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 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 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 uncoor-
Gaussian noise (AWGN) is assumed at the relays and the for each user/relay and relay/destination pair. Additive white unit variance. All the channels, from users to relays and relays are complex Gaussian random variables with zero mean and

\[ h_{s,r} \sim \mathcal{CN}(0,1), \quad h_{r,d} \sim \mathcal{CN}(0,1), \] 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:

\[ y_r = P_1 h_{1,r} x_1 + P_2 h_{2,r} x_2 + w_r \] (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

\[ \frac{P_1 |h_{1,r}|^2}{2 R_1 - 1} > \frac{P_2 |h_{2,r}|^2}{2 R_2 - 1}, \] (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.

Table 1 shows the relay signal processing actions depending on all the decoding outcomes. The relay pre-processing functionality shown in the table can be compactly modeled as follows:

<table>
<thead>
<tr>
<th>dec?</th>
<th>( x_1 )</th>
<th>( x_2 )</th>
<th>none</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_{r,1} )</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( b_{r,1} )</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( a_{r,2} )</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( b_{r,2} )</td>
<td>0</td>
<td>( h_{2,r} )</td>
<td>0</td>
</tr>
<tr>
<td>( q_{r,1} )</td>
<td>( x_1 )</td>
<td>( x_1 + h_{1,r} w_r )</td>
<td>( x_1 + h_{1,r} h_{2,r} w_r + h_{2,r} w_r )</td>
</tr>
</tbody>
</table>

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 1. 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:

\[
\begin{align*}
A_{1,1} &= \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}, \\
A_{1,2} &= \tilde{B}_{i} = 0_{2x2}, \\
B_{1,2} &= \begin{bmatrix} 0 & -1 \\ 0 & 0 \end{bmatrix}.
\end{align*}
\]

\[
A_{2,1} = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}, \\
A_{2,2} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}.
\]

The matrix of transmitted symbols is

\[
\begin{align*}
Z &= \sum_{r=1}^{2} \sum_{i=1}^{2} g_{r,i} (A_{r,i} q_{r,i} + B_{r,i} q_{r,i}^*) = \begin{bmatrix} g_{1,1} q_{1,1} & -g_{1,2} q_{1,2} \\ g_{2,1} q_{2,1} & g_{2,2} q_{2,2} \end{bmatrix}. 
\end{align*}
\]

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 \( Z \) 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 \( f \) 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:

\[
\begin{align*}
\tilde{y}_d &= \begin{bmatrix} g_{1,1} f_1 q_{1,1} + g_{2,2} f_2 q_{2,2} \\ -g_{1,2} f_1 q_{1,2} + g_{2,1} f_2 q_{2,1} \end{bmatrix} + \begin{bmatrix} w_{1,d} \\ w_{2,d} \end{bmatrix} \\
&= \begin{bmatrix} f_1 (g_{1,1} q_{1,1} + f_{2,2} q_{2,2}) \\ f_2 (g_{2,1} q_{2,1} + f_{1,2} q_{1,2}) \end{bmatrix} + \begin{bmatrix} w_{1,d} \\ w_{2,d} \end{bmatrix}
\end{align*}
\]

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 \( \Sigma_w \) of the noise vector. The entries of this 2x2 matrix are:

\[
\begin{align*}
[\Sigma_w]_{1,1} &= g_{1,1}^2 |f_1|^2 |b_{1,1}|^2 \sigma_a^2 + g_{2,2}^2 |f_2|^2 |b_{2,2}|^2 \sigma_a^2 + \sigma_w^2 \\
[\Sigma_w]_{2,2} &= g_{1,2}^2 |f_1|^2 |b_{1,2}|^2 \sigma_a^2 + g_{2,1}^2 |f_2|^2 |b_{2,1}|^2 \sigma_a^2 + \sigma_w^2 \\
[\Sigma_w]_{1,2} &= [\Sigma_w]_{2,1} = 0
\end{align*}
\]

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):

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

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 \( b_{r,1} \neq 0 \)
In Fig. 2(c) we set the channel from the SU to one of the relays to a low value $\mathbb{E}[|h_{1,2}|^2]=0.1$. 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 $\alpha$ 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 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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