doi:10.3772/j.issn.1006-6748.2014.04.006

Uplink user allocation scheme in cognitive coexistent cellular network①

Liu Tingting (刘婷婷)② *, Wang Mao **, Shu Feng **, Wang Jianxin **, Pan Ziyu *
(* School of Communication Engineering, Nanjing Institute of Technology, Nanjing 211167, P. R. China)
(** School of Electronic Engineering and Optoelectronic Techniques, Nanjing University of Science and Technology, Nanjing 210094, P. R. China)

Abstract

In order to address spectrum resource scarcity in traditional cellular networks, television (TV) white space is considered as a potential solution to offload a portion of network traffic and enlarge network capacity. This paper describes a cognitive cellular network which allocates low geometry users to the TV white space based on a proportional fair criterion. An uplink user allocation scheme is proposed and the validity of the proposed scheme is established by simulation of the cellular network usage in conjunction with the TV white space. The simulation results show clear improvements in both the user and the system performance with the cognitive coexistent cellular network compared with the traditional cellular network, and that the performance of the proposed user allocation scheme is superior to other user allocation schemes.

Key words: cognitive radio, TV white space, spectrum efficiency, system throughput, fractional frequency reuse

0 Introduction

In recent years, cellular networks (CN) have evolved from providing mobile communication with a limited data rate to supporting universal mobile broadband services, which has led to a large rate demand that cannot be accommodated within the original spectrum authorized to these systems. Further increases in spectrum demand for mobile communication system have been predicted in the next two decades and there are not enough available resources for future allocation[1]. On the other hand, the next generation network (NGN) is expected to provide improved connected services which are always available. In order to achieve this goal, communication technologies are converging towards a frequency reuse factor of one to improve bandwidth efficiency, or try to increase cell density to enlarge system capacity. However, the cell edge areas are largely influenced by the inter cell interference when frequency reuse converges to one, and increase of cell density and maintenance of a large number of base stations are very expensive to increase capacity.

At the same time, Federal Communications Commission (FCC) has reported that some of the licensed spectrum resources are underutilized including parts of the television (TV) spectrum[2]. The unused TV spectrum is known as ‘white space’ and FCC permits to smartly use this TV white space, provides that it should not cause any interference to licensed users[3,4]. This is encouraging new spectrum allocation that will enable dynamic spectrum access to the spectrum assigned to the TV system to fully exploit the bandwidth usage efficiency[5,6].

Three different approaches to the primary-secondary spectrum sharing have been investigated: underlay, overlay and interweave operation[7]. In the underlay approach, cognitive users transmit their signals using a relatively low power which is close to the noise level, meaning that the transmissions of the cognitive users are unnoticed by the primary users. In the overlay approach, the cognitive users know in advance the message transmitted by the primary users, which allows the cognitive users to design their transmitting signals to mitigate the interference to the primary users. In the interweave approach, the cognitive users can discover the spectrum usage opportunities by spectrum sensing or by accessing a spectrum usage data base[2,8-10]. FCC has endorsed the consideration of the interweave approach for the usage of secondary spectrum within the TV white space, and the orthogonal frequency division

① Supported by the National Natural Science Foundation of China (No. 61271230), the Starting Fund for Science Research of NJIT (No. YKJ201205) and the Open Research Fund of National Mobile Communications Research Laboratory (No. 2013D02).
② To whom correspondence should be addressed. E-mail: liutt@njit.edu.cn
Received on Mar. 23, 2014

multiple access (OFDMA) has been recognized as a candidate for a cognitive system because of its flexibility[11].

In this paper, an OFDMA-based interweave approach is applied to enable spectrum sharing between a primary TV system and the traditional cellular network. There are some reasons for allocating TV spectrum for secondary usage[12]. Firstly, FCC has noted that there are several unused TV wide bands in almost every area. Hence, secondary usage of these bands can provide significant additional capacity. Secondly, the TV spectrum is mainly located in a relatively low band around 470MHz – 700MHz which is appealing due to its good propagation properties for long distance communication. Finally, the TV system is relatively simple since its rather static network design and available spectrum resources in each area are stable and knowable. In order to use the appealing TV white space, several interference avoidance mechanisms must be supported by the cognitive users, including cognitive radio capability, location awareness and internet access[3,13,14]. By using these TV white spaces, the cellular network has additional bandwidth and two carrier frequencies, which can help offload some traffic from the traditional cellular networks. Several studies have undertaken research into the optimal resource allocation on one band whilst considering the protection of the primary users[15-19]. Ref. [20] selected the cognitive user causing the minimum interference to the primary user to transmit. Ref. [21] proposed the round-robin allocation scheme under the outage probability protection criterion for the primary users. The energy efficiency can be further improved when a statistics-based allocation scheme is employed. Ref. [22] proposed a strategy that chose the cognitive user with the best instantaneous channel quality to guarantee the protection of the primary users.

However, in this paper, assuming that the primary TV primary users are not active, we focus on how to jointly use two frequency bands with different properties. A method is proposed on how to properly use the TV white spaces and the cellular legal spaces to get some extra gains. In particular, the merits of this paper can be summarized as follows. 1) TV white spaces are taken into consideration to enlarge the capacity of the traditional cellular networks using a proposed scheme which jointly uses the TV white spaces and the legal cellular spectrum. 2) An important policy which is easy to implement in practice is established in this paper. 3) It is shown how the proposed scheme is superior compared to other user allocation schemes.

This paper is organized as follows. In Section 1, the system model of the cognitive cellular network is described. The proposed user allocation scheme is explained in Section 2. Numerical results are shown in Section 3 and conclusions are given in Section 4.

1 System model

The cognitive cellular system that we are describing is depicted in Fig. 1. The cognitive users (in this paper, they are cellular system subscribers with cognitive capability) in the protection region are forbidden to use the TV white space, thus the potential users are outside the TV protection region. Each hexagon represents a cell which has three sectors as shown in Fig. 1. According to the requirements of FCC, users need to sense the TV white space after finding the available resources from an Internet database. There are a couple of factors in the cellular network which make this approach to spectrum sensing feasible. Firstly, users are naturally coalesced by sectors where users in the same sector can easily form a coalition to sense the spectrum cooperatively[23]. Secondly, a dedicated resource is used as a control channel to transmit users' sensing decisions or observation data, without occupying extra resources assigned to the users.

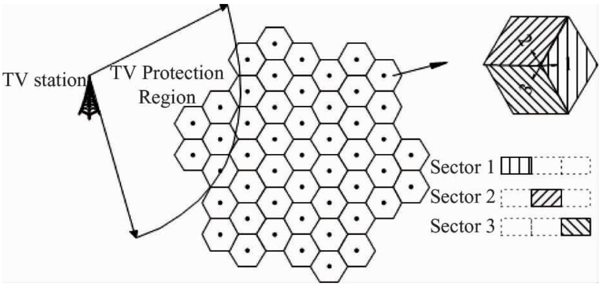


Fig. 1 Deployment of the cognitive cellular network

In the uplink, a reuse factor of 1/3 is employed so that the total bandwidth is equally divided into three parts. There is no neighboring sector sharing the same frequency, as depicted in the right part of Fig. 1. The interference from other sectors is lowered. This small frequency reuse factor leads to inefficient bandwidth usage. As we mentioned before, there are two traditional ways to increase system capacity, which are increasing the overall frequency reuse factor or increasing the network density. However, in this paper, a new method of increasing the system capacity is introduced: spectrum sharing between TV white space and the traditional cellular network. The following will discuss how to make use of the extra bandwidth and how the propagation property of the TV spectrum efficiently improves user performance and system throughput compared to a traditional cellular system.

2 Uplink user allocation scheme

In a traditional cellular network, users on the cell edge area usually suffer from loss of coverage, severe degradation of performance or even instability. In the cognitive cellular network, we are interested in how to make use of the TV white space to improve the system capacity and most of all, the performance of individual users.

Suppose there are N users served by a sector in a cellular network with total bandwidth of 3W at frequency $f_C = 2\text{GHz}$. The reuse factor 1/3 is employed and the bandwidth in each sector is W, the resources used by a user are $B = W/N$, P_S is the user's transmitting power and η_C is the channel gain in the traditional cellular network (calculated using COST 231 channel model for 2GHz[24]), and is the inverse of the path loss. N_o is the noise spectral density. It is assumed that the vacant TV bandwidth is the same as the cellular bandwidth, e. g. bandwidth 3W at frequency $f_{TV} = 600\text{MHz}$ and η_{TV} is the channel gain in TV spectrum (calculated using Hata channel model for 600MHz[24]). The difference in path loss between the two channel models is shown in Fig. 2. It can be seen that the path loss at 600MHz is much smaller than that at 2GHz, i. e. $\eta_{TV} >> \eta_C$. Path loss is the main factor of user's receiving power degradation.

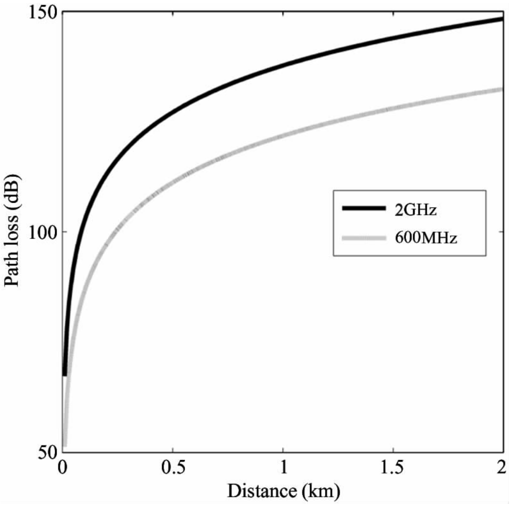


Fig. 2 Path loss of two different frequencies

The capacity of user u_i in the cellular network is shown in

$$C(u_i) = B \cdot \log_2\left(1 + \frac{P_S \cdot \eta_C(u_i)}{B \cdot N_o}\right) \tag{1}$$

In this case, there are two independent band resources in the cognitive cellular network where users can be assigned to use the free TV spectrum or legal cellular spectrum, and it is assumed that $|\Theta_{TV}|$ users are moved to TV white space while the rest of the users $|\Theta_C| = |\overline{\Theta}_{TV}| = N - |\Theta_{TV}|$ stay in the cellular band. Although the users assigned to the TV white space will have high spectrum efficiency, the bandwidth assigned to each user in this band will be decreased as more users are moved in.

The capacity of the remaining cellular users is shown as

$$C_C(u_i) = \frac{B}{|\Theta_C|/N} \cdot \log_2\left(1 + \frac{P_S \cdot \eta_C(u_i)}{\frac{B}{|\Theta_C|/N} \cdot N_o}\right) \tag{2}$$

The capacity of users moved to TV white space is written as

$$C_{TV}(u_i) = \frac{B}{|\Theta_{TV}|/N} \cdot \log_2\left(1 + \frac{P_S \cdot \eta_{TV}(u_i)}{\frac{B}{|\Theta_{TV}|/N} \cdot N_o}\right) \tag{3}$$

For low geometry users who are power limited users, i. e. cell edge users, the capacity gain $G_C(u_i)$ when it stays in the cellular band is as

$$\begin{aligned} G_C(u_i) &= \frac{C_C(u_i)}{C(u_i)} \\ &= \frac{\frac{B}{|\Theta_C|/N} \cdot \log_2\left(1 + \frac{P_S \cdot \eta_C(u_i)}{\frac{B}{|\Theta_C|/N} \cdot N_o}\right)}{B \cdot \log_2\left(1 + \frac{P_S \cdot \eta_C(u_i)}{B \cdot N_o}\right)} \\ &\approx \frac{\frac{B}{|\Theta_C|/N} \cdot \frac{P_S \cdot \eta_C(u_i)}{\frac{B}{|\Theta_C|/N} \cdot N_o}}{B \cdot \frac{P_S \cdot \eta_C(u_i)}{B \cdot N_o}} \\ &= \frac{\eta_C(u_i)}{\eta_C(u_i)} = 1 \end{aligned} \tag{4}$$

When it is assigned to TV white space, the capacity gain $G_{TV}(u_i)$ is given in

$$\begin{aligned} G_{TV}(u_i) &= \frac{C_{TV}(u_i)}{C(u_i)} \\ &= \frac{\frac{B}{|\Theta_{TV}|/N} \cdot \log_2\left(1 + \frac{P_S \cdot \eta_{TV}(u_i)}{\frac{B}{|\Theta_{TV}|/N} \cdot N_o}\right)}{B \cdot \log_2\left(1 + \frac{P_S \cdot \eta_C(u_i)}{B \cdot N_o}\right)} \\ &\approx \frac{\frac{B}{|\Theta_{TV}|/N} \cdot \frac{P_S \cdot \eta_{TV}(u_i)}{\frac{B}{|\Theta_{TV}|/N} \cdot N_o}}{B \cdot \frac{P_S \cdot \eta_C(u_i)}{B \cdot N_o}} \end{aligned}$$

$$= \frac{\eta_{TV}(u_i)}{\eta_C(u_i)} \quad (5)$$

Since $\eta_{TV} >> \eta_C$, $\frac{\eta_{TV}(u_i)}{\eta_C(u_i)} >> 1$. From the results of Eqs(4) and (5), it is concluded that low geometry users do not gain from staying in the cellular spectrum but they will benefit from moving to the TV white space due to the reduction of path loss. Hence, an important policy is therefore established that those low geometry users have a higher priority to be assigned to the TV white space. The next step is to decide the optimal solution that maximizes the utility function. In this case, there are $N-1$ possible user assignment pairs on two bands which are $(1, N-1)$, $(2, N-2)$, …, $(i, N-i)$, …, $(N-1, 1)$, where $(i, N-i)$ signifies that the highest i high geometry users stay in the cellular band while the remaining $N-i$ low geometry users are assigned to the TV white space.

The utility function UF of the cognitive cellular network is constructed as

$$UF = \sum_{\Theta_C} \log(C_C(u_i)) + \sum_{\Theta_{TV}} \log(C_{TV}(u_j)) \quad (6)$$

$$\hat{\Theta}_C = \max_{\Theta_C}\{UF\} \quad (7)$$

The utility function is established according to the proportional fair criterion. It means that when optimal $|\hat{\Theta}_C|$ users are moved to the TV white space, the total capacity is maximized.

The process of the algorithm is shown below:

Step 1: Downlink pilot strength measurement.

Step 2: Sort users according to user's geometry measured in Step 1.

Step 3: Hypothesis-test-move the lowest geometry users to TV white space individually until the value of UF starts to decrease. Get the optimal allocation pair and allocation finish.

Step 4: Start uplink transmission.

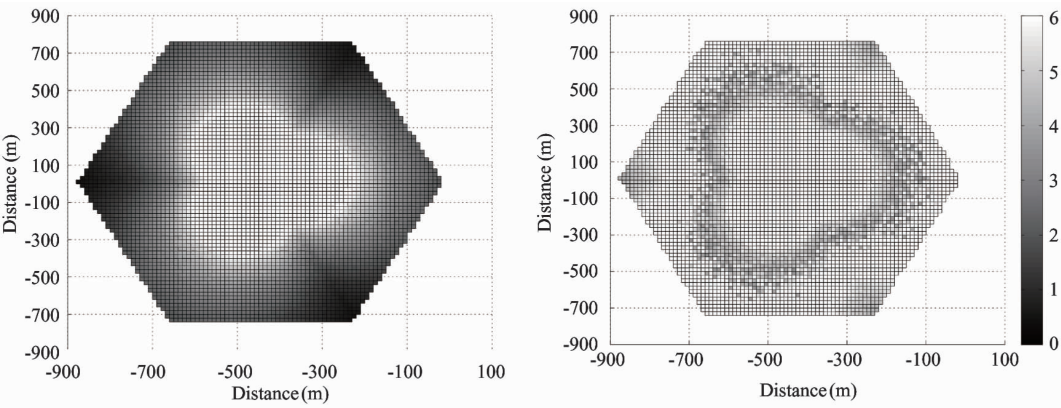
3 Simulation results

In this section, the performance gains of the proposed cognitive cellular network over traditional cellular networks is evaluated. Furthermore, the proposed user assignment scheme and other user allocation schemes are compared. The simulation parameters used in our simulation are listed in Table 1. The system in this simulation is assumed to be time division dual (TDD) and full buffer traffic model.

Table 1 Simulation parameters

Parameter	Value
Carrier frequency of traditional cellular band	2GHz
Carrier frequency of TV white space	600MHz
Propagation model for 2GHz	COST 231
Propagation model for 600MHz	Hata
Bandwidth for each band	5MHz
Sub carrier numbers	512
Sub carrier interval	9.6kHz
Noise spectrum density	−174dBm
User's transmit power (Cellular band/ TV white space)	20dBm/23dBm
User's antenna gain (Cellular band/ TV white space)	0dBi/ −3dBi
Antenna height (Base/ User)	30m/2m
Noise Figure (Base/ User)	6dB/10dB

Fig. 3 shows the effect of the proposed cognitive cellular network where spectrum efficiency improvement at the edge of a sector can be seen clearly. It shows that users on cell edges experience low spectrum efficiency (depicted as dark) in Fig. 3 (a), while the spectrum efficiency of a cell edge user is enhanced in the cognitive cellular network in Fig. 3 (b). Also it can be seen from Fig. 3 that the users in the cell center still have high spectrum efficiency with the proposed model, therefore, the overall spectrum efficiencies of users are enhanced in the proposed cognitive cellular network.

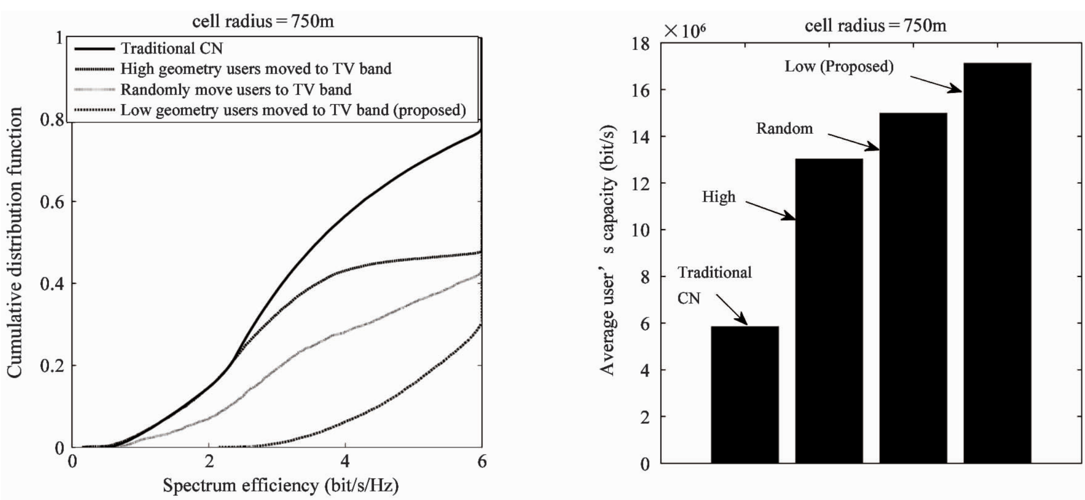


(a) Traditional cellular network (b) Cognitive cellular network

Fig. 3 Spectrum efficiency improvement

Fig. 4(a) is the spectrum efficiency cumulative distribution function (CDF) plot in different assignment schemes. The second curve in Fig. 4(a) represents the opposite user assignment scheme (assigning high geometry users to TV white space). The third curve randomly assigns users to the TV white space, while the fourth curve is the proposed assignment scheme that assigns low geometry users to the TV white space. As seen from this plot, the opposite user assignment scheme would provide a benefit to the high geometry users but users on the cell edge still have low spectrum efficiencies. The random assignment scheme would increase users' spectrum efficiencies but not enough. Therefore, the proposed method is the optimal solution to fully exploit the benefits of the TV white spaces and dramatically improve the spectrum efficiencies of all users. It can be noticed that the spectrum efficiency is less than 6bits/Hz/s which is the constraint in practical usage and assigning low geometry users to the TV band achieves the highest spectrum efficiency. It is known that as cell radius increases, the edge user's spectrum efficiency is decreased because of the increased link budget. However, it can be seen from Fig. 4(a) that the cell edge user's spectrum efficiency in the proposed cognitive cellular system is dramatically improved compared with that in the traditional cellular network of the same cell radius. In other words, the proposed cognitive cellular system can cover a larger area than the traditional cellular system does in the context of the same user's spectrum efficiency on the cell edge. In this way, it is not necessary to increase cell density to enlarge the system capacity.

Fig. 4(b) shows the average sector capacity using different assignment schemes. It can be seen that the cognitive cellular network has more sector capacity than the traditional cellular network has. The proposed user assignment scheme gains the highest average sector throughput in three different assignments. The simulation results demonstrate the validity of the proposed assignment scheme again.



(a) Spectrum efficiency CDF plot (b) Average sector capacity

Fig. 4 Performance comparison between the proposed assignment scheme and the other schemes

When low geometry users are moved to TV white space, the spectrum efficiency is dramatically improved. In this case, users in the cognitive cellular system are not power limited anymore. If a 1/3 reuse factor is still employed, users become resource limited. In order to further improve the system reuse factor, fractional frequency reuse (FFR) can be applied to both bands [25]. FFR, which is a flexible bandwidth management in OFDMA system, is taken into consideration in the long term evolution (LTE) [26]. Fig. 5 shows the frequency partitions using FFR. The frequency is divided into four partitions: one partition is Ω_4, with frequency reuse factor of 1 (no interference blocking capability), and three partitions Ω_1, Ω_2, Ω_3 with reuse factor of 1/3 (two interference blocking capabilities). The spectrum efficiency of users in partition Ω_4 will be decreased because of the increased interference. Since relatively high geometry users do not need to improve spectrum efficiency but have larger bandwidth requirements, they should be assigned to the Ω_4 partition in each band. Fig. 6 shows the improvement of the proposed assignment using the FFR plan in the cognitive cellular network. The proposed assignment scheme is compared with the traditional cellular network using FFR and a random assignment scheme. The random assignment scheme is conducted by moving users to the TV white space stochastically and randomly assigning one user to reuse one partition. It can be seen in Fig. 6 that the proposed user assignment scheme gains the most average sector spectrum efficiency and average sector throughput, respectively. The simulation results show that the proposed allocation scheme is also valid in the environment of the cognitive cellular network using fractional frequency reuse.

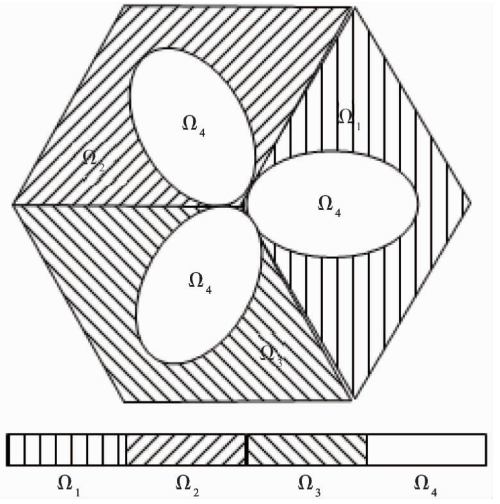


Fig. 5 Frequency partitions in both bands

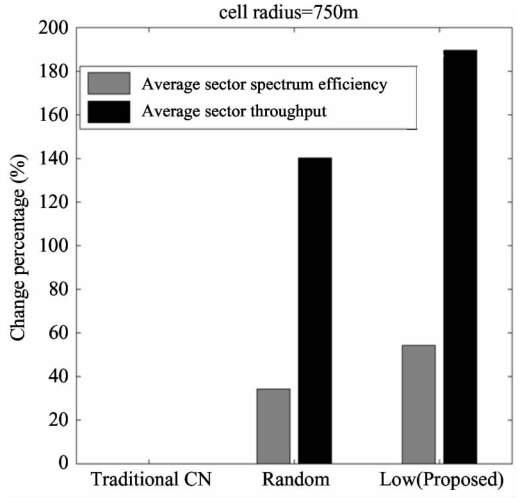


Fig. 6 Improvement of the proposed assignment using the FFR plan

4 Conclusion

Increasing system throughput and improving cell edge user's performance are crucial issues in cellular networks. In this article, a cognitive cellular network is modeled in which an uplink user allocation scheme is proposed. In a cognitive cellular network, there are two bands which have different propagation properties. The proposed user assignment allows low geometry users to fully exploit the low path-loss property in the TV spectrum, which improves spectrum efficiency for cell edge users and increases system capacity. The cognitive cellular network allows cell density to be decreased while guaranteeing an improved quality of service to cell edge users at the same time. Additionally, the proposed assignment scheme is also effective in the fractional frequency reuse environment.

References

[1] International Telecommunications Union. Estimated spectrum bandwidth requirements for the future development of IMT-2000 and IMT-advanced. ITU-R Report M, 2006

[2] Kolodzy P, Avoidance I. Spectrum policy task force. ET Docket, No. 02-135 Federal Communication Commission, Washington, DC, 2002

[3] Federal Communication Commission. In the Matter of Unlicensed Operation in the TV Broadcast Bands. ET Docket No. 04-186. 2010

[4] León O, Hernández-Serrano J, Soriano M. Securing cognitive radio networks. *International journal of communication systems*, 2010, 23(5): 633-652

[5] Mitola J, Maguire Jr G Q. Cognitive radio: making software radios more personal. *IEEE Personal Communications*, 1999, 6(4): 13-18

[6] Haykin S. Cognitive radio: brain-empowered wireless communications. *IEEE Journal on Selected Areas in Communications*, 2005, 23(2): 201-220

[7] Goldsmith A, Jafar S A, Maric I, et al. Breaking spectrum gridlock with cognitive radios: An information theoretic perspective. *Proceedings of the IEEE*, 2009, 97 (5): 894-914

[8] Yucek T, Arslan H. A survey of spectrum sensing algorithms for cognitive radio applications. *IEEE Communications Surveys & Tutorials*, 2009, 11(1): 116-130

[9] Tandra R, Mishra S M, Sahai A. What is a spectrum hole and what does it take to recognize one. *Proceedings of the IEEE*, 2009, 97(5): 824-848

[10] Zhang X, Wu Q, Wang J. Optimization of sensing time in multichannel sequential sensing for cognitive radio. *International Journal of Communication Systems*, 2013, 26 (2): 222-235

[11] Li L, Xu C, Fan P, et al. Resource allocation in orthogonal frequency division multiple access-based cognitive radio systems with minimum rate constraints. *International Journal of Communication Systems*, 2014, 27(8): 1147-1159

[12] Sachs J, Maric I, Goldsmith A. Cognitive cellular systems within the TV spectrum. In: Proceedings of the IEEE Symposium on New Frontiers in Dynamic Spectrum, 2010. 1-12

[13] Zhang W, Yeo C K. Cluster-based adaptive multispectrum sensing and access in cognitive radio networks. *Wireless Communications and Mobile Computing*, 2012, DOI:10.1002/wcm. 2319

[14] Chen H, Chen H H. Spectrum sensing scheduling for group spectrum sharing in cognitive radio networks. *International Journal of Communication Systems*, 2011, 24 (1): 62-74

[15] Jiang T, Wang H, Leng S. Channel allocation and reallocation for cognitive radio networks. *Wireless Communications and Mobile Computing*, 2013, 13(12): 1072-1081

[16] Chu F S, Chen K C. Radio resource management of self-organizing OFDMA wireless mesh networks. *Wireless Communications and Mobile Computing*, 2011, 11(3): 306-320

[17] Plummer A, Biswas S. Distributed spectrum assignment for cognitive networks with heterogeneous spectrum opportunities. *Wireless Communications and Mobile Computing*, 2011, 11(9): 1239-1253

[18] Audhya G K, Sinha K, Ghosh S C, et al. A survey on the channel assignment problem in wireless networks. *Wireless Communications and Mobile Computing*, 2011, 11(5): 583-609

[19] Shatila H, Khedr M, Reed J H. Opportunistic channel allocation decision making in cognitive radio communications. *International Journal of Communication Systems*, 2014, 27(2): 216-232

[20] Li D. Performance analysis of uplink cognitive cellular networks with opportunistic scheduling. *IEEE communications letters*, 2010, 14 (9): 827-829

[21] Ding H, Ge J, Benevides da Costa D, et al. Energy-efficient and low-complexity schemes for uplink cognitive cellular networks. *IEEE Communications Letters*, 2010, 14 (12): 1101-1103

[22] Xu T, Ge J, Ding H. Opportunistic scheduling for uplink cognitive cellular networks with outage protection of the primary user. *IEEE Communications Letters*, 2013, 17 (1): 71-74

[23] Dai Z Y, Liu J, Long K P. Cooperative transmissions for secondary spectrum access in cognitive radios. *International Journal of Communication Systems*, 2014, 27 (11): 2762-2774

[24] Goldsmith A. Wireless communication. Cambridge University Press, 2005

[25] Wang M M, Borran J, Ji T, et al. Interference management and handoff techniques. *IEEE Vehicular Technology Magazine*, 2009, 4(4): 64-75

[26] Khan F. LTE for 4G mobile air interface technologies and performance. Cambridge University Press, 2009

Liu Tingting, born in 1982. She received the Ph. D degree in Communication and Information System from Nanjing University of Science and Technology in 2011. She also received the B. S. degree in Communication Engineering from Nanjing University of Science and Technology in 2005. Her research interests include cognitive radio, interference control and resource allocation.