Time-Frequency Spectrum Leasing for OFDM-Based Dynamic Spectrum Sharing Systems

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Abstract—In cognitive radio systems, Dynamic Spectrum Leasing (DSL) can improve the efficiency of spectrum utilization. In DSL, the primary user who has the license for a part of the bandwidth, decides to lease it to a secondary user or not. In this paper, we assume an OFDM-based system and perform the leasing operation in this system where the primary user leases the spectrum for a number of OFDM symbols to secondary users in exchange of a better quality-of-service achieved by secondary network cooperation. The secondary users use a part of the spectrum for relaying the primary data to the primary receiver and the rest of the spectrum for their own transmissions. More precisely, we propose a time-frequency domain leasing scheme. Simulation results show that both primary and secondary users benefit from this proposed spectrum sharing strategy.

I. INTRODUCTION

As the use of wireless systems increases, spectrum becomes a scarce resource for next generation communication systems. Dynamic Spectrum Sharing (DSS) has been proposed for better spectrum utilization compared to classical fixed spectrum allocation [1]. DSS can be divided into Dynamic Spectrum Access (DSA) and Dynamic Spectrum Leasing (DSL). In DSA, the user who has the license for a specific part of the spectrum (referred to as primary users), utilize the spectrum regardless of other unlicensed users who try to utilize the spectrum opportunistically (referred to as secondary users). The secondary users look for unused parts of the spectrum, called ”spectrum holes” for data transmission. In DSL however, the primary user leases its own spectrum to secondary users in exchange of a remuneration achieved by the cooperation of the secondary network in the primary transmission [2].

Different DSL schemes are proposed in the literature. For instance in [3], a model is considered in which the primary user guarantees the quality-of-service for secondary users which means that the primary can not withdraw the leased spectrum unconditionally which may leads to frequent handovers of secondary users. In [4], the authors proposed power control for secondary users via a game theory based spectrum leasing scheme by considering a specified interference level for the primary user. Resource allocation for spectrum underlay with attention to quality-of-service constraints for secondary users as well as interference constraints for the primary user is explored in [5]. A game-theoretic approach and the properties of equilibrium points for spectrum leasing are discussed in [6]. The interactions between sellers and buyers in the leasing process including competition, pricing, and decisions are discussed in [7] and [8]. The achievable rate region and the multiplexing gain of a cognitive user channel as well as the throughput achieved by a cognitive network with a single cognitive user and multiple pairs of secondary users are discussed in [9]. In [10], competition between secondary users to obtain a specific bandwidth of the shared spectrum is investigated. In [11], a spectrum leasing scheme is proposed in which the primary user leases the spectrum to a subset of a secondary ad hoc network for a fraction of transmission time-slot. The secondary users utilize this leased resource for their own transmissions as well as for relaying the primary transmitter’s signal to the primary receiver.

In this paper, we propose a time-frequency domain leasing method for an OFDM system as an alternative to the single carrier time domain method proposed in [11]. In our proposed method, the primary transmitter leases the spectrum to a subset of secondary users by first dividing the frame duration in two parts. One part is dedicated for the primary transmission and the other part is used for the secondary transmission. However, in contrast to the approach in [11] where the secondary users divide the rest of the time-slot among secondary transmission and relaying the primary users’ data (time domain leasing), in the proposed scheme, the secondary users allocate some subcarriers for relaying the primary data and use the rest of the subcarriers for their own transmissions within their allocated time-slot. Therefor we have a two-dimensional, i.e., a time-frequency domain leasing.

The rest of this paper is organized as follows. In Section II, we explain the considered system model. The evaluation of the data rates and the solution of the proposed leasing problem are provided in Section III. In Section IV, we provide the simulation results and discussions. Finally, Section V concludes the paper.

II. SYSTEM MODEL

We consider a primary link composed of a transmitter and a receiver at a normalized distance 1, and a secondary ad hoc network at a distance $d$ ($0 < d < 1$) from the primary transmitter as shown in Fig. 1. Notational conventions used
The primary transmitter determines $\alpha$. By knowing this parameter, the secondary users choose the number of subcarriers for their own transmissions and consequently the rest of the subcarriers are used for primary signal relaying. The number of these subcarriers is chosen so that to provide an equal achievable rate for the secondary network and the secondary to primary transmission link. Note that the primary knows the strategy of secondary nodes for choosing the number of subcarriers, therefore it tries to select the parameter $\alpha$ in a way to achieve the highest possible rate.

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### TABLE I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{T}$</td>
<td>Primary Transmitter</td>
</tr>
<tr>
<td>$P_{R}$</td>
<td>Primary Receiver</td>
</tr>
<tr>
<td>$S_{T}$</td>
<td>Secondary Transmitter</td>
</tr>
<tr>
<td>$S_{R}$</td>
<td>Secondary Receiver</td>
</tr>
<tr>
<td>$h_{P_{S}}$</td>
<td>Channel coefficients between PT and SR</td>
</tr>
<tr>
<td>$h_{S_{P}}$</td>
<td>Channel coefficients between ST and PR</td>
</tr>
<tr>
<td>$h_{i_{i}}$</td>
<td>Channel coefficients between $S_{T}$ and $S_{R}$</td>
</tr>
<tr>
<td>$h_{P}$</td>
<td>Channel coefficients between PT and PR</td>
</tr>
<tr>
<td>$d_{i}$</td>
<td>Distance between $S_{T}$ and $S_{R}$</td>
</tr>
<tr>
<td>$I_{M}$</td>
<td>Unit matrix with size $M$</td>
</tr>
<tr>
<td>$h_{P_{S}(n)}$</td>
<td>Channel coefficients between PT and PR at subcarrier $n$</td>
</tr>
<tr>
<td>$h_{S_{P}(n)}$</td>
<td>Channel coefficients between ST and PR at subcarrier $n$</td>
</tr>
<tr>
<td>$h_{S_{i_{j},P}(n)}$</td>
<td>Channel coefficients between $S_{T_{i}}$ and PR at subcarrier $n$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Number of OFDM symbols, leased to a secondary network</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Number of subcarriers for secondary network transmission</td>
</tr>
<tr>
<td>$k$</td>
<td>Number of secondary users for cooperation</td>
</tr>
<tr>
<td>$\dagger$</td>
<td>Hermitian</td>
</tr>
<tr>
<td>$N_{s}$</td>
<td>Number of symbols in a frame of OFDM</td>
</tr>
</tbody>
</table>

### III. Spectrum Leasing Analysis

#### A. Achievable Rates

In this section we calculate the rates achieved by both the primary and the secondary networks. The primary user tries to maximize its achievable rates by selecting the appropriate parameter $\alpha$. With no cooperation, (i.e., when $\alpha = 0$) the primary direct link rate ($R_{dl}$) in an OFDM-based system with $M$ subcarriers is given by [12]:

$$ R_{dl} = \log_{2} \det \left\{ I_{M} + \frac{\rho P H_{P} H_{P}^{\dagger}}{N_{0}} \right\} $$

where $H_{P} = \text{diag}(h_{P_{1}}, h_{P_{2}}, ..., h_{P_{M}})$ is the diagonal matrix of channel frequency coefficients with $M$ coefficients in the primary link, $\rho P = P_{P}/M$ is the allocated power to each subcarrier, $P_{P}$ is the power of the primary transmitter and $N_{0}$ is the single-sided power spectral density of the white Gaussian noise. We assume that an equal power is allocated
to the subcarriers. In the case where the secondary users cooperate, the primary transmitter leases a number of $\alpha$ OFDM symbols and the achievable rates are given by:

$$R_{\text{coop}} = \min \{(N_s - \alpha)R_{PS}, \alpha R_{SP}\}$$  \hspace{1cm} (2)

where $R_{PS}$ is the rate of the link between PT and SR. We assume that this rate is determined by the worst channel gain between PT and SR and thus $R_{PS}$ can be written as:

$$R_{PS} = \log_2 \det \left\{ I_M + \min_{i \in k} \left\{ H_{PS}^i H_{PS}^i \right\} \frac{\rho_p}{N_0} \right\}$$  \hspace{1cm} (3)

where $H_{PS}^i = \text{diag}(h_{PS_i(0)}, h_{PS_i(1)}, ..., h_{PS_i(M-1)})$ is the diagonal matrix of channel coefficients between PT and SR. In the cooperation mode, we assume that the secondary users decode and forward the primary signal by using distributed space-time coding (DSTC) [13]. The orthogonality among these codes prevent the interference caused from signals transmitted from ST to PR. By using this code the achievable rate at the PR is:

$$R_{SP} = \log_2 \det \left\{ I_{M-\gamma} + \sum_{i \in k} SNR_i \right\}$$  \hspace{1cm} (4)

where $SNR_i = \rho_i H_{S_i P} H_{S_i P}^H / N_0$, $\rho_i = P_i / M$ and $H_{S_i P} = \text{diag}(h_{S_i P(0)}, h_{S_i P(1)}, ..., h_{S_i P(M)})$ is the matrix that contains the channel coefficients between ST$_i$ and the PR with $M - \gamma$ coefficients. By allocating $\gamma$ subcarriers to the secondary network transmission, the achievable rate for each secondary link is calculated as:

$$R_i = \sum_{n=1}^{\gamma} \log_2 (1 + \frac{|h_{ij(n)}|^2 P_j / M}{N_0 + I})$$  \hspace{1cm} (5)

where $I = \sum_{j=1, j \neq i}^{k} |h_{ij(n)}|^2 P_j / M$ is the interference caused by the other secondary transmissions.

### B. Solving the Leasing Problem

Here, the leasing process consists in finding the parameter $\alpha$ so as to maximize the rates achieved by the primary network. This is achieved by solving the following optimization problem:

$$\hat{\alpha} = \arg \max_{0 \leq \alpha \leq 1} \{ R_P(\alpha) \}$$  \hspace{1cm} (6)

where

$$R_P(\alpha) = \begin{cases} R_{dl} & \alpha = 0 \\ R_{coop} & 0 < \alpha \leq 1 \end{cases}$$

The primary transmitter tries to select $\alpha$ so as to maximize its own link’s rate. As (2) is the minimum of the two functions, when $\alpha$ increases, one of these functions increases and the other decreases. Obviously, the maximum of the minimum of these two functions is obtained where these functions are equal. The primary may approximate $\alpha$ by setting the two parts of (2) equal, as follows:

$$(N_s - \alpha) M \log_2 (1 + \frac{\rho_p}{d^2 N_0}) = \alpha (M - \gamma) \log_2 (1 + \frac{k \rho_i}{(1-d)^2 N_0})$$  \hspace{1cm} (7)

where the average power of channel coefficients between PT and SR are replaced by $1/d^2$ and the channel coefficients between ST and PR by $1/(1-d)^2$ and the powers of all STs are assumed to be equal. The obtained $\alpha$ from (7) depends on $\gamma$ which is determined by the STs. The primary transmitter calculates $\gamma$ by knowing the strategy of secondary network subcarrier allocation ($R_{SP} = \sum_{i=1}^{k} R_{S_i}$) and the distance between ST$_i$ and SR$_i$ as:

$$\alpha (M - \gamma) \log_2 (1 + \frac{k \rho_i}{(1-d)^2 N_0}) = \alpha \log_2 (1 + \frac{\rho_i}{d^2 (N_0 + J)})$$  \hspace{1cm} (8)

where $J = (k-1) E[|h_{ij}|^2] P_j / M$. By setting $F = 1 + \frac{k \rho_i}{(1-d)^2 N_0}$ and $G = 1 + \frac{\rho_i}{d^2 (N_0 + J)}$, the best $\gamma$ for the secondary network is:

$$\hat{\gamma} = M \log_2 F / \log_2 FG$$  \hspace{1cm} (9)

The primary transmitter determines the optimal $\alpha$ for leasing to the secondary network by replacing the obtained $\hat{\gamma}$ from (9) in (8):

$$\hat{\alpha} = N_s \log_2 \frac{X}{\log_2 XYZ}$$  \hspace{1cm} (10)

where $X = 1 + \frac{\rho_p}{d^2 N_0}$, $Y = 1 + \frac{k \rho_i}{(1-d)^2 N_0}$ and $Z = 1 - \frac{\hat{\gamma}}{M}$. Finally, the achievable rates in cooperation mode are:

$$R_{\text{coop}} = (N_s - \hat{\alpha}) R_{PS} = \hat{\alpha} R_{SP}$$  \hspace{1cm} (11)

where $R_{PS}$ and $R_{SP}$ are defined in (3) and (4), respectively.

The primary user compares the rates in (1) and (11). If the rates achieved with cooperation in primary link are larger than those achieved in the direct link, then the primary network decides to cooperate with the secondary network.
IV. SIMULATION RESULTS

For simulation, it is assumed that all the transmitters use an OFDM modulation with $M = 100$ subcarriers. The frame is composed of $N_s$ OFDM symbols. $N_0$ is set to 1 and all the transmitter powers are set to $P = P_i = 1$.

Figure 3 shows the normalized primary link rates when different number of secondary users are in operation. We observe that when there is only one ST, it is better for the PT to use cooperation when ST is in the middle of the path. By increasing the number of STs, thanks to DSTC, the cooperation rate will increase. This rate increment is more important when the secondary nodes are close to the PT. However, when the secondary nodes are close to PR, there is no significant difference between the achievable rates in direct link and cooperation link.

Figure 4 shows the primary achievable rate for three STs and for different distances $d_{ii}s$. It can be observed from this Figure that when ST$_i$ and SR$_i$ are close together, the primary achieves higher rates (because the channel condition is better) and therefore, the secondary transmitters need to allocate less number of subcarriers for this link and hence more subcarriers are used to transmit the primary signal leading to higher achievable rates for the primary link.

Figure 5 shows the achievable rates of the secondary link with three different $d_{ii}s$. This Figure has similar conditions to Fig. 4. When ST and SR are in short distance, the achievable rates in the secondary link increases.

In Fig. 6, the normalized area of the resources allocated for cooperation by secondary network in different locations between PT and PR is shown. The cooperation area is the number of subcarriers in a number of $\alpha$ OFDM symbols allocated for primary signal retransmission by secondary nodes, as shown in Fig. 2 (part ST to PT). We observe from Fig. 6 that increasing $d_{ii}$, will decrease the dedicated area by ST for primary signal relaying. By increasing the distance between ST and SR, the secondary nodes need more subcarriers for their link’s rate and so less subcarriers will be dedicated for cooperation. When the secondary network gets closer to the PR, the channel condition in secondary to primary link becomes better and the secondary users choose more subcarriers for their own transmissions and hence the cooperation area will decrease.

V. CONCLUSION

In this paper we proposed a time-frequency domain spectrum leasing method for DSS systems over frequency-selective fading channels. The leasing method proposed in this paper may serve in a DSS system design where the aim of leasing
is to provide some resources to secondary users while, at the same time, increasing the rate of the primary network. We observed that leasing the spectrum to a secondary network by the primary user may increase the achievable rates of both primary and secondary users which may be interpreted as a better quality-of-service for both systems.

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REFERENCES