Cooperative Spectrum Sensing Techniques in Cognitive Radio

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Abstract:
Cognitive radio has become an effective theory to solve the inefficiency of the spectrum usage. One of the main requirements of cognitive radio systems is the ability to reliably detect the spectrum hole. Previous works on the problem of detection for cognitive radio have suggested the necessity of user cooperation to enable the detection at the low signal-to-noise ratios experienced in practical situations. This paper introduces energy sensing and the cooperative sensing techniques: AND model, OR model, counting model, double threshold model, likelihood ratio model, linear cooperation model and DWCS model. It is proved that significant cooperative gain can be achieved by the proposed models in reducing interference and improving spectrum usage.

With the rapid development of wireless communications, spectrum resources become increasingly scarce. On the other hand, a statistics shows that the utilization of spectrum resources is at a very low level in terms of time and space. This paradox can be largely attributed to current fixed spectrum allocation policy. Cognitive Radio (CR) is a novel wireless communication technology that can intelligently be aware of and adapt to its surrounding environment. By detecting and utilizing spectrum resources, CR can solve current unreasonable spectrum allocation problem quite well[1].

Recently, the Federal Communications Commission (FCC) passed the proposal on spectrum reuse, allowing unlicensed operation in the bands of licensed users, such as TV broadcast bands[2]. In order to ensure the licensed user's use of specific band, the cognitive user has to accurately detect whether current band is used by a licensed user. As a result, spectrum sensing makes a critical part of CR technology.

Among existing spectrum sensing techniques in CR, energy sensing has been widely applied. Its algorithm is simple and it does not require transcendental knowledge of the licensed user's signals, so it is quite suitable for cognitive radio systems with low receiving Signal-to-Noise Ratio (SNR) of cognitive users. Due to special environments of wireless communications, such interference factors as multi-path and shadow effect are present during signal propagation. Some cognitive users may be found with quite low spectrum detection probabilities at some special geographical locations, which leads to increasing interference onto the licensed users. To solve this problem, energy sensing-based cooperative detection techniques should be used. Currently, cooperative detection techniques have become key technologies in CR, attracting wide attention.

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1 Energy Sensing

A cognitive user is supposed to detect N consecutive sampling points in the band of a licensed user each time:

$$y_i=\begin{cases} n_i, & H_0 \\ h\times x_i+n_i, & H_1 \end{cases} \quad i=1,2\cdots N \tag{1}$$

where n_i is the noise of the sampling point i (Here it is assumed that the noises of N sampling points are independent and identically-distributed cumulative Gaussian white noise and $n_i:N(0,\sigma^2)$; x_i is licensed user signal at sampling point i; y_i is signal i detected by the cognitive user; and h is channel gain. As energy sensing requires very short detection time, h is supposed to keep unchanged during detection. Binary hypothesis is adopted here: H_0 means there is not any licensed user signal, and the band is idle; while H_1 indicates the licensed user is using the band.

The objective of energy sensing is to decide whether H_0 or H_1 is true by sensing the energy of signal y_i. The output of energy detector is as follows:

$$T=\sum_{i=1}^{N}|y_i|^2 \tag{2}$$

According to the central limit theorem, when N is large enough (often no less than 10), T values approximate Gaussian distribution. Due to its simple mathematical expressions, Gaussian distribution is often used in energy sensing:

$$E(T)=E(\sum_{i=1}^{N}|y_i|^2)=\begin{cases} N\sigma^2 & H_0 \\ N\sigma^2+P & H_1 \end{cases} \tag{3}$$

$$Var(T)=Var(\sum_{i=1}^{N}|y_i|^2)=\begin{cases}2N\sigma^4 & H_0\\ 2N\sigma^4+4\sigma^2P & H_1\end{cases} \quad (4)$$

where $P=|h|^2\sum_{i=1}^{N}|x_i|^2$, that is, the energy of a sample signal detected by the cognitive user.

In energy sensing, a threshold η is predefined. If $T\geqslant\eta$, H_1 is true, which means the licensed user is using current band. On the contrary, if $T<\eta$, H_0 is true, indicating the current band is idle. Because T values approximate Gaussian distribution, the detection probability P_d and false alarm probability P_f can be calculated with the following formulas:

$$P_d=P(T\geqslant\eta/H_1)=Q(\frac{\eta-E(T/H_1)}{\sqrt{Var(T/H_1)}}) \quad (5)$$

$$P_f=P(T\geqslant\eta/H_0)=Q(\frac{\eta-E(T/H_0)}{\sqrt{Var(T/H_0)}}) \quad (6)$$

where $Q(\eta)=\frac{1}{\sqrt{2\pi}}\int_{\eta}^{\infty}e^{-x^2}dx$ is the cumulative distribution function of Gaussian distribution.

If the detection probability P_d of the system is given, the threshold η can be calculated with Formula (5) and the false alarm probability P_f can be optimized. Similarly, if the false alarm probability P_f is given, the threshold η can be obtained with Formula (6) and the detection probability P_d can be optimized.

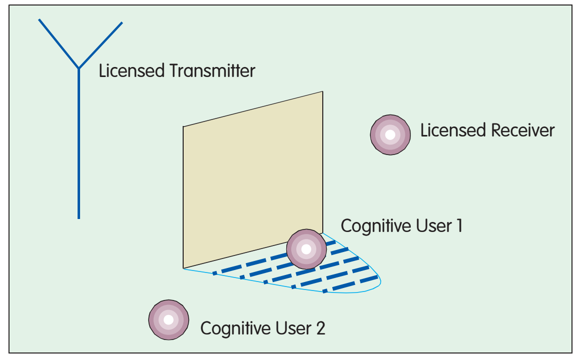
2 Cooperative Detection Techniques

Due to the presence of such interference factors as multi-path and shadow effect in wireless channels, energy sensing conducted by a single cognitive user may perform quite poor in some cases. Figure 1 illustrates how Cognitive User 1 wrongly finds that the current band is idle due to shadow effect and uses the band, thus bringing interference on licensed receiving user. To solve such a problem, cooperative detection techniques should be used. For example, in Figure 1, with cooperative detection by Cognitive Users 1 and 2, the usage of current band can be accurately detected despite shadow effect.

The cooperative detection algorithms in CR mainly fall into two categories: hard decision based and soft decision based.

2.1 Hard Decision Based Algorithms

In the hard decision based cooperative detection algorithms, each cognitive user first decides its detection result as either 0 or 1; and then sends its decision to the processing center for cooperative detection. The common algorithms using hard decision include AND, OR, and counting algorithms.



▲Figure 1. Impact of shadow effect on cognitive users.

2.1.1 AND Algorithm

AND algorithm[3] is quite simple. First, all cognitive users detect the signals of a band and judge if the band is idle; then, their decisions are sent to the processing center; finally, upon receiving all decisions from the cognitive users in a given range, the processing center adopts AND algorithm to decide if the band is being used by a licensed user. That is to say, only when all users detect the signals of the licensed user, the band is regarded occupied. Supposing there are K cognitive users participating in cooperative detection, the detection probability P_d and false alarm probability P_f calculated with AND algorithm are as follows:

$$P_d=\prod_{i=1}^{K}P_{d,i} \qquad i=1,2\cdots K \quad (7)$$

$$P_f=\prod_{i=1}^{K}P_{f,i} \qquad i=1,2\cdots K \quad (8)$$

From the above formulas, it can be seen that AND algorithm reduces both P_d and P_f of the system, which means more interference and higher spectrum utilization than traditional non-cooperative algorithms. Here, it is assumed that the interference boundary tolerated by a licensed user is $1-P_d$ and a simple analysis on the optimization of P_f is made.

Supposing the detection probability required by the system is P_d, the average detection probability of K cooperative cognitive users is:

$$\overline{P_{d,i}}=\sqrt[K]{P_d} \qquad i=1,2\cdots K \quad (9)$$

The decision threshold can be obtained from Formula (9) and Formula (5):

$$\eta_i=\sqrt{Var(T_i/H_1)}\,Q^{-1}(\overline{P_{d,i}})+E(T_i/H_1) \quad (10)$$

So the false alarm probability of the entire system (i.e. P_f) is:

$$P_f=\prod_{i=1}^{K}Q(\frac{\sqrt{Var(T_i/H_1)}\,Q^{-1}(\overline{P_{d,i}})+E(T_i/H_1)-E(T_i/H_0)}{\sqrt{Var(T_i/H_0)}}) \quad (11)$$

Formula (8) shows that the bigger the number of the cognitive users who participate in spectrum sensing, the smaller the P_f is. According to Formula (9) and the characteristics of exponential functions, the bigger the number of the cooperative cognitive users, the larger the average detection probability $\overline{P_{d,i}}$ is. From Formula (10) and the characteristics of $Q(x)$ function, it can be concluded that the larger the average detection probability, the smaller the decision threshold η_i, which leads to a larger P_f of the cognitive user i ($\overline{P_{d,i}}$). As a result, the increase in number of cognitive users worsens P_f. There should be an optimal number of cooperative users K, under which not only the required detection probability of the system (i.e. P_d) can be met, but also the minimum P_f can be produced. At present, this optimal number is usually obtained by means of searching with computers.

The above analysis assumes the average detection probability of K cooperative cognitive users (i.e. $\overline{P_{d,i}}$). In reality, cognitive users often have different detection probabilities because their channel conditions vary. This makes it more difficult to determine the optimal number of cooperative cognitive users.

2.1.2 OR Algorithm

OR algorithm is basically similar to AND algorithm except that with OR algorithm, the system determines that one band is being used by a licensed user so long as a cognitive user detects the signals of the licensed user. The detection probability P_d and false alarm probability P_f calculated with OR algorithm are as follows:

$$P_d=1-\prod_{i=1}^{K}(1-P_{d,i}) \qquad i=1,2\cdots K \quad (12)$$

$$P_f=1-\prod_{i=1}^{K}(1-P_{f,i}) \qquad i=1,2\cdots K \quad (13)$$

Formulas (12) and (13) suggest that OR algorithm increases both P_d and P_f of the system. Like AND algorithm, there exists an optimal number of cooperative users when P_d is given. In fact, with OR algorithm, the P_f will be increased whenever a new cooperative user joins. Moreover, the increase of the cooperative cognitive users will decrease the detection probability of each user ($P_{d,i}$), the false alarm probability of each user ($P_{f,i}$) and the false alarm probability of the system (P_f).

2.1.3 Counting Algorithm

Counting algorithm[4] is an improvement of AND algorithm and OR algorithm. With this algorithm, when the processing center receives the decisions of cognitive users of a given range, it counts the number of cognitive users that have detected the signals of a licensed user and the system decides that a band is being used only when a certain number limit is reached. In some sense, AND algorithm and OR algorithm can be regarded as two special cases of counting algorithm. In AND algorithm, the number limit is K (i.e. all cognitive users); while in OR algorithm, the number limit is 1.

In counting algorithm, the decision rule for each cognitive user is as follows:

$$R_i=\begin{cases}0 & T\leqslant\eta_i\\ 1 & T\geqslant\eta_i\end{cases}\qquad(14)$$

And the discrete distribution of R_i is:

$$R_i:\begin{pmatrix}0 & 1\\ 1-P_{f,i} & P_{f,i}\end{pmatrix} H_0$$
$$R_i:\begin{pmatrix}0 & 1\\ 1-P_{d,i} & P_{d,i}\end{pmatrix} H_1\qquad(15)$$

At the processing center, the decision rule is:

$$R=\begin{cases}0 & \sum_{i=1}^{K}R_i\leqslant\beta\\ 1 & \sum_{i=1}^{K}R_i>\beta\end{cases}\qquad(16)$$

Let's simply analyze the detection probability P_d and false alarm probability P_f of the system. Suppose the cognitive users are independent of each other. According to the central limit theorem, $\sum_{i=1}^{K}R_i$ basically approximates Gaussian distribution and its mean and variance can be computed as follows:

$$M=E(\sum_{i=1}^{K}R_i)=\sum_{i=1}^{K}E(R_i)=\begin{cases}\sum_{i=1}^{K}P_{f,i} & H_0\\ \sum_{i=1}^{K}P_{d,i} & H_1\end{cases}\qquad(17)$$

$$V=Var(\sum_{i=1}^{K}R_i)=E(\sum_{i=1}^{K}R_i)^2-(E(\sum_{i=1}^{K}R_i))^2$$
$$=\begin{cases}\sum_{i=1}^{K}P_{f,i}-\sum_{i=1}^{K}P_{f,i}^2 & H_0\\ \sum_{i=1}^{K}P_{d,i}-\sum_{i=1}^{K}P_{d,i}^2 & H_1\end{cases}\qquad(18)$$

Hence, P_d and P_f of the system are:

$$P_d=Q(\frac{\beta-M_{H_1}}{\sqrt{V_{H_1}}})\qquad(19)$$

$$P_f=Q(\frac{\beta-M_{H_0}}{\sqrt{V_{H_0}}})\qquad(20)$$

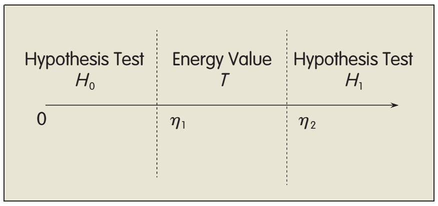
When the system detection probability P_d is given, the threshold β and corresponding P_f can be obtained on the precondition that the detection probability and false alarm probability of each cognitive user are known. In fact, it is quite complicated to optimize the values of M, V, P_d and P_f in Formulas (17), (18), (19) and (20) at the same time, that is, to get the minimum P_f by optimizing the parameter of each cognitive user with P_d being given. Currently, the optimal values are often obtained by means of computer simulations.

2.2 Soft Decision Based Algorithms

In case of good channel conditions, the hard decisions of cognitive users are often highly reliable. However, when the detected signal energy approximates the threshold, errors are likely to occur in the hard decisions. In this case, soft decision approach can be introduced. In soft decision based cooperative detection algorithms, each cognitive user first makes soft decision, whose result may be a likelihood ratio or an energy value; and then the decision is sent to the processing center. Common soft decision based cooperative detection algorithms include double threshold energy detection, likelihood ratio detection and linear cooperation[5-6]. In addition, this paper proposes a CR system based on Distributed Wireless Communications System (DWCS).

2.2.1 Double Threshold Energy Detection

The double threshold energy detection algorithm[7] takes advantage of both hard decision and soft decision approaches. As shown in Figure 2, two energy thresholds (η_1 and η_2, which are different for each user) are involved in this algorithm. Each user makes decisions



▲Figure 2. Double threshold energy detection.

based on the following rule:

$$R=\begin{cases}0 & T\leqslant\eta_1\\ T & \eta_1<T<\eta_2\\ 1 & T\geqslant\eta_2\end{cases}\qquad(21)$$

Each cognitive user sends its decision R_i to the processing center. Upon receiving the decisions from cognitive users, the center first classifies the decisions of all users. In case the decision is 0 or 1, a hard decision based algorithm (AND, OR or counting) will be used. Here, an example for OR algorithm is used to make comparisons. If the result is an energy value T_i, soft decision will be made at the processing center based on the following rule:

$$S=\begin{cases}0 & \sum_{i=1}^{M}T_i\leqslant\eta_s\\ 1 & \sum_{i=1}^{M}T_i\geqslant\eta_s\end{cases}\qquad(22)$$

Suppose the first M users provide soft decisions and the threshold for soft decision is η_s. As $\sum_{i=1}^{M}T_i$ approximate Gaussian distribution, the distribution of S can be computed with the probability density function.

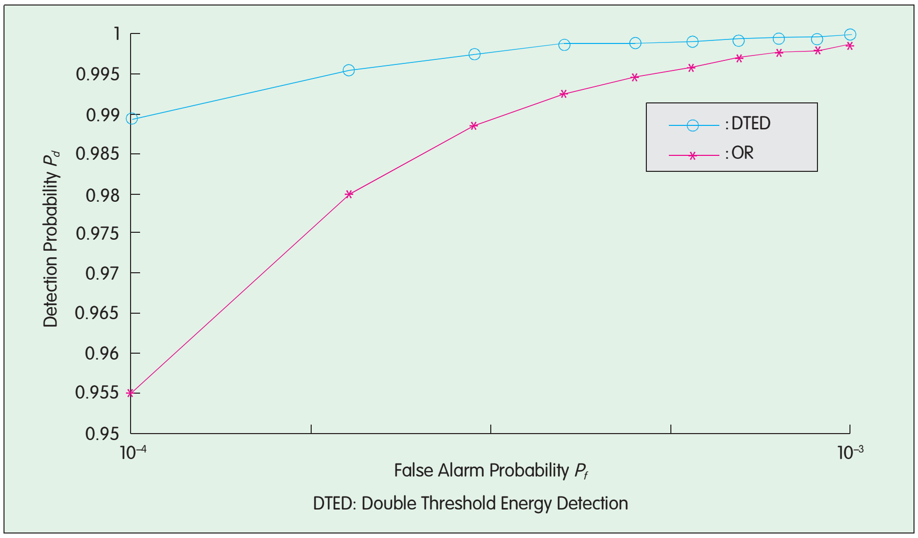
As a result, the final decision rule is:

$$R=\begin{cases}H_1 & S+\sum_{i=M+1}^{K}R_i\geqslant 1\\ H_0 & \text{others}\end{cases}\qquad(23)$$

In double threshold energy detection algorithm, hard decision is used by the cognitive users with good channel conditions, while soft decision is used by the users with poor channel condition. The simulation results in Figure 3 show that this algorithm can significantly improve the spectrum detection performance compared with conventional OR algorithm.

2.2.2 Likelihood Ratio Detection

The likelihood ratio algorithm uses likelihood ratios as the basis for detection, which is purely a soft decision algorithm. Theory study and simulations demonstrate that likelihood ratio



▲ Figure 3. Double threshold energy detection algorithm vs. OR algorithm.

detection is currently the best detection method, but it involves a very complicated algorithm. During likelihood ratio detection, each cognitive user detects the signals of current band, converts the energy value of detected signal into a likelihood ratio and sends it to the processing center. The processing center, based on the likelihood ratio of each user, uses certain algorithm to decide if the current band is idle. For user i, the energy value (T_i) of the signal it detects can be converted into a likelihood ratio with the following formula:

$$\lambda_i = \frac{p_1(T_i)}{p_0(T_i)} \tag{24}$$

As T_i approximates Gaussian distribution, the following formulas can be deducted from Formulas (3) and (4):

$$p_1(T_i) = \frac{1}{\sqrt{2\pi(2N\sigma^4+4\sigma^2P)}} e^{\frac{-(T_i-N\sigma^2-P)^2}{2(2N\sigma^4+4\sigma^2P)}} \tag{25}$$

$$p_0(T_i) = \frac{1}{\sqrt{4\pi N\sigma^4}} e^{\frac{-(T_i-N\sigma^2)^2}{4N\sigma^4}} \tag{26}$$

At the processing center, joint detection can be made by multiplying likelihood ratios of all users:

$$R = \begin{cases} 0 & \prod_{i=1}^{K}\lambda_i \leqslant \eta \\ 1 & \prod_{i=1}^{K}\lambda_i > \eta \end{cases} \tag{27}$$

Ideally, the threshold η is 1. But in actual application, the threshold η has to be determined with several measurements or by means of simulations. In some special cases, the likelihood ratios of some users may be too large or too small, thus affecting the performance of joint detection. To solve this problem, Reference [8] suggests an improved likelihood ratio algorithm:

$$\lambda_i = \begin{cases} a & \frac{p_1(T_i)}{p_0(T_i)} \leqslant a \\ \frac{p_1(T_i)}{p_0(T_i)} & a < \frac{p_1(T_i)}{p_0(T_i)} < b \\ b & \frac{p_1(T_i)}{p_0(T_i)} \geqslant b \end{cases} \tag{28}$$

2.2.3 Linear Cooperation

The linear cooperation model is also a soft decision algorithm. Compared with likelihood ratio algorithm, it can considerably decrease the complexity with little performance loss. As a result, it has gradually become one of hot topics in cooperative detection techniques for CR networks. In the following, several linear cooperation algorithms for energy detection are discussed.

In linear cooperation model, each cognitive user first detects the energy value (i.e. T_i) of the signal on current band, and directly sends T_i to the processing center. Upon receiving signal energy values from all users, the processing center weights the received values:

$$S = \sum_{i=1}^{K} T_i \times \omega_i \tag{29}$$

where $\omega_1, \omega_2 \cdots \omega_k$ are weighting coefficients.

Similarly, the weighted energy values S approximate Gaussian distribution. Therefore, after the mean and variance of S are calculated and an overall decision threshold η is set, the detection probability P_d and false alarm probability P_f can be worked out with Gaussian function.

The key of linear cooperation algorithm lies in the settings of weighting coefficients (i.e. $\omega_1, \omega_2 \cdots \omega_k$). At present, the most commonly-used methods for calculating weighting coefficients are as follows:

(1) Mean Weighting

The coefficient of weighted mean is: $\omega_i = 1/K$, $i = 1,2 \cdots K$. The weighted mean method is similar to counting algorithm. The difference between them is that in counting algorithm, the processing center only gets binary decision information (i.e. 0 or 1), while in weighted mean method, the center gets detection information of all cognitive users. Obviously, the later is better than counting algorithm.

(2) SNR Weighting

Considering the differences among cognitive users' channel conditions, the weighted mean method is not a reasonable weighting method. In weighted SNR method, the users with good channel conditions, i.e. the users with high SNR of their received signals, obtain high weighted coefficients. The coefficient of weighted SNR is calculated as follows:

$$\omega_i = \frac{\gamma_i}{\sum_{i=1}^{K}\gamma_i}, \qquad i = 1,2 \cdots K \tag{30}$$

where $\gamma_i = \frac{P_i}{\sigma_i^2}$ is the received SNR of Cognitive User i.

(3) Optimal Weighting

The way to calculate the optimal weighting coefficient is very complicated. So far, there is no clear analytic solution for it. Reference [9] presents a method of computing the optimal weighting coefficient by means of gradual searching and simulations show that the optimal linear cooperation algorithm works almost the same as likelihood ratio algorithm. Reference [10] discusses an optimal linear cooperation algorithm based on linear-quadratic fusion strategy.

When the received SNR of the cognitive user is quite low, the weighted SNR method is almost as good as the optimal linear cooperation algorithm. In actual systems, the cognitive user is usually far away from the licensed user and the received SNR is often very low.

Therefore, weighted SNR method is often used.

2.2.4 DWCS Algorithm

DWCS was first proposed by the Wireless and Mobile Communication Technology R&D Center of Tsinghua University[11]. It is designed to solve a series of cellular communication problems with a distributed network architecture. The DWCS is introduced in CR systems for the following two reasons:

(1) In cooperative CR systems with centers, a control channel from the cognitive user to the processing center is required no matter if hard decision or soft decision approach is adopted. In case of hard decision, only the binary codes "0" and "1" are transmitted, so the requirement for the control channel is very low; in case of soft decision, high requirements are imposed on the control channel because soft information has to be transmitted on it.

(2) In CR systems, the received SNRs of the signals to be detected by the cognitive users are often low, so the terminals (i.e. cognitive user receivers) must be highly sensitive, which leads to high costs of terminals. Application of DWCS architecture can better solve the above two problems.

The distributed CR system has the following three main features:

(1) It is configured with lots of distributed antennas, which are connected to the processing center via optical fiber cables.

(2) The detection of current spectrum is done by distributed antennas. The antennas send the detection results to the processing center, and the center adopts either hard or soft decision approach. Often, the soft decision approach is preferred.

(3) Once the processing center finds current spectrum is idle, it notifies all cognitive users within the antenna range of the availability of the band via these distributed antennas.

In addition to solving the problems of control channel and terminal users, the distributed CR system can use any of the above cooperation methods for spectrum sensing, so it has great potential advantages. Because the optical fiber-based channel is much better than the old wireless channel from the cognitive user to the processing center, more gains are obtained with the distributed CR system in terms of detection performance. In actual applications, the distributed CR system can be used for indoor coverage, Local Area Network (LAN) and burst communications. The research on such subjects of distributed CR system as cooperative cognition, data convergence and resource allocation has already been in progress and deepened.

3 Conclusion

In recent years, CR draws widespread attention as a new technology for solving spectrum resource scarcity. The spectrum sensing is a quite important part in CR. This paper discusses energy sensing, the common spectrum sensing algorithm in CR, as well as some cooperative detection algorithms such as AND, OR, counting, double threshold energy detection, likelihood ratio detection, linear cooperation, and DWCS. These cooperative spectrum sensing techniques can significantly improve the system's spectrum detection performance, reduce interference and increase spectrum utilization. As a result, they are widely applied in CR systems. However, few issues are subject to further study, including their optimization algorithm and how to decrease the complexity of these algorithms.

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Wang Haijun is a doctoral degree candidate at the Wireless and Mobile Communication Technology R&D Center of Tsinghua University. He is mainly engaged in the research of software defined radio, CR, cooperative communication and broadband wireless access. So far, he has participated in two foundation-funded projects, applied for two patents and published two papers.

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