A Cooperative Protocol for Spectral-Efficient Cognitive Relay Networks

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***Abstract*—In this paper we propose a cooperative protocol for cognitive wireless networks that can improve the overall system spectral efficiency when a secondary user (SU) incorrectly transmits over the same resource with the primary user (PU). The interfering transmissions are received at relay nodes, that form the cooperative network, and are decoded with successive interference cancellation (SIC). Depending on the decoding results, each relay applies independently a space-time code (STC) to the result and then the relays forward the coded signals simultaneously. The advantages of the protocol are first that it operates passively without the need for source cooperation, and second that it does not adopt a different mode of cooperation for different average channel conditions. Comparative simulations with a state-of-the-art multi-source transmission protocol reveal that our protocol can minimize the impact of incorrectly detecting a PU transmission from the perspective of the overall system spectral efficiency.**

***Index Terms*—Cognitive network, cooperative protocol, successive interference cancellation, Alamouti code, space-time block coding, distributed space-time coding, wireless networks.**

I. Introduction

In a cognitive wireless network, a primary user (PU) is allocated time/frequency resources that can also be accessed from a secondary user (SU) when they are not used by the PU. Even though the probability α of detecting a transmission from the PU can be increased with sensing algorithms, there is still the possibility that the SU falsely detects that a resource is free. A transmission in this case leads to interference or collision. However, in certain cases the interfering SU and PU transmissions may be a desired event from the perspective of the overall system spectral efficiency. The reason is that orthogonality is optimal only in the low signal-to-noise-ratio (SNR) regime [1]. Orthogonal channel access is suboptimal in the high SNR regime for the multiple input single output (MISO) uplink AWGN and fading channels [1]. This means that in the high SNR regime more than one users can transmit simultaneously towards a single destination leading to higher spectral efficiency or multiplexing gain. This can be implemented with successive interference cancellation (SIC) [1].

Nevertheless, a MISO channel may be a small part of a modern wireless network. In the context of cognitive networks it is possible that several nodes exist in the neighborhood of the PU and the SU and they act as *relays*. A representative *cooperative* network is illustrated in Fig. 1(a) where the PU and the SU communicate through relays to a final destination (this scenario can occur in a WiFi mesh network, uplink relay-based cellular network, etc.). Hence, for this network the question is how to recover efficiently from a false PU inactivity

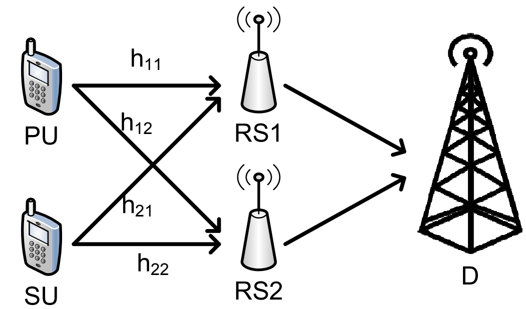

Fig. 1. The cognitive wireless cooperative network model we consider in this paper consists of two users and two relays in an uplink transmission scenario.

detection and a subsequent SU transmission. Clearly there is a need for a protocol that also exploits the relays.

Cooperative protocols that improve spectral efficiency when multi-source communication is allowed have been investigated considerably in the literature. These protocols can be used as a recovery mechanism in our setup. For the topology illustrated in Fig. 1(a), a decode-and-forward (DF) protocol that was presented in [2] was shown to perform very well in the low SNR regime. Contrary to the above, it was shown in [3], [4] that amplify-and-forward (AF) performs better in the high SNR regime because of low noise amplification at the relays. The work in [2] is essentially the implementation of the Han and Kobayashi [5] DF scheme but for the topology in Fig. 1(a), although enhanced with multiple base stations (destination nodes in our setup). For the same topology a compress-and-forward (CF) scheme [6] performs better than AF and DF but under the assumption of a non-fading channel and full-duplex relay operation [3]. However, under the same power constraints for the sources and the relays, AF was shown to be better than CF. The first limitation of the previous works is the suboptimal performance of DF and AF for different average channel conditions. Since the average SNR depends on user location it requires constant monitoring and system adaptation in order to select the optimal mode. The second problem is that DF requires source cooperation. This is clearly not applicable in a cognitive network since a false detection of PU inactivity and a subsequent transmission is an event that we cannot control disallowing any form of source cooperation.

In this paper we depart from the previous works and we develop a protocol that unifies AF and DF allowing uncoordinated operation of the PU and the SU for every average channel condition. During the fraction of resources α, the relays use a distributed space-time code (DSTC) in order to extract a diversity gain from the presence of two relays for the benefit of the PU [7], [8]. During the fraction $1-\alpha$ where the PU and SU interfere, their signals are received at the two relays. Unlike related work, decoding of the interfering signals is performed passively with SIC at the relays and the sources remain completely agnostic. Depending on the results of SIC, the relays apply an adaptive analog/digital DSTC.

II. Cooperative Protocol

A. System Model and Assumptions

We denote with α the detection probability of the PU from the SU, while it may also be a deterministic parameter that indicates the minimum desired fraction of resources from the PU. For this fraction α of the resources a DSTC protocol is used that is a hybrid version of the protocols reported in [7], [8]. This protocol selects the optimal behavior between applying DSTC for decoded [7] or non-decoded analog signals [8]. Hence, when α=1 the system operates under the optimal behavior from the perspective of the PU since it exploits the relays for a full diversity gain and without allowing any SU interference. The protocol we describe in the next subsection is named distributed space-time coding for interfering signals (DSTCIF), and is used during the fraction $1-\alpha$ of the total resources where a false detection and transmission from the SU occurred. The SU always transmits during the fraction $1-\alpha$ of the resources.

Every node in our system model has a single omni-directional antenna that can be used both for transmission and reception while all nodes have the same average power constraint. We denote the channel from the s-th user to the r-th relay as $h_{s,r}$, and the channel from the r-th relay to destination as $h_{r,d}$. We assume that the fading coefficients are independent and $h_{s,r} \sim \mathcal{CN}(0,1)$, $h_{r,d} \sim \mathcal{CN}(0,1)$, i.e. they are complex Gaussian random variables with zero mean and unit variance. All the channels, from users to relays and relays to destinations are considered to be block-fading Rayleigh. The channel coefficients are quasi-stationary, that is they remain constant for the complete duration of a block transmission for each user/relay and relay/destination pair. Additive white Gaussian noise (AWGN) is assumed at the relays and the destinations. Each transmitted block consists of L symbols.

Regarding the required CSI at a relay, only the knowledge of the channel from the users to that specific relay is needed in order to decode the interfering symbols and calculate the power scaling factor. No further channel knowledge is required. However, channel state information at the final receiver/destination (CSIR) can be obtained by sending training signals from the relays and the users.

B. Relay Preprocessing

We give particular emphasis in the actions taking place at the relays. Assume that the PU and SU desire to communicate at rates of R_1 and R_2 bits/symbol, and with power P_1 and P_2 respectively. Also assume that the total power dedicated to each transmitted symbol is normalized to unity. In the first time slot both users broadcast their information blocks x_1 and x_2 simultaneously, i.e. they interfere. Thus, the baseband model for the received superimposed signals at relay r is:

$$y_r = P_1 h_{1,r} x_1 + P_2 h_{2,r} x_2 + w_r \tag{1}$$

After the users interfere, each relay attempts to decode both information blocks by employing ordered SIC (OSIC). That is, the information block with the highest energy-per-bit is decoded first while the other information block is treated as noise [1]. To be more specific since we have assumed $\mathbb{E}[|x_1|^2] = \mathbb{E}[|x_2|^2] = 1$, if the condition

$$\frac{P_1 |h_{1,r}|^2}{2^{R_1}-1} > \frac{P_2 |h_{2,r}|^2}{2^{R_2}-1}, \tag{2}$$

is true, then the symbols from from the PU are decoded first. In case the information block is correctly decoded, it is then subtracted from the aggregate signal y_r. The successful decoding of the complete data block x_1 is verified with the use of an error cyclic redundancy check (CRC) code. Thus, upon the successful decoding, and with CSIR at the relay, we can completely remove/cancel a complete information block from the aggregate signal y_r.

Even though the previous approach ensures optimal performance under two interfering users [1], it does not ensure also the correct decoding of both symbols. This means that there are potentially four decoding outcomes for SIC at a relay. Depending on the result, the relay will transmit different signals in the next time slot. To denote these signals that the relays transmit we use the notation $q_{r,i}$ where r indicates the relay and i denotes the user.

dec?	x_1, x_2	x_1	x_2	none
$a_{r,1}$	0	0	0	$\frac{h_{1,r}^* h_{2,r}}{\lvert h_{1,r}\rvert^2}$
$b_{r,1}$	0	0	$\frac{h_{1,r}^*}{\lvert h_{1,r}\rvert^2}$	$\frac{h_{1,r}^*}{\lvert h_{1,r}\rvert^2}$
$a_{r,2}$	0	0	0	$\frac{h_{2,r}^* h_{1,r}}{\lvert h_{2,r}\rvert^2}$
$b_{r,2}$	0	$\frac{h_{2,r}^*}{\lvert h_{2,r}\rvert^2}$	0	$\frac{h_{2,r}^*}{\lvert h_{2,r}\rvert^2}$
$q_{r,1}$	x_1	x_1	$x_1 + \frac{h_{1,r}^*}{\lvert h_{1,r}\rvert^2} w_r$	$x_1 + \frac{h_{1,r}^* h_{2,r} x_2 + h_{1,r}^* w_r}{\lvert h_{1,r}\rvert^2}$

TABLE I
CONDITIONAL RELAY PREPROCESSING

Table I shows the relay signal processing actions depending on all the decoding outcomes. The relay pre-processing functionality shown is the table can be compactly modeled as follows:

$$q_{r,1}[1] = x_1[1] + a_{r,1} x_2[1] + b_{r,1} w_r$$
$$q_{r,2}[1] = x_2[1] + a_{r,2} x_1[1] + b_{r,2} w_r$$

The adopted signal notation covers every possible packet decoding outcome at the relay through the complex gain variables $a_{r,1}, b_{r,1}, a_{r,2}, b_{r,2}$, that are also defined in Table I. One notes in this table that irrespectively of the decoding results at the relay, they both remain consistent with respect to what they will transmit for the information block of each specific user. For example, $q_{r,2}$ will always contain an equalized version of symbol x_2 from the second user plus whatever signal remains depending on the SIC results. *This is a key benefit of our scheme that ensures that the relays operate autonomously and consistently without the need for coordination depending on the local results of the SIC.* At this point we can see more clearly that when a symbol is successfully decoded, there is a digital packet available for transmission. However, when the signal is not decoded, then the relays transmit the sufficient statistic for the block from source i in $q_{r,i}$.

C. Distributed Space-Time Coding

Now we describe the actual STC operations at the relay that are executed for the signals denoted as $q_{r,i}$. The relays apply an orthogonal Alamouti-type of code for $q_{r,i}$ irrespectively of the SIC decoding results. These STC matrices are defined as follows:

$$\begin{aligned}\mathbf{A}_{1,1} &= \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}, \mathbf{A}_{1,2} = \mathbf{B}_{1,1} = \mathbf{0}_{2x2}, \mathbf{B}_{1,2} = \begin{bmatrix} 0 & -1 \\ 0 & 0 \end{bmatrix} \\ \mathbf{A}_{2,1} &= \mathbf{B}_{2,2} = \mathbf{0}_{2x2}, \mathbf{A}_{2,2} = \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix}, \mathbf{B}_{2,1} = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}\end{aligned}$$

The matrix of transmitted symbols is

$$\mathbf{Z} = \sum_{r=1}^{2}\sum_{i=1}^{2} g_{r,i}(\mathbf{A}_{r,i}q_{r,i} + \mathbf{B}_{r,i}q_{r,i}^*) = \begin{bmatrix} g_{1,1}q_{1,1} & -g_{1,2}q_{1,2}^* \\ g_{2,2}q_{2,2} & g_{2,1}q_{2,1}^* \end{bmatrix}.$$

In the above matrix the rows indicate the relay and the columns the time slot, while $g_{r,i}$ is the power scaling coefficient for symbol $q_{r,i}$ as we defined it earlier. This is essentially the distributed STC codeword but in the general case it contains completely different signals and thus it is not in the well-known form of the Alamouti STC. In the case that both symbols are decoded at both relays then $\mathbf{Z}$ effectively reduces to an Alamouti code for the symbols x_1, x_2 since $q_{1,1} = q_{2,1} = x_1$ and $q_{1,2} = q_{2,2} = x_2$.

After the STC is applied, the two relays broadcast the ST-coded symbols. Let us denote with $\mathbf{f}$ the vector of the channel gains for the links between the relays and the destination. The channels remain constant for at least two successive symbol transmissions as we stated in our assumptions. The received signal at the destination over two consecutive slots will be the vector:

$$\begin{aligned}\mathbf{y}_d &= \underbrace{\begin{bmatrix} f_1 \\ f_2 \end{bmatrix}^T}_{\mathbf{f}} \underbrace{\begin{bmatrix} g_{1,1}q_{1,1} & -g_{1,2}q_{1,2}^* \\ g_{2,2}q_{2,2} & g_{2,1}q_{2,1}^* \end{bmatrix}}_{\mathbf{Z}} + \begin{bmatrix} w_{1,d} \\ w_{2,d} \end{bmatrix}^T \\ &= \begin{bmatrix} f_1 g_{1,1}q_{1,1} + f_2 g_{2,2}q_{2,2} & -f_1 g_{1,2}q_{1,2}^* + f_2 g_{2,1}q_{2,1}^* \end{bmatrix} \\ &+ [w_{1,d} \quad w_{2,d}]\end{aligned}$$

Next, we create the equivalent channel model by taking the complex conjugate of the second column of $\mathbf{y}_d$. The resulting signal is denoted as $\tilde{\mathbf{y}}_d$. So we have:

$$\begin{aligned}\tilde{\mathbf{y}}_d &= \begin{bmatrix} g_{1,1}f_1q_{1,1} + g_{2,2}f_2q_{2,2} \\ -g_{1,2}f_1^*q_{1,2} + g_{2,1}f_2^*q_{2,1} \end{bmatrix} + \begin{bmatrix} w_1 \\ w_2^* \end{bmatrix} \\ &= \begin{bmatrix} g_{1,1}f_1 + g_{2,2}f_2a_{2,2} & g_{1,1}f_1a_{1,1} + g_{2,2}f_2 \\ g_{2,1}f_2^* - g_{1,2}f_1^*a_{1,2} & -g_{1,2}f_1^* + g_{2,1}f_2^*a_{2,1} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \\ &+ \begin{bmatrix} g_{1,1}f_1b_{1,1}w_{r1} + g_{2,2}f_2b_{2,2}w_{r2} \\ -g_{1,2}f_1^*b_{1,2}w_{r1} + g_{2,1}f_2^*b_{2,1}w_{r2} \end{bmatrix} + \begin{bmatrix} w_1 \\ w_2^* \end{bmatrix} \\ &= \mathbf{H}\mathbf{x} + \mathbf{w}_d\end{aligned}$$

Although the signal model is similar to a DSTC based on the Alamouti scheme, note that the values of the complex parameters denoted by a, b determine the final channel matrix. This means that the symbol decoding is not decoupled as in the typical Alamouti case, unless the two symbols are decoded at both relays, i.e. when $a = b = 0$. In this case our model reduces to the classic DSTC protocols that are used only when all the packets/symbols are decoded. However, even if the previous is not the case, the destination still receives two observations over two slots that it can optimally solve with a linear 2x2 MIMO MMSE detector.

Before we proceed with our decoding scheme we have to describe the power allocation method we employ in this paper. The available relay power is denoted as P_r. The scaling coefficient applied by the relay r for symbol i is $g_{r,i} = \sqrt{\frac{P_r/2}{E[|q_{r,i}|^2]}}$. Thus, the relays splits equally the available power between the two successive ST-coded symbols that it transmits.

D. Decoding

From the received signal model in (3) we can calculate the covariance matrix $\mathbf{\Sigma_w}$ of the noise vector. The entries of this 2x2 matrix are:

$$[\mathbf{\Sigma_w}]_{1,1} = g_{1,1}^2|f_1|^2|b_{1,1}|^2\sigma_1^2 + g_{2,2}^2|f_2|^2|b_{2,2}|^2\sigma_2^2 + \sigma_w^2$$

$$[\mathbf{\Sigma_w}]_{2,2} = g_{1,2}^2|f_1|^2|b_{1,2}|^2\sigma_1^2 + g_{2,1}^2|f_2|^2|b_{2,1}|^2\sigma_2^2 + \sigma_w^2$$

$$[\mathbf{\Sigma_w}]_{1,2} = [\mathbf{\Sigma_w}]_{2,1} = 0$$

Again, depending on the decoding result of SIC at the relay we have a different noise covariance matrix at the final destination. For final decoding of the transmitted symbols we apply MMSE equalization for the signal model in (3):

$$\hat{\mathbf{x}} = \text{HDD}\{(\mathbf{H}^H\mathbf{\Sigma_w}^{-1}\mathbf{H} + \mathbf{I})^{-1}\mathbf{H}^H\mathbf{\Sigma_w}^{-1}\tilde{\mathbf{y}}_d\},$$

where HDD stands for hard decision decoding. Thus, decoding at the final destination is conditioned on what is decoded at the relays. This makes sense from the perspective of a communication system since the final receiver must have this knowledge in order to know how to equalize.

Now this creates the requirement that the relay must indicate in the preamble of each packet the local decoding results with SIC. As we already explained the relays manipulate information at the block level which means that if they decode for example a block from both SU and PU, then for all the symbols of this block it will be $a_{r,1}$=$b_{r,1}$=0. For another case that x_1 is not decoded this means from table I that $b_{r,1} \neq 0$

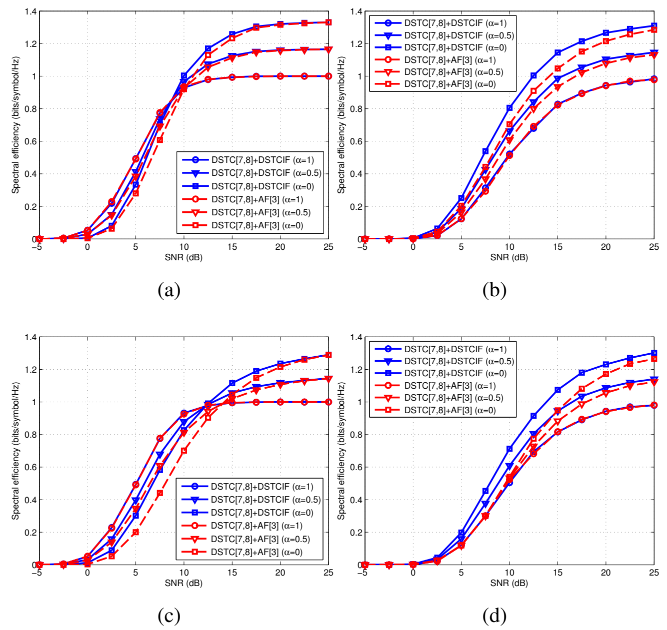

Fig. 2. Spectral efficiency results: a) average channel gain for all channels is 1, b) $\mathbb{E}[|h_{1,2}|^2]$ =0.1, c) $\mathbb{E}[|h_{2,1}|^2]$=0.1, d) $\mathbb{E}[|h_{1,2}|^2]$=$\mathbb{E}[|h_{2,1}|^2]$=0.1 .

which is another binary result that has to be communicated for a complete block. Thus, the overhead of indicating the above local results at each relay for each block they forward is negligible (4 bits for every data block).

III. Performance Evaluation

We implemented the proposed cooperative protocol and we evaluated its spectral efficiency through Monte Carlo simulations. Results correspond to the transmission of 5000 blocks with L=1000 bits each. QPSK was used by the PU and the SU. The average channel gains between all the nodes is equal to 1 unless otherwise specified. For each value of the transmit SNR we tested different channel coding rates for all systems and we selected the optimal to present in the figures. The spectral efficiency is calculated by considering the modulation scheme, channel coding, and L.

Results for symmetric links are illustrated in Fig. 2(a). The proposed scheme can outperform AF for every SNR value. Beyond 7,5dB the gains are maximized when α is reduced which means that simultaneous transmission if beneficial for the overall spectral efficiency. However, for a SNR lower than 7,5 dB an increasing rate of false PU inactivity detections (lower α) and transmissions results in spectral efficiency reduction. In Fig. 2(b) the average channel gain from the PU to the second relay is $\mathbb{E}[|h_{1,2}|^2]$=0.1. Nevertheless, the overall system performance is improved considerably. Since the SU has very good channel it can use more efficiently the $1-\alpha$ resources than the PU. Hence, the overall system performance is always improved as α is decreased and the best performance occurs when it becomes zero. Hence, the cost of false detections and transmissions is not so critical for these channel gains.

In Fig. 2(c) we set the channel from the SU to one of the relays to a low value $\mathbb{E}[|h_{2,1}|^2]$=0.1. Clearly below 10dB allocating the resources to the PU is the optimal course of action since the channel from the SU is poor. Hence, for $\alpha < 1$ the performance is always decreased. But even when the SU transmits, the DSTCIF system can still provide benefits over AF. Our protocol in this case ensures that if a false PU detection occurs, and a subsequent transmission follows, the simultaneously accessed resource is exploited in the best possible way. Finally, the most important benefits occur when the channels from both users to another relay are low. In Fig. 2(d) we see that our scheme always offers a performance increase as α is reduced, while the performance gap with AF is extended (e.g. 1.1 vs. 0.9 bit/symbol/Hz for 15dB).

IV. Conclusions

In this paper we proposed a cooperative protocol for cognitive wireless networks that can improve the spectral efficiency of the system when a SU incorrectly transmits over a specific resource. The protocol has the benefit that it operates passively without the need to adopt a different cooperative mode at the sources or the relays (AF or DF) for different average channel conditions. Performance results indicate that when the SU has very good channel towards the relays, the impact on the overall system spectral efficiency is positive. However, when the SU has poor channel on average, then a false PU detection and transmission is more harmful since it hurts the overall performance besides the PU. However, under any channel condition our protocol always performs better than a state-of-the-art multi-source cooperative protocol. Our future work will be focused on deriving a performance model for our protocol.

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