A New Transmit Power Control Scheme Based on Location-awareness in Cognitive Networks

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ABSTRACT
To solve the problem that the traditional spectrum sensing can only obtain the limited information of primary user and the efficiency of spectrum usage is low, this paper proposes a spectrum situation scheme to obtain the interference distribution information of primary user in frequency and spatial domain. This scheme uses surface spline interpolation based on the information returned by a small amount of sensor nodes. On this basis, a new transmit power control mechanism based on location-awareness is proposed. This mechanism realizes the power control according to three kinds of position relations between primary user and secondary user. It can solve the concurrent communication interference problem. Simulation analysis shows that this mechanism can increase the capacity of cognitive network while maintaining a quality-of-service for primary user by limiting the interference generated by secondary user.

Categories and Subject Descriptors
C.2.1 [Computer-Communication Networks]: Network Architecture and Design –Wireless communication, Network topology.

General Terms
Design

Keywords
Cognitive networks, surface spline interpolation, location-awareness, power control.

1. INTRODUCTION
In cognitive networks, to effectively find the spectrum holes and use it is the key of the research [1]. Spectrum sensing is a key technology in cognitive networks. Under the existing spectrum sensing framework, it can only detect the presence or absence of the primary user (PU), but can't obtain spatial information of PU include the position and transmit power. So the frequency resources are almost used in temporal and frequency domain. In space, the efficiency of spectrum usage is low [3]. In order to improve the efficiency, the concurrent communication interference problem must be overcome. Spatial information of PU, especially, the location information, is a necessary condition for making full use of spatial holes. To deal with the concurrent communication interference problem, the primary exclusive region (PER) model is designed [6-7]. In this region, the secondary user (SU) is rejected to communicate. Power control is the key to limit the interference generated by SU. To minimize the interference to PR, the power of secondary transmitter (ST) is controlled based on the information of spectrum sensing [8-9]. However, in above research, the position and transmit power of primary transmitter (PT) is unknown. The power of ST is controlled simply not to maximize the spectrum utilization rate.

In this paper, to improve the spectrum utilization rate in frequency and spatial domain, a spectrum situation scheme to obtain the interference distribution information of PU is proposed. This scheme uses surface spline interpolation based on the information returned by a small amount of sensor nodes. After obtaining the spectrum situation, the correlation of the PT's transmit radius, the distance from SU to PU and the capacity of cognitive network is analyzed. We propose a secondary user power control mechanism based on location-awareness. This mechanism realizes the power control according to three kinds of position relations between ST and PT. The concurrent communication interference problem is solved and SU can obtain more opportunities to access the licensed frequency band. Then, the interference that ST conducts to (primary receiver) PR in the PER is estimated. The missed detection of PR is calculated assuming there is no power control. The position estimation error is taken into consideration to enhance the robustness of the scheme.

The rest of this paper is organized as follows: Section 2 presents the network model. Section 3 presents the spatial interpolation method and the estimation of PT's spatial information. Section 4 presents the power control mechanism based on location-awareness. In section 5, the performance of the proposed scheme is analyzed. Section 6 concludes the entire discussion.

2. NETWORK MODEL
We consider a scenario in which Wireless sensor networks (WSN) is used to sense spectrum. Wireless sensor nodes which are

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randomly distributed in a specific area send the power and position information to the fusion center through common control channel. The fusion center estimates signal strength of each point in the area by surface spline interpolation.

In the wireless channel, we consider only the path loss. The channel model is expressed as:

$$h = A / d^{\alpha} \tag{1}$$

Where d is the distance between transmitter and receiver. A is the frequency-dependent constant and α is the path loss exponent. In the subsequent analysis, we normalize A to 1 for simplicity. We consider $\alpha \geq 2$ which is typical in practical scenarios. Assuming that the channel noise is the Gauss white noise whose power is δ^2 .For the signal model, we assume no multiuser detection. Each user, either primary or secondary, has no knowledge of other users' signals and treats them as interference. Furthermore, the signals of different users are statistically independent.

3. SPECTRUM SITUATION SCHEME

3.1 Surface Spline Interpolation

Expression of surface spline function is given by:

$$W(x, y) = a_0 + a_1 x + a_2 y + \sum_{i=1}^{n} F_i r_i^2 \ln(r_i^2 + \varepsilon) \tag{2}$$

Where $a_0, a_1, a_2, F_i (i = 1, 2, \ldots, n)$ are the undetermined coefficients. $r_i^2 = (x - x_i)^2 + (y - y_i)^2$. ε is the experience parameters to adjust the curvature size of surface. In practical scenarios, ε is from 10^{-4} to 1. There are n+3 undetermined coefficients in the surface spline function (2).We solve the problem by the following equations:

$$\begin{cases} W_j = a_0 + a_1 x_j + a_2 y_j + \sum_{i=1}^{n} F_i r_{ij}^2 \ln(r_{ij}^2 + \varepsilon) \\ (j = 1, 2, \ldots n; r_{ij}^2 = (x_i - x_j)^2 + (y_i - y_i)^2) \\ \sum_{i=1}^{n} F_i = 0; \sum_{i=1}^{n} F_i x_i = 0; \sum_{i=1}^{n} F_i y_i = 0 \end{cases} \tag{3}$$

Where (x_i, y_i) and (x_j, y_j) are the interpolation nodes. c_j is the parameter related to the elastic coefficient. The matrix expression of (3) is given by:

$$AX = B \tag{4}$$

A is expressed as:

$$\begin{bmatrix} c_1 & \mathrm{r}_{12} \ln(r_{12}^2 + \varepsilon) & \cdots & \mathrm{r}_{1n} \ln(r_{1n}^2 + \varepsilon) & 1 & x_1 & y_1 \\ \mathrm{r}_{21} \ln(r_{21}^2 + \varepsilon) & c_2 & \cdots & \mathrm{r}_{2n} \ln(r_{2n}^2 + \varepsilon) & 1 & x_2 & y_2 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ \mathrm{r}_{n1} \ln(r_{n1}^2 + \varepsilon) & \mathrm{r}_{n2} \ln(r_{n2}^2 + \varepsilon) & \cdots & c_n & 1 & x_n & y_n \\ 1 & 1 & \cdots & 1 & 0 & 0 & 0 \\ x_1 & x_2 & \cdots & x_n & 0 & 0 & 0 \\ y_1 & y_2 & \cdots & y_n & 0 & 0 & 0 \end{bmatrix} \tag{5}$$

$$X = (F_1, F_2, \ \ldots, F_n, a_0, a_1, a_2) \tag{6}$$

$$B = (W_1, W_2, \ \ldots, W_n, 0, 0, 0) \tag{7}$$

To guarantee the stability of the solution, we use the method of generalized inverse solution.

3.2 PT's Spatial Information

3.2.1 Accuracy analysis of spectrum situation map

The relative error of reconstruction is defined as:

$$e = \frac{\left\| \hat{x} - x \right\|}{\left\| x \right\|} \tag{8}$$

Where $\hat{x}$ is the reconstructed image in vector form. x is the original image in vector form.

3.2.2 PT's position and transmit power

The location of the peak value of the power strength in the reconstructed map can be taken as an estimate of the transmitter position and the peak value is the transmit power [10]. The error of PT's position is given by:

$$\Delta d = \sqrt{(x - x_0)^2 + (y - y_0)^2} \tag{9}$$

Where (x, y) is estimated position. (x_0, y_0) is the real position.

The relative error of transmit power is defined as:

$$p_e = \frac{\left\| \hat{p} - p \right\|}{\left\| p \right\|} \tag{10}$$

$\hat{p}$ is the estimated transmit power and p is the real transmit power.

4. POWER CONTROL MECHANISM

Under the existing spectrum sensing framework, interference of SU to PU is difficult to be evaluated due to lack of the spatial information of PU. In order to ensure that the interference does not exceed the interference threshold, once SU detects that the licensed frequency band is occupied, it will quit the band. However, we can obtain the position and transmit power of PT based on the spectrum situation map. A new transmit power control mechanism based on the position and transmit power of PT is proposed. In this mechanism, SU can still communication even though the licensed frequency band is occupied. The position estimation error of PT is taken into consideration to enhance the robustness of the scheme.

4.1 Transmit Radius Model

In Figure 1, the signal to interference and noise ratio (SINR) of PR is given by:

$$SINR = \frac{P_{pri} R_0^{-\alpha}}{\sigma^2 + I} \geq \eta \tag{11}$$

Where η is the minimum SINR of PR. R_0 is the actual communication radius of PT. α is the path loss exponent. P_{pri} is the transmit power of PT. I is the interference generated by ST. δ^2 is the power of Gauss white noise . The derivation of the formula (11) is given by:

$$R_0 \le \left(\frac{P_{pri}}{\eta(I+\sigma^2)} \right)^{1/\alpha} \quad (12)$$

$$I \le \frac{P_{pri} R_0^{-\alpha}}{\eta} - \sigma^2 = I_{th} \quad (13)$$

$$R_0 \le R_0^u = (P_{pri} / \sigma^2 \eta)^{1/\alpha} \quad (14)$$

Where I_{th} is the interference threshold of PR and R_0^u is the maximum communication distance between the primary transmitter and receiver when there is no interference.

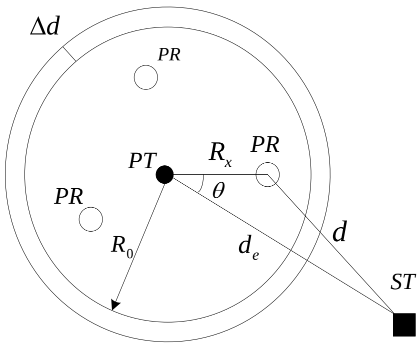

Figure 1.Transmission radius model

4.2 Transmit Power and Network Capacity

The transmit power of ST must satisfy the requirements:

$$I(P_t) = k_0 P_t / d^\alpha \le I_{th} \quad (15)$$

From (15), we know the maximum transmit power is：

$$P_{t\max} = I_{th} d^\alpha / k_0 \quad (16)$$

$I(P_t)$ is the interference received by PR. P_t is the transmit power of ST. k_0 is the coefficient related to transmit and receive antennas. We normalize k_0 to 1 for simplicity. d is the distance between transmitter and receiver. $P_{t\max}$ is the maximum transmit power on the premise of not exceeding the interference threshold.

From the Shannon formula, we know that the cognitive network capacity is:

$$\mathrm{C} = \log\left(1 + \frac{P_{t\max}}{P_{pri} d_e^{-\alpha} + \sigma^2} \right) \quad (17)$$

Where d_e is the distance between PT and ST.

4.3 Transmit Power Control Mechanism

Figure 2 is the power control model based on location-awareness. It is divided into three cases according to the distance between ST and PT. Δd is the position error area of PT. The acquiescent communication radius of ST is r . Dashed circle is the communication range of ST after power control.

4.3.1 CASE 1: $d_e \ge R_0 + \Delta d + r$

In this case, the distance from ST to the nearest PR is $d = d_e - R_0 - \Delta d \ge r$. ST can increase the transmit power on the premise of not exceeding the interference threshold of the nearest PR. Communication radius will expand to r' .So it can communicate with the SR further. The interference received by PR which is the nearest to ST is less than the threshold, the interference received by other PR is certainly less than the threshold.

From Figure 1, within communication range of PT, the interference received by any PR is:

$$I = \frac{k_o P}{(R_x^2 + d_e^2 - 2R_x d_e \cos\theta)^{\alpha/2}} \quad (18)$$

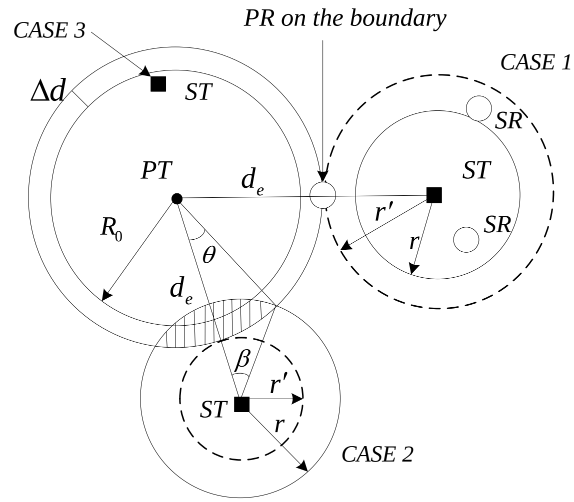

Figure 2.Power control scheme model

4.3.2 CASE 2: $R_0 + \Delta d + r > d_e > R_0 + \Delta d$

In order to not exceed the interference threshold, ST doesn't work in the traditional scheme. In this scheme, ST can continue to work by reducing power while the interference to PR is no more than the threshold.

In figure 2, If ST continues to work without power control. PR in shadow area will be interfered. We define the probability of missed detection of the PR, Pm, as the ratio of shadow area to the circle area with radius R=$R_o + \Delta d$. According to plane geometry and cosine theorem, the shadow area can denote as:

$$S = R^2(\theta - \sin\theta \cdot \cos\theta) + r^2(\beta - \sin\beta \cdot \cos\beta) \quad (19)$$

Where

$$\theta = \arccos\left(\frac{R^2 + d_e{}^2 - r^2}{2Rd_e} \right) \quad (20)$$

$$\beta = \arccos\left(\frac{r^2 + d_e{}^2 - R^2}{2rd_e} \right) \quad (21)$$

We can get the probability of miss detection as:

$$P_m = \frac{R^2(\theta - \sin\theta \cdot \cos\theta) + r^2(\beta - \sin\beta \cdot \cos\beta)}{\pi \cdot R^2} \quad (22)$$

4.3.3 CASE 3: $d_e \le R_0 + \Delta d$

In this case, the ST is on the primary exclusive region, so it doesn't work as the traditional scheme.

5. NUMERICAL ANALYSIS

5.1 Spectrum Situation Map and Spatial Information of PT

5.1.1 Construction of spectrum situation map

Wireless sensor nodes are randomly distributed in a specific area to perceive the signal strength. PU and SU coexist in the same area.

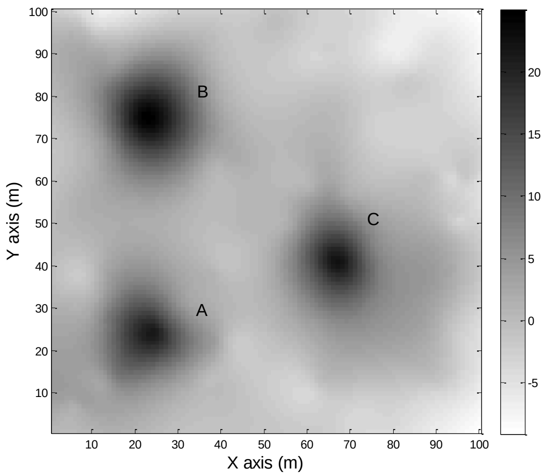

Figure 3.Spectrum situation map based on surface spline interpolation

Figure 3 is the spectrum situation map. In the $100m \times 100m$ square area, 256 wireless sensor nodes which are randomly distributed send the signal strength and its position information to the fusion center through the common control channel. The reconstruction error is mainly due to the density of interpolation nodes, the curvature parameter ε , and the shadow fading. From Figure 3, we can see 3 PT in the area. According to the formula (8), when the number of random sampling point is 256, ε =1, the relative error is 0.47%.

5.1.2 The position and transmit power of PT

The estimation error of position and signal strength can be calculated by formula (9), (10). Simulation analysis is shown in Table 1. The position error is 1 and it is accurate compared to the area which is $100m \times 100m$. The maximum relative error of power estimation is 1.99%.It is accurate because the literature [11] shows that the relative error is accurate when it is less than 10%.

Table 1. The PT's location and transmit power analysis

	PT A	**PT B**	**PT C**
original map (x, y, p)	(23,24,30.79)	(21,74,32.80)	(67,39,31.81)
reconstructed map $(\hat{x}, \hat{y}, \hat{p})$	(23,23,30.01)	(20,74,32.32)	(67,40,32.45)
error of PT's position Δd	1	1	1
relative error of power p_e	0.69%	1.57%	1.99%

5.2 Simulation Analysis of Power Control

5.2.1 The relationship between PT's transmit radius and PR's interference threshold

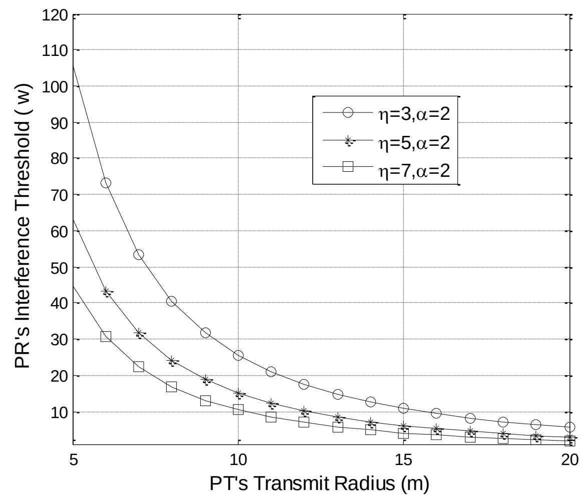

Figure 4.The relationship between PT's transmit radius and PR's interference threshold

Figure 4 indicates the relationship between PT's communication radius and PR's interference threshold for different minimum signal-to-noise ratio η . The lower the ratio, the greater the interference threshold, and thus the stronger the ability to withstand interference is. PR is far away from the PT, the signal received by PR is weak and the interference threshold is low.

5.2.2 CASE 1

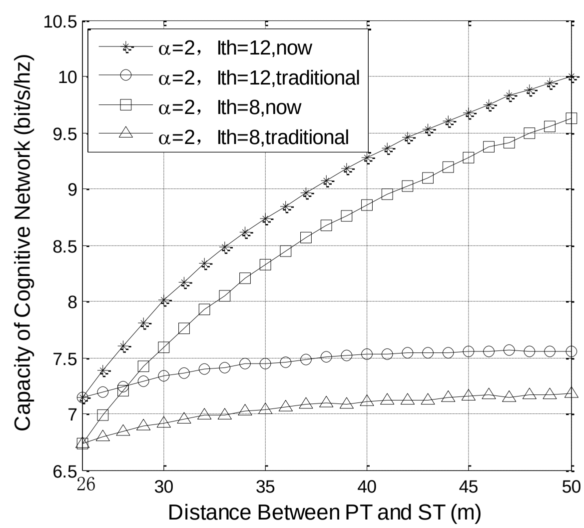

Figure 5.Compare our scheme with the traditional scheme in case 1

Simulation results in 5.2.1 show that, when $\alpha = 2$, $\delta^2 = 1$, $R_o = 15$, η=3 , the interference threshold is $I_{th} = 12$. Figure 5 is the comparative analysis of this scheme and traditional scheme for different interference threshold. The capacity of cognitive network improves significantly in this scheme. It will increase with increasing interference threshold. In other words, when the PR's ability of anti-interference is strong, the capacity of cognitive network will increase.

Figure 6 shows that the interference received by PR at any position can be calculated through the angle θ and the distance R_x from PT to PR.

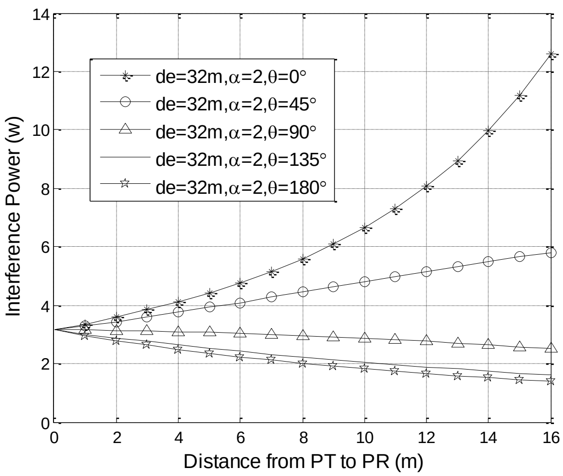

Figure 6.Interference received by PR in any position

5.2.3 CASE 2

Figure 7 indicates the capacity of cognitive network for different interference threshold. In the traditional scheme, the ST doesn't work, so the capacity of cognitive network is zero. In this scheme, the capacity increases obviously with the increase in the distance between ST and PT.

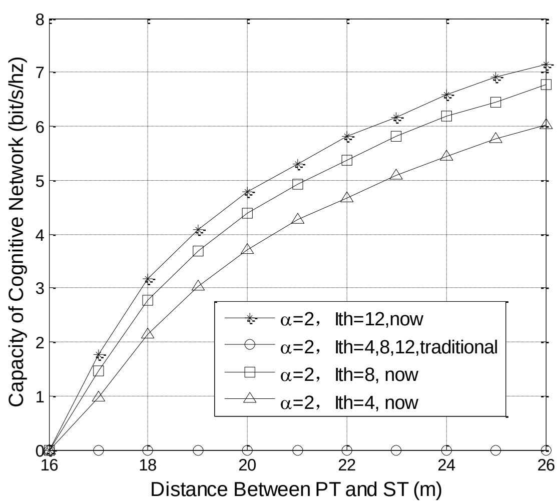

Figure 7.Compare our scheme with the traditional scheme in case 2

In the traditional scheme, if ST continues to work, PR will miss detection of the received signal because the interference is above the threshold. Figure 8 shows that the missed detection probability will increase with the expansion in ST's communication radius. So this scheme for power control is significant.

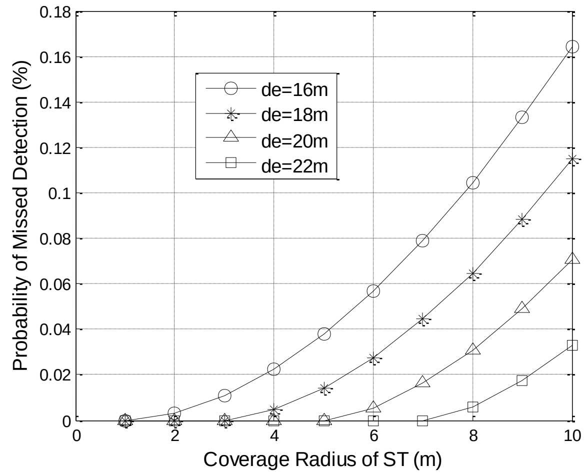

Figure 8.Probability of missed detection

5.2.4 Effect of position error on the performance of cognitive network

Figure 9 shows the effect of position error on the capacity of cognitive network. In the traditional scheme, ST works with a fixed power, so the capacity is not affected by the position error. But this scheme is related to position error. The capacity of cognitive network decreases with the increase in position estimation error. The error is small, so the decrease in capacity is not obvious.

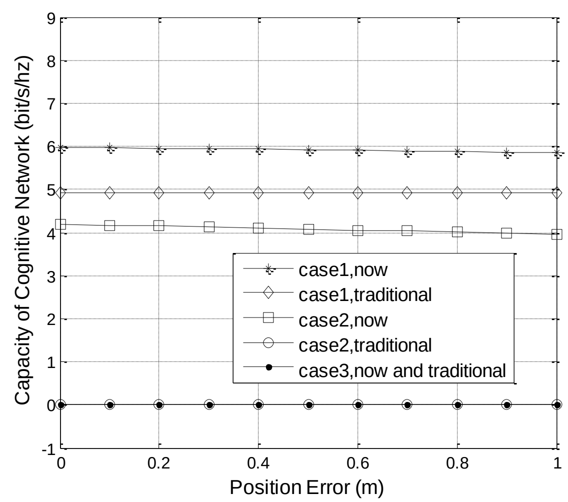

Figure 9.Effects of position errors on the capacity of cognitive network

6. CONCLUSION

This paper constructs the spectrum situation map by the surface spline interpolation. The position and transmit power of PT is obtained. On this basis, a new transmit power control mechanism based on location-awareness is proposed. It realizes power control according to three kinds of position relations between ST and PT. In this scheme, SU obtains more opportunities to access the licensed frequency band. So the capacity of cognitive network increases. It effectively solves the concurrent communication interference problem, thereby improving the spectrum utilization.

The position estimation error of PT is taken into consideration to enhance the robustness of the scheme. The capacity of cognitive network decreases with the increase in error. In future work, we will study how to construct the spectrum situation map more accurately and find the balance between primary and secondary users network to maximize the efficiency of spectrum usage.

7. ACKNOWLEDGEMENT

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