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A Study of Cognitive Technology OFDM System and Frame Structure

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Abstract

For mobile communication system with multi-service of multiple users, spectrum utilization rate is low and user's QoS requirements need to be improved. The paper proposed a cross-layer based on cognitive radio technology and OFDM technology model and designed the core technology of this frame structure model such as service division, spectrum sensing and spectrum aggregation in detail. Comprehensive judgment through the service needs of different users, and the spectrum holes judgment, not only meet different user's QoS, but also improve spectrum utilization and increase the system suitability. Finally, the simulation analysis of the model's performance shows that the model can not only reasonable use of the spectrum holes, and better meet the user's QoS requirements.

Keywords: *cognitive radio; OFDM; system model; frame structure*

1. Introduction

In recent years, with the rapid development of mobile communication technology, the demand for user data transmission rates and bandwidth has increased. At the same time, the problem of radio spectrum resources scarcity has been more and more serious and the authorized bandwidth is underutilized. The LTE (Long Term Evolution, LTE) system uses MIMO (Multiple Input Multiple Output)/OFDM (Orthogonal Frequency Division Multiplexing) as the key technology to effectively improve the quality of service of the 3GPP (The 3rd Generation Partnership Project) system [1]. And the use of cognitive radio (Cognitive Radio, CR) can effectively improve the situation of lack of spectrum resources [2]. Cognitive Radio users (CRUs) dynamically sense spectrum holes to access on condition that they will not affect the normal communication of authorized users [3].

OFDM technology can not only be more flexible to dynamically allocate available spectrum, but also dynamically adjust modulation, demodulation and encoding methods on each sub-channel based on the fading on each subcarrier, which makes the OFDM technology one of the preferred key technologies for mobile communication system of the next generation. In order to make the users' data rate higher, it is possible to increase the users' access bandwidth and also avoid the waste of scattered spectrum by adopting the spectrum aggregation (Spectrum Aggregation, SA) technology [4]. Especially, the DOFDM (Discontinuous Orthogonal Frequency Division Multiplexing) technology in the SA has good spectral compatibility and it can provide greater bandwidth for users who need high quality of service (Quality of Service, QoS).

In view of the present situation of the mobile communication that the QoS requirements of multi-user with multi-service continually increase while the radio spectrum resources are seriously scarce and considering the mentioned technical factors above, in this paper, we propose a new OFDM system model based on cognitive radio and the corresponding system frame structure.

2. System Model and Associated Implementation

2.1. System Model

Figure 1 shows the proposed OFDM system based on cognitive radio cross-layer model. The model incorporates the spectrum aggregation, service divisions and other factors

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and can be more flexible to adapt to multiservice multiuser system. In this model, the spectrum holes of the current wireless network environment was sensed and judged through the spectrum sensing technology at first. And then pass on the available spectrum information to the OFDM system to allocate subcarriers and power according to the current channel state and the spectrum use status. At last the data stream is transmitted by the OFDM system.

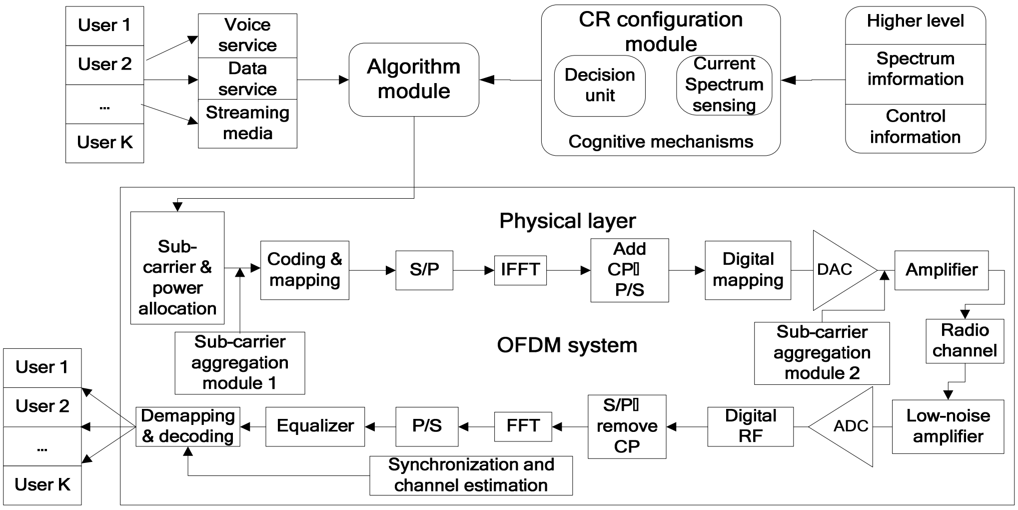

Figure 1. Proposed OFDM System Based on Cognitive Radio Cross-layer Model

The model consists of five modules, namely: CR configuration module, service judgment module, scheduling algorithm module, subcarriers modules and OFDM system module. The following sections describe the basic functions of these five modules:

(1) CR configuration module: judge the current spectrum resource then control processing based on the judgment result, so that cognitive users can use the CR perception result reasonably.

(2) Services judgment module: according to the existing services type (namely, voice services, data services and streaming media services) and different requirement of data rates, maximum tolerable delay and maximum packet error rates, etc. of them, do the scheduling and allocation for user resource to meet the QoS requirements of different users.

With reference to the IEEE802.1d standard [5], the users' QoS requirements for different type services are shown in Table 1.

(3) Scheduling algorithm module: multi-user scheduling and subcarrier allocation, based on specific algorithms and optimization functions, the spectrum information CR module perceived, user services information and the current radio channel information status.

(4) Subcarriers aggregation module: this diagram contains two different subcarrier aggregation modules: direct bandwidth aggregation module and multi-carrier aggregation module. The former applies to continuous or smaller spacing subcarriers; The latter applies to the larger spacing subcarriers [6]. Which mode should Sub-carrier aggregation module use depends on the current scattered degree of the sub-carriers. There are three cases: (i) if the subcarriers allocated are continuous or smaller spacing, the direct bandwidth aggregation module should be used and the multi-carrier aggregation module shielded; (ii) when the subcarriers allocated with large intervals, the multi-carrier aggregation module will be activated and the direct bandwidth aggregation module shielded; (iii) if both continuous and large intervals subcarriers are allocated, two modules should be enabled simultaneously. The direct bandwidth aggregation module is responsible for continuous or smaller interval subcarriers and the multi-carrier aggregation module for larger interval subcarriers.

(5) OFDM system module: Set the user number K and the subcarrier number N and suppose each user only has one type of services or has many types of services. On the transmit side, k users' data flow take channel coding and interleaving separately and change into K

parallel data stream to be modulated. Under control of the adaptive allocation algorithm, the K parallel data stream is mapped to different subcarriers and modulated. N modulated symbols are processed by IFFT to obtain time domain signal. After adding cycle guard intervals and up-converting, the signal is transmitted. The receiving side of multiuser OFDM system has K different users. When the signal reach the k-th user through the fading channel, the receiving side processing procedure reverse to the sending side. The receiver implement down conversion, remove the guard interval and then carry on FFT. And under the control of the allocation algorithm, the k-th user only demodulates subcarriers which assigned to him, transform the parallel data into serial data stream flow, and finally de-interleaved and decode to obtain the user's information data.

Table 1. The Key Performance Parameters of Different Services

Service type application	Data rates	Delay	Information loss (PLR)
Conversational voice	4~64kbit/s	<150ms preferred; <400ms limit	<3% PLR
Voice Messaging	4~32kbit/s	<1s play back; <2s record	<3% PLR
Video	16~384 kbit/s	<150ms preferred; <400ms record	<1% PLR
Streaming Audio/voice	16~128 kbit/s 16~384 kbit/s	<10s	<1% PLR
Data	10kb~1Mb	<15s preferred; <60s acceptable	0

2.2. Spectrum Sensing Algorithm

Spectrum sensing mainly perceived spectrum holes. Cognitive users analysis and judge authorized users' transmitter signal to determine whether the authorized users' transmitter in working condition. If the authorized users' transmitter is not in working condition, that is to say the spectrum is idle.

The signals can be affected by multipath fading and shadows effects, etc. in actual cognitive radio environment. So CR system might misjudge and generate interference to authorized users. The cooperative spectrum sensing algorithm proposed here enhances the overall perceived performance greatly by using a plurality of spatial differences of users [7].

Spectrum holes detection is generally based on the results of spectral estimation for judging. In this paper, we divided spectrum holes into the white hole (can be fully used by cognitive users), the gray hole (can be selectively used by cognitive users) and the black hole (occupied by authorized users so can not be used by cognitive users) according to the current use status of the spectrum. For the current low spectrum utilization rate, we adopt the following cooperative spectrum sensing algorithm to effectively improve the spectrum utilization in the paper.

Firstly, Judge the white hole by comparing perceptive signal power spectrum with setting maximum power spectrum.

In the cognitive radio system with bandwidth B ,the maximum tolerable interference power spectrum was set as $\eta_{\max}$. There are following expression.

$$N_{\max} = \frac{P_s}{SNR_{\min}} \quad (1)$$

$$\eta_{\max} = \frac{N_{\max}}{B} \quad (2)$$

Where P_s represents transmission power of cognitive radio system, $N_{\max}$ represents maximum acceptable interference power under ensuring communication quality in CR system.

$SNR_{\min}$ represents the system minimum signal to noise ratio. If user's sensing signal power spectrum dose not exceed the maximum allowable interference power spectrum $\eta_{\max}$, we can judge with current band white hole. Then judge gray hole under the premise of non-white hole. The judgment algorithm is expressed as follows.

(1) With bandwidth B, limit CR user interference signal power spectrum which is greater than the maximum interference power spectrum B_s, namely, we demand that the band occupancy rate α is less than the setting threshold α_{th}. It is expressed as follows:

$$\alpha = \frac{B_s}{B} < \alpha_{th} \quad (3)$$

$$\alpha_{th} = \frac{3B_{\Delta}}{B} \quad (4)$$

Where B_{Δ} represents allowed sensing narrow bandwidth.

(2) Assume β represents the ratio of CR user interference signal power spectrum peak and $\eta_{\max}$. Order $\beta < \beta_{th}$, where β_{th} represents setting threshold.

(3) Then define ratio of the cognitive user's interference signal average power and $N_{\max}$ as γ, $\gamma < \gamma_{th}$, γ_{th} represents set threshold. We can calculate power spectrum $\hat{S}(f)$ through WOSA (Weighted Overlapped Segment Averaging)[8], then calculate interference signal average power by the following formula.

$$\overline{P} = \frac{1}{B}\int_{f\in B}\hat{S}(f)\,df \quad (5)$$

In non-white hole band, if the frequency band meets formula (3), (4) and (5), then it can be judged as gray hole so can be selective use by CR users, otherwise the frequency band is black hole.

2.3. Spectrum Aggregation

Cognitive radio technology has greatly improved spectrum efficiency. In actual study, cognitive radio still faces many challenges, including the following aspects:

(1) If CR users spectrum obtained by the spectrum sensing is not continuous (in time) or irregular (in space), in order to avoid waste of these scattered spectrum and to further improve spectrum efficiency, how to aggregate these spectrum together is a major challenge recognized cognitive radio.

(2) Owing to multi-users have different services in cognitive system, how to consider cognitive user s' services with the detected spectrum hole together, for instance, meeting user's QoS requirements as well as effectively improving the spectrum utilization is another issue to be resolved. Limited to current research on spectrum aggregation techniques, we take a simply spectrum aggregation technology in this paper.

In this paper, spectrum holes are divided into continuous and discontinuous spectrum by time; by space divided into regular and irregular spectrum. For regular continuous spectrum, we can use the traditional method of spectrum allocation, otherwise use DOFDM technology processing for irregular non-continuous spectrum.

3. System Frame Structure

In the context of LTE-A, we have proposed a new model of OFDM system based on cognitive radio in the second section. In this section, a new OFDM frame structure based on cognitive radio is proposed. It is based on the system module, multi-user's services and the possibility of spectrum aggregation.

The frame structure is given as following Figure 2.

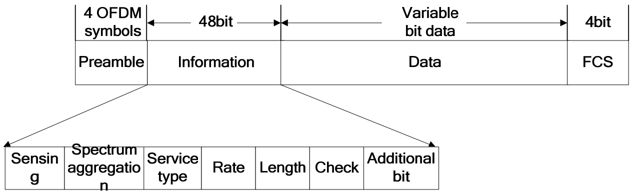

Figure 2. The Frame Structure Diagram

The frame structure includes 10 different sections which can be divided into four parts: the leader sequence, the information field (including sensing field, carrier aggregation field, the service type, the rate field, length field, check and additional bit), data field, and FCS (Frame Check Sequence) field.

The frame structure is under the premise of 1024 subcarrier number, maximum multi-path delay for 200ns and the frame length 5ms [9]. The ratio of data detection transmission time and the sensing time is 1/21 according to IEEE802.22.2 standard [10] and literature [11]. Each section function and occupied bits are described as following.

(1) Preamble: 4 OFDM symbols. Its function is to achieve frame detection, frame synchronization, AGC, frequency offset estimation and channel estimation functions, etc. [12].

(2) Sensing field: 7 bits. Represent the number of all subcarriers.

(3) Spectrum aggregation: 14 bits. It is used to represent staring number and final number of subcarrier. Subcarriers are 1024, uniformly distributed in the subcarrier number 0 on both sides (not including 0), the subcarrier number in the range from -512 to 512, the starting and stopping subcarrier are expressed with 7bit (including 1bit positive and negative bit).

(4) Service type field: 2 bits. It is used to represent user's service type. It is shown as Table 2.

Table 2. The Content of Service Type Field

Service type field	Service type
00	Null
01	Audio service
10	Data service
11	Streaming media service

(5) Rate field: 4 bits. Modulation mode is divided into downlink and uplink data modulation in LTE-A system, as shown in Table 3. Downlink data modulation way mainly contains QPSK, 16-QAM and 64-QAM. Uplink data modulation way mainly applies π/2 shift BPSK, QPSK, 8-PSK and 16-QAM.

Table 3. The Content of Rate Field

Rate field	Modulation	Code rate	Coding bits	Data bits
1000(uplink)	BPSK	1/2	1	1/2
1001(uplink)	BPSK	3/4	1	3/4
1010(uplink)	QPSK	1/2	2	1
1011(uplink)	QPSK	3/4	2	3/2
1100(uplink)	16-QAM	1/2	4	2
1101(uplink)	16-QAM	3/4	4	3
0010(downlink)	QPSK	1/2	2	1
0011(downlink)	QPSK	3/4	2	3/2
0100(downlink)	16-QAM	1/2	4	2
0101(downlink)	16-QAM	3/4	4	3
0110(downlink)	64-QAM	2/3	6	4
0111(downlink)	64-QAM	3/4	6	9/2

(6) Length field: 16 bits. It is used to indicate the total number of effective bits carried by data segment.

(7) Check field: 1 bit. It is used to check error in data rate segment and length segment through odd-even check.

(8) Additional bits: 4 bits. It is used to ensure frame information field can occupy all valid bits when valid bit in information field can not be completely filled by other fields.

(9) Data field: It is used to represent that the frame can carry the number of valid data bits. There are different data bits for different services (audio service are 320 bits, data services are 40 k-bits, streaming media services are 20 k-bits).

(10) FCS: 4 bits. It is used to check whether data is correct in the frame.

4. Simulation Analysis

In this paper, system model and frame structure are simulated under matlab 7.0 simulation environment, and export spectrum test results.

We assume that the numbers of subcarriers are 1024, system bandwidth is 10MHz, transmitted power is 0.5W, cyclic prefix length is 256, and symbol rate is 25Mbps in multi-user CR-OFDM downlink. In the simulation, the number of radio channel is 6 tracks, the largest multi-path delay is 10us, and maximum Doppler shift is 30Hz. Physical layer uses QPSK modulation and demodulation, and LTE-A system simulation is set to single-input single-output. At the same time, set B_{Δ} =39980.01Hz, β_{th} =3dB, $\gamma_{th} = \beta_{th} / B$.

Firstly, multiply test the spectrum of the real state. Since the band use condition changes over time, we derived a detection result randomly and a part of subcarrier band states are shown in Figure 3. In the figure, the vertical axis represents the sate of detected frequency bands: 0 represents the frequency band is detected as white empty state,0.5 represents gray state and 1 represents black state.

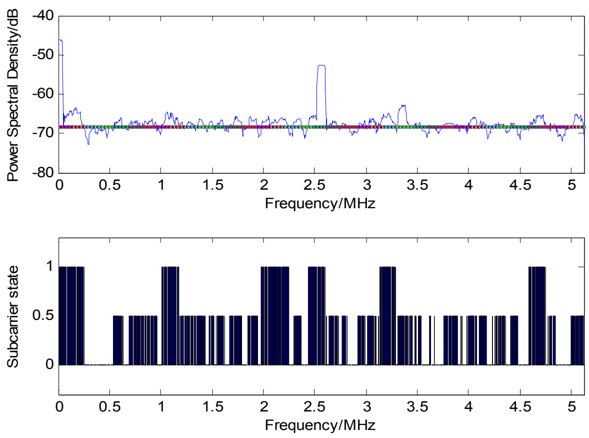

Figure 3. The Detection Result of a Random Subcarrier Frequency State

Table 4 shows that matlab exports available bands percentage in the different test cases.

Table 4. Subcarrier Spectrum State Detection Statistics

Statue / Time	White hole	Gray hole	Black hole	Available
1	6.25%	57.03%	36.72%	63.28%
2	7.03%	53.91%	39.06%	60.94%
3	6.38%	55.47%	38.15%	61.85%

Figure 3 and Table 4 show that cognitive radio users can occupy more than 60% of frequency bands in a certain period in which the gray state occupy more than half of the bands. So we can use spectrums aggregation techniques to aggregate some of the bands.

Secondly, in order to verify system performance, this paper took simulation and analysis on the proposed system model with the new frame structure under the conditions of minimizing bit error rate. Under different SNR, the bit error rate and packet error rate between CR-based OFDM system and SISO LTE-A system are compared respectively. As is shown in Figure 4 and Figure 5.

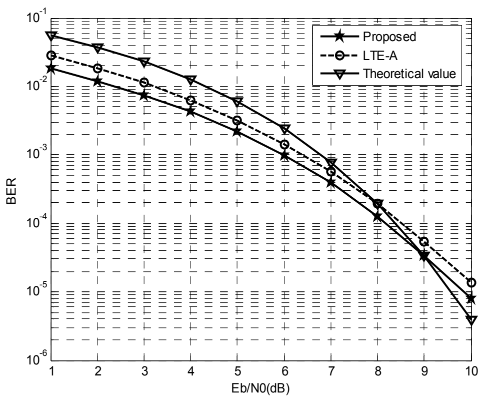

Figure 4. The Bit Error Rate under Different Eb/N0

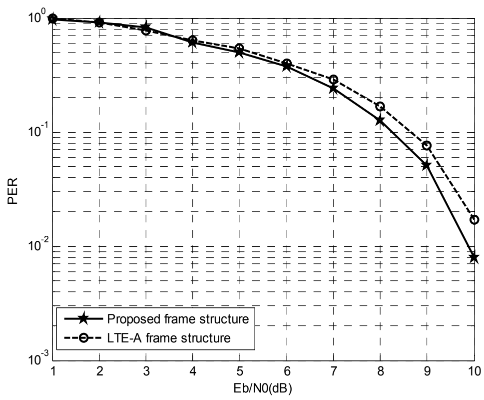

Figure 5. The Packet Error Rate under Different Eb/N0

In Figure 4, the simulation results show that with the same channel transmission conditions, the same modulation mode and constraints of given transmission rate, the BER of adding CR mechanisms are always below the not joined CR mechanisms under different SNR. This indicates that the proposed system model can meet requirements of the bit error rate the users' QoS under the condition of using the available licensed spectrum rationally. And Close to the theoretical value.

The simulation results in Figure 5 show that, with SNR increasing, the packet error rate of the proposed system model frame structure will gradually decline compared with SISO frame structure of LTE-A system and the packet error rate of frame structure meet user's QoS requirements in different SNR.

According to the above simulation results, the proposed system model and frame structure are superior to the current performance of LTE-A system that it can better meet users' QoS requirements. And the adding spectrum sensing and spectrum aggregation technologies can improve spectrum utilization to a certain extent and provide users with greater bandwidth.

5. Conclusion

In the context of LTE-A research background, a new OFDM system based on cognitive radio cross-layer model and a suitable frame structure are proposed in this paper. The proposed cross-layer model adds functions of service type judgment, spectrum holes sensing and spectrum aggregation. Its advantages are: (1) the system allows different users to have different services and expand the system application scope; (2) the fragmented spectrums are aggregated and used together. And the system can meet users' bandwidth requirements and effectively improve the frequency spectrum utilization.

Compared with LTE-A standard frame structure, the frame structure of this paper has following advantages.

(1) Have cognitive function to sensing current bandwidth use condition and adopt spectrum aggregation technique. Different kinds of spectrum holes (continuous, small intervals or large intervals) can be used through cognitive radio technology, so it can enlarge the using range of spectrum hole and improve the utilization rate of spectrum.

(2) Fully consider the differences in rate of different services. Adopt appropriate coding rate and transmission rate to specific service, so it can better meet the needs of users.

(3) Carrier aggregation field of the frame structure indicates sub-carriers' position which contain information that needs to be received in the receiver side. It can simplify the complexity of the receive facility and avoid blind reception.

(4) The check field in the frame structure ensures information accuracy of information field and length field. And FCS field is to ensure accuracy of transmitted data and improve transmission quality.

Based on this paper's study, the subcarrier allocation algorithm under increasing different services, sub-channel allocation algorithms based on spectrum aggregation and spectral characteristics analysis algorithms, etc. worth to research.

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