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Interference-constrained adaptive simultaneous spectrum sensing and data transmission scheme for unslotted cognitive radio network

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Abstract

Cognitive radio (CR) is widely recognized as a novel approach to improve the spectrum efficiency. However, there exists one problem needed to be resolved urgently, that is the two conflicting goals in CR network: one is to minimize the interference to primary (licensed) system; the other is to maximize the throughput of secondary (unlicensed) system. Meanwhile, the secondary user (SU) has to monitor the spectrum continuously to avoid the interference to primary user (PU), thus the throughput of the secondary system is affected by how often and how long the spectrum sensing is performed. Aiming to balance the two conflicting goals, this article proposes a novel Interference-Constrained Adaptive Simultaneous spectrum Sensing and data Transmission (ICASST) scheme for unslotted CR network, where SUs are not synchronized with PUs. In the ICASST scheme, taking advantage of the statistic information of PU's activities, the data transmission time is adaptively adjusted to avoid the interference peculiar to unslotted CR network; the operation of spectrum sensing is moved to SU receiver from SU transmitter to increase the data transmission time and hence improve the throughput of SU. Simulation results validate the efficiency of ICASST scheme, which significantly increases the throughput of secondary system and decreases the interference to PU simultaneously.

1 Introduction

Cognitive radio (CR) [1,2] is one of the most promising and revolutionary technologies to improve the spectrum efficiency by allowing secondary users (SUs) to access the temporarily unoccupied spectrum allocated to primary users (PUs). So far, two kinds of CR network have been discussed: one is the *slotted CR network* where SUs only needs to detect PUs at some specified moments to learn the accurate state of the spectrum [3]; the other is the *unslotted CR network*, where PU may access the channel at any time, e.g., when SU is temporarily transmitting data on the spectrum [4]. Obviously, considering the heterogeneity of primary network and discontinuity of the allocated spectrum, the unslotted CR network model is more realistic but faces more challenges. Thus, this article mainly focus on the unslotted CR network.

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In the design of CR network, especially for the unslotted CR network, there exist two conflicting goals, namely, to minimize the *interference* to primary system and to maximize the *throughput* of secondary system [5]. The aim of this article is to design a novel spectrum sensing and data transmission scheme to strike a good balance between the two conflicting goals for unslotted CR network.

As for the interference to PU in the unslotted CR network, it can be classified into two categories: *missed-detection interference* and *unslotted interference*. The missed-detection interference is caused by the missed detection in spectrum sensing due to the noise uncertainty and wireless fading channel [6,7]. The unslotted interference results from the fact that SU cannot precisely predict the time PU accesses the channel again. There has been an extensive research on missed-detection interference, such as decreasing it through cooperative spectrum sensing [8,9], limiting it by maximizing the throughput or sensing efficiency [10,11] and so on. However, the research on the unslotted interference is still in its early stage, and existing research mainly includes: Zvaifler et al. [4] adds a prediction time slot to predict the state of channel in the next time slot; Kohavi [12] decides whether to sense the channel or to transmit data based on previous sensing results, and Ref [13] adaptively adjusts the transmission time based on the prior knowledge of PU's activity. Nevertheless, [4,12,13] only decrease the unslotted interference and don't take the throughput of secondary system into account and hence don't resolve the two conflicting goals. Hence, this article mainly focuses on simultaneously increasing the throughput and decreasing the unslotted interference.

As for the throughput of secondary system, it is affected by how often the spectrum sensing takes place and the durations of spectrum sensing. This is because that SU has to monitor the spectrum continuously to avoid the interference to PU, which inevitably decreases the data transmission time and hence the throughput of secondary system. Generally, the CR system adopts the periodic sensing strategy, as depicted in Figure 1, where each frame consists of one spectrum sensing slot t_s and one data transmission slot T_p - t_s. The length of t_s is chosen to maximize the channel utilization [3], sensing efficiency [10] or system throughput [14], while limiting the interference to PU. But [3,10,14] still don't get rid of the influence of spectrum sensing on throughput in essence. Although recently [15] proposes a scheme where the throughput is not influenced by spectrum sensing, it only considers the missed-detection interference and doesn't consider the unslotted interference. Besides, the throughput of secondary system is limited in the scenario where PU reclaims the channel and there is no other idle channel to switch to, and relative research has been done about this scenario. Ref [16] designs a link maintenance protocol to achieve continuous communication for SU, Refs [17,18] suggests transmitting data on the channel at a lower transmission power assuming SU always has data to transmit. This article aims to increase the throughput of secondary system by jointly considering the influence of spectrum sensing.

To resolve the two conflicting goals in unslotted CR network, this article proposes a novel Interference-Constrained Adaptive Simultaneous spectrum Sensing and data Transmission (ICASST) scheme. In the ICASST scheme, exploiting the statistic information of PU's activities, the unslotted interference is decreased by adaptively adjusting the data transmission time; the throughput of secondary system is significantly increased by enabling simultaneous spectrum sensing and data transmission. The ICASST scheme consists of two stages: Stage I is designed for the situation where there exists idle channel; Stage II is designed for the scenario where no channel is sensed idle but SU still has data to transmit. In Stage II, SU decides whether to transmit data at a lower power according to the length of SU's queue, where the transmission power is limited by PU's outage probability.

The remainder of this article is organized as follows. Section 2 presents the PUs' activity model and the SU's queueing model. Section 3 depicts the frame structure and procedures of ICASST scheme. Sections 4 and 5, respectively, gives the theoretical analysis of Stage I and Stage II of ICASST scheme. The simulation results in Section 6 validate the efficiency of ICASST scheme and evaluate its cost. Finally, this article is concluded in Section 7.

2 System model

In this article, perfect spectrum sensing is assumed based on the following two facts: first, how often and how long the spectrum sensing is performed have bigger influence on the overall performance of CR network than the spectrum sensing algorithms itself; secondly, this article mainly focuses on the unslotted interference rather than the missed-detection interference. Subsequently, the PU's activity model and SU's queueing model are introduced, respectively.

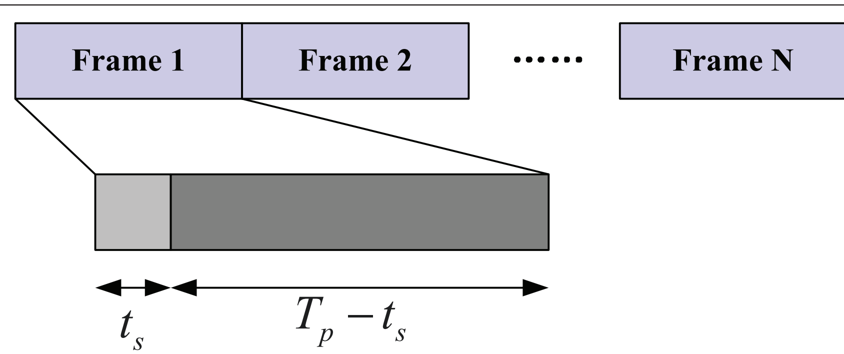

Figure 1 Frame structure of the periodic spectrum sensing.

2.1 The PU's activity model

The PU's activity is modeled as a renewal process alternating between ON (busy) state and OFF (idle) state. The ON state represents that the channel is used by PU, while the OFF state means that the channel is unused. Let random variables τ_1 and τ_0 represent the sojourn time of ON and OFF states, respectively, and assume that τ_1 and τ_0 are independent of each other. Denote $f_1(s)$ and $f_0(s)$ as the probability density functions (PDF) of τ_1 and τ_0. The channel utilization u is defined as follows:

$$u = \frac{\int_0^{\infty} sf_1(s)ds}{\int_0^{\infty} sf_1(s)ds + \int_0^{\infty} sf_0(s)ds} = \frac{\bar{\tau}_1}{\bar{\tau}_1 + \bar{\tau}_0} \quad (1)$$

where $\bar{\tau}_1$ and $\bar{\tau}_0$ denote the average sojourn time of ON and OFF state, respectively.

2.2 The SU's queueing model

In this article, we assume that the CR system adopt a queue to prevent the packet loss and store the unprocessed data temporarily. The queueing system model [19] is shown in Figure 2, the arrival process is molded as a Poisson process and $A(t)$ represents the amount of arrival data (in bits) over the time interval $[0, t)$, $R(t)$ denotes the amount of the departure data in the time interval $[0, t)$, $Q(t)$ is the length of queue at time t and the buffer size is L bits.

3 Overall description of ICASST scheme

To illustrate the ICASST scheme explicitly, first, the related symbols are given in Table 1 then, the frame structure and procedures are shown in Sections 3.1 and 3.2, respectively.

3.1 Frame structure of ICASST scheme

Figure 3 demonstrates the frame structure of the proposed ICASST scheme, which is divided into two stages. In ICASST scheme, both of the transmission time in Stage I and Stage II are adaptively adjusted. As illustrated in the bottom of Figure 3, spectrum sensing is performed at SU Rx (receiver), which firstly decodes the data transmitted from SU Tx (transmitter) treating the PU's signal as interference, and then utilizes the remainder of the decoded signal to detect PU's signal.

Stage I occurs when SU Rx reports to SU Tx that the channel is idle and SU Tx happens to have data to transmit. According to the prior statistic knowledge of PU's activity, SU Tx firstly estimates the switch point t_{sp1}, and then calculates the adaptive transmission time T_1^i based on the estimated t_{sp1}. Subsequently, SU Tx transmits data within the time interval T_1^i, meanwhile, SU Tx informs SU Rx of the adaptive T_1^i. After that, SU Rx feeds the sensing result back to SU Tx at the end of T_1^i. At last, SU Tx decides whether to continue Stage I or start Stage II in accordance with the sensing result.

Stage II is started when current channel is reclaimed by PU but there exists no idle channel to switch to. First, when SU RX informs SU Tx that no idle channel is sensed, SU Tx decides whether to transmit data in the light of the queue's length $Q(t)$. If $Q(t) < Q_{th}$, then SU Tx transmits data at a lower transmit power P_s, which is constrained by PU's outage probability. Furthermore, the transmission time T_2^j is also adaptively adjusted to limit the missed spectrum opportunity, which is defined as the available time interval that is not discovered by the SU. Similarly, SU Tx sends the T_2^j to SU Rx, and SU Rx feeds the sensing result back to SU Tx at the end of T_2^j. According to the sensing result, SU Tx decides whether to continue Stage II or restart Stage I.

3.2 Pseudocode of ICASST Scheme

To make ICASST scheme clearer, the pseudocode of Stages I and II are given in Tables 2 and 3, respectively.

4 Stage I: interference time constrained adaptive simultaneous spectrum sensing and data transmission

In Stage I, the data transmission time is adaptively adjusted subject to the interference time constraint. Here, we assume that the SU Tx know the statistical

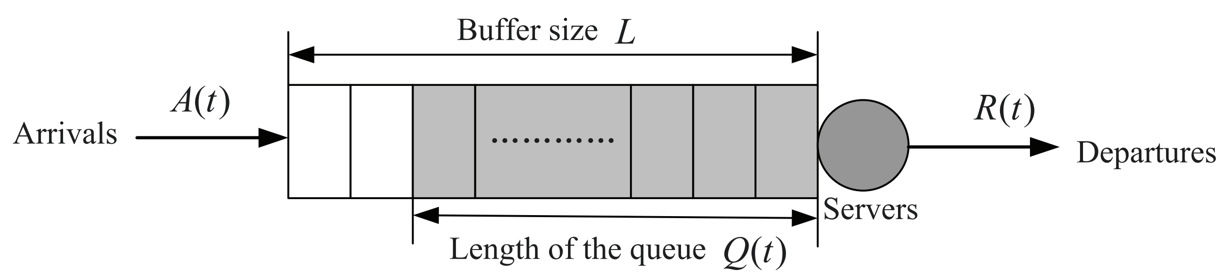

Figure 2 Queueing system model.

Table 1 Notations

Symbol	Meaning
t_{sp1}	the most recent time when the channel switches from ON state to OFF state
t_i	the time of the ith data transmission of SU in Stage I
$T_1^i = t_{i+1} - t_i$	the ith data transmission time period in Stage I
t_{sp2}	the most recent time when the channel switches from OFF state to ON state
t'_j	the time of the jth data transmission in Stage II
$T_2^j = t'_{j+1} - t'_j$	the jth data transmission time period of Stage II
P_s	the transmission power of SU in Stage II
Q_{th}	the threshold to the queue length of SU transmitter in Stage II

information of the PU's activity, including the mean, the variance and the PDF of PU's ON and OFF periods.

4.1 Adaptive algorithm for adjusting the transmission time T_1^i in Stage I

The aim of the adaptive algorithm is to limit the interference time generated in the scenario where the licensed channel switches from OFF state to ON state while SU Tx is transmitting data on the channel.

Given that the channel is in OFF state at t_i, the conditional probability that the channel keeps being in OFF state during T_1^i is

$$\Pr\{\mathcal{H}_0(t_{i+1})|\mathcal{H}_0(t_i)\} = \frac{\int_{t_i+T_1^i-t_{sp1}}^{\infty} f_1(s)ds}{\int_{t_i-t_{sp1}}^{\infty} f_1(s)ds} = \frac{1-F_0(t_i+T_1^i-t_{sp1})}{1-F_0(t_i-t_{sp1})} \quad (2)$$

where $\mathcal{H}_0(t)$ denotes that the channel is in OFF state at time t, and $\mathcal{H}_1(t)$ denotes that the channel is in ON state at time t. Then, the probability that the channel turns from OFF state to ON state at the time of t_{i+1} is

$$\Pr\{\mathcal{H}_1(t_{i+1})|\mathcal{H}_0(t_i)\} = 1 - \Pr\{\mathcal{H}_0(t_{i+1})|\mathcal{H}_0(t_i)\} = \frac{F_0(t_i+T_1^i-t_{sp1})-F_0(t_i-t_{sp1})}{1-F_0(t_i-t_{sp1})} \quad (3)$$

Similarly, the probability that the channel switches from OFF state to ON state in the middle of the ith transmission is

$$\Pr\{\mathcal{H}_1(t_i+s)|\mathcal{H}_0(t_i)\} = 1 - \Pr\{\mathcal{H}_0(t_i+s)|\mathcal{H}_0(t_i)\} = \frac{F_0(t_i+s-t_{sp1})-F_0(t_i-t_{sp1})}{1-F_0(t_i-t_{sp1})} \quad (4)$$

where $0 < s < T_1^i$. The PDF of the residual time s of channel's OFF state is the derivative of (4) with respect to s:

$$f_{R1}(s) = \frac{f_0(t_i+s-t_{sp1})}{1-F_0(t_i-t_{sp1})},\ 0 < s < T_1^i \quad (5)$$

Then, the average interference time is calculated as follows:

$$I(T_1^i, c_1) = \int_0^{T_1^i} (T_1^i - s) f_{R1}(s)ds = \frac{(T_1^i+c_1)[F_0(T_1^i+c_1)-F_0(c_1)] - \int_{c_1}^{T_1^i+c_1} s f_0(s)ds}{1-F_0(c_1)} \quad (6)$$

where $c_1 = t_i - t_{sp1}$ is the time interval starting from the most recent channel switch point t_{sp1} to the ith SU transmission.

It can be seen from (6) that the interference time $I(T_1^i, c)$ is related to the transmission time interval T_1^i

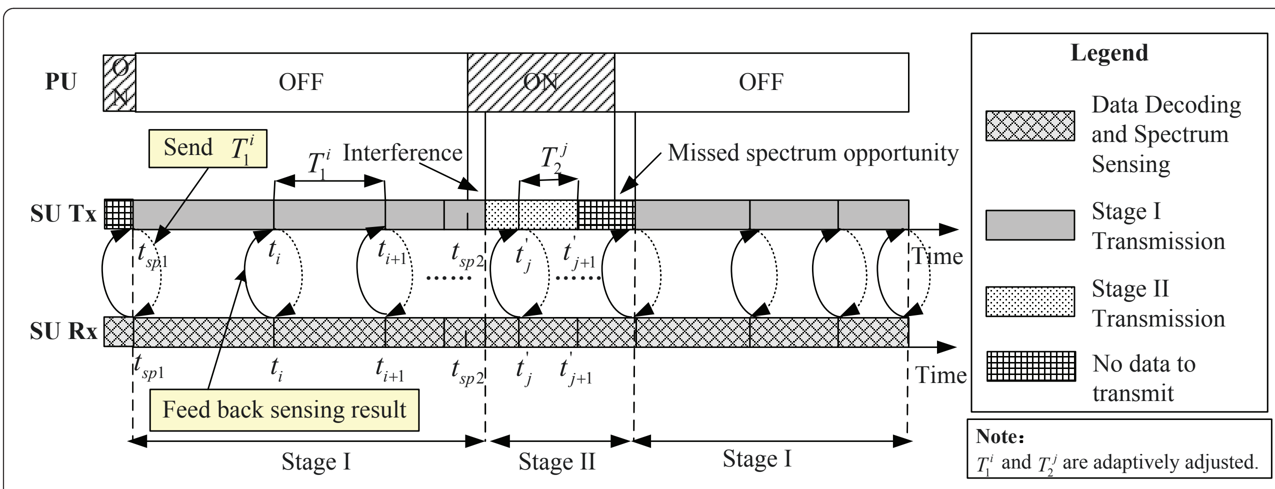

Figure 3 Frame structure of the proposed ICASST scheme.

Table 2 Pseudocode of the Stage I in ICASST Scheme

```
Stage I Adaptive Transmission
{
    SET the index i to 1;
    Estimate t_sp1 with the algorithm stated in Section 4.2;
    Adaptation: Calculate T_1^i according to the algorithm stated in
    Section 4.1;
    SU Tx sends T_1^i to SU Rx;
    SU Tx transmits data within the transmission time T_1^i;
    SU Rx feeds the sensing result ChannelState back to SU Rx at the
    end of T_1^i;
    i = i + 1;
    IF ChannelState = Busy THEN
        CALL Stage II Adaptive Transmission;
    ELSE
        GOTO Adaptation;
    END IF
}
```

and the time interval c_1. While the second variable c_1 can't be controlled, the interference time $I(T_1^i, c_1)$ is limited by adjusting the transmission time interval T_1^i. It is noticed that the interference time $I(T_1^i, c_1)$is a monotonically increasing function of T_1^i, because the derivative of (6) with respect to T_1^i is positive, that is to say

$$\frac{\partial I(T_1^i, c_1)}{\partial T_1^i} = \frac{F_0(T_1^i + c_1) - F_0(c_1)}{1 - F_0(c_1)} > 0 \tag{7}$$

Let α represents the prescribed interference parameter, considering $I(T_1^i, c_1)$ is a monotonically increasing function of T_1^i, the optimal transmission time interval $T_{1,\mathrm{opt}}^i$ satisfying the interference limit is

$$\begin{aligned} &\max T_1^i \\ &\text{s.t. } I(T_1^i, c_1) = \frac{(T_1^i + c_1)[F_0(T_1^i + c_1) - F_0(c_1)] - \int_{c_1}^{T_1^i + c_1} s f_0(s) ds}{1 - F_0(c_1)} \le \alpha \end{aligned} \tag{8}$$

What is worth mentioning is that larger α results in larger interference time $I(T_1^i, c_1)$, larger transmission time T_1^i and hence larger throughput of secondary system. Therefore, α can be seen as a tradeoff parameter between the interference time and the throughput of secondary system.

Equation (8) shows that $T_{1,\mathrm{opt}}^i$ is a function of c_1, and $T_{1,\mathrm{opt}}^i$ declines dramatically to a very small value with the increase of c_1. However, in reality every system has a minimum transmission time interval $T_{1,\ \mathrm{min}}$. Besides, the maximum transmission time interval $T_{1,\ \mathrm{max}}$ is given to further limit the interference. Here, we suggest setting $T_{1,\ \mathrm{max}}$ to be $\max_x f_0(x)$. Therefore, the adaptive transmission time $T_{1,\mathrm{adp}}^i$ is set to be

$$T_{1,\mathrm{adp}}^i = \max\{T_{1,\min}, \min\{T_{1,\max}, T_{1,\mathrm{opt}}^i\}\} \tag{9}$$

Table 3 Pseudocode of the Stage II in ICASST Scheme

```
Stage I Adaptive Transmission
{
    SET the index j to 1;
    Judgement: IF Q(t) > Q_th THEN
        Estimate t_sp2 with the algorithm stated in Section 5.3;
        Calculate T_2^j according to the algorithm stated in Section 5.2;
        SU Tx sends T_2^j to SU Rx;
        Calculate the transmission power P_s with the algorithm stated
        in section 5.1;
        SU Tx transmits data with transmission time T_2^j and
        transmission power P_s;
        SU Rx feeds the sensing result ChannelState back to SU Rx at
        the end of T_2^j;
        j = j + 1;
        IF ChannelState = Idle THEN
            CALL Stage I Adaptive Transmission;
        ELSE
            GOTO Judgment;
        END IF
ELSE
    SU Tx waits T_w seconds;
        GOTO Judgment;
END IF
    }
```

4.2 Algorithm for estimation of t_{sp1}

It is clear from (6), (8), and (9) that the calculation of the adaptive transmission time $T_{1,\mathrm{adp}}^i$ depends on the information of the switch point time t_{sp1}. Thus, it is very important to estimate t_{sp1} for the proposed ICASST algorithm. Denote t'_{sp1} and $\hat{t}_{\mathrm{sp1}}$ as the old channel switch point and the estimated new channel switch point, respectively, and the real value of the new switch point is $t_{\mathrm{sp1}} = t_i + s$.

In this article, minimum mean square error (MMSE) principle is adopted to estimate the new channel switch point t_{sp1}. Given that the channel state is ON at t_{i+1} and is OFF at t_i, the conditional probability density function of the residual time s of channel's OFF state is:

$$f_{R1|t_i}(s) = \frac{f_{R1}(s)}{\Pr\{\mathcal{H}_1(t_i + T_1^i)|\mathcal{H}_0(t_i)\}} = \frac{f_0(t_i + s - t'_{\mathrm{sp1}})}{F_0(t_i + T_1^i - t'_{\mathrm{sp1}}) - F_0(t_i - t'_{\mathrm{sp1}})}, 0 < s < T_1^i \tag{10}$$

Then the mean squared estimation error ε between the estimated value $\hat{t}_{\mathrm{sp1}}$and real value t_{sp1} is

$$T_2^j \tag{11}$$

where $c_1' = t_i - t_{\text{sp1}}'$ is the time interval between the old channel switch point t_{sp1}' and the ith transmission.

The optimal estimate of the new channel switch point t_{sp1}^* is the one which minimizes the mean squared estimation error ε, and the expression of t_{sp1}^* is

$$t_{\text{sp1}}^* = \arg \min_{t_i < \hat{t}_{\text{sp1}} < t_i + T_1^i} \left\{ \varepsilon = E\left[\left(\hat{t}_{\text{sp1}} - t_{\text{sp1}} \right)^2 \right] \right\} \tag{12}$$

5 Stage II: outage probability limited adaptive simultaneous spectrum sensing and data transmission

The condition to start Stage II is that there is no idle channel and the queue length $Q(t)$ is bigger than the queue length bound Q_{th}. The transmission power P_s in Stage II is lower than that in Stage I and is constrained by the outage probability of PU. What's more, the data transmission time T_2^j is also adaptively adjusted with the aim of limiting the missed spectrum opportunity, which is the time interval when PU is inactive but not detected by the SU.

5.1 Transmission power P_s under outage probability constraint

When there is no idle channel detected by SU Rx and the queue length $Q(t)$ is larger than the queue length bound Q_{th}, the SU Tx is allowed to transmit data at a lower transmission power under the outage probability constraint in this article.

The outage probability constraint can be expressed as follows:

$$\Pr\left\{ B\log_2\left(1 + \frac{P_{\text{pri}}|h_p|^2}{P_s|h_{\text{sp}}|^2 + \sigma_n^2} \right) \le R_{\min} \right\} \le P_{\text{out}} \tag{13}$$

where h_p denotes the channel between PU Tx and PU Rx, h_{sp} denotes the channel between SU Tx and PU Rx, B is the bandwidth of the channel, σ_n^2 is the variance of noise, P_s is the transmission power of SU Tx in Stage II, P_{pri} is the transmission power of PU, and $R_{\min}$ is the required minimum transmission rate for PU with outage probability P_{out}.

It is noticed that $|h_p|^2$ obeys chi-square distribution and its cumulative distribution function (CDF) is $F_{|h_p|^2}(x) = 1 - \exp(-x/2\sigma_{hp}^2)$, where $\sigma_{h_p}^2$ represents the variance of h_p. Thus, the equation given in (13) can be simplified as follows:

$$1 - \exp(-C \times (P_s|h_{\text{sp}}|^2 + \sigma_n^2)/2\sigma_{h_p}^2) \le P_{\text{out}} \tag{14}$$

where $C = \left(2^{R_{\min}/B} - 1\right)/P_{\text{pri}}$. Since the left side of (14) is a concave function of $P_s|h_{\text{sp}}|^2$, then (14) can be further simplified by utilizing Jensen's inequality [20]. Jensen's inequality states that if $f(x)$ is a concave function, then $E[f(X)] \le f(E[X])$, where $E[x]$ denotes the expectation of x. Therefore,

$$E\left[1 - \exp\left(-C(P_s|h_{\text{sp}}|^2 + \sigma_n^2)/2\sigma_{h_p}^2\right)\right] \le 1 - \exp\left(-C(P_s\sigma_{h_{\text{sp}}}^2 + \sigma_n^2)/2\sigma_{h_p}^2\right) \tag{15}$$

where $\sigma_{h_{\text{sp}}}^2$ is the expectation of $|h_{\text{sp}}|^2$, i.e., the variance of h_{sp}.

Now, we consider the stronger constraint

$$1 - \exp(-C(P_s\sigma_{h_{\text{sp}}}^2 + \sigma_n^2)/2\sigma_{h_p}^2) \le P_{\text{out}} \tag{16}$$

Thus, the transmission power constraint of P_s is

$$P_s \le -(2\sigma_{h_p}^2 \times \ln(1 - P_{\text{out}}) + C\sigma_n^2)/(C\sigma_{h_{\text{sp}}}^2) \tag{17}$$

5.2 Adaptive algorithm for adjusting the transmission time T_2^j in Stage II

The basic idea of this adaptive algorithm is the same to the one in Section 4.1, and the difference is that in this part we will focus on the average duration of the missed spectrum opportunity, whose expression is

$$M(T_2^j, c_2) = E\left[(T_2^j - s)\right] = \frac{(T_2^j + c_2)[F_1(T_2^j + c_2) - F_1(c_2)] - \int_{c_2}^{T_2^j + c_2} sf_1(s)ds}{1 - F_1(c_2)} \tag{18}$$

where s is the residual time of the PU's OFF state, $c_2 = t_j' - t_{\text{sp2}}$ is the time interval between the most recent channel switch point t_{sp2} and the jth transmission of Stage II.

Similarly, the expression of the adaptive transmission time $T_{2,\text{adp}}^j$ in Stage II is

$$T_{2,\text{adp}}^j = \max\left\{T_{2,\min}, \min\left\{T_{2,\max}, T_{2,\text{opt}}^j\right\}\right\} \tag{19}$$

where $T_{2,\min}$ and $T_{2,\max}$ denote the prescribed minimum and maximum transmission time interval of Stage II respectively, $T_{2,\text{opt}}^j$ represents the solution of the following optimization problem

$$\begin{aligned} &\max T_2^j \\ &\text{s.t. } M(T_2^j, c_2) = \frac{(T_2^j + c_2)[F_1(T_2^j + c_2) - F_1(c_2)] - \int_{c_2}^{T_2^j + c_2} sf_1(s)ds}{1 - F_1(c_2)} \le \beta \end{aligned} \tag{20}$$

Where β is the prescribed parameter of the missed spectrum opportunity.

5.3 Algorithm for estimation of t_{sp2}

The algorithm for estimating t_{sp2} is also based on MMSE principle, thus the optimal estimate of the new channel switch point t^*_{sp2} is the one which minimizes the mean squared estimation error ε' between the estimated value $\hat{t}_{sp2}$ and the real value t_{sp2}. Therefore, the expression of t^*_{sp2} is

$$t^*_{sp2} = \arg \min_{t'_j < \hat{t}_{sp2} < t'_j + T^j_2} \left\{ \varepsilon' = E\left[\left(\hat{t}_{sp2} - t_{sp2} \right)^2 \right] \right\} \quad (21)$$

where the expression of ε' is

$$\varepsilon' = E\left[\left(\hat{t}_{sp2} - t_{sp2} \right)^2 \right] = \left(\hat{t}_{sp2} - t'_{sp2} \right)^2 - \frac{2 \times \left(\hat{t}_{sp2} - t'_{sp2} \right) \times \int_{c'_2}^{c'_2 + T^j_2} s f_1(s) ds}{F_1(c'_2 + T^j_2) - F_1(c'_2)} + \frac{\int_{c'_2}^{c'_2 + T^j_2} s^2 f_1(s) ds}{F_1(c'_2 + T^j_2) - F_1(c'_2)} \quad (22)$$

where $c'_2 = t'_j - t'_{sp2}$, and t'_{sp2} is the old channel switch point.

6 Simulation results

This section includes two parts: Section 6.1 evaluates the performance of ICASST scheme, and Section 6.2 discusses its cost.

6.1 Performance evaluation

Numerical simulations are performed to evaluate the proposed ICASST scheme compared with the traditional periodic sensing scheme which is described in Figure 1 and the schemes in [13] and [15]. Ref [13] dynamically adjusts the data transmission time but doesn't consider the influence of spectrum sensing on the throughput of secondary system. Ref [15] avoids the influence of spectrum sensing but it only takes the missed-detection interference into account and doesn't consider the unslotted interference. The ICASST scheme jointly considers the influence of spectrum sensing on the throughput of secondary system and the unslotted interference.

The performance metrics used to evaluate the proposed ICASST scheme are the throughput of secondary system and the interference index. The interference index is defined as the ratio of the unslotted interference time to the total simulation time. The simulation results describe the variation trend of throughput and interference index versus the channel utilization u, which is defined in Section 2.1 by (1). The same to [13], two kinds of distributions for PU's activity are considered in this article: the memoryless one, such as exponential distribution; and the one with memory, e.g., Lognormal distribution and Pareto distribution.

6.1.1 The case of exponential distribution

Figures 4 and 5, respectively, exhibits the variation of the throughput of secondary system and interference index against channel utilization when PU's activity follows exponential distribution. Figures 4 and 5 shows that when PU's activity follows exponential distribution, the ICASST scheme converges to the scheme in [15], while the scheme in [13] converges to the periodic scheme. This can be explained by the memoryless feature of the exponential distribution, because the information of the previous channel state is not helpful, i.e., the interference time $I(T^i_1, c_1)$ is not related to the time interval c_1, where $c1 = t_i - t_{sp1}$.

For the periodic scheme, it can be concluded form Figure 4 that the throughput of secondary system is more dependent on the spectrum sensing slot t_s than the total period T_p. This is because that longer sensing time t_s results in shorter data transmission time and hence lower throughput. Figure 5 shows that the interference index is only dependent on the total period T_p and is irrelevant to the sensing slot t_s. This is due to the perfect spectrum sensing assumption in this article. And if it is not perfect spectrum sensing, then larger t_s will lead to smaller interference index. What is worth mentioning is that larger T_p leads to larger interference index, because larger T_p results in bigger possibility of interfering with PU.

6.1.2 The case of lognormal distribution

Figures 6 and 7, respectively, describes the variation of the throughput of secondary system and interference index against channel utilization when PU's activity follows lognormal distribution. First, the simulation results in Figure 6 prove that the throughput of ICASST scheme is significantly higher than that of periodic sensing scheme. This is mainly because that the data transmission time of ICASST scheme takes a much larger percentage than that of periodic sensing scheme. And because of the same reason, the throughput of the ICASST scheme is also significantly larger than that of the scheme in [13]. Second, the throughput of ICASST scheme is also higher than the scheme in [15] due to the existence of Stage II in ICASST scheme, which increases the system throughput.

Figure 7 shows that the interfere index of ICASST scheme is much lower than that of periodic scheme and the scheme in [15]. This is because that the ICASST scheme efficiently reduces the unslotted interference through adaptively adjusting the data transmission time according to the statistic information of PU's activity and the estimated channel switch point. It is noticed that the interference index of ICASST scheme is similar to that of the scheme in [13], but the throughput of ICASST scheme can be much higher. This result validates the conclusion that the ICASST scheme increases the throughput and decreases the interference simultaneously.

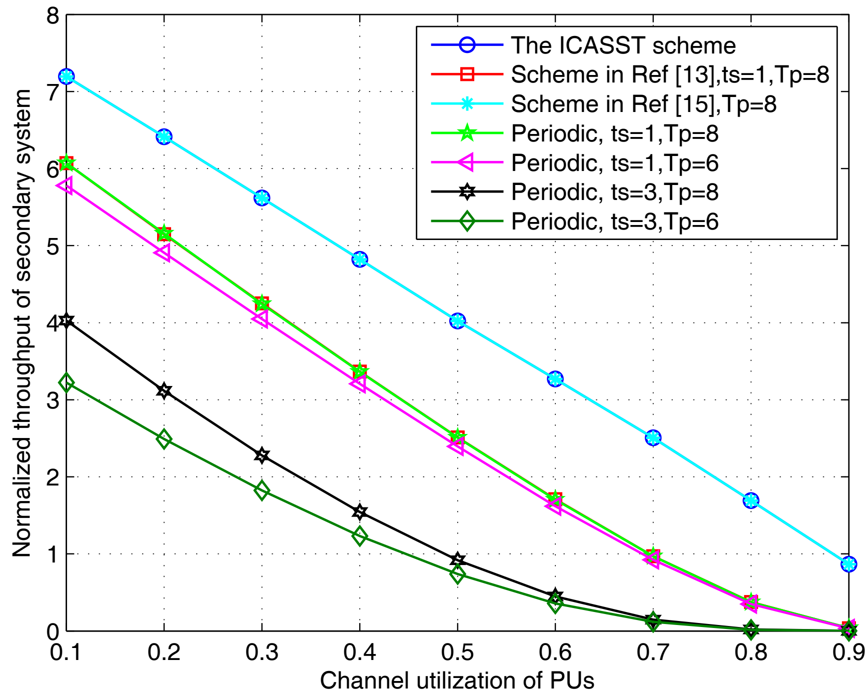

Figure 4 Throughput of secondary system against channel utilization when PU's activity follows exponential distribution.

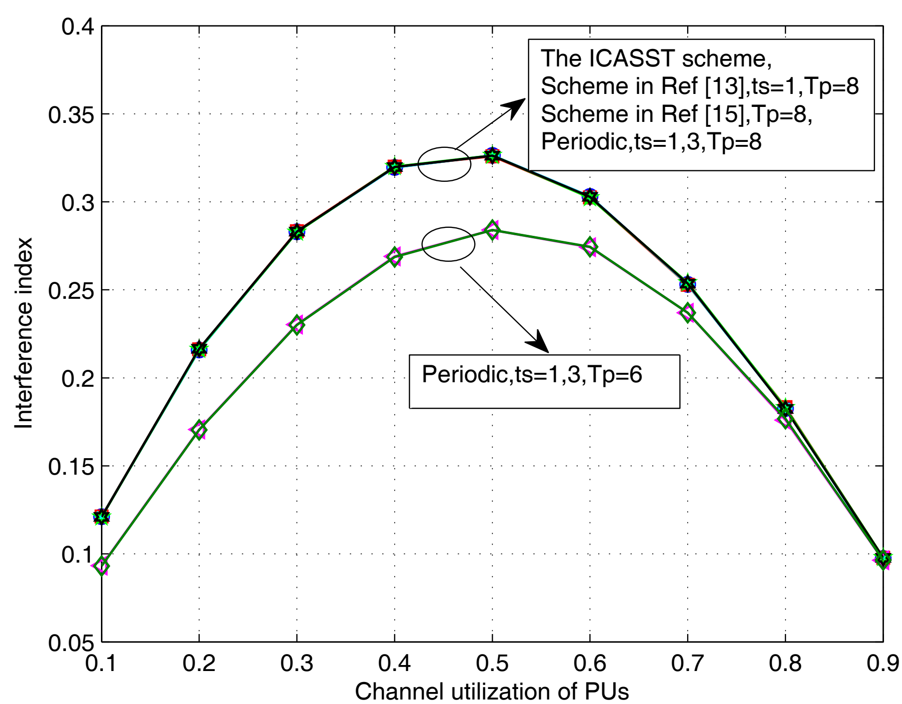

Figure 5 Interference index against channel utilization when PU's activity follows exponential distribution.

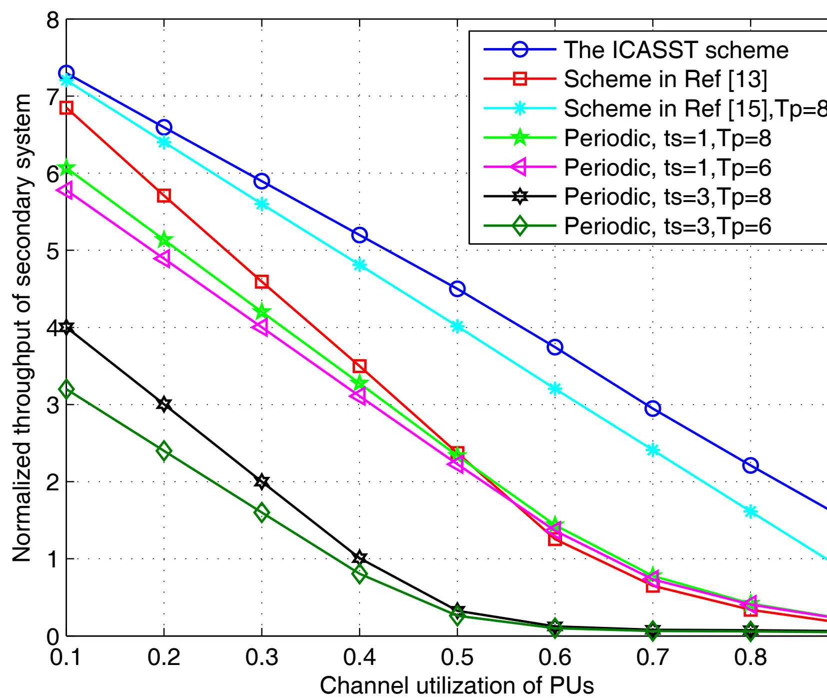

Figure 6 Throughput of secondary system against channel utilization when PU's activity follows Lognormal distribution.

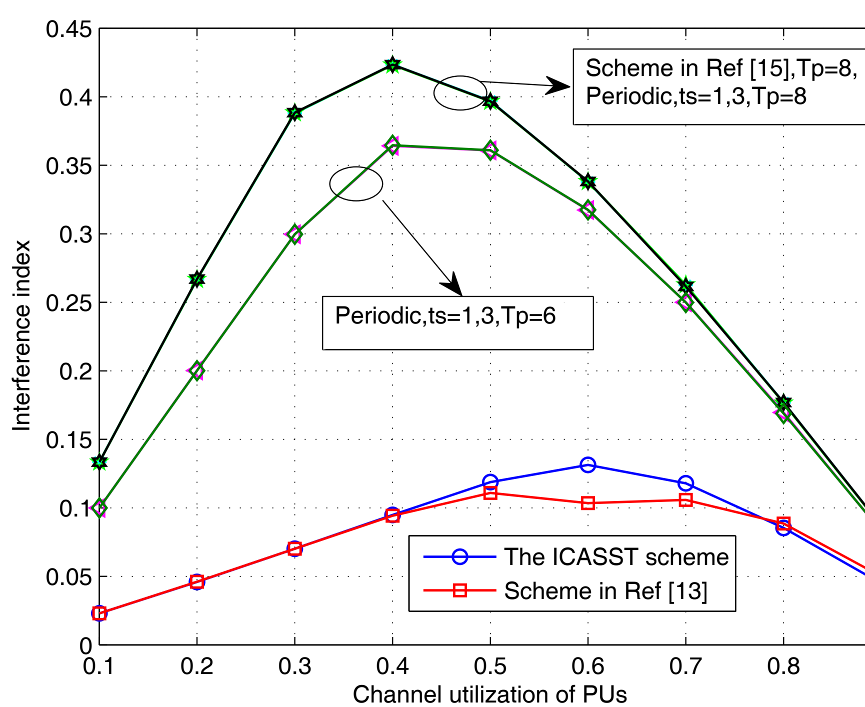

Figure 7 Interference index against channel utilization when PU's activity follows Lognormal distribution.

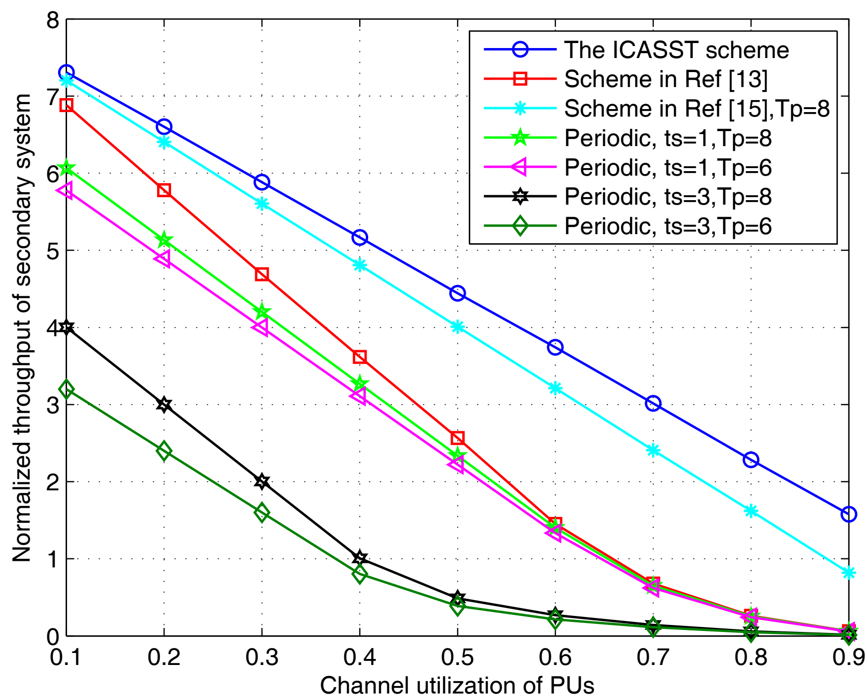

Figure 8 Throughput of secondary system against channel utilization when PU's activity follows Pareto distribution.

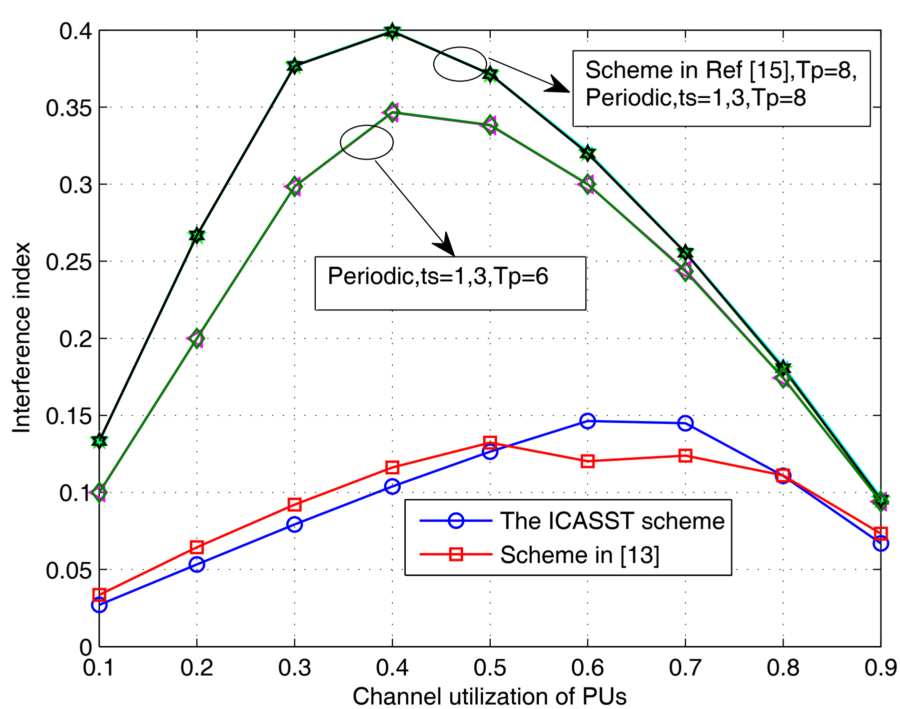

Figure 9 Interference index against channel utilization when PU's activity follows Pareto distribution.

6.1.3 The case of Pareto distribution

Figures 8 and 9, respectively, depict the variation of the throughput of secondary system and interference index against channel utilization when PU's activity follows Pareto distribution. It is clear that the variation trends in Figures 8 and 9 are similar to those in Figures 6 and 7. That is to say, when PU's activity follows Pareto distribution, the ICASST scheme can also significantly increases the throughput and decreases the interference index compared with existing schemes.

6.2 Cost of ICASST scheme

Section 6 has evaluated the efficiency of ICASST scheme, and this section will discuss its cost. First, in the ICASST scheme two feedback channels are introduced, one is used to send the transmission time, and the other one is used to feed the spectrum sensing result back. Second, additional computation is needed in ICASST scheme to decrease the unslotted interference. The details about the feedback overhead and computation cost are analyzed in Sections 6.2.1 and 6.2.2.

6.2.1 The cost of feeding back adaptive spectrum sensing time and spectrum sensing result

In the ICASST scheme, the adaptive spectrum sensing time in SU Rx is equal to the adaptive data transmission time in SU Tx, and both of them are measured in the minimum time unit. According to the statistic information about the PU's activity, the feedback overhead for adaptive spectrum sensing time is set to be D bits, that is to say, the maximum transmission time or spectrum sensing time is 2^D time units. The feedback overhead for spectrum sensing is only one bit, which equals to one when the channel is in ON state, and equals to zero while the channel is in OFF state.

Since the number of the feedback times is relevant to the changes of the channel state in the ICASST scheme, the cost of feedback is further evaluated by the feedback frequency, which is defined as the number of the feedback times over the times of the changes of the channel state. To illustrate the cost of the feedback, the blue line in Figure 10 shows that the average feedback frequency declines from 2.5 to 0.5 when the channel utilization increases from 0.1 to 0.9. That is to say, the feedback frequency is approximately equal to the frequency of the changes of the channel state. Thus, the feedback overhead has little effect on the overall performance of the CR system.

6.2.2 The cost of computing the adaptive transmission time

As shown in (8) and (9), to get the adaptive transmission time, an optimization problem has to be resolved first. What's more, the expressions of the CDF and PDF are different for different distribution of PU's activity. It

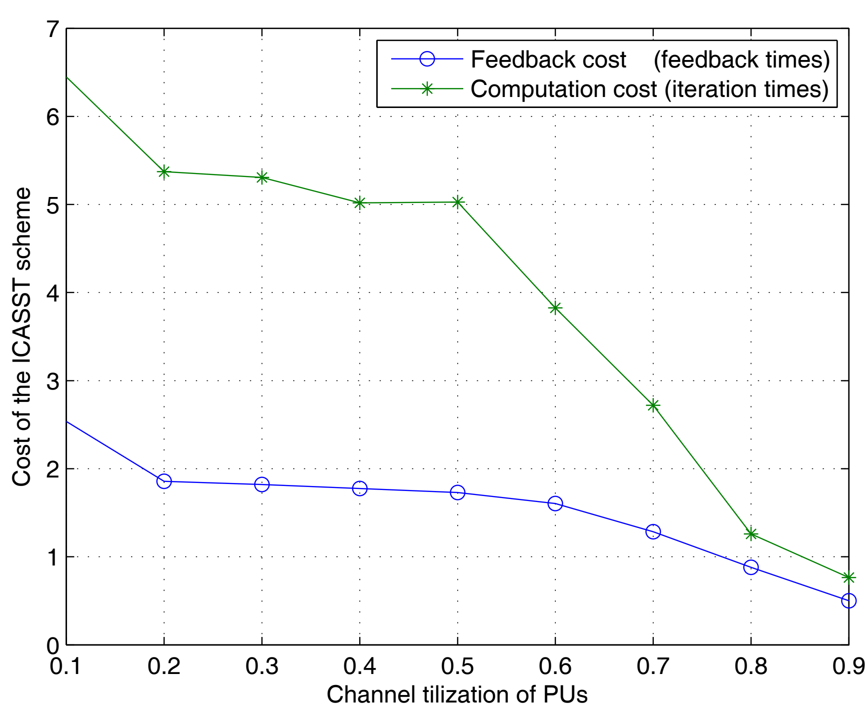

Figure 10 **Cost of ICASST scheme against the channel utilization**.

is not convenient to analyze the complexity of the computation of the adaptive transmission time directly. Thus, to illustrate the cost of computing the adaptive transmission time, this article adopts the times of the iterations to approximate the complexity of the adaptive transmission scheme. The green line in Figure 10 illustrates the number of the iteration times for calculating one adaptive transmission time. It can be seen from this line that the iteration numbers decreases from 6.5 to 0.7 with the increase of the channel utilization from 0.1 to 0.9. Therefore, the cost of computing the adaptive transmission time is relatively small.

In conclusion, the cost of the ICASST scheme declines with the increase of channel utilization. Besides, from Figures 4, 6, and 8, it can be concluded that the cost of ICASST scheme is directly proportional to the throughput of secondary system. Generally speaking, a conclusion can be drawn from Figure 10 that the cost of the ICASST scheme is relatively small compared with its efficiency.

7 Conclusion

This article balanced the two conflicting goals in unslotted CR network by proposing a novel spectrum sensing and data transmission scheme. Relative analysis and simulation results validated that the proposed ICASST scheme simultaneously increased the throughput of sec-ondary system and reduced the unslotted interference. The efficiency of the ICASST scheme is due to releasing SU Tx from spectrum sensing and utilizing the statistic information of the PU's activity. Meanwhile, the efficiency was at the expense of computing the adaptive trans-mission time and sending the adaptive spectrum sensing time and spectrum sensing result. But as analyzed in Section 7, the cost of ICASST scheme was relatively small compared with its efficiency. In conclusion, this article proposed a novel scheme that significantly increased the throughput and reduced the unslotted interference simultaneously at the cost of limited computation and feedback.

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Competing interests

The authors declare that they have no competing interests.

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