Enhanced Adaptive Beamforming and Null Steering Algorithms in Cognitive Radio System

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ABSTRACT

The spectrum efficiency of mobile communication networks can be improved dramatically adopting multiple antennas technologies. In order to guarantee the licensed rights of primary user (PU), the cognitive radio system should perform in a relatively low interference manner when it gets access to the spectrum of licensed networks. In this paper, we explore a uniformly distributed circular antenna array to implement beamforming algorithm that is accomplished by optimization method at the base station of cognitive radio networks, and therefore we can suppress the interference to PU by steering quite low transmission power toward PU and constructing a narrow beam toward cognitive user (CU). By reducing the constraint number of the optimization problem, we also propose a null steering algorithm that steers rather low radiation power toward PU, while the other areas in the same cell are covered by radiation power except the local area around PU. It is pursued to reduce the computation load and enlarge the capacity of cognitive radio networks extremely. The simulation results demonstrate that the proposed algorithms process superior performance.

Key Words : DOA, Antenna Array, Adaptive Beamforming, Null Steering, Optimization Problem

Ⅰ. Introduction

Cognitive radio has been proposed as a potent solution for alleviating the scarcity of spectrum resources as a result of the fixed license spectrum policy[1]. However, the proposed application of cognitive radio accompanies with severe interference to PU and a pernicious influence on the performance of licensed systems when cognitive radio performs spectrum sharing with licensed primary systems. Thus, the issue of interference has been thrown into sharp focus and it is essential that we exploit effective measures to solve this problem.

With progressions in combating the interfering, many techniques have enabled us to preserve PU potently. A spectrum sensing method is introduced and enhanced in[2], which is implemented to detect signals and classify signal types, and then, carrying out other operations, such as dynamic frequency hopping (DFH)[3], CU makes use of the vacant frequencies but CU should vacate the frequency or hop to other unoccupied frequency bands as long as PU is enabled. Although co-channel interference is eliminated reasonably by above methods, spectrum sensing and DFS are mainly used for signal detection and spectrum sharing in order to enlarge system capacity, respectively. However, it is not enough to mitigate interference only at user terminals that there is another severe interference resource that radiates from the base station of cognitive radio.

In up to date studies, smart antenna technologies such as beamforming are exploited to reduce interference to PU in cognitive radio networks, which constructs a main beam toward CU while steers null radiated power toward PU. In[4], maximum signal-to-interference ratio (SIR)

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and minimum mean square error (MMSE) beamforming algorithms that reduce multipath and co-channel interference were investigated adopting a linear antenna array. An interference reduction method of beamforming was proposed in[5] that the SIR of CU was maximized. Further studies have been performed in[6] where the algorithms of joint beamforming and power allocations were developed. However, most contributed studies on beamforming deploying linear antenna array that results in limiting the performance of beamforming. The radiated beam pattern of linear antenna array is symmetrical, i.e. only half of the total cell circle is under control while the other side is out of reach.

In this paper, we explore uniform circular antenna array and concentrate on minimizing interference to PU while enhancing power efficiency and system capacity. Firstly, the DOA of incident signals is estimated by MUSIC algorithm[7]. Then, we propose an adaptive algorithm based on the preliminary work[8] that calculates a set of beam-forming weights by optimization solution. In this algorithm, our target aims higher beamforming gain in the direction of CU and minimizes the gain in the direction of PU. At the same time, the gains in the directions except CU and PU are constrained so as to decrease system power consumption. Thirdly, in order to reduce the computation load and enlarge the system capacity, we proposed a loose constraint optimization problem by which the radiation power of cognitive radio transmitter is null in the direction of PU while the radiation power is not suppressed in other directions.

The paper is organized as follows. In section Ⅱ, we present multiple antennas, the system model and formulate some basic problems in our scheme. Section Ⅲ describes the principle of the adaptive beamforming and the null steering algorithms. In addition, the computational complexity is analyzed. In section Ⅳ, we show the simulation results to evaluate the performance of our algorithm. Section Ⅴ concludes the paper.

Ⅱ. System Description

2.1 Circular antenna array

In our scheme, the uniform circular antenna array with M elements is implemented and a schematic diagram of antenna array with 8 elements is shown in Fig. 1. For ease of analysis, we only take the azimuth angles into account in the propagation scheme. After obtaining the DOA information of incident signals, the steering vector of an M-element array is given by

$$V(\theta)=\begin{bmatrix} e^{-j\omega r\cos(\theta-\phi_1)/c} \\ e^{-j\omega r\cos(\theta-\phi_2)/c} \\ \vdots \\ e^{-j\omega r\cos(\theta-\varphi_M)/c} \end{bmatrix}^H \tag{1}$$

where $\omega=2\pi f_c$ (f_c is the carrier frequency), r is the radius of circular array, θ is the azimuth angle of incident signal with respect to antenna array, $\phi_i=\frac{2\pi}{M}i\ (i=1,\cdots,M)$ is the angle distri-bution of antenna elements, and c is the light speed.

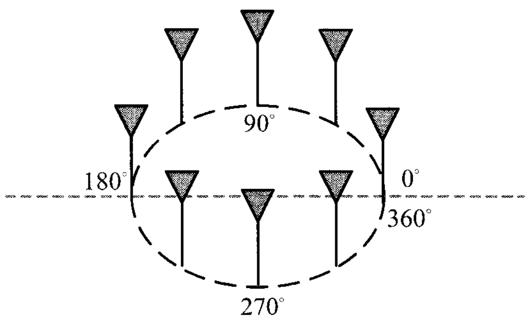

Fig. 1. An example of a Circular Antenna Array with 8 elements

2.2 System Model

The system model is illustrated in Fig. 2, where the cognitive network shares frequency spectrum with primary network. In general, it is mixed that the distribution of cognitive radio system and primary system, thereby the cell size

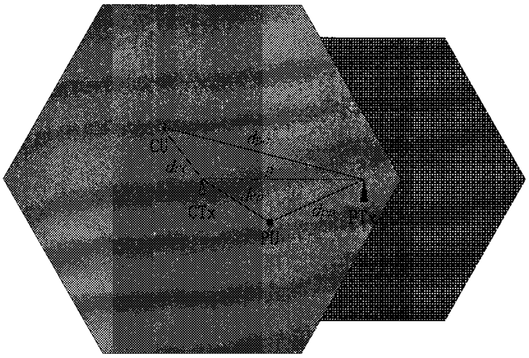

Fig. 2. System Model

relationship between them is indeterminate because it depends on different situations. If the cell of CR system is too small, there is not enough frequency resource to deploy CR system, which results in worthless of cognitive radio. On the other hand, if the cell of CR system is too large, it will increase difficulty and complexity to carry out spectrum sensing. In our work, we only consider IEEE 802.22 standard in which cognitive radio is deployed in rural areas and therefore we assume that the radius of cognitive radio d is a little larger than that of primary network D ($d > D$). PTx and CTx are transmitters of primary and cognitive networks, respectively. We only analyze the downlink of the cognitive network where CTx is equipped with an M-element circular array antenna. d_{cp}, d_{cc}, d_{pc} and d_{pp} are interpreted as distances between transmitters and users. Accordingly, the DOAs that are denoted by θ_{cp}, θ_{cc}, θ_{pc} and θ_{pp} are azimuth angles of incident signals.

Due to spectrum sharing, the received signals at PU are contaminated by the signals from CTx and as well the received signals at CU are interfered by the signals from PTx. $W=[w_1, w_2, \cdots, w_M]^H$ is a transmit beamforming weight vector in cognitive radio network. The beamforming gain in the direction of θ can be written as

$$G(\theta) = V(\theta)\, W \tag{2}$$

and we assume that the path loss with a factor α is in a large scale wireless channel, so the channel state information for a user in the direction of θ can be expressed as

$$H = d^{-\alpha}\, V(\theta) \tag{3}$$

Adding channel and noise to transmitted signals, the received signals at CU and PU can be expressed as

$$\begin{aligned} y_c &= H_{cc} W s_c + H_{pc} W s_p + n_c \\ y_p &= H_{pp} W s_p + H_{cp} W s_c + n_p \end{aligned} \tag{4}$$

where n_c and n_p are noise for CU and PU that are zero-mean Gaussian with same variance σ^2, while s_c and s_p are the independent signals of CU and PU, respectively.

Let P_c and P_p denote the transmitted power of CTx and PTx, respectively. The signal to interference and noise ratio (SINR) of the cognitive and primary receiver can be expressed as

$$\begin{aligned} SINR_c &= \frac{P_c |H_{cc} W|^2}{P_p |H_{pc} W|^2 + \sigma^2} \\ SINR_p &= \frac{P_p |H_{pp} W|^2}{P_c |H_{cp} W|^2 + \sigma^2} \end{aligned} \tag{5}$$

Ⅲ. The Proposed Algorithms and Solutions

In this section, the proposed adaptive transmit beamforming algorithm is derived firstly, which is combined with DOA estimation at cognitive transmitter. By using this algorithm, we dominate the radiation power towards CU and minimize the radiation power (interference to PU) below a threshold I_0 in the direction of PU. Simultaneously, undesired side lobe is constrained. We pursue to realize higher power efficiency with narrower beam and lower interference to PU. Furthermore, the null steering method is formulated.

3.1 The Adaptive Beamforming Algorithm

There is no cooperation between PTx and CTx, so we cannot dominate the behavior of PTx and only consider adjusting CTx to construct transmit beamforming by calculating a set of weights $W=[w_1,w_2,\cdots,w_M]^H$. Given the DOA estimated by MUSIC algorithm, the optimization problem at CTx is

$$\begin{aligned} &\max\ SINR_c \\ &s.t. \\ &P_c|H_{cp}W|^2 \le I_0 \\ &P_c < P_{\max} \\ &|G(\theta_{cc})|^2 = 1 \\ &|G(\theta_i)|^2 \le 0.01,\ \theta_i \notin [\theta_{cc}-\Delta\theta, \theta_{cc}-\Delta\theta] \end{aligned} \tag{6}$$

where $\Delta\theta$ is interpreted as a minimum resolution angle, I_0 is a threshold that denotes maximum interference to PU, $P_{\max}$ is the maximum transmit power of CTx, θ_{cc} denotes the DOA of CU. $|G(\theta_i)|^2 \le 0.01,\ \theta_i \notin [\theta_{cc}-\Delta\theta,\ \theta_{cc}+\Delta\theta]$ is contained in (6) in order to suppress the side lobe and the interference received at PU as much as possible, and moreover, the total transmitted power at CTx is decreased as a result of the constraint value that is constrained below 0.01 equaling 20 in dB. Due to the located relationship of different users, the transmit beamforming algorithm is explained in two cases.

3.1.1 Case 1

If the angle of PU satisfies $|\theta_{cp}-\theta_{cc}| > \Delta\theta$, we maintain a high beamforming gain in the direction of CU while minimize beamforming gain in the direction of PU and constrain the beamforming transmission gains outside the angle range of $[\theta_{cc}-\Delta\theta,\ \theta_{cc}+\Delta\theta]$. Thus, the optimization problem is performed same as (6).

3.1.2 Case 2

If $|\theta_{cp}-\theta_{cc}| \le \Delta\theta$, the PU and CU are located at the same location almost, so we do not put a high beamforming gain in the direction of θ_{cc} for cognitive user, on the contrary, minimize the beamforming gain in the direction θ_{cc} as well as constrain other outside directions. Based on (2) and (3), $H_{cc}W$ equals to $d_{cc}^{-\alpha}G(\theta_{cc})$. In the first place, we add a constraint $\theta_{cp}=\theta_{cc}, |\theta_{cc}-\theta_{cp}| \le \Delta\theta$ to the optimization problem which is an extension of case 1 and then modify (6) as follows

$$\begin{aligned} &\max\ SINR_c \\ &s.t. \\ &\theta_{cp}=\theta_{cc},\ |\theta_{cc}-\theta_{cp}| \le \Delta\theta \\ &P_c d_{cp}^{-2\alpha}|G(\theta_{cp})|^2 \le I_0 \\ &P_c < P_{\max} \\ &|G(\theta_{cc})|^2 = 1 \\ &|G(\theta_i)|^2 \le 0.01,\ \theta_i \notin [\theta_{cc}-\Delta\theta, \theta_{cc}+\Delta\theta] \end{aligned} \tag{7}$$

According to (5), the interference to PU and $SINR_c$ will increase as P_c increases. We can get a maximum value of $G(\theta_{cp})$ which satisfies the maximum interference to PU, i.e. the optimization problem is a tradeoff between $SINR_c$ and the interference to PU. Therefore, (7) can be expressed to a mini-max optimization problem as below

$$\begin{aligned} &\min \underbrace{\max}_{\theta_{cp}-\Delta\theta < \theta_j < \theta_{cp}+\Delta\theta} |G(\theta_j)| \\ &s.t. \\ &\theta_{cp}=\theta_{cc},\quad |\theta_{cc}-\theta_{cp}| \le \Delta\theta \\ &|G(\theta_{cc})|^2 = 1 \\ &|G(\theta_i)|^2 \le 0.01,\quad \theta_i \notin [\theta_{cc}-\Delta\theta, \theta_{cc}+\Delta\theta] \end{aligned} \tag{8}$$

3.2 The Adaptive null steering Algorithm

By cancelling the side lobe constraint and the main beam construction, we can perform the adaptive null steering algorithm. As proposed in this algorithm, we pursue to suppress interference to PU and enlarge the capacity of cognitive system to accommodate more cognitive users. We perform this algorithm by constructing the proposed array radiated pattern, in which the weight vector must be calculated firstly through optimization solution. The optimization problem is formulated as

$$\min \underbrace{\max}_{\theta_{cp}-\Delta\theta \le \theta_j \le \theta_{cp}+\Delta\theta} |G(\theta_j)|$$
$$s.t. \qquad (9)$$
$$\theta_{cp}=\theta_{cc}, \quad |\theta_{cc}-\theta_{cp}| \le \Delta\theta$$

The optimization problem (8) and (9) can be solved feasibly by convex optimization methods [9], so that the antenna weights can be calculated and then the radiation pattern of antenna array can be formed consequently.

3.3 The Distribution of CU for Null Steering Algorithm

Considering null steering algorithm, the coverage of radiated power is expanded, and hence we make further analysis to evaluate the system capacity by the viable distribution of CU in cognitive network. When PTx uses omni-directional antenna, we give $g_p(\theta)=1$. Consequently, From (5) and (7), we can get

$$SINR_c = \frac{c(d_{cp}/d_{cc})^{2\alpha}|g_c|^{-2}}{1+\gamma_p(d_{pp}/d_{pc})^{2\alpha}} \qquad (10)$$

Referring to the method used in [10], we use the upper and lower bounds to illustrate the distribution of CUs. Finally, we can derived

$$d_{lb}^{*2\alpha}+\gamma_p\frac{d_{pp}^{2\alpha}}{\left(D-d_{lb}^{*}\right)^{2\alpha}}d_{lb}^{*2\alpha}=\frac{d_{cp}^{2\alpha}c}{Tg_c^2}$$
$$d_{ub}^{*2\alpha}+\gamma_p\frac{d_{pp}^{2\alpha}}{\left(D-d_{ub}^{*}\right)^{2\alpha}}d_{ub}^{*2\alpha}=\frac{d_{cp}^{2\alpha}c}{Tg_c^2} \qquad (11)$$

In (11), γ_p, d_{lb}^* and d_{ub}^* are interpreted as SNR of PU, lower and upper bounds, respectively. T is the value of minimum $SINR_c$. By simulating the lower and upper bounds, we will illustrate the feasible distribution of cognitive user in section Ⅳ.

3.2 Computaiton Complexity Analysis

In our case, we recorded one point computational time to evaluate complication for adaptive algorithms. In simulation, we set initial point is (1,1) with a same iteration number 10. As shown in Table. 1., from initial point to objective point, the cost time of null steering algorithm is about 0.065s less than that of beamforming algorithm. For comparison, the computational time of LMS algorithm is also given above. Obviously, the computational time increases as the computational complexity increases, and therefore there is a tradeoff between better improvement and computational complexity.

Table 1. Computational Time

Algorithms	Initial	Iteration	Object	Time
Null Steering	(1,1)	10	(0.7242, 0.2734)	0.142 sec
Beamforming	(1,1)	10	(0.6710, 0.2203)	0.207 sec
LMS	(1,1)	10	(0.4924, 1.0381)	0.081 sec
Environment	Windows XP; 2.4GHz CPU; 2G RAM			

Ⅳ. Simulation Results

This section illustrates the performance of the proposed algorithms by simulation. We use the case of a 16-element circular antenna array at cognitive radio base station and the radius of circular array r is half of λ (λ is the wave length of carrier and equal to c/f_c). The minimum resolution angle between users is given by 15° that approximates half beam width and three times as the minimum resolution angle of DOA estimation by MUSIC.

With various signal processing technologies, the signals types can be distinguished, and then their direction of arrival can be calculated continuously. In this paper, we assume that the classification of signal type has been achieved and there are only two signal types which are cognitive and primary signals. The DOA estimation using MUSIC is simulated and shown in Fig. 3 and Fig. 7. For adaptive beamforming algorithm, the estimated angles of PU and CU are 110° and 200° as shown in Fig. 3. In Fig. 7, the estimated angle of PU is set to 180° which is used for implementing null steering algorithm.

To illustrate the improvement of adaptive

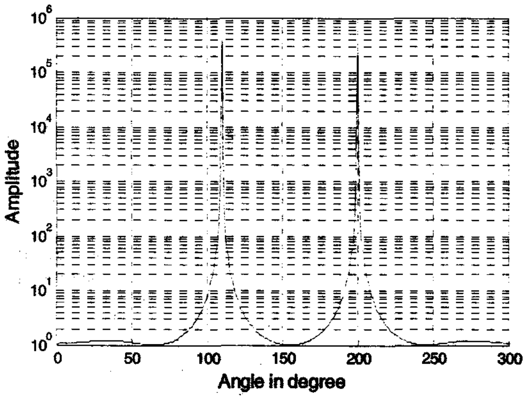

Fig. 3. DOA Estimation for Adaptive Beamforming

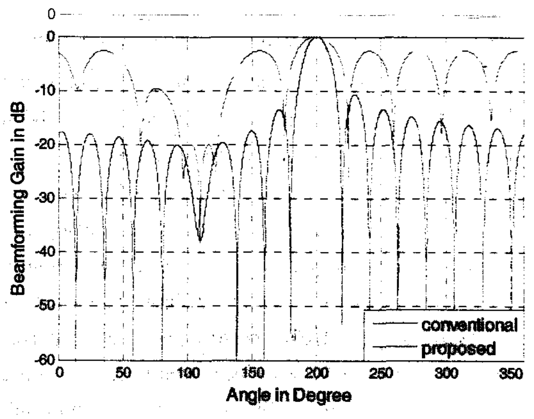

Fig. 8. Radiated Pattern of Null Steering

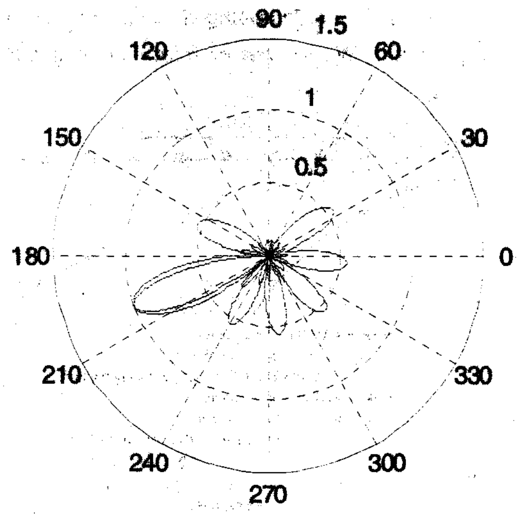

Fig. 9. Radiated Pattern In Polar Coordinate

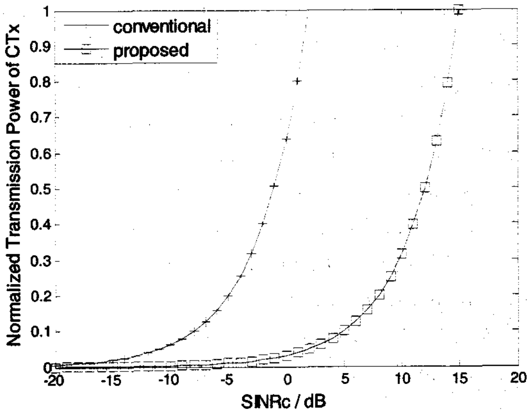

Fig. 6. Normalized Transmission Power of CTx vs. SINRc

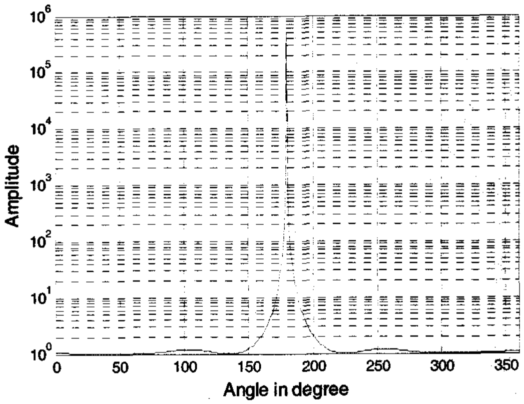

Fig. 7. DOA Estimation for Null Steering Algorithm

beamforming algorithm comparing with conventional one, the case of single CU and single PU is simulated and shown in Fig. 4

and Fig. 5. By comparison, the proposed beam pattern exhibits a narrower beam width in the direction of CU and lower power radiation which is about 15 dB lower than conventional one in undesired directions.

In Fig. 6, the normalized total power of CTx versus $SINR_c$ is indicated, by which the proposed algorithm consumes less energy than conventional one correspond to a given $SINR_c$. Consequently, our adaptive beamforming algorithm not only deeply suppresses the interference to PU, but also saves a lot of transmission power.

The radiated pattern of adaptive null steering algorithm is shown in Fig. 8 and Fig. 9. As we can see, there is a hollow sector in the direction of PU, which is called null steering region and it keeps the interference radiated from CTx away from PU. However, the region except the hollow sector part of the celluar is in the reach of transmitted power of CTx so as to serve CUs. The coverage of CTx is more larger than that of a single narrow beam so that the system could accommodate more cognitive users.

In Fig. 10, we assume that the celluar radius d of cognitive radio is 1.5 kilometers, $\gamma_c = 20dB$, $\gamma_p = 10dB$ and the DOA of PU is $180°$. The feasible distribution of CU is limited in the coverage of lower and upper bounds, where the

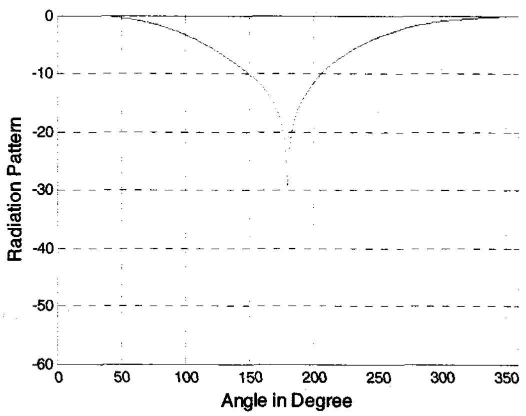

Fig. 8. Radiated Pattern of Null Steering

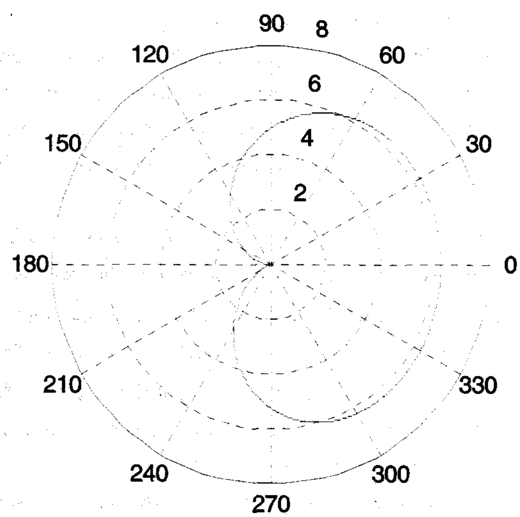

Fig. 9. Radiated Pattern In Polar Coordinate

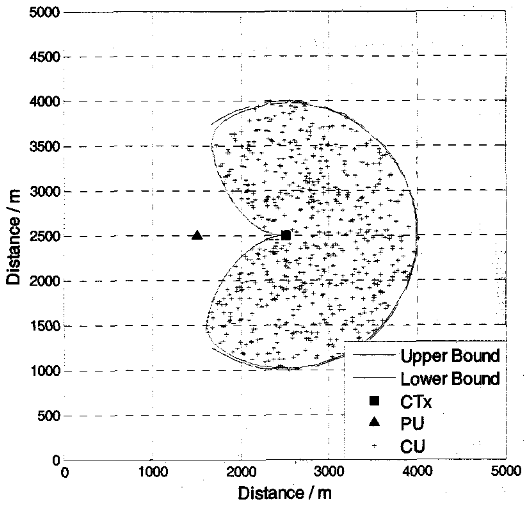

Fig. 10. Feasible Distribution of CU

$SINR_c$ is no less than $6dB$. Through simulation, the result shows that the interference mitigation and capacity performance of the system have been greatly enhanced by null steering algorithm.

In the case of antenna array application, we focus on the coverage of antenna and analyzing the radiation beam pattern, as a result, we usually only consider the large scale fading. However, if we analyze the BER performance at receiver terminal, we should consider small scale fading which is mainly brought by multi-path propagation.

To analyze BER performance at receiver, we adopt ITU-R M. 1225 multipath delay profile and Jakes method. We set carrier frequency at 2 GHz,

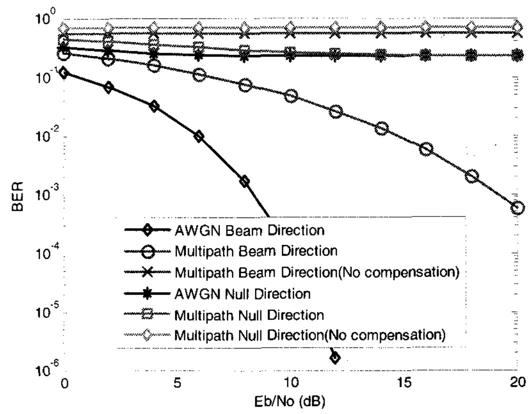

Fig. 11. BER Performance

QPSK modulation and vehicular speed at 3 km/h. In Fig. 11, the BER performance of cognitive receiver is simulated in two directions which are beam direction and null direction. Multipath fading impacts BER performance heavily and the BER becomes worse if there is no compensation measure as shown in Fig. 11. The BER in the direction of beam is much better than that of null part because in the beam direction CU is in the coverage of radiation beam while there is almost no signal power radiation in the direction of null part.

V. Conclusion

In this paper, two adaptive algorithms are proposed and deployed in different situations. By implementing adaptive beamforming algorithm, the cognitive radio network operates in a power saving manner and PU is protected from interference at the same time. This algorithm is applicable in the case that there is no strict requirement of computation load. It is practical that the relay networks can profit from the power efficiency of this algorithm. Additionally, simulation analysis demonstrated the considerable performance of adaptive null steering algorithm. With the aim of interference elimination, the adaptive null steering algorithm also enlarges cognitive system capacity and alleviates the optimization load.

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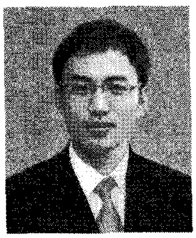

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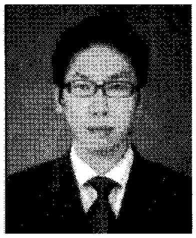

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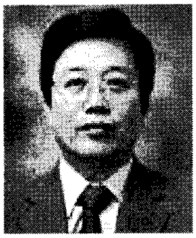

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