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QoE-based resource allocation protocols in cognitive OFDMA network with hybrid model

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Abstract: A resource allocation protocol is presented in an orthogonal frequency division multiple access (OFDMA) cognitive radio (CR) network with a hybrid model which combines overlay and underlay models. Without disrupting the primary user (PU) transmissions, the overlay model allows the secondary user (SU) to utilize opportunistically the idle sub-channels; the underlay model allows the SU to occupy the same sub-channels with PU. The proposed protocols are designed for maximizing the quality of experience (QoE) of CR users and switching dynamically between the overlay and underlay models. QoE is measured by the mean opinion score (MOS) rather than simply fulfilling the physical and medium access control (MAC) layer requirements. The simulations considering the file transfer and video stream services show that the proposed resource allocation strategy is spectrum efficient.

Key words: resource allocation; cognitive radio network; orthogonal frequency division multiple access (OFDMA); quality of user experience; mean opinion score
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Recently, cognitive radio (CR) technology has emerged to solve the spectrum shortage[1]. It enables a secondary user (SU) to dynamically borrow and reuse the licensed spectrum allocated to the primary user (PU), under the condition that no harmful interference is caused to the primary services. Generally, a SU has two kinds of coexisting mechanisms with the PU: overlay and underlay[2]. The overlay model allows multiple SUs to utilize opportunistically the idle sub-channels without disrupting the PU transmissions. In the underlay model, the SU can transmit signal simultaneously with the PU if the interference caused to the PU is below a given threshold. As an application, the CR-based orthogonal frequency division multiplexing (OFDM) and orthogonal frequency division multiple access (OFDMA) system has obtained increasing research interest[3-4]. However, most prior works only focus on the physical or MAC layer network performances and lack consideration of user satisfaction in the high layer.

Quality of experience (QoE) is used to describe the overall performance of a network from the user perspective. High network quality of service (QoS) cannot always assure high QoE, especially for the SU in a CR network[5]. The direct measurement of QoE needs complex user evaluation during communication service and it requires much time and effort. Recently, an objective measure of QoE has been proposed to generate the relationships between QoS and QoE[6]. A common measure is the mean opinion score (MOS), which can be determined from the subjective ratings by real users or predicted from objective measurements of properties of the delivered goods such as audio, video, or files.

In this paper, we use MOS to evaluate the system performance considering the transmission rate, packet error probability and signal-to-noise ratio. Under some certain scenarios, allocating more spectrum resources to one user with a kind of service cannot increase MOS value rapidly and also may not improve user experience. Therefore, designing a QoE-based resource allocation in a CR network will significantly improve the spectrum usage. Our main contributions are that we present a new resource allocation protocol for the multiple SUs in a hybrid model, which combines overlay and underlay models depending on the available number of OFDM sub-channels. The system performance is evaluated using the percentage of satisfied users.

1 QoE-Based OFDMA System Model

We consider an OFDMA CR network with several SUs and PUs uniformly distributed in the area. A base station (BS) is located at the center of this area to provide multiple access, downlink transmissions and resource allocations for both PUs and SUs. The OFDMA system shares a bandwidth B spanned around a transmission frequency f_c and is shared among N_p PUs and N_s SUs. The available bandwidth is divided into N subcarriers, and n of them

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constitute one sub-channel which is a basic resource block that users can occupy. As shown in Fig. 1, four possible occupying statuses of sub-channels are defined as $\{B_P, B_S, B_{PS}, B_\theta\}$. Here, B_P denotes a sub-channel set occupied by the PUs and the accessing SUs can utilize them in an underlay model. B_S denotes the sub-channel set occupied by SUs, while B_{PS} denotes the sub-channel set shared between the multiple PUs and SUs. B_θ is the available idle sub-channel set.

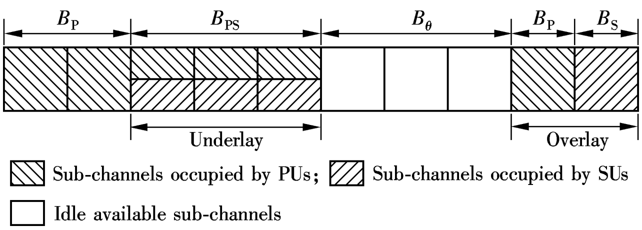

Fig. 1 OFDMA CR network with hybrid model

Clearly, the service quality of the PU has been completely guaranteed because of the priority use of subcarriers. However, the SUs may suffer performance deterioration. We use MOS to evaluate the QoE of the SU in order to optimize the spectrum resource allocation. MOS is described as a real number ranging from 1 to 5, with a satisfaction threshold commonly set to be 4.

Two types of the SU services including file transfer and video streaming are considered in this paper. As for file transfer service, the MOS model[7] can be denoted as

$$\mathrm{MOS_f} = a\log(br(1-P_e)) \tag{1}$$

where r is the transmission rate; P_e denotes the target packet error probability; a and b are constants which are determined by the required MOS value and the target rate.

As for the video streaming, MOS can be described as a bounded logarithmic function[8]:

$$\mathrm{MOS_v(PSNR_v)} = \begin{cases} 1 & \mathrm{PSNR_v} < \mathrm{PSNR_{1.0}} \\ d\log(\mathrm{PSNR_v}) + e & \mathrm{PSNR_{1.0}} < \mathrm{PSNR_v} < \mathrm{PSNR_{4.5}} \\ 4.5 & \mathrm{PSNR_v} \geqslant \mathrm{PSNR_{4.5}} \end{cases} \tag{2}$$

where

$$d = \frac{3.5}{\log\mathrm{PSNR_{4.5}} - \log\mathrm{PSNR_{1.0}}} \tag{3}$$

$$e = \frac{\log\mathrm{PSNR_{4.5}} - 4.5\log\mathrm{PSNR_{1.0}}}{\log\mathrm{PSNR_{4.5}} - \log\mathrm{PSNR_{1.0}}} \tag{4}$$

PSNR (peak signal-to-noise ratio) is related to the date rate of a video stream and it can be modeled as [9]

$$\mathrm{PSNR_v} = u + v\sqrt{\frac{R_v}{w}}\left(1 - \frac{w}{R_v}\right) \tag{5}$$

The parameters u, v and w characterize a specific video stream. $\mathrm{PSNR_{1.0}}$ and $\mathrm{PSNR_{4.5}}$ in Eqs. (2) and (3) represent the PSNR threshold when the MOS values achieve 1.0 and 4.5, respectively.

2 QoE-Based Resource Allocation Protocols

In this section, we present the resource allocation protocols to maximize the QoE of the SU when users enter and leave the OFDMA system.

The PU has the priority to utilize the sub-channels. Therefore, the system allocates spectrum resources to the PU immediately when it is ready for data transmission. The detailed resource allocation protocol when the PU arrives is shown as follows.

1) If the sub-channels that are allocated to the PU are occupied by the SU (denoted as SU_k), the transmission power of SU_k should be reduced to avoid causing interference to the PU. The coexisting system model between the PU and SU is the underlay model.

2) SU_k should employ more idle sub-channels if its MOS value is less than 4.

3) When the PU has finished the transmission, it will release the OFDMA sub-channels (denoted as B_r).

When the PU leaves the system, it will release occupied sub-channels. If the released sub-channels B_r is operated in the underlay model ($B_r \subset B_{PS}$), SU will increase transmission power to improve its QoE. If B_r is solely occupied by the PU ($B_r \subset B_P$), the system will allocate them to the SU_j which meet the following constraints:

$$\left.\begin{aligned} j &= \arg\min_j \mathrm{MOS}(\mathrm{SU}_{k,j}) \\ k &= \arg\max_k f'_k \end{aligned}\right\} \tag{6}$$

where $\mathrm{MOS}(\mathrm{SU}_{k,j})$ denotes the MOS value of the j-th SU with the k-th service type; f'_k implies the variation speed of MOS function with the current MOS value in the k-th service.

It is spectrum efficient if we allocate some of the idle sub-channels to the SU whose MOS value is sensitive to the spectrum resources allocation. Therefore, the average MOS value can be increased by employing only a small number of sub-channels. When a new SU accesses the system, the resource reallocation protocol among different SUs will be triggered if there are not enough available idle sub-channels. The detailed flowchart contains four main steps:

1) If there are sufficient idle sub-channels, the accessing SU (denoted as $\mathrm{SU_a}$) will take full advantage of them in order to ensure that the MOS value is above 4. If not, go to step 2).

2) If there are any sub-channels solely occupied by the multiple PUs, $\mathrm{SU_a}$ can utilize them and operate in the underlay model. Once the MOS value is less than 4 and $B_P = \varnothing$, go to step 3). $\mathrm{SU_a}$ will be reallocated more sub-channels from other SUs.

3) We check whether the average MOS value of the service type (denoted as service A) which $\mathrm{SU_a}$ belongs to

is less than the threshold (it is usually set to be 3.5 in this paper). If yes, go to step 4). If not, we check whether the MOS value of SU_a increases to be above the average values of service A. This constraint is described as

$$\text{MOS}(SU_a) > \frac{1}{N^A}\sum_{N^A}\text{MOS}(SU^A) \tag{7}$$

where N^A is the number of SUs with service A; SU^A denotes the set of SUs with service A. If yes, SU_a accesses to the system successfully. Otherwise, SU_m, which has the maximum MOS value of service A, releases some parts of its subcarriers to SU_a and goes back to step 3). This protocol tends to maximize the average MOS value of all users within the given service.

4) If the average MOS value of service A is not satisfied, SU_a must request spectrum resources allocation from the SUs of other service types. Therefore, the index of the SU with service B that is released by the system must meet the following constraints:

$$\left.\begin{aligned} j &= \arg\max_j \text{MOS}(SU_{B,j}) \\ B &= \arg\min_B f'_B \end{aligned}\right\} \tag{8}$$

It means that its QoE will not drop rapidly when lending sub-channels.

When SU (denoted as SU_l) leaves the system, the resource allocation protocol is illustrated as follows:

1) SU_l releases the occupied sub-channels which is denoted as $B_i = \{B_P, B_S\}$.

2) The released sub-channels must be delivered to the SUs whose QoE will increase quickly by allocating more spectrum resources. Therefore, the protocol will find the SU_j which meets Eq. (6).

3) If the MOS value of SU_j is greater than 4.5, SU_j will not be allocated for more sub-channels and the resource allocation ends. However, if B_S is empty, SU_j occupies the sub-channels in set B_P. Otherwise, SU_j occupies the sub-channels in set B_S.

4) If B_i is empty, the resource allocation will be finished. Otherwise, go to step 2). In order to protect the transmissions of PUs, B_S has the priority to be used rather than B_{PS}. It is because when SU_l leaves, B_{PS} turns to be B_P which is occupied by the PUs.

3 Simulations

The performance of the proposed protocols is evaluated in this section. The typical urban macro-cell channel presented by the organization of the Wireless World Initiative New Radio (WINNER)[10] is used, which models channel attenuation as frequency selective fading, distance dependent path loss and log-normal shadowing. The detailed simulation parameters are shown in Tab. 1.

For all users, packet arrivals are modeled as a Poisson process. The average inter-arrival and service time of the PUs and SUs are illustrated in Tab. 1, in which the file transfer service time is normalized. Two services, file transfer and video services, are simulated in this system. As shown in Eq. (1), the MOS function parameters of file transfer service a, b and P_e are set to be 2.1, 0.3 and 0.2, respectively. It can make the SU be satisfied (MOS > 4) with a rate of 400 kbit/s, and obtain a small MOS value with a rate of less than 10 kbit/s. As for the video service, $PSNR_{1.0}$ and $PSNR_{4.5}$ are set to be 20 and 35 dB.

Tab. 1 Simulation parameters

Parameter	Value
Channel bandwidth per subcarrier/kHz	39
Number of subcarriers N	60, 80, 120
Number of subcarriers per sub-channel	4
Number of PUs	10
Number of F-SUs	10
Number of V-SUs	10
Modulation/coding rate	1/2-convolutional code
Average SNR at transmitter in overlay model/dB	30
Average SNR at receiver in overlay model/dB	22
Average SNR at transmitter in underlay model/dB	20
Average SNR at receiver in underlay model/dB	13
Average inter-arrival time of PUs and SUs/min	2
Average service time of PUs and SUs in file-service/min	1
Average service time of SU in video-service/min	2

Fig. 2 shows the MOS value vs. the cumulative distribution function (CDF) of the SUs' number under three scenarios, the PUs, F-SUs (the SUs with file transfer service) and V-SUs (the SUs with video service). The number of OFDMA sub-channels are simulated with 120, 80 and 60 carriers. The F-SUs have less service time than the V-SUs, meanwhile the V-SUs must achieve a larger rate by employing more sub-channels to obtain a MOS value which is the same as that for the F-SUs. Therefore, the F-SUs obtain more satisfaction than the V-SUs. In the proposed protocol, the SUs can utilize the shared sub-channels of the PUs by reducing transmission power and maximize the average MOS value by reallocating spectrum resources among the SUs. Therefore, all the SUs can achieve satisfaction under scenario 1, while the MOS values of all the F-SUs and 50% V-SUs are greater than 4 under scenario 2 even when there are not enough sub-channels available. When the number of overall sub-channels is limited to 60, the MOS CDF performances of the F-SUs decrease slightly, and the requirements of 90% users are satisfied. Under scenario 3, approximate 30% V-SUs have failed to access the CR network. However, more than 50% V-SUs still achieve medium satisfaction whose MOS values are greater than 3.5. Therefore, the proposed protocols in CR networks can make the accessing users satisfied even when the available resources are not sufficient.

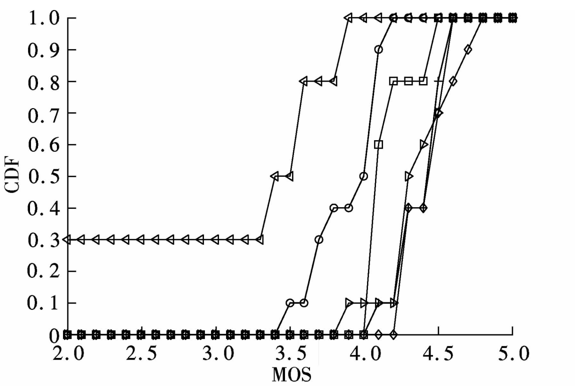

Fig. 2 MOS value vs. CDF of the SUs' number under three coexistence scenarios

4 Conclusion

Prior works in CR research have been focused on the physical or MAC layer optimization and lack consideration of user satisfaction in the high layers. In this paper, the resource allocation protocols are proposed in an OFDMA CR network with a hybrid model, which combines overlay and underlay models. They are designed with the object of maximizing the QoE which is measured by the MOS function. The simulation results show that the proposed strategy is spectrum efficient and it can make the SUs satisfied even when the available resources are not sufficient.

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认知 OFDMA 混合网络模型中基于 QoE 的资源分配协议

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摘要:提出了一种应用于基于正交频分多址接入(OFDMA)的认知网络模型中的资源分配协议,其认知网络采用了融合 overlay 和 underlay 的混合网络模型. 在不影响主用户通信质量的前提下,overlay 模型允许认知用户利用主用户未使用的空闲子信道;underlay 模型允许认知用户和主用户共同占用子信道. 该协议旨在最大化认知用户的体验质量(QoE),动态地在 overlay 和 underlay 模型之间切换,并通过平均意见分数(MOS)函数进行量化,而非简单地满足各个用户在物理层和 MAC 层的限制条件. 从对认知用户的文件传输和视频服务的仿真结果可看出,所提出的资源分配协议具有较高的频谱效率.

关键词:资源分配;认知无线网络;正交频分多址接入;用户体验质量;平均意见分数

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