Optimizing Interference Cancellation in Cooperative Wireless Networks with Relay Selection

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***Abstract*—Successive interference cancellation (SIC) is a decoding scheme that allows multiple sources to transmit simultaneously over the wireless medium to a single destination. The power level that each symbol is received has a direct impact on the performance of SIC. Thus, optimizing SIC entails careful power allocation at the transmitting sources or in a network setup, the scheduling of the sources that will transmit simultaneously. In this paper we consider a two-hop multi-relay cooperative network setup. In this setting instead of pro-actively scheduling the sources or employing power allocation, we investigate a reactive scheme for optimizing the performance of SIC that operates after the sources have transmitted. We propose distributed relay selection as the means to improve SIC. We investigate different relay selection policies depending on channel state information (CSI) availability at the relays and the performance optimization objective. Simulation results for our *SIC-aware* relay selection schemes demonstrate that it offers a viable option for improving the performance of SIC.**

I. Introduction

Interference is a fundamental problem in wireless networks and it can be attacked in several ways. One approach for completely eliminating interference in a controlled network environment is with a multiple access (MA) protocol. Carrier sense with multiple access (CSMA) is used predominantly in Wireless LANs (WLANs) like IEEE 802.11 and it is essentially a listen-before-talk approach. However, in modern cellular networks liker LTE-A the flat frequency reuse makes the presence of interference unavoidable in every practical setting [1]. The use of advanced inter-cell interference coordination (ICIC) schemes is necessary. With ICIC the macro base stations (MBS) coordinate so that they minimize the transmitted power in the same frequency/time slot (resource block). Thus, even with ICIC interference is still present although at reduced power levels. This means that it is necessary to employ additional mechanisms for combating interference. The last resort is to process the interfering signals at the receiver by using interference cancellation (IC). Different IC schemes exist and include ML and successive IC (SIC), that are optimal but non-linear [2]. IC schemes with linear complexity include MMSE and zero-forcing that are however suboptimal. All these schemes can be used in LTE-A wireless cellular systems for combating interference at the receiver [3]. In this paper we focus on SIC since it is characterized by lower implementation complexity than ML. Furthermore, recent research prototypes have verified the expected theoretical performance [4].

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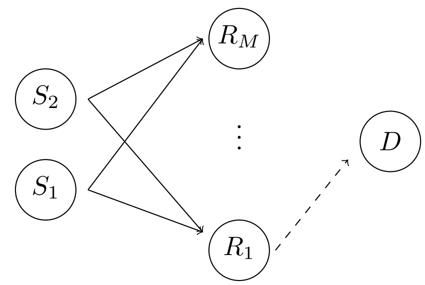


Fig. 1. Network model. The two sources S_1 and S_2 transmit simultaneously and the signals interfere at the relays. The relay selection policies investigated in this paper are responsible for identifying the relay that must forward its signal in order to improve interference cancellation at D.

However, one well-known problem with SIC is its sensitivity to the cancellation order of the interfering signals. A detection error for a specific symbol propagates to the detection of the remaining symbols [2]. This observation motivated the research on power allocation schemes for SIC. The aim is to allocate the available power to the transmitted symbols in such a way that the errors in the decoding chain are minimized. This research avenue was studied thoroughly in the context of CDMA that is inherently a multiple access scheme based on interfering transmissions [5], [6]. Considering the benefits of SIC in a network setting seems a more promising avenue but only a few works consider this possibility. In [7] the authors considered link scheduling in a network setting so that SIC is optimized with respect to the decoding order of the interfering signals. In [8] the authors studied jointly the problem of power allocation at the sources and interference avoidance. With this scheme, SIC is used on-demand and when it is optimal while interference is avoided by orthogonalizing channel access.

In this paper we aim at a different approach towards improving the performance of SIC in a network. Our idea is based on the observation that in a wireless network there are potentially several other nodes that may overhear the interfering signal (Fig. 1). If these nodes are willing to cooperate, then they can forward the locally received interfering signal to the destination. In this context we want to improve interference cancellation at the destination by identifying the optimal relay for forwarding the locally received interfering signals. Our approach is completely reactive in the sense that we improve the performance of SIC after the two transmissions interfere. Thus, we envision that our scheme may also be employed as a mechanism to recover from collisions when channel access in normally orthogonalized.

Selecting the best node/relay for forwarding a signal is on its own an important problem in the context of cooperative systems. In [9], [10] the authors propose simple protocols for optimal relay selection that are able to achieve full diversity in fading channels. For cooperative networks that employ physical layer network coding (interfering signals) the problem of relay selection was studied in [11]. For multi-source multi-destination networks the problem of relay selection was considered in [12]. In that work the authors focused on power allocation schemes for a single relay shared between many sources. In [13] the authors considered relay selection and power allocation in a two-hop multi-source multi-destination mesh network where fixed relay nodes use the decode-and-forward protocol. One recent interesting work that considers SIC for a relay network, but for a system with full channel state information (CSI) and beamforming, can be found in [14].

The contributions of this paper are the following: First, we propose distributed relay selection as the means to improve SIC. A single relay node is selected to amplify and forward the locally received interfering signals. Second, we investigate different relay selection policies depending on channel state information (CSI) availability at the relays and the performance optimization objective.

II. System Model and Assumptions

In this paper we consider a network model where two sources S_1, S_2 simultaneously transmit over the wireless channel. A set $\mathcal{R} \triangleq \{R_1, R_2, ..., R_M\}$ of M nodes overhear the transmissions from the sources and are willing to help as relays. The relay that will forward the interfering signals to the destination node is selected in a distributed fashion as we will describe later in this paper. In Fig. 1 we present the network topology that we study in this paper and it includes the sources, the relays, and the destination. Every node has a single omni-directional antenna that can be used in half-duplex mode for transmission and reception while all nodes have the same average power constraint. We denote the complex channel gain from the s-th source to the r-th relay as $h_{s,r}$, and the channel from the r-th relay to destination d 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. Source s transmits at a power level of P_s Watts. All the channels, from sources to relays and relays to destination are considered to be block-fading Rayleigh. The channel coefficients are quasi-stationary, that is they remain constant for the coherence period of the channel for each source/relay and relay/destination pair. Additive white Gaussian noise (AWGN) is assumed at the relays and the destinations with zero mean variance σ_r^2 and σ_d^2 respectively.

One common assumption in communication systems is that CSI is available at the receiving end of a communication link (CSIR). This assumption is generally valid in real life scenarios since this information can be obtained easily through preambles or pilots. In our setup, the observation leads to the conclusion that CSI for the channels formed between the sources and the relay can be assumed to be readily available at the respective relay. Similarly, the destination can also have knowledge of the channel from the relays to the destination. Channel state information at the transmitter (CSIT) is also possible to be obtained for each relay-destination link under the channel reciprocity assumption. We also develop relay selection policies for this last case where CSIT is also available at each relay.

III. Basic System Operation with a Single Relay

According to the basic communication setup we described in the previous section, the destination will receive a signal from the selected relay. When the destination receives this signal it calculates the power of the signals from the two sources through packet preambles. Assume now that the signal from S_1 has the highest power at the destination. Then we apply ordered SIC, and so the signal from S_1 will be decoded first. At the destination the SNR for the signal from S_1 is

$$\mathrm{SNR}_{1,r,d} = \frac{P_1 g_r^2 |h_{r,d}|^2 |h_{1,r}|^2}{g_r^2 |h_{r,d}|^2 (P_2 |h_{2,r}|^2 + \sigma_r^2) + \sigma_d^2}, \tag{1}$$

where g_r^2 is the necessary power scaling at the relay. With the assumption of perfect SIC with no error propagation, the signal from S_1 is completely removed from the aggregate. This leads to the following result for the SNR of S_2:

$$\mathrm{SNR}_{2,r,d} = \frac{P_2 g_r^2 |h_{r,d}|^2 |h_{2,r}|^2}{P_r |h_{r,d}|^2 \sigma_r^2 + \sigma_d^2} \tag{2}$$

Thus, S_2 is left to combat only the amplified noise introduced at the relay and the noise at the destination.

The previous description of our system considers the actions taking place at the final destination that decodes the information. However, at the relays the signals are received at different power levels. For a distributed system like the wireless network we consider, this means that there is no information exchange between the network nodes and in particular between the relays. Thus, each relay will only know the local power levels of the interfering signals. Assuming again that the signal from S_1 is stronger than S_2 then the relay r estimates locally the SNR for each signal if SIC was applied locally:

$$\mathrm{SNR}_{1,r} = \frac{P_1 |h_{1,r}|^2}{P_2 |h_{2,r}|^2 + \sigma_r^2}, \quad \mathrm{SNR}_{2,r} = \frac{P_2 |h_{2,r}|^2}{\sigma_r^2} \tag{3}$$

What these expressions mean is that the values of $\mathrm{SNR}_{1,r}$ and $\mathrm{SNR}_{2,r}$ are different at each relay r. Thus, in our system relay selection offers a control knob for adjusting the final SNR of the two signals at the destination. This is the main observation that we exploit in the next section.

IV. Relay Selection Policies

A. SIC-Aware Relay Selection for Outage Optimization

For the first system configuration we consider that each source desires to communicate at a rate of R bps. Each source applies an AWGN capacity-achieving code of R bps. In our system we desire to minimize the probability that both users are simultaneously in outage. If the signal from relay r is forwarded, the probability of the aforementioned event at the destination is equal to:

$$p_{out}(r,R) = \Pr\left\{ \mathrm{SNR}_{1,r,d} < 2^R - 1, \mathrm{SNR}_{2,r,d} < 2^R - 1 \right\} \quad (4)$$

Thus, if the effective post-processing SNR that a cooperative protocol can achieve for a specific source is increased, this will lower the outage probability for that specific source. By observing (4) we see that our in order to minimize this probability we must ensure that at least one source can be decoded. That is we have to maximize the maximum post-processing SNR regardless of the specific source. The optimal relay selection policy can be obtained from (1), (2) and (4). Under the assumption of CSIT at the relays we have that this policy is:

$$r^* = \arg\max_{r\in\mathcal{R}} \left\{ \max\left(\mathrm{SNR}_{1,r,d}, \mathrm{SNR}_{2,r,d}\right) \right\} \quad (5)$$

This is a policy that ensures the minimization of the outage probability metric defined in (4) in a slow fading channel. Our relay selection policy can also be defined when CSIT is not available at the relay (without knowing $h_{r,d}$), and in this more challenging case the relays use the local knowledge regarding which source signal is stronger:

$$r^* = \arg\max_{r\in\mathcal{R}} \left\{ \max\left(\mathrm{SNR}_{1,r}, \mathrm{SNR}_{2,r}\right) \right\} \quad (6)$$

In the above the SNR expressions are obtained from (3). The throughput-optimal policy without the channel coding assumption is different for slow fading channel as we will see next.

B. SIC-Aware Relay Selection for Throughput Optimization

Next we investigate a different objective. We now seek to maximize the sum throughput that the complete system experiences. Thus, instead of using the outage probability again as the performance metric, we consider an aggregate throughput formula. Since we consider optimal AWGN channel coding in the previous case, in this system configuration uncoded transmission takes place. The result can be easily generalized when the error correcting capability of the code is considered together with the reduction in the effective throughput.

For this new objective we have to consider the bit error rate (BER) and the resulting normalized throughput for both sources. For packets with length L bits and under BPSK modulation the instantaneous throughput is equal to

$$\begin{aligned} T(r)_{|P_1|h_{1,r}|^2 > P_2|h_{2,r}|^2} &= (1 - Q(\sqrt{2\mathrm{SNR}_{1,d}^{SIC}}))^L \\ &+ (1 - Q(\sqrt{2\mathrm{SNR}_{2,d}^{SIC}}))^L \end{aligned} \quad (7)$$

where $Q(\cdot)$ is the Gaussian Q function. Note that the normalized throughput above is conditioned on the event that the signal from source 1 is stronger that the signal from source 2.

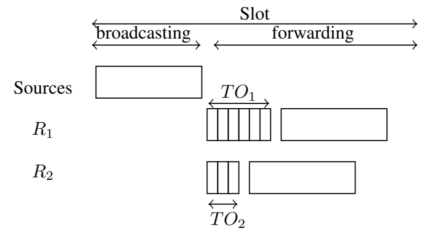


Fig. 2. Channel access from the relays based on a timer.

The policy that we propose can be directly derived from (7) by selecting the best relay that maximizes this expression. Thus, the *SIC-aware* relay selection policy we propose is:

$$r^* = \arg\max_{r\in\mathcal{R}} \left\{ T(r) \right\} \quad (8)$$

This policy also considers the existence of CSIT at the relay for the channel from the relay to the destination. When we do not know the channel from the relay to destination, this is taken into account with by slightly modifying the previous expressions. In this case because the relays cannot estimate the end-to-end instantaneous T, similarly with our approach in the previous subsection, the relays use the following estimate for the throughput:

$$\begin{aligned} \widehat{T}(r)_{|P_1|h_{1,r}|^2 > P_2|h_{2,r}|^2} &= (1 - Q(\sqrt{2\mathrm{SNR}_{1,r}}))^L \\ &+ (1 - Q(\sqrt{2\mathrm{SNR}_{2,r}}))^L \end{aligned} \quad (9)$$

And then we have that the relay selection policy is:

$$r^* = \arg\max_{r\in\mathcal{R}} \left\{ \max\left(\widehat{T}(r)\right) \right\} \quad (10)$$

C. Enforcing the Relay Selection

The previous relay selection policies may be easily implemented in a centralized fashion but this is not possible if we require distributed operation. We adopt the following simple approach to accomplish this purpose. A relay accesses the channel by setting a specific timer depending on the a scaled rate metric that comes from our previous analysis. In particular this timer is set equal to:

$$TO_r = \left\lfloor \frac{1}{\log_2(1 + \mathrm{SNR}_{1,r})} \right\rfloor \quad (11)$$

Now in the case that the relay has set the timer as described before, the result is that this timer will expire first for the relay that has calculated a higher rate. Fig. 2 depicts this channel access scheme. Note that the duration of the timer is very small relative to the packet duration (a few PHY symbols compared to a few thousand symbols) and that is why we ignore its duration later in our evaluation.

V. Performance Evaluation

Simulation Parameters. We implemented the two proposed *SIC-aware* relay selection (SICRS) policies and we evaluated their performance in terms of the achieved throughput and the outage probability under different channel conditions through Monte Carlo simulations. We also implemented the source power allocation (SPWR) algorithm [5], where the transmission power levels for the two sources P_1 and P_2 are optimized numerically so that SIC performance is maximized. As a baseline system we also consider a typical SIC setup. The topology of Fig. 1 was used and in all the tested systems and in every system one relay transmits to the single destination. Different numbers of available relays were considered. We present the averaged results for 2000 packet transmissions that have a length of 1000 bits while BPSK modulation was used. A Rayleigh quasi-static block-fading wireless channel model was employed. Furthermore, we also assume that the noise over the wireless spectrum is AWGN with the variance of the noise to be 10^{-9} W/Hz. The channel gains between the nodes vary independently but they are characterized by the same average transmit SNR ($P_1/\sigma_d^2 = P_2/\sigma_d^2$).

Results. First we considered throughput optimization. Results for a packet length of 1000 bits can be seen in Fig. 3(a). We see that SPWR with SIC performs best when the transmit SNR is below 25 dB. With our SICRS scheme, a single relay forwards the interfering signal from the two available relays nodes ($M = 2$). This approach is better when the transmit SNR has a relatively high value as we can observe. However, recall that the transmitted bitstreams do not use channel coding which means that they under-perform in the lower SNR regime. Nevertheless, the results for SICRS are considerably better than using SIC on its own and they even approach the performance of SPWR at the benefit of no average channel CSIT requirement.

Next we present results for different configurations of the SICRS system and again a packet length of L=1000 bits in Fig. 3(b). In this case our proposed *SIC-aware* relay selection policy can out-perform SPWR that we presented in the previous figure as the number of available relays is increased beyond $M = 2$. This behavior of SICRS leads to one of the main points that we want to communicate in this paper. That is power allocation for SIC can indeed provide performance gains for SIC, but a more coarse "power allocation" is possible to be exercised through relay selection and it is also very effective. *More specifically instead of configuring the precise power level at the source, we exploit the channel's intrinsic behavior that randomly sets the received signal power levels through fading*. When CSIT is available at the relays for their respective channel towards the destination, we observe that the performance of SCIRS is as expected even better. The reason is that the end-to-end BER and packet loss rate can be estimated better through (9). Also it is interesting to note that the performance of a system with $M = 3$ available relays and CSIR, is almost similar to the performance of a system that has fewer available relays ($M = 2$) but requires CSIT. Thus, our framework offers two potential ways for optimizing the performance of SIC, either by focusing on obtaining better CSIT or by recruiting more available relays.

Next we consider outage minimization that corresponds to a system that employs channel coding at the sources. When the optimization objective is outage minimization, the results

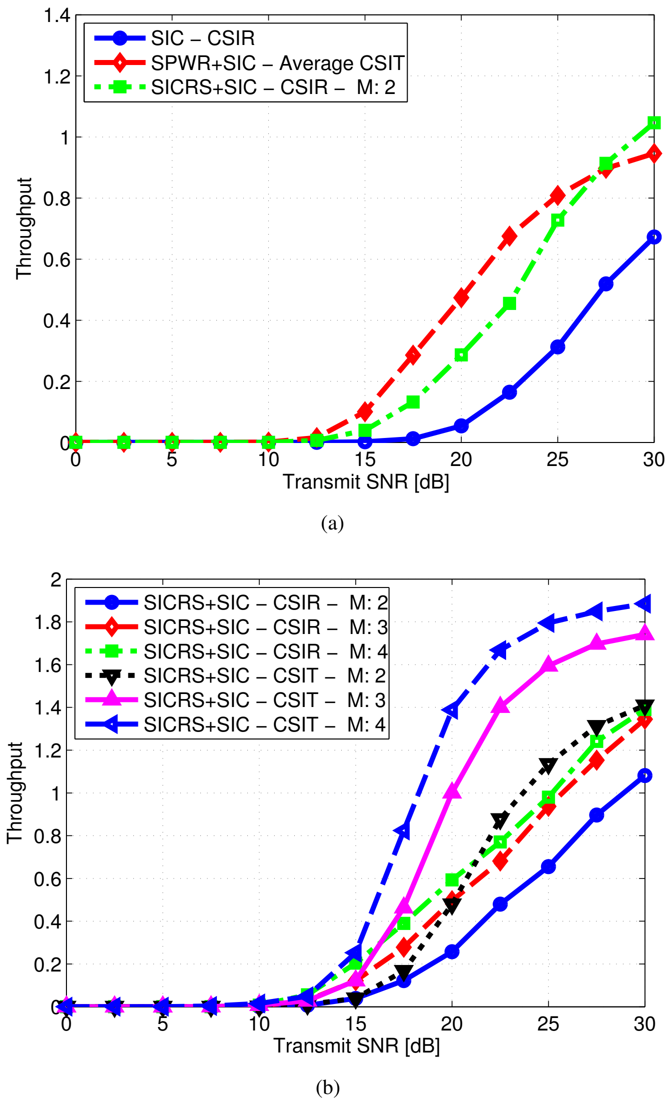
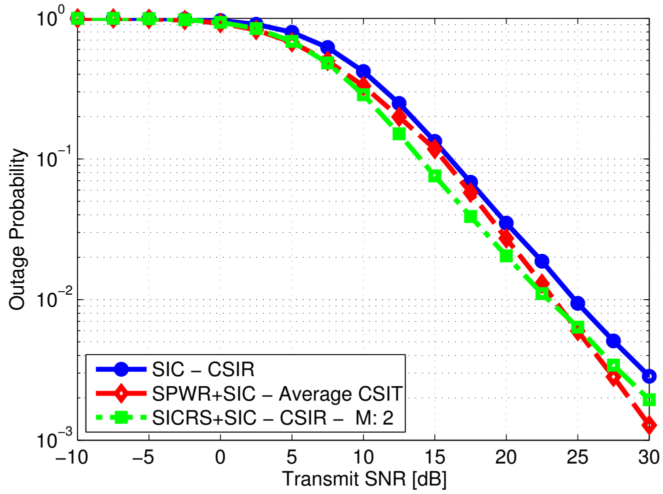
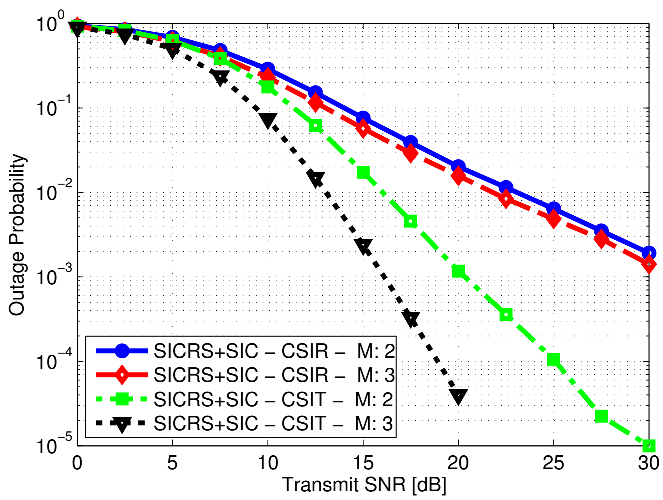


Fig. 3. Results for throughput optimization.

are different in the sense that the optimal policy in this case is to maximize the maximum SNR at the receiver. The results depicted in Fig. 4(a) show that the outage probability is nearly the same for all the schemes. Thus, with channel coding SICRS even with $M = 2$ available relays approaches and even surpasses the performance of SPWR. This means that channel coding also works in favor of SICRS. Again, the advantage of the SICRS scheme is that it only requires CSIR at the receiving end while SPWR requires average SNR at the sources in order to optimally allocate the available power. In Fig. 4(b) we present results for SICRS and the case of higher number of available relays, and CSIT availability at the relays. When a third relay is available we have minor performance improvement, that is however better than SPWR that we observed in the previous figure. The results clearly show the having CSIT at the relay is more important in this case when compared to throughput optimization.



(a)



(b)

Fig. 4. Results for outage optimization.

VI. Conclusions

In this paper we proposed relay selection as a useful technique to improve SIC at a destination in a two-hop two-source multi-relay network. Distributed relay selection seems to offer a coarse way of adjusting the power levels of the signals that are used for SIC. This is contrary to fine-tuning that is possible when employing power allocation at the transmitting sources. Simulation results for several configurations of the proposed scheme showed significant performance gains over power allocation. This suggests that a *SIC-aware* relay selection approach can be a viable option for improving SIC. There is still considerable future work that includes a performance analysis of our scheme and its evaluation for larger number of simultaneously cancelled users.

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