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Informed spectrum usage Based on Location-awareness in Cognitive Networks

Fangwei Li[1], Zhuxun Peng[1,*] and Jiang Zhu[1]

[1]Chongqing University of Posts and Telecommunications, Chongqing, China

Abstract

This paper proposes a spectrum situation scheme to obtain the interference distribution information of primary user in spatial domain. A reliable spatial interpolation technique, surface spline interpolation, is applied to interference cartography. Using this information, a secondary network can detect the location and transmit power of the primary transmitter .On this basis, a new transmit power adaptive scheme based on location-awareness is proposed. This scheme realizes the power control according to three kinds of position relations between primary user and secondary user. The secondary user can use spectrum opportunities without causing harmful interference to primary user. Simulation analysis shows that this scheme can increase the capacity of cognitive network while maintaining a quality-of-service for primary user by limiting the interference generated by secondary user.

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

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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 analysed. We propose a secondary user power adaptive scheme based on location-awareness. This scheme realizes the power control according to three kinds of position relations between ST and PT. The concurrent communication interference problem is solved and ST 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

[*]Corresponding author. Email:pengzhux@163.com

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 adaptive scheme based on location-awareness. In section 5, the performance of the proposed scheme is analysed. 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 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

The spectrum situation map can indicate the interference distribution of the primary users in the space. The position and transmit power of PT can be estimated according to paper [10].So the information of PT can be obtained by the spectrum situation map. In this paper, the spectrum situation map is constructed by surface spline interpolation. The surface spline function is a powerful tool for surface approximation estimation. It forms a smooth surface by the interpolating of discrete data. The conditions for the utility of spline function are strict. The prominent advantage of surface spline function is that the point plane coordinates are not ordered by regular lattice and the conditions of natural boundary is instead of the boundary derivative information. Therefore, the surface spline interpolation method is very suitable for the construction of spectrum situation map.

3.1. Surface Spline Interpolation

Expression of surface spline function is given by:

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

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 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:

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

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:

$$\begin{bmatrix} c_1 & r_{12}\ln(r_{12}^2 \quad \varepsilon) & \cdots & r_{1n}\ln(r_1 \; + \;) & 1 & x_1 & y_1 \\ r_{21}\ln(r_{21}^2 + \varepsilon) & c_2 & \cdots & r_{2n}\ln(r_2 \quad \varepsilon) & 1 & x_2 & y_2 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ r_{n1}\ln(r_{n1}^2 + \varepsilon) & r_{n2}\ln(r_{n2} + \varepsilon) & \cdots & c_n & 1 & x_n & y_n \\ 1 & 1 & \cdots & 1 & 0 & 0 & 0 \\ x_1 & & \cdots & x_n & 0 & 0 & 0 \\ y_1 & y & \cdots & y_n & 0 & 0 & 0 \end{bmatrix} \tag{5}$$

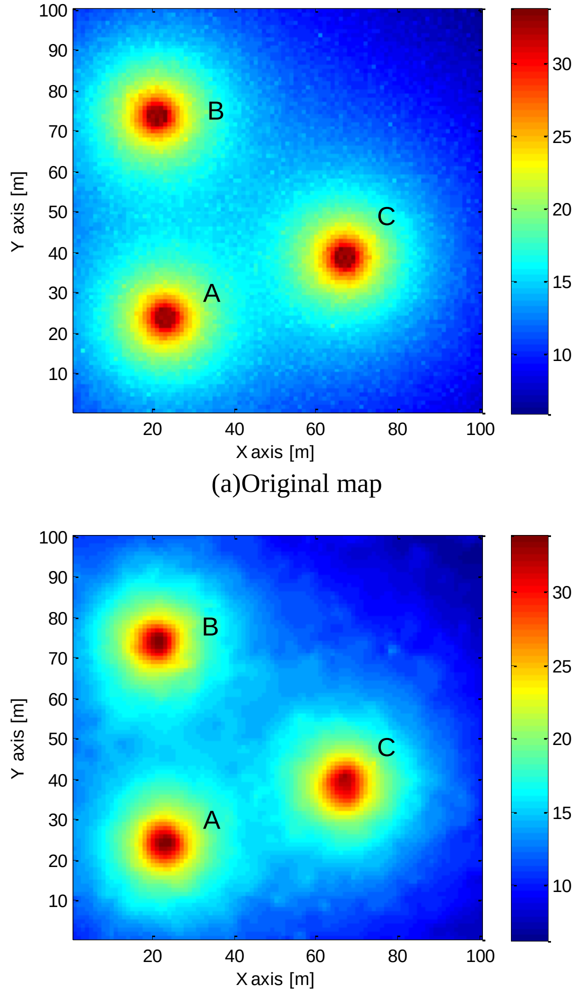
$$X = (F_1, F_2, \ldots, F_n, a_0, a_1, a_2) \tag{6}$$

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

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

3.2. Construction of Spectrum Situation Map

Set up a $100m \times 100m$ square area as the inspection area. Wireless sensor nodes which are randomly distributed will report the signal intensity and position information to the fusion center. The spectrum situation map is constructed by surface spline interpolation method in fusion center. Figure 1 is the original and reconstructed spectrum map based on the surface spline interpolation method. The color represents the intensity of signal.



(a)Original map

(b)Reconstructed map

Figure 1.Spectrum situation map

3.2.1Accuracy analysis of spectrum situation map

The accuracy of an situation map reconstruction method is investigated by checking the root mean square error (RMSE) of the estimation respect the true map, as in

$$RMSE = \sqrt{\frac{1}{A}\iint_A [\hat{w} \quad w]^2 dA} \qquad (8)$$

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

3.2.1PT'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:

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

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

The relative error of transmit power is defined as:

$$p_e = \frac{\|\hat{p} - p\|}{\|p\|} \qquad (10)$$

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

4. Transmit power adaptive

Under the existing spectrum sensing framework, the interference of ST 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 transmit power adaptive scheme based on the position and transmit power of PT is proposed. In this scheme, ST can still work 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

Figure 2 is the transmission radius model. The signal to interference and noise ratio (SINR) of PR is given by:

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

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:

$$R_0 \leq \left(\frac{p_{pri}}{\eta(I + \sigma^2)} \right)^{1/\alpha} \qquad (12)$$

$$I \leq \frac{P_{pri} R_0^{-\alpha}}{\eta} - \sigma^2 = \ _{th} \qquad (13)$$

$$R_0 \leq R^u \quad (P_{pri} / \sigma^2 \eta)^{1/\alpha} \qquad (14)$$

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.

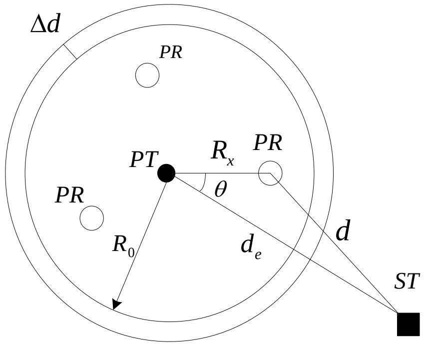


Figure 2. Transmission radius model

4.2. Transmit Power and Network Capacity

The transmit power of ST must satisfy the requirements:

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

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

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

$I(P_t)$ 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:

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

Where d_e is the distance between PT and ST.

4.3. Transmit Power Control Mechanism

Figure 3 is the power adaptive model based on location-awareness. It is divided into three cases according to the distance between ST and PT. Δd is the position error of PT. The acquiescent communication radius of ST is r . Dashed circle is the communication range of ST after power adaptive.

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

In this case, the distance from ST to the nearest PR is $d = d_e - R_0 - \Delta d \geq r$. 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. When 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 2, within communication range of PT, the interference received by any PR is:

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

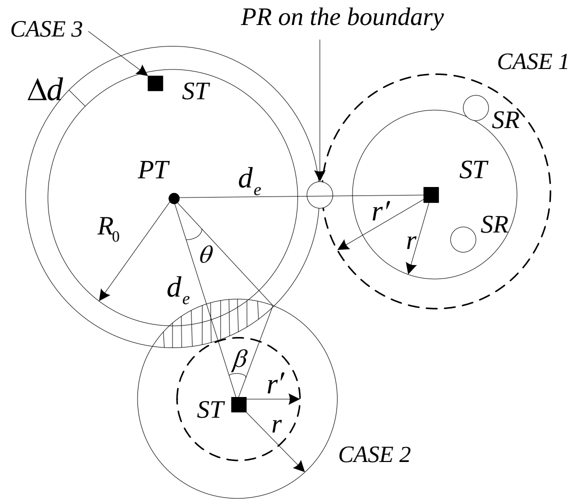


Figure 3. Power adaptive model

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

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 3, 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 $R{=}R_0 + \Delta d$. According to plane geometry and cosine theorem, the shadow area can denote as:

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

Where

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

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

We can get the probability of miss detection as:

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

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

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

5. Simulation Results

Simulations are conducted in Matlab. Invariant parameters are listed in Table I.

Table 1. Simulation parameters

Parameter	Value
Area dimensions	$100m \times 100m$
Curvature ε	1
Number of sensors	100
white Gauss noise power δ^2	-3dbm

Path loss exponent α	2
radius of detected region r	10m
Transmit power of PT P_{pri}	46dBm
minimum SINR of PR η	10dB

5.1 Spectrum situation map and spatial information of PT

5.1.1 Construction of spectrum situation map

The reconstruction error of the spectrum is mainly due to the density of the interpolation node, the curvature parameter, and the shadow fading. The influence of different interpolation node density and curvature on the construction of situation map is analysed.

Figure 4, with the increase of the number of sensors, the mean square error decreases gradually. ε is the empirical parameters to adjust the curvature. When the curvature of the surface is relatively large, it is small, and vice versa.

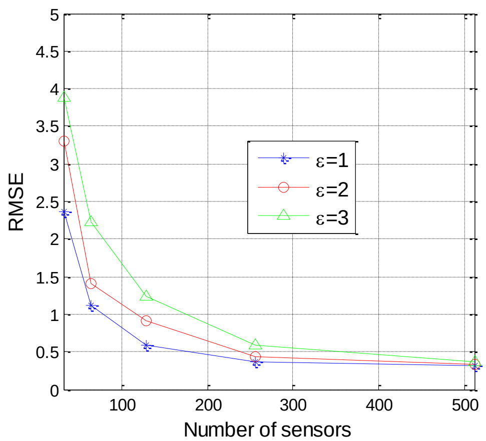


Figure 4. Mean square error

Figure 1 indicates that there three PUs in the situation map. 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%.

5.1.2 The position and transmit power of PT

Table 1. The PT's location and transmit power

	PT A	**PT B**	**PT C**
original map (x, y, p)	(23,24,46.0)	(21,74,46.0)	(67,39,46.0)
constructed map $(\hat{x},\hat{y},\hat{p})$	(23,23,45.1)	(20,74,45.3)	(67,40,45.2)
error of PT's position Δd	1	1	1
relative error of power p_e	1.96%	1.52%	1.74%

5.2 Simulation analysis of power adaptive

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

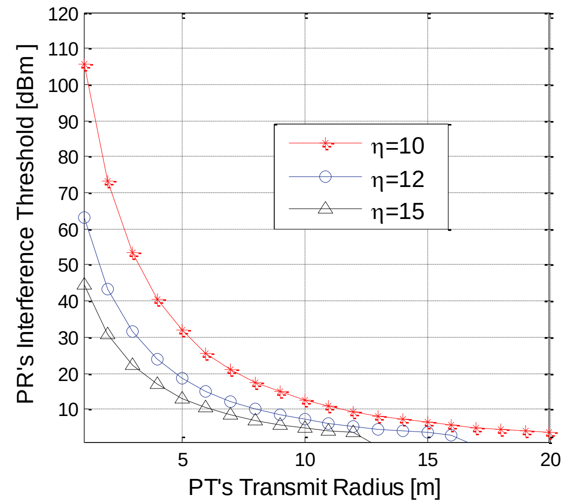


Figure 5. The relationship between PT's transmit radius and PR's interference threshold

Figure 5 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

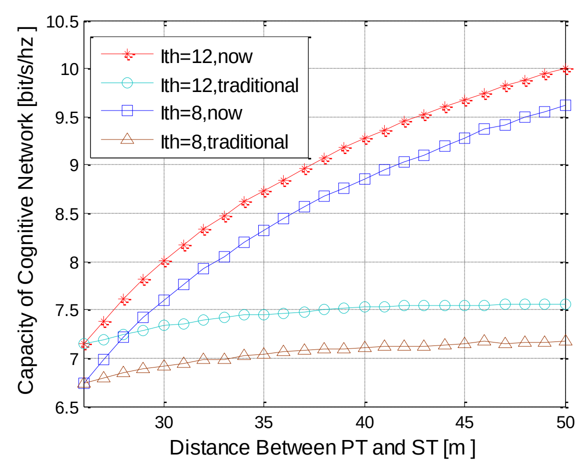


Figure 6. Compare our scheme with the traditional scheme in case 1

Simulation results in 5.2.1 show that, when $\alpha = 2$, $\delta^2 = -3dBm$, $R_o = 15m$, η=10, the interference threshold is $I_{th} = 12$. Figure 6 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 7 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.

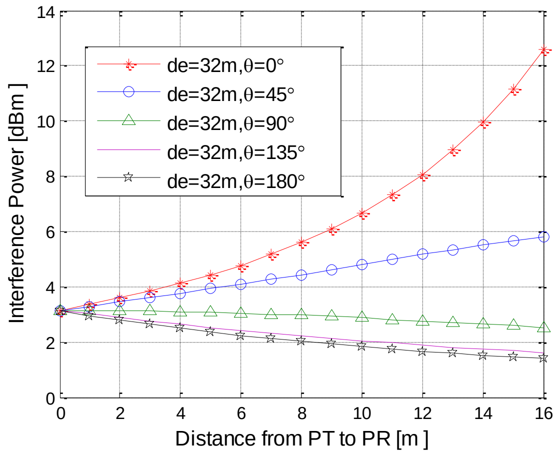


Figure 7. Interference received by PR in any position

5.2.3CASE 2

Figure 8 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.

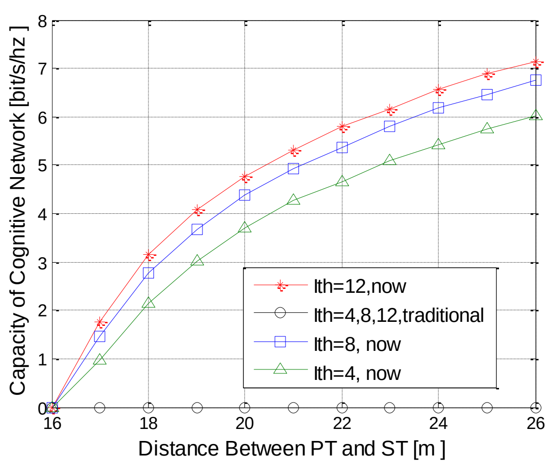


Figure 8. Compare our scheme with the traditional scheme in case 2

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 9 shows that the missed detection probability will increase with the expansion in ST's communication radius. So this scheme for power control is significant.

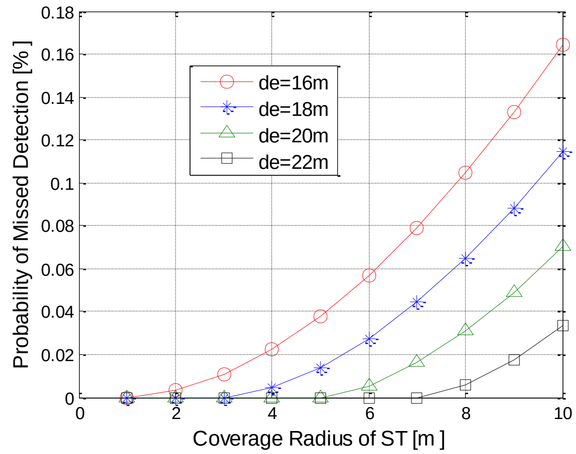


Figure 9. Probability of missed detection

5.2.4 Effect of position error on the performance of cognitive network

Figure 10 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.

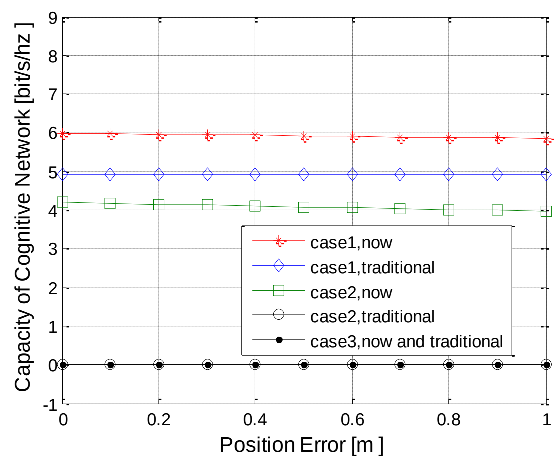


Figure 10. Effects of position errors on the capacity of cognitive network

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.

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