in the case of $d_{sp} = \max(r_p |\sin q|, d)$. Substituting k_m into (24), we obtain

$$\tilde{p}_m^* = \bar{p}_m (R_1^p - R_{3\min}^p)(R_1^p - R_3^p)^{-1} \tag{32}$$

Substituting (32) into (26), we obtain the maximum average throughput of the SUs in the case of $k = k_m$ in the proposed definition:

$$(1 - q)(1 - \tilde{p}_f^*)R_2^s + q\tilde{p}_m^* R_3^s \tag{33}$$

where $\tilde{p}_f^*$ is obtained by substituting $p_m^* = \tilde{p}_m^*$ into (25).

Subtracting (30) from (33), we obtain the following:

$$(\bar{p}_f - \tilde{p}_f^*)(1 - q)R_2^s + (\tilde{p}_m^* - \bar{p}_m)qR_3^s \tag{34}$$

It is easy to prove (34) is greater than zero. That is, the definition of spectrum holes based on the throughput loss is more advantageous than the one based on the collision probability constraint in terms of spectrum utilization.

The traditional scheme uses (29), while the proposed scheme uses (25). The computing complexity of the proposed scheme is not much higher than that of the traditional scheme. However, the overhead in the proposed scheme is more than the traditional schemes due to the information required to transmit. The additional overhead is limited in small-scale network.

5.2 Comparison to the Bayesian Criteria

Using Bayesian criterion, the optimization objective is defined as a risk function involving the miss detection and false alarm probabilities as follows [14]:

$$\mathcal{R} = b(I_{ps} + I_{sp})qp_m(e) + L_s(1 - q)p_f(e) \tag{35}$$

where I_{ps} is the interference power from the PT to the SR, I_{sp} is the interference power from the ST to the PR, and L_s is the signal power received by the SR. Both p_m and p_f are a function of the detection threshold e. $b \geq 1$ is the penalty parameter to place a higher priority on the PUs link.

The sensing threshold is designed to minimize the risk in the different cases of location information:

$$\left. \frac{d\mathcal{R}}{de} \right|_{e = e^*} = 0 \tag{36}$$

and

$$\left. \frac{d^2\mathcal{R}}{de^2} \right|_{e = e^*} > 0 \tag{37}$$

Substituting (31) and (32) into (36), we obtain

$$e^2 - s_w^2 e - C = 0 \tag{38}$$

where

$$C = gs_w^4 / 2 + \frac{(2g + 1)s_w^4}{gN} \ln \frac{L_s(1 - q)\sqrt{2g + 1}}{b(I_{ps} + I_{sp})} \tag{39}$$

We obtain the optimal detection threshold:

$$e^* = \begin{cases} \frac{1}{2}\left(s_w^2 + \sqrt{s_w^4 + 4C}\right) & s_w^4 + 4C \ ? \ 0 \\ + ? & s_w^4 + 4C < 0 \end{cases} \tag{40}$$

Substituting e^* into (7) and (8), we obtain $p_m(e^*)$ and $p_f(e^*)$. From (17), we obtain the optimal throughput of the SUs.

The traditional scheme uses (40), while the proposed scheme uses (25). The computing complexity of the proposed scheme is not much higher than the traditional scheme. Additionally, the overhead in the proposed scheme is nearly equivalent to the traditional schemes, as both needs to transmit more information.

6. Numerical Simulation and Analysis

Numerical simulations in **Fig. 2**, **Fig. 3**, and **Fig. 4** were conducted using the conditions described in **Table 1**.

Table 1. the Parameters and Their Value in the Following Numerical Simulations

| Parameter	Physical Meaning	Value in Fig. 2	Value in Fig. 3	Value in Fig. 4
N	the number of samples	20	20	10~160
r	distance from PT to ST	0.1~20m	12m	13m
q	the probability that the PUs occupy the authorized spectrum band	0.4	0.1~0.9	0.4
q	angle between the communication direction from PT to PR and X-axis	90°	90°	90°
f	angle between the communication direction from ST to SR and X-axis	0°	0°	0°
s_w^2	one-sided power spectral density	0.0001W/Hz	0.0001W/Hz	0.0001W/Hz
a	the pathloss exponent	4.2	4.2	4.2
P_p	transmission power of PT	1W	1W	1W
r_p	communication distance of the PUs	8m	8m	8m
P_s	transmission power of ST	0.5W	0.5W	0.5W
r_s	communication distance of the SUs	4m	4m	4m
d	radius of protected region	0.1m	0.1m	0.1m

Fig. 2 shows that the throughput of the SUs for different definitions varies with the distance, r. It is worth noting the selection of the throughput loss percentage of PUs, k. Let the penalty parameter $b = 1$. We obtain the optimal threshold e^* from (40). We then obtain $p_m(e^*)$ and $p_f(e^*)$ from (6) and (7). By substituting them into (17) we obtain the throughput of the SUs. At the same time, we calculate the throughput loss percentage k. With r varying from 0.1m to 20m, we select the maximum value of k as the throughput loss percentage. The throughput of the SUs is optimized as described in section4.3, with the maximum value of k. $\bar{p}_m$ is obtained from (31). The throughput of the SUs is optimized as described in section5.1 using $\bar{p}_m$.

Fig. 2 shows that the throughput of the SUs for the proposed definition is greater than that of the definitions in [10] and [14]. As r increases, the advantage of the proposed definition is

more obvious compared to other definitions. This is because the definition in [10] is for temporal spectrum holes. However, as r increases, the SNR decreases. The false probability increases to satisfy the relatively small collision probability. As a result, the SUs lose spatial spectrum. When $r > 10$, the throughput sharply decreases. However, for the definition in [14] and the proposed definition, the SUs utilize both temporal and spatial spectrum holes. As r increases, the influence of ST on the PR decreases. We increase the collision probability P_3 to utilize more spatial spectrum opportunity. There is obvious improvement in the throughput of the SUs. In [14], the optimization objective is a risk function $\mathcal{R}$, not the throughput of SUs. Therefore, compared with the Bayesian criterion, the throughput of the SUs increases significantly with the proposed definition.
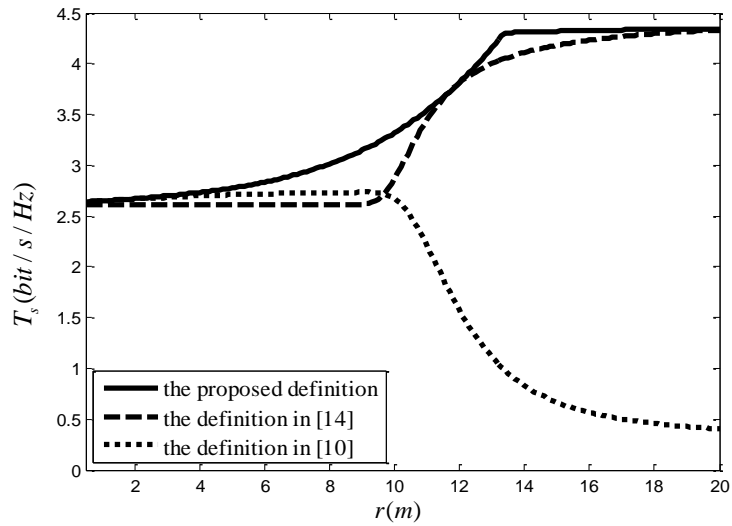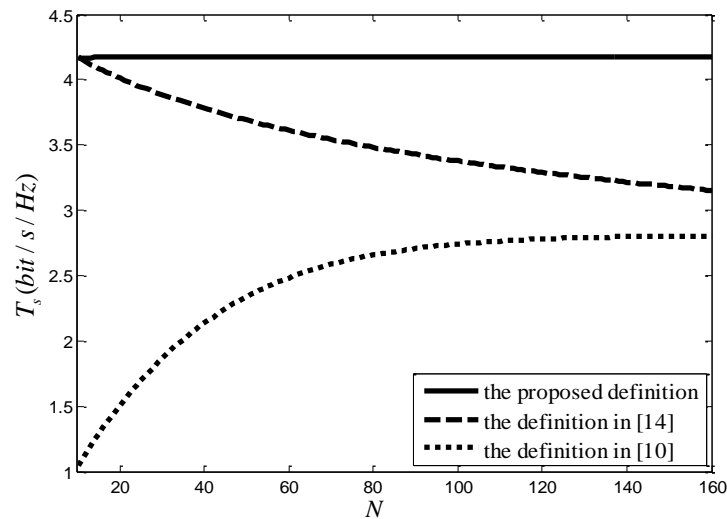

Fig. 2. Throughput comparison of SUs
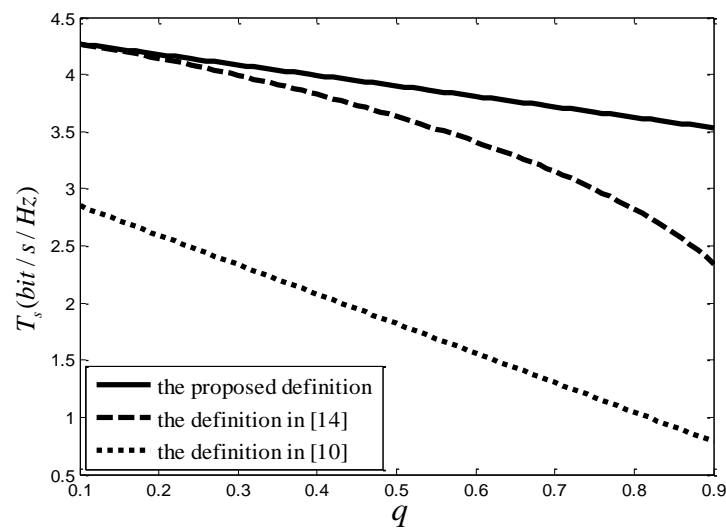
Fig. 3. Throughput comparison of SUs vs. q

Fig. 3 shows the throughput of SUs for different definitions varies with the probability q.
As shown, the throughput of the SUs for all definitions decreases as q increases. This is because the increase in q results in less temporal spectrum holes for SUs to utilize. In this process, the throughput for the proposed definition decreases less than that of the other definitions. This is because, in the case of $r = 12$, the SUs mainly utilize spatial spectrum holes.

Fig. 4 shows the throughput of SUs for different definitions with various numbers of samples N. It is shown that the throughput of the SUs for all definitions vary as N increases. For the proposed definition, it nearly remains unchanged. For the definition in [10], the throughput increases. However, for the definition in [14], it decreases. This shows that the proposed definition is insensitive to sensing accuracy.

Fig. 4. Throughput comparison of SUs vs. N

7. Conclusion

In this paper, throughput loss is used to indicate the impact of SUs on PUs. This specifies the definition of spectrum holes, and unifies the impact of SUs on PUs in the spatial-temporal spectrum holes. In a typical cognitive radio system, theoretical analysis and numerical simulations show that, when compared to previous definitions of spectrum holes, the proposed definition significantly improves the spectrum utilization, and is insensitive to sensing accuracy.

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