Relay-Assisted Spectrum and Infrastructure Sharing between Multiple Operators

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Abstract: Relay-assisted physical resource sharing has the potential to improve the spectral efficiency, enhance the coverage, and decrease the expenditures for operators. By sharing the infrastructure (relay) and the spectrum, a new type of interference is created on the physical layer. Handling the interference demands novel physical layer techniques that are investigated in SAPHYRE project. In this paper, we describe three relay sharing examples where the spectrum and the infrastructure (relay) are shared between multiple operators and introduce initial physical layer solutions. The first example considers a DS/CDMA system and studies the resource allocation problem using a game theory approach. The results show that the proposed approach can achieve a significant gain in a heavily loaded system. The second one deals with a MIMO system and introduces a sub-optimal transmit strategy inspired by the interference channel. Numerical results demonstrate that the proposed approach results in significant gains in terms of sum rate compared to an exclusive assignment of the resources. The last case is inspired by wireless network coding and shows the hierarchical exclusive code (HXC) design of a 2-source relay network.

Keywords: Interference relay channel, spectrum and infrastructure sharing, DS/CDMA, game theory, block diagonalization, wireless network coding

1. Introduction

Coverage in wireless cellular networks is an important user-centric performance factor. In order to support cell-edge users with high-data rate services under agile frequency reuse there are several options for service providers and operators. One possibility is to install new small base stations and reduce cell sizes. This leads to femtocells which offer significant advantages for next-generation broadband wireless communication systems [1]. Another approach is to install additional relay stations at certain points in the existing cellular infrastructure [2] to improve coverage by assisting cell edge users in their multiple access attempt to the base station.

Cooperative communications is proposed to improve the reliability in wireless communications [3]. There, multiple wireless devices (possibly user terminals) help each other by relaying messages for each other [4]. In a cellular context, the relay stations are dedicated to assist communications, they do not move and they do not need an artificial incentive for helping the mobile terminals.

In this work, we consider a relay-assisted interference channel (IFC), in which multiple terminals simultaneously use one relay to transmit their data to separate receiver nodes. Figure 1 shows two possible system models that are considered in the framework of the SAPHYRE project where spectrum and infrastructure sharing between multiple operators are investigated. In a cellular context, this
models the case in which one relay assists mobiles from different operators to communicate with their separate base stations. This is an example of spectrum and infrastructure sharing since the relay and the spectrum are used by multiple operators.

![Figure 1: Multi-operator interference relay channel: each operator has one transceiver pair. Different colors stand for different operators. Left: K operators share a relay that uses an amplify and forward (AF) relaying strategy. Right: 2 operators shares a relay that uses a hierarchical decode and forward (HDF) relaying strategy.](image)

Three different aspects of this sharing scenario will be investigated throughout the paper. In the first place the achievable minimum square error (MSE) performance of a relay assisted IFC applying the amplify-and-forward strategy will be analyzed in terms of a two-level Stackelberg game given the relay amplification matrix $A$. Then different techniques to design such a matrix and its impact on the sum rate and sharing gain of the overall system are discussed. Finally, the hierarchical decode-and-forward strategy such as the design of corresponding modulation alphabets will be introduced and fundamental limits will be discussed.

## 2. Relaying Techniques for Physical Resource Sharing

### 2.1 Game theory based resource allocation

First, we study the achievable MSE performance of a relay assisted IFC in which the mobiles act selfishly to find their signature sequences, while the relay determines its amplify-and-forward strategy based on a system wide utility function [5]. The conflict situation is modeled as a two-level Stackelberg game in normal form [6], with the relay as the leader, and the non-cooperating terminals as followers.

The system model under investigation is shown in Figure 1(a). We consider DS/CDMA with processing gain $N$. Assuming flat fading, each node has a single antenna and there is no direct link between the $k$th transceiver pair. The discrete-time signal received by the relay in each symbol interval, is the received vector

$$y_r = \sum_{k=1}^{K} \sqrt{P_k} h_k b_k s_k + n_r \quad (1)$$

of dimension $N$, where $P_k$, $b_k$, and $s_k$ are the transmit power, the unit-modulus information symbol, and the unit-norm spreading code of the $k$-th user, respectively; $h_k$ is the channel gain between the $k$-th user and the relay, modeled as a standard complex white Gaussian process; $n_r$ is the thermal noise at the relay, a zero-mean white Gaussian process with variance $\sigma^2$. Further, $s_k$ and $n_r$ are assumed to be independent for all $k$.

At the relay, the received signal is first normalized by $\sqrt{P_t}$, where $P_t = E[\|y_r\|^2]$. Then, the received vector is linearly processed by the matrix $A$ with power constraint $\text{tr}(A^H A) = N^2$, and finally it is forwarded to the $K$ terminals.
We assume that each transmitter is interested in communicating with just one of the IFC terminals, and therefore we can denote each transmitter-receiver link by the same index $k$. Then, considering the case when a direct link between transmitters and receivers is not available, and assuming a flat fading channel between the relay and the receivers, the signal received by the $k$-th receiver, is

$$y_k = g_k A y_r + n_k \quad (2)$$

where $g_k$ accounts for the power normalization term $P_t$, and for the channel gain between the relay and the $k$-th receiver, modeled as a complex white Gaussian process. Moreover, $n_k$ is the thermal noise at the receiver, a zero-mean white Gaussian process with variance $\sigma^2$. Let $R_k$ be the covariance matrix of the received data vector at the $k$-th receiver.

In the sequel the problem of non-cooperative spreading code and linear receiver choice for individual MSE minimization, and the problem of relay matrix design for global MSE minimization will be addressed from a game-theoretic point of view. The resource allocation process is assumed to take place in a hierarchical way. First, the relay chooses its amplify-and-forward matrix, and announces it to all users. Then, the multiple access users non-cooperatively react to the relay’s choice by selfishly choosing their spreading codes and linear receive filters. This decision-making process is well-modeled by a two-level Stackelberg game. We will focus on the non-cooperative game that is played by the multiple access users after the relay matrix $A$ has been announced, and then we will turn to the problem of optimum relay matrix design.

2.1.1 Non-cooperative MSE minimization

We now address the problem of the optimal spreading code and receive filter choice for non-cooperative, individual MSE minimization in a relay-assisted IFC, given the relay matrix $A$. We assume each transmitter to know $P_k$, $h_k$ for all $k$. However, we do not assume the coefficients $\{g_k\}_{k=1}^K$ to be known by the users. This is a typical situation in the considered amplify-and-forward relay-aided system, where no direct link between transmitters and receivers is present. Each player wants to minimize its MSE with respect to its transmit spreading code $s_k$, and the corresponding receive linear filter $c_k$. With $u_k = \text{MSE}_k$ the $k$-th player’s utility function, its best response is given as

$$\arg \min_{s_k, c_k} u_k(s_k, c_k). \quad (3)$$

Assuming a linear receive filter $c_k$ is used, the mean square error for user $k$ is

$$\text{MSE}_k = 1 + c_k^H R_k c_k - 2 \cdot \text{Re} (g_k \sqrt{P_k} h_k c_k^H A s_k). \quad (4)$$

The minimization of (4) with respect to $c_k$ yields the MMSE receiver $c_k = g_k \sqrt{P_k} h_k R_k^{-1} A s_k$. The minimization with respect to $s_k$ leads to $s_k/\|s_k\| = A^H c_k/\|A^H c_k\|$

For $d_k = A^H c_k$ we obtain the best response dynamics for all $k = 1, \ldots, K$ as

$$d_k = g_k \sqrt{P_k h_k A^H R_k^{-1} A s_k}, \quad s_k/\|s_k\| = d_k/\|d_k\|. \quad (5)$$

2.1.2 Numerical results

In this part we present numerical results to confirm the merits of the proposed resource allocation policies. In our simulations we considered a DS/CDMA system with processing gain $N = 32$, and we compare three different systems with linear MMSE reception with: (i) spreading code optimization, and relay matrix optimization; (ii) spreading code optimization, and relay matrix set to $A = \sqrt{N} I_N$; (iii) random spreading codes, and relay matrix set to $A = \sqrt{N} I_N$. With $P_{\text{max}}$ being the maximum feasible transmit power for all users, and we have chosen $P_k \in [0; P_{\text{max}}]$ randomly and have defined $\text{SNR} = P_{\text{max}}/\sigma^2$. Further, with $H$ and $G$ being random variables modeling the channel complex gains $h_k$ and $g_k$, we define $\alpha^2 = E[|G|^2/|H|^2]$. In the simulations we set $\alpha = 10^{-2}$.
In Figure 2 we consider a system with $K = 22$ and $K = 12$ users respectively, and plot the system’s total MSE (TMSE) normalized with respect to the number of users, versus the SNR. As expected, comparing the system with spreading code optimization and that with random spreading codes, we see that a large gain is obtained when $K = 22$. Indeed, in this case we have a high network load, and therefore the system employing random spreading codes is impaired by a large multiuser interference, whereas in the system employing optimized spreading codes multiuser interference is completely suppressed thanks to the orthonormality among codes. Obviously, when the load of the network is lower, spreading code optimization achieves a lower gain with respect to the case of random spreading codes. On the other hand, contrasting the system with optimum relay matrix choice, to that without relay optimization, we get an opposite behavior. This is also expected, since setting the relay matrix to the identity means that we are giving the same amount of power to all of the $N$ eigenvalues of $A$, whereas the TMSE is affected by only the $K$ largest eigenvalues of $A$. Therefore, the lower $K$ is, the more power is wasted by setting $A = \sqrt{N}I_N$.

### 2.2 Beamforming techniques for single relay sharing

In this section, we present one relay assisted communication scenario where two independent transceiver pairs belonging to two operators use one relay to unidirectionally exchange information using the same spectrum. All terminals as well as the relay have multiple antennas and operate in half-duplex mode. A simple initial proposal which is inspired by the IFC is demonstrated in the following.

The system model is shown in Fig. 1(a) with $K = 2$, where two transmitters (TXs) transmit data to their target receivers (RXs) with the assistance of a shared relay. In this work, a one-way relaying protocol with an amplify and forward strategy is applied at the relay. The TXs and RXs of the $i$th operator are equipped with $M_{T,i}$ and $M_{U,i}$ antennas respectively, where $i \in \{1, 2\}$. The relay has $M_R$ antennas. The channel is flat fading. We assume that a single data stream per UT is transmitted.

The transmission process is divided into two phases. During the first phase, both TXs transmit to their desired RXs and the relay. The received signal at each RX and the relay is

$$y_i^{(1)} = H_{ii}f_is_i + H_{ji}f_js_j + n_j^{(1)},$$
$$y_R = H_{1R}f_is_1 + H_{2R}f_2s_2 + n_R,$$

where $i \in \{1, 2\}$ and $i \neq j$. The precoder at each TX is $f_i \in \mathbb{C}^{M_{T,i} \times 1}$ and the transmitted data signal is $s_i$. In the second phase, all the TXs remain silent and the relay amplifies the received signal $y_R$ and forwards it to the RXs. The signal received at the RXs during phase 2 are given by

$$y_i^{(2)} = \gamma_0H_{R,i}Ay_R + n_i^{(2)},$$
where $A \in \mathbb{C}^{M_R \times M_R}$ is the relay amplification matrix and $\gamma_0 \in \mathbb{R}^+$ is chosen such that the transmit power constraint at the relay is fulfilled. For simplicity, $\gamma_0$ is calculated via the approximation $\|\gamma_0 F_{RR} H^M R\|^2 \approx \gamma_0^2 (M_{T,1} M_R P_{T,1} + M_{T,2} M_R P_{T,2} + M_R \sigma_n^2) = P_{T,R}$, where $P_{T,R}, P_{T,1}$ and $P_{T,2}$ are the transmit power of the relay, of $TX_1$, and of $TX_2$ respectively. Applying the linear receive filters $w_i^H$ and $w_j^H$ at each RX, we finally get the received signals

$$y_i = w_i^H \left[ \gamma_0 H_{R,i} A H_{iR} H_i \right] f_i s_i + w_i^H \left[ \gamma_0 H_{R,i} A H_{jR} G_i \right] f_j s_j + w_i^H \left[ \gamma_0 H_{R,i} A n_{R} + n_i^{(1)} \right] e_i + n_i^{(2)},$$

where $n_i^{(1)}$, $n_i^{(2)}$ and $n_R$ contain independent, identically distributed additive white Gaussian noise samples with the variance $\sigma_n^2$. If the relay amplification matrix $A$ is known, the system model can be simplified to a classical two-user IFC based on the equivalent channels $H_1, H_2, G_1$, and $G_2$. Thus, we propose a two-step procedure. In the first step, the interference relay channel is converted to the conventional interference channel by choosing a specific relay amplification matrix. Then, in the second step, arbitrary transmission techniques for the IFC channel can be applied. In our work, we use an algorithm based on flexible coordinated beamforming [7].

To design the relay amplification matrix $A$, we have investigated five algorithms which are inspired by well-known two-way relaying strategies, i.e., the algebraic norm maximization (ANOMAX) algorithm [8] and the discrete Fourier Transform (DFT) matrix in [8], the dual channel matching (DCM) in [9], and the ZF and the MMSE method in [10].

After the design of $A$, all the equivalent channel matrices $H_i$ and the interference matrices $G_i$ can be estimated from the downlink dedicated pilot transmission. Then the relay assisted IFC corresponds to a conventional IFC model. We assume that $H_i$ and $G_i$ are available at the TXs.

For designing $w_i$ and $f_i$, we propose a method called flexible coordinated beamforming for the interference relay channel (IRC FlexCoBF). The original FlexCoBF algorithm [7] has been designed to iteratively suppress the inter-user interferences on the downlink of multi-user MIMO systems, which utilizes either block diagonalization (BD) [11] or regularized block diagonalization (RBD) [12] at the transmitter combined with MRC at the receiver. Inspired by this idea, we have derived a method suitable for the IRC, i.e., IRC FlexCoBF BD and IRC FlexCoBF RBD. The IRC FlexCoBF RBD converges to IRC FlexCoBF BD in the high SNR region while it outperforms BD at low SNRs due to the regularization.

![Figure 3: Multi-operator interference relay channel: we compare the sum rate of proposed algorithms in uncorrelated Rayleigh fading for $M_{T,i} = M_{U,i} = M_R = 2$. Left: Sum rate of the interference channel. Right: Sum rate of the interference relay channel.](image_url)

To compare the performance of the proposed beamforming matrix design, we consider an uncorrelated Rayleigh fading channel and set $M_{T,i} = M_{U,i} = M_R = 2$. The transmit power of the TXs is
\[ P_{T,1} = P_{T,2} = P_T \] and the SNR is defined as \[ P_T / \sigma_n^2. \]

Now we choose IRC FlexCoBF RBD as the precoder at the TXs. The sum rates of different relaying strategies are compared in Fig. 3(a). We observe that all the proposed AF relay precoders almost give the same sum rate, of which ANOMAX performs slightly better than others. With respect to the complexity consideration, we propose to use the DFT as the relay amplification matrix and use it in the following simulations.

We refer to the ratio of throughput (TP) \( TP_{IRC} / TP_{RC} \) as the sharing gain due to the use of the shared relay instead of accessing the relay in a TDMA mode. This sharing gain of the IRC over the RC is shown in Fig. 3(b), where IRC FlexCoBF and Eigen are applied at the TX for the IRC and the RC, respectively. It can be seen that the IRC utilizing either IRC FlexCoBF RBD or IRC FlexCoBF BD provides a sharing gain over RC which uses the relay exclusively. For IRC FlexCoBF BD, the sharing gain becomes larger as the SNR increases. When IRC FlexCoBF RBD is applied, there is even an improvement at low SNRs due to the regularization of RBD. This shows that relay sharing is more advantageous compared to the exclusive use of the infrastructure resources (i.e., the relay in the considered scenario).

2.3 Wireless Network Coding with Hierarchical Decode and Forward Strategy

2.3.1 Background And Related Work

Multi-node and multi-source wireless communication scenarios are currently under heavy investigation in the research community. Generally, these can be seen as similar to the Network Coding (NC) paradigm which has a great potential to increase the throughput of complicated communication networks. An extension of NC principles into the wireless (signal space) domain is however non-trivial [13].

Limited code design and capacity region results are available for the simplest possible scenario of the 2-Way Relay Channel (2-WRC). The authors of [14] concentrate on the distance optimization of the relay hierarchical mapping regions as a function of the channel parametrization. Lattice code-based constructions usually do not consider an impact of the channel parametrization. The results of this paper are also based on our earlier work [15], [13].

2.3.2 Concept of Sharing PHY Layer in Multi-Source and Multi-Node Networks

In a general multi-source and multi-node communication network all network nodes (relays) contribute to providing data flows without an explicit routing. It can be described as a flood of the information having different “colors” (from individual sources) at the inputs. The network processes the “rainbow” mixture-color not distinguishing individual sources. The destinations pick a particular “color” from the received flood with the help of various forms of the available side-information. Since the mixture-data flow represents jointly (but not necessarily individually distinguished) data streams, we call those data as hierarchical data and corresponding relay processing as a hierarchical decode and forward (HDF) relay strategy [13]. The simplest particular network example capable of demonstrating some related general concepts is the 2-Source Relay Network (Fig. 1(b)).

2.3.3 Layered design of HDF

We show that Hierarchical eXclusive Code (HXC) for HDF relaying strategy can be designed in a layered manner. The inner layer guarantees the exclusive law and the outer layer provides the capacity achieving properties. The layered design stands on the results presented in [13].

2.3.4 Fundamental limits

Fig. 4 shows comparisons of the hierarchical symmetric capacity with various channel parametrizations with the alphabet constrained cut-set bound (both first and second order bound) and the unconstrained AWGN cut-set bound capacity. We see that HXA outperforms the classical C-MAC capacity second order cut-set bound (sum-rate per user) and closely approaches the first order cut-set bound.
Figure 4: A comparison of capacities $C_{AB}$, $C_0$, $C_s$, $C_{HBC}$ for BPSK alphabet and various channel phase parametrizations.

Figure 5: Hierarchical minimum distance of QPSK and the proposed 4-ary alphabet.

for medium to high signal to noise ratios. This means that the 2-WRC behaves at the MAC stage as if there was just one user alone. However, the performance is strongly affected by the choice of constellations [13].

2.3.5 Parametric design

The unavoidable channel parametrization in 2-WRC can have a dramatic effect on the overall system performance. The undesirable effects of channel parametrization are observed in an analysis of hierarchical minimum distance [16]. To avoid the adverse parametrization we propose design of suitable modulation alphabets in $\mathbb{C}^2$ [17] and an optimization of multidimensional Frequency Shift Keying (FSK) modulation [18]. Fig. 5 presents the comparison of the proposed alphabet versus classical linear modulation.

3. Conclusions

This paper summarizes three novel physical layer concepts related to the relay-assisted communications models, where the spectrum and the infrastructure (relay) are shared between multiple operators. The first proposal introduces a novel spreading code and relay amplification design in a DS/CDMA system. By using a game theoretic approach, a large gain can be obtained when the system is heavy
loaded with multiple operators. The second proposal develops a sub-optimal transmit strategy in a wireless system where the relays and other nodes have multiple antennas. The numerical results demonstrate that a significant sharing gain is achieved in terms of the sum rate using the proposed beamforming design inspired by the interference channel. The third concept proposes to use WNC principles to investigate the 2-source relay network. It introduces a HDF relaying strategy and shows that the hierarchical exclusive code for the HDF relaying strategy can be designed in a layered manner.

References


