Cooperative Cognitive Radio Networking Using Quadrature Signaling

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Abstract—A quadrature signaling based two-phase cooperation framework for cooperative cognitive radio networking is proposed. By leveraging the degrees of freedom provided by orthogonal modulation, secondary users are able to relay the traffic of primary users and transmit their own in the same time slot without interference. To evaluate the cooperation performance of the proposed framework, a weighted sum throughput maximization problem is formulated, and closed-form solutions of the optimal power setting/allocation are obtained in the amplify-and-forward and decode-and-forward relaying modes. Simulation results validate the efficiency of the proposed framework.

I. INTRODUCTION

It is recognized that the licensed spectrum is underutilized by its primary users (PUs) [1]. To improve the spectral efficiency and utilization, the concept of cognitive radio networking (CRN) which enables secondary users (SUs) to opportunistically share or reuse the licensed spectrum has attracted considerable attention [2]–[6]. By using dynamic spectrum sensing, SUs can opportunistically access spectrum holes for secondary transmissions without interfering with the PUs [4]. In this type of CRN, known as interweave, the SUs must terminate secondary transmissions and look for other spectrum holes when the PUs reclaim the spectrum, which implies that the secondary transmission opportunities using spectrum sensing are highly random and are dependent on the activities of PUs. In addition, it is critical to attain accurate spectrum sensing in interweave CRN; and the SUs have to exert extra power and time to improve the sensing accuracy.

Due to the challenges of accurate spectrum sensing and random transmission opportunities, an alternative for SUs to gain transmission opportunities is to cooperatively negotiate with the PUs for secondary transmission opportunities by providing tangible service for PUs, e.g., improving the primary transmission performance and/or saving the PUs’ energy, so that the PUs are willing to yield transmission opportunities for SUs as a reward. Such cooperation between the PUs and SUs is referred to as overlay CRN or cooperative CRN (CCRN) [8].

Recently, several cooperative schemes have been proposed to exploit the time, frequency, and space domains for user collaborations in a CCRN [7]–[10]. A three-phase time division multiple access (TDMA) based scheme is presented in [8], where the PU broadcasts its traffic in the first phase; one or more SUs cooperatively relay the PU’s traffic to the primary destination in the second phase; and, as a reward, the SUs transmit the secondary traffic to the secondary destinations in the third phase. The duration of each phase and the power of transmission/relaying play a critical role in achieving cooperation gain. If the duration of the third phase cannot meet the minimum requirement of secondary transmissions, the SUs have no motivation to participate in cooperation. A two-phase frequency division multiple access (FDMA) scheme is studied in [9]. The PU yields a fraction of its licensed bandwidth for secondary transmissions; then the SUs can cooperate with the PU in the remaining bandwidth in a two-phase manner. Although the SUs can obtain continuous transmission opportunities and the PU can save energy by reducing transmission bandwidth, this framework can not be adopted by the PUs who aim to improve throughput rather than save energy. In [10], a two-phase space division multiple access (SDMA) is proposed. In this framework, each SU leverages the degrees of freedom (DoFs) provided by spatially located multiple antennas to simultaneously relay the primary traffic and transmit the secondary traffic on a non-interference basis. In this way, a two-phase scheme can be achieved at the expense of using multiple antenna systems.

In this paper, a quadrature signaling based two-phase cooperation framework for CCRN is proposed. The SU exploits the DoFs provided by quadrature phase shift keying (QPSK) to attain an orthogonal scheme, i.e., the SU uses in-phase binary phase shift keying (I-BPSK) to relay the PU’s traffic, and uses the quadrature BPSK (Q-BPSK) to transmit the secondary traffic. This enables the SU to access the same spectrum for secondary transmission in a two-phase mode. To evaluate the cooperation performance, a weighted sum throughput optimization problem is formulated. With the help of primal-dual sub-gradient algorithms, closed-form solutions of the optimal power setting and allocation for the SU under the amplify-and-forward (AF) and decode-and-forward (DF) relaying modes are given. The effectiveness of the proposed framework is validated by simulations.

The remainder of the paper is organized as follows. Section II describes the system model and problem formulation. In Section III, closed-form solutions are obtained. Simulation results are given in Section IV, followed by concluding remarks and discussions of future work in Section V.

II. SYSTEM MODEL AND PROBLEM FORMULATION

In this section, we describe the networking architecture and formulate the cooperation as a weighted sum throughput max-
imization problem to evaluate the cooperation performance.

A. System Description

We consider a CCRN environment consisting of a primary network (PN) with a primary base station (PBS) and multiple PUs, and a secondary network (SN) with a secondary base station (SBS) and multiple SUs, as shown in Fig. 1. In the PN, a PU can occupy the licensed spectrum for a continuous time slot with duration $T + \Delta T$ allocated by the PBS on a non-interference basis. If a PU is far away from its intended PBS or the link between the PU and PBS is blocked by buildings, so that the direct transmission of PU cannot support the primary service, the PU is willing to select an SU as a relay. In this context, a PU communicates with the PBS and an SU communicates with the SBS; thus four nodes are involved in cooperative communications, as shown in Fig. 1.

In the uplink for instance, when the PBS detects that the link quality between the PU and PBS is too poor, the PBS informs the PU to engage a relay to improve signal reception. If the PU decides to find an SU to cooperate, the time frame is divided into two segments as shown in Fig. 2(a). The first segment with length $\Delta T$ is used to select the most effective SU among candidate SUs, i.e., multi-user coordination. In the multi-user coordination process, each candidate SU optimizes the relaying strategy in terms of relaying mode, i.e., AF or DF, and the optimal power setting/allocation. Due to space limitation, the relay selection process is omitted here, and the details on multi-user coordination are omitted due to space limitation. The second segment with length $T$ is for a two-phase cooperation with the selected SU.

The channel between any two users is assumed to be a quasi-static Rayleigh flat fading model, i.e., the channel states of all links are invariant during the time duration of cooperative communication between the PU and the SU, e.g., the channel states are constants within the length of a frame for the PU and SU cooperation. For simplicity, the channel state information (CSI) seen at the SU is assumed known.

For the two-phase cooperation with length $T$ between the PU and SU, in the first phase, the PU broadcasts the primary traffic to the SU and PBS using BPSK modulation. Upon receiving the PU’s traffic, in the second phase, the SU uses QPSK to relay the PU’s traffic and transmits its own traffic in orthogonal channels simultaneously in the manner described in [11], i.e., the SU forwards the PU’s traffic using the I channel with power $(1 - \alpha)P_S$ and transmits its own traffic using the Q channel with power $\alpha P_S$. The transmission signal constellations for the PU and SU are shown in Fig. 2(b).

Channel gains from the PU to the SU, from the PU to PBS, from the SU to PBS, and from the SU to SBS are denoted by $\gamma_{PS}$, $\gamma_{PB}$, $\gamma_{SP}$, and $\gamma_{SB}$, respectively. In the following, the signal-to-noise ratio (SNR) of the primary and secondary links under the AF and DF relaying modes are analyzed.

If the SU uses the AF relaying mode to forward the primary traffic, in the first phase, the PU broadcasts the primary signal using BPSK modulation with power $P_P$ to the SU and PBS. After receiving the PU’s signal, the SU forwards it using the I channel of the QPSK modulation with power $(1 - \alpha)P_S$, and transmits its own signal using the Q channel with power $\alpha P_S$. After receiving the primary signal in the first and second phases, the PBS adopts maximal ratio combining (MRC) to decode the primary traffic; then the SNR of the primary signal at the PBS is obtained as

$$SNR_{PB}^{AF} = \gamma_{PB}P_P + \gamma_{SP}\gamma_{PS}P_P P_S (1 - \alpha) \gamma_{SB}P_S (1 - \alpha) + \gamma_{PS}P_P + 1.$$  \hspace{1cm} (1)

Similarly, the SNR of the secondary signal at the SBS is given by $SNR_{SB}^{DF} = \alpha \gamma_{SB}P_S$.

When the SU uses the DF mode to relay the primary traffic, after receiving the primary signals in the first phase, the SU will relay the primary traffic and transmit its own in the second phase if no error is detected after decoding the primary signals, e.g., through using a cyclic redundancy check (CRC) by the SU. Otherwise, the SU will neither relay the primary traffic nor transmit its own traffic. Let $P_e$ denote the probability that the SU detects an error in the PU’s signal. Assuming independent bit errors, then $P_e = 1 - (1 - BER)^L \approx L \times BER$, where $BER = \frac{1}{2}(1 - \sqrt{\frac{P_P + P_S}{P_P P_S + 1}})$ is the BPSK bit error rate (BER).
and $L$ is the number of bits of the PU’s traffic in a frame for a small BER and large $L$. Thus, the SNRs received at the PBS and SBS are given by

$$SNR_{PB}^{DF} = \begin{cases} P_{P}^*\gamma_{PB} + (1 - \alpha)P_{S}\gamma_{SP}, & \text{w.p. } 1 - P_{e}; \\ P_{P}\gamma_{PB}, & \text{w.p. } P_{e}; \end{cases}$$

and

$$SNR_{SB}^{DF} = \begin{cases} \alpha P_{S}\gamma_{SB}, & \text{w.p. } 1 - P_{e}; \\ -\infty, & \text{w.p. } P_{e}; \end{cases}$$

respectively, where $-\infty$ implies that no useful signal is received by the SBS, i.e., the SU does not transmit.

### B. Problem Formulation

To evaluate the cooperation performance, a throughput maximization problem under certain throughput and power constraints in CCRN is formulated. Instead of maximizing either the PU’s or the SU’s throughput, a general metric of weighted sum throughput, namely $C_{WSum}$, which incorporates both the PU and SU’s throughput with a weighting parameter, is proposed. The optimization problem is formulated as

$$\max_{\alpha, P_{P}, P_{S}} C_{WSum} = (1 - \zeta)C_{P} + \zeta C_{S}$$

subject to:

$$C_{P} > K C_{PB} \geq C_{PT} \quad \text{for } K \geq 1$$

$$C_{S} \geq C_{ST}$$

$$P_{S} \leq P_{SM}$$

$$0 < \alpha < 1$$

where $\zeta$ is a weight that strikes a balance between the PU’s throughput, $C_{P}$, and the SU’s throughput, $C_{S}$, by cooperation. When the AF mode is used, the achievable throughput of the PU and SU are denoted by $C_{P} = C_{PB}^{AF}$ and $C_{S} = C_{SB}^{AF}$, respectively. In general, the weight $\zeta$ reflects the cooperation needs of the PU. For example, if the PU is suffering from a deep fade and cannot communicate with its PBS without the help of an SU, a large $\zeta$ can be used to favor the SU, and vice versa. In the extreme case when $\zeta = 0$ or $\zeta = 1$, the objective function is reduced to maximize the PU’s throughput or SU’s throughput. Denote by $C_{PB} = \log_{2}(1 + P_{P}\gamma_{PB})$ as the direct transmission throughput of the PU without cooperation, and $K$ as the throughput gain that the PU wants to achieve through cooperation, or the PU needs to cooperate with one SU if the achievable $C_{PB}$ is below its minimum throughput requirement, $C_{PT}$. The first constraint in (4) shows that, by cooperating with an SU, the PU can achieve a higher throughput, which should be above $C_{PT}$. The second constraint indicates that the achieved throughput of the SU should meet its minimum throughput requirement, denoted by $C_{ST}$. Otherwise, the SU may not be able to establish a connection with its SBS and the secondary transmission becomes useless. These two constraints represent the cooperation benefit that motivates the PU and SU to cooperate with each other. The third constraint indicates that the transmission relaying power of the SU should be bounded by $P_{SM}$. Lastly, $\alpha$, the fraction of the power the SU uses for transmitting its own traffic, should be selected from $(0,1)$. In a special case when $\alpha = 1$, the SU transmits only its own traffic without relaying the PU’s traffic. Also, the SU only helps to forward the PU’s traffic without transmitting its own traffic when $\alpha = 0$, which is referred to as a conventional relaying scenario.

### III. Optimization of the Relaying Strategy

In this section, the constrained optimization problem in terms of the optimal transmission/relaying power of the SU in (4) is solved by applying the Karush-Kuhn-Tucker (KKT) conditions, under the AF and DF relaying modes, respectively. To achieve a simplified computation, the cooperative region is deduced by solving throughput and power constraints, then the constrained problem is transferred to a non-constrained one.

#### A. AF Relaying Mode

When the SU uses the AF relaying mode to forward the PU’s traffic, for simplicity, consider that the duration of each USE is equally divided, i.e., both of them have length $\frac{T}{2}$. In this case, the achievable throughput per Hz per second, i.e., the spectral efficiency, of the PU and SU are respectively given by $C_{PB}^{AF} = \frac{1}{2}\log_{2}(1+S\text{SNR}_{PB}^{AF})$ and $C_{SB}^{AF} = \frac{1}{2}\log_{2}(1+S\text{SNR}_{SB}^{AF})$. Suppose the PU wants to cooperate with an SU if its achievable cooperative throughput is higher than the direct link, i.e., $K = 1$ in (4). Using the Lagrange multiplier method, the problem can be solved by obtaining the optimal $P_{S}^{*}$ and $\alpha^{*}$ as follows:

$$P_{S}^{*} = \left[ \frac{\sqrt{B} - A}{2\ln 2\lambda_{2}(\gamma_{PS} + 1)\lambda_{3}\gamma_{SB}} \right]^{+}$$

and

$$\alpha^{*} = \frac{C(P_{P}\gamma_{PS} + \gamma_{SB}P_{S} + 1)}{D_{\gamma SP}^{PS}}$$

where $A, B, C$ and $D$ are constants determined by channel gains and the power of the PU.
in (4). By mathematical manipulations, we can obtain the following inequalities:
\[
\begin{align*}
\gamma_{SP} &> \frac{\gamma_{PS}(\gamma_{PS}P_P + 1)(1 + \gamma_{PB}P_P)}{P_S(\gamma_{PS} - \gamma_{PB}^2P_P - \gamma_{PB})} \quad (7) \\
\gamma_{PS} &> \frac{\gamma_{PB}^2P_P + \gamma_{PB}}{P_S} \quad (8) \\
\gamma_{SB} &> \frac{\exp(2C_{ST}\ln 2) - 1}{P_S} \quad (9)
\end{align*}
\]
which give the cooperative region in the AF mode. That is, if channel gains are above the thresholds derived in (7)-(9), the PU and SU can cooperate with each other to achieve certain cooperation benefit. In general, the SU checks the cooperative region based on the CSI and \( P_P \). If the channel gains are within the region, the SU calculates the optimal \( \alpha \) which yields
\[
\alpha_{AF}^* = \frac{E(\gamma_{PS}P_S + P_P\gamma_{PS} + 1)}{\gamma_{PS}P_S(\gamma_{PS}P_S + 1)} \quad (10)
\]
where
\[
E = 2\gamma_{PS}\gamma_{PB} + \gamma_{PS}^2\gamma_{PB}\gamma_{PS} + \gamma_{PS}P_S + \gamma_{PB}\gamma_{PS} + \gamma_{PB}^2\gamma_{PB}\gamma_{PS} + \gamma_{PB}
\]
\[
F = \gamma_{PS}\gamma_{PB} + \gamma_{PS}^2\gamma_{PB}\gamma_{PS} + \gamma_{PS}P_S + \gamma_{PB}\gamma_{PS} + \gamma_{PB}^2\gamma_{PB}\gamma_{PS} + \gamma_{PB}
\]
if \( C_{WSum} \) has a single extremum with respect to \( \alpha \in (0, 1) \).

If \( C_{WSum} \) is an increasing function with respect to \( \alpha \in (0, 1) \), then the SU can only select the \( \alpha \) that meets its throughput requirement, which is derived as
\[
\alpha_{AF}^* = \frac{(\gamma_{SB}P_S + P_P\gamma_{PS} + 1)(\gamma_{PS}P_S + 1)}{\gamma_{SB}P_S(\gamma_{PS}P_S + 1)} \quad (11)
\]

### B. DF Relaying Mode

When the SU uses the DF relaying mode, assume that the SU can detect errors in the primary signals such as with the help of channel coding scheme adopted by PU. In the second phase, the SU will neither relay the PU’s traffic nor transmit its own when any errors are detected in the primary signal received in the first phase, i.e., the SU will keep silent. Therefore, the achieved throughput of the PU is determined by the direct transmission from the PU to the PBS. In the case when no error is detected, the achievable throughput of the PU is a combination of the direct and relaying transmissions. Hence the throughput of the PU is given by
\[
C_{PB}^{DF} = \begin{cases} 
\frac{1}{2} \log_2(1 + P_P\gamma_{PB} + (1 - \alpha)P_S\gamma_{SP}), & \text{w.p. } 1 - P_e; \\
\frac{1}{2} \log_2(1 + P_P\gamma_{PB}), & \text{w.p. } P_e.
\end{cases}
\]
Similarly, the throughput of the SU in the second phase of cooperative transmission is
\[
C_{SB}^{DF} = \begin{cases} 
\frac{1}{2} \log_2(1 + \alpha P_S\gamma_{SB}), & \text{w.p. } 1 - P_e; \\
0, & \text{w.p. } P_e.
\end{cases}
\]

Therefore, the expected throughput of the PU and SU can be derived as
\[
\hat{C}_{PB}^{DF} = \frac{1 - P_e}{2} \log_2(1 + P_P\gamma_{PB} + (1 - \alpha)P_S\gamma_{SP})
+ \frac{P_e}{2} \log_2(1 + P_P\gamma_{PB})
\]
and
\[
\hat{C}_{SB}^{DF} = \frac{1 - P_e}{2} \log_2(1 + \alpha P_S\gamma_{SB}).
\]

Similar to that in the AF case, the optimal \( P_S^* \) and \( \alpha^* \) can be jointly obtained by applying the KKT conditions to solve the optimization problem. For simplicity, we simplify the analysis by deriving \( \alpha^* \) for a given \( P_S^* \), then the Lagrangian function is given by
\[
L(\alpha) = (1 - \alpha)\hat{C}_{PB}^{DF} + \alpha\hat{C}_{SB}^{DF} + \lambda_2[C_{ST} - \hat{C}_{SB}^{DF}]
+ \lambda_1[\log_2(1 + P_P\gamma_{PB}) - \hat{C}_{PB}^{DF}].
\]

By solving the Lagrangian function, the optimal \( \alpha^* \) is obtained as
\[
\alpha_{DF}^* = \frac{G}{\gamma_{SP}\gamma_{SB}P_S(\lambda_1 + \lambda_2 - 2)}
\]
where
\[
G = \gamma_{SP}(2 - 2\zeta - 2\gamma_{SB}P_S - \lambda_1 + \lambda_2\gamma_{SB}P_S)
+ \gamma_{SB}(\lambda_2 + 2\lambda_2P_P\gamma_{PB} - 2\zeta - 2\zeta P_P\gamma_{PB})
\]
and \( \lambda_1 \) and \( \lambda_2 \) can be iteratively obtained by a relaxation algorithm.

Similarly, the cooperative region is derived from the throughput constraints of the PU and the SU, which are given by
\[
\gamma_{SP} > \frac{P_P\gamma_{PB}(1 + P_P\gamma_{PB})}{\gamma_{SP}} P_S\gamma_{SB} \quad (18)
\]
\[
\gamma_{SB} > \frac{(\ln 2)C_{ST}}{\sqrt{\gamma_{SB}} + 1} P_S^{-1} \quad (19)
\]
where \( \gamma_{PS} = \frac{L^2_{PS}}{(1 - L^2_{PS})^2} \). Notice that there are only two thresholds for the DF case, while there are three thresholds for the AF case. That is, when the DF is applied, the SU does not need to check the cooperative region if the transmission from the PU to the SU fails. On the contrary, given that the SU successfully receives the traffic from the PU, the SU only needs to check whether channel gains between the SU and the SBS, and between the SU and the PBS are sufficiently good to satisfy the throughput requirements of both the PU and the SU. Therefore, the SU only needs to check the channel gain thresholds of \( \gamma_{SP} \) and \( \gamma_{SB} \) in the DF case.

### IV. Theoretical and Simulation Results

In this section, the cooperation performance of the proposed framework is evaluated via simulations using Matlab.

The throughput performance of the PU and the SU for AF is shown in Fig. 3. In this simulation, \( \gamma_{PB}, \gamma_{PS}, \gamma_{SB} \), and \( \gamma_{SP} \) are set as 0.28, 21.1, 32.3, and 30.3, respectively. Due to the severe fading, the direct link throughput of PU is \( C_{PB}^{AF} = 0.35 \text{ bps/Hz} \). The power of the PU and the SU are
$P_P = 1 \text{ mW}$ and $P_S = 2 \text{ mW}$, and the weight is $\zeta = 0.3$. According to (10), $\alpha^*$ is obtained as 0.52. It is shown in Fig. 3 that the maximum throughput is achieved when $\alpha$ is around 0.52, and the throughput of the PU and the SU are $C_{SB}^{AF} = 2.53 \text{ bps/Hz}$ and $C_{PB}^{AF} = 1.89 \text{ bps/Hz}$, respectively. The simulation results validate the theoretical analysis, and the optimal power allocation can be done by using (10). It is also observed that by the PU and SU cooperation, the PU can achieve 5.4 times throughput compared with direct transmission while the SU can also achieve a higher throughput than its minimum throughput requirement, $C_{ST} = 1 \text{ bps/Hz}$.

When the channel gains are $\gamma_{PB} = 0.53$, $\gamma_{PS} = 7.6$, $\gamma_{SB} = 22.5$, and $\gamma_{SP} = 25.3$, and the power of the PU and the SU are $P_P = 1$ and $P_S = 1$, the AF mode cannot provide a feasible solution for user cooperation, and SUs then check whether the DF protocol can be applied. Fig. 4 plots the throughput performance of the PU and the SU for the DF protocol. According to the analytical result for DF, the optimal $\alpha^* = 0.31$ is obtained by (17). It can be seen in the figure that the maximal weighted sum throughput in the stimulation is achieved when $\alpha$ is about 0.31, and the SU achieves $C_{SB}^{DF} = 1.51$ which is larger than $C_{ST} = 1 \text{ bps/Hz}$ and the PU achieves $C_{PB}^{DF} = 1.54 \text{ bps/Hz}$.

In this context, the SU will choose the AF relaying mode to cooperate with the PU. As can be seen, both the PU and the SU can achieve higher throughput when the SU uses the AF mode than when it uses the DF mode.

V. CONCLUSION AND FUTURE WORK

In this work, we have developed a novel cooperation framework for CCRN, based on quadrature modulation. By exploiting the DoF in orthogonal modulation, an SU can simultaneously relay the PU’s traffic and transmit its own without interference. The user cooperation has been formulated as a weighted sum throughput maximization problem, under minimal user throughput requirement and power constraints. The optimal power setting and allocation have been analyzed and closed-form solutions have been derived for both AF and DF modes.

In future work, further studies on the cooperative region will be undertaken. We plan to extend the proposed cooperation framework to study the multi-user diversity gain for a PU to cooperate with multiple SUs. User cooperation frameworks based on other signaling techniques such as polarization modulation are also under investigation.

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