

# OPTIMAL SPECTRUM LEASING AND NETWORK BEAMFORMING FOR TWO-WAY RELAY NETWORKS

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## ABSTRACT

We propose a resource sharing scheme between a primary pair (which owns the spectrum resources) and a secondary pair (which owns a relay infrastructure) in a collaborative manner. The secondary network allows the primary pair to use the relays in order to establish a bidirectional communication between its transceivers. In exchange for this cooperation, the primary pair assigns a portion of its spectral resources to the secondary pair, thereby enabling a two-way communication between the secondary transceivers. Assuming an amplify-and-forward relaying scheme, the relays collectively build two network beamformers, each of which enables communication between the two transceivers in one pair. We propose a max-min optimization problem to calculate the two network parameters in semi-closed forms.

**Index-Terms:** Two-way relaying, resource sharing, network beamforming, distributed beamforming, spectrum leasing.

## 1. INTRODUCTION

A two-way relay network consists of two transceivers and a network of distributed relays which collaborate to establish a bidirectional communication between the two transceivers. The two transceivers exchange their information symbols through the relays by employing amplify-and-forward (AF) relaying protocol. Based on different design criteria, numerous two-way relay techniques have been studied in the literature, [1–5]. However, the problem of spectral, temporal and, relay resource sharing between two or multiple networks with different priorities has yet to be studied in depth.

The problem of multiuser two-way communication between multiple transceiver pairs has been studied in [6–8], where the problem of interference management is addressed without assuming any priority between different pairs. In [9, 10], the problem of resource sharing is studied for the case where a high-priority source-destination pair and multiple low-priority source-destination pairs are to share their resources in a one-way information exchange scheme. The authors of [11] and [12] introduced the concept of spectrum leasing to study the problem of resource sharing between a source-destination pair with high priority and a network of several source-destination pairs with lower priorities. In these studies, the transmitter in each pair aims to establish a one-way communication with its peer receiver.

Unlike, we herein study the problem of optimal resource sharing between two transceiver pairs with different priorities: a primary pair, which owns the spectrum resources, and a secondary pair, which owns a relay infrastructure. We assume that there is no direct link between each of the two transceivers, thereby exchanging information through the relay infrastructure is inevitable. We propose

an optimal collaborative resource sharing scheme between the two network, under a constraint on the primary network rate.

*Notation:*  $E\{\cdot\}$  stands for statistical expectation. Matrices and vectors are represented by uppercase and lowercase boldface letters, respectively.  $(\cdot)^T$  and  $(\cdot)^H$  are, respectively, Transpose and Hermitian (conjugate) transpose operators. The notation  $\mathbf{I}$  denotes the identity matrix,  $\text{diag}(\mathbf{a})$  denotes a diagonal matrix whose diagonal entries are the elements of the vector  $\mathbf{a}$ , and  $\odot$  represents Schur-Hadamard (element-wise) vector product.

## 2. SYSTEM MODEL

We consider a communication scheme comprising of two transceiver pairs and a network of  $n_r$  relay nodes. Assuming that there is no direct connection between the transceivers in each pair, they wish to exchange their information using the relays infrastructures. The primary pair requires a guaranteed minimum data rate between its transceivers. The transceivers in the secondary pair are allowed to communicate with each other using the RF resources of the primary pair for a fraction of the time. In exchange for this cooperation, the primary transceivers are allowed to exploit the secondary network relay infrastructure to achieve a required data rate. The transmission scheme in our model is assumed to be time-slotted with time frames of  $T$  seconds duration. Each time frame is divided into two time intervals, called subframes, where the first subframe is dedicated to the transceivers in the primary pair and the second subframe is leased to the secondary transceivers. We define  $\alpha$  as the portion of the time frame where the primary spectrum is leased to the secondary transceivers.

The primary (secondary) transceivers PTRX<sub>1</sub> and PTRX<sub>2</sub> (STRX<sub>1</sub> and STRX<sub>2</sub>) transmit their information symbols to the relays with transmit powers  $p_1$  and  $p_2$  ( $p_3$  and  $p_4$ ), respectively. Furthermore, it is assumed that the channels are frequency flat. The  $n_r \times 1$  vector of the complex channel coefficients, corresponding to the links between PTRX<sub>1</sub> (PTRX<sub>2</sub>) and the relays, is represented as  $\mathbf{f}_1$  ( $\mathbf{f}_2$ ). Similarly, the  $n_r \times 1$  vector of the complex channel coefficients corresponding to the links between STRX<sub>1</sub> (STRX<sub>2</sub>) and the relays, is represented as  $\mathbf{g}_1$  ( $\mathbf{g}_2$ ). The underlying communication scheme is shown in Fig. 1.

We use the well-known frequency efficient transmission protocol, MABC (for multiple access broadcast channel), along with the amplify-and-forward (AF) relaying scheme, to establish a bidirectional communication between the primary (secondary) transceivers. We assume that all noise components at the relays as well as those at the transceivers are zero-mean independent complex Gaussian variables. The vector  $\mathbf{w}_1$  ( $\mathbf{w}_2$ ) contains the beamforming weights used in the primary (secondary) subframe. Each relay uses its weight

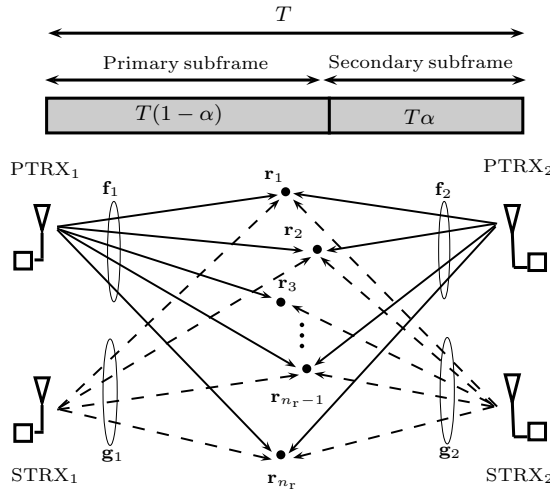


Fig. 1. Sharing resources between two bidirectional relay networks.

to properly adjust the amplitude and the phase of the signal it received in the previous time-slot, and then transmits the outcome to the corresponding transceivers. We emphasize that each transceivers in a pair can cancel the self-interference signal (i.e., a part of the received signal at a transceiver which is a modified version of the signal transmitted by the same transceiver in the previous time slot).

In our design approach, a control channel is needed between the primary and secondary networks for coordination. Moreover, we assume that the knowledge of  $\mathbf{f}_1$  and  $\mathbf{f}_2$  ( $\mathbf{g}_1$  and  $\mathbf{g}_2$ ) is available at both primary (secondary) transceivers. This assumption, is frequently used in the literature on two-way relaying [1–5]. Based on these assumptions, the transceivers in each pair can obtain their corresponding optimal beamforming vectors, cancel their self-interference signals, and decode their corresponding desired information symbols. Using the results of [3], the total power consumed in the primary and secondary subframes are respectively given as

$$\begin{aligned} p_p(p_1, p_2, \mathbf{w}_1) &= p_1 + p_2 + \mathbf{w}_1^H (p_1 \mathbf{D}_1 + p_2 \mathbf{D}_2 + \mathbf{I}) \mathbf{w}_1 \\ p_s(p_3, p_4, \mathbf{w}_2) &= p_3 + p_4 + \mathbf{w}_2^H (p_3 \mathbf{E}_1 + p_4 \mathbf{E}_2 + \mathbf{I}) \mathbf{w}_2. \end{aligned} \quad (1)$$

where we use the following definitions:  $\mathbf{F}_1 \triangleq \text{diag}(\mathbf{f}_1)$ ,  $\mathbf{F}_2 \triangleq \text{diag}(\mathbf{f}_2)$ ,  $\mathbf{G}_1 \triangleq \text{diag}(\mathbf{g}_1)$ ,  $\mathbf{G}_2 \triangleq \text{diag}(\mathbf{g}_2)$ ,  $\mathbf{D}_1 \triangleq \mathbf{F}_1 \mathbf{F}_1^H$ ,  $\mathbf{D}_2 \triangleq \mathbf{F}_2 \mathbf{F}_2^H$ ,  $\mathbf{E}_1 \triangleq \mathbf{G}_1 \mathbf{G}_1^H$ , and  $\mathbf{E}_2 \triangleq \mathbf{G}_2 \mathbf{G}_2^H$ . Note that  $\mathbf{D}_1$ ,  $\mathbf{D}_2$ ,  $\mathbf{E}_1$  and  $\mathbf{E}_2$  are diagonal matrices. Moreover, the received SNRs corresponding to the signals received at PTRX<sub>1</sub>, PTRX<sub>2</sub>, STRX<sub>1</sub> and STRX<sub>2</sub> are respectively given as  $\text{SNR}_1(p_2, \mathbf{w}_1) = \frac{p_2 \mathbf{w}_1^H \mathbf{h}_p \mathbf{h}_p^H \mathbf{w}_1}{\mathbf{w}_1^H \mathbf{D}_1 \mathbf{w}_1 + 1}$ ,

$$\text{SNR}_2(p_1, \mathbf{w}_1) = \frac{p_1 \mathbf{w}_1^H \mathbf{h}_p \mathbf{h}_p^H \mathbf{w}_1}{\mathbf{w}_1^H \mathbf{D}_2 \mathbf{w}_1 + 1}, \text{SNR}_3(p_4, \mathbf{w}_2) = \frac{p_4 \mathbf{w}_2^H \mathbf{h}_s \mathbf{h}_s^H \mathbf{w}_2}{\mathbf{w}_2^H \mathbf{E}_1 \mathbf{w}_2 + 1},$$

$$\text{and} \quad \text{SNR}_4(p_3, \mathbf{w}_2) = \frac{p_3 \mathbf{w}_2^H \mathbf{h}_s \mathbf{h}_s^H \mathbf{w}_2}{\mathbf{w}_2^H \mathbf{E}_2 \mathbf{w}_2 + 1}, \text{ where we use the following definitions: } \mathbf{h}_p \triangleq \mathbf{F}_1 \mathbf{f}_2 \text{ and } \mathbf{h}_s \triangleq \mathbf{G}_1 \mathbf{g}_2.$$

The information theoretic rates of each transceiver is also defined as  $R_i(\cdot, \cdot) = \frac{1}{2} \log(1 + \text{SNR}_i(\cdot, \cdot))$ , for  $i = 1, 2, 3, 4$ . In the next section, we use the proposed data model to design our spectrum leasing scheme.

### 3. SPECTRUM SHARING NETWORK DESIGN

In order to obtain the optimal values for beamforming vectors,  $\mathbf{w}_1$  and  $\mathbf{w}_2$ , the optimal values of the transceiver transmit powers,

$p_1, p_2, p_3$  and  $p_4$ , and the optimal value of the time sharing factor  $\alpha$ , let us consider the following optimization problem:

$$\begin{aligned} & \underset{\{p_i\}_{i=1}^4, \alpha, \mathbf{w}_1, \mathbf{w}_2}{\text{maximize}} \quad \frac{\alpha}{2} \min(R_3(p_4, \mathbf{w}_2), R_4(p_3, \mathbf{w}_2)) \\ & \text{subject to} \quad p_p(p_1, p_2, \mathbf{w}_1) \leq P_p, \quad p_s(p_3, p_4, \mathbf{w}_2) \leq P_s \\ & \quad \frac{(1-\alpha)}{2} \min(R_1(p_2, \mathbf{w}_1), R_2(p_1, \mathbf{w}_1)) \geq \eta \\ & \quad 0 \leq \alpha \leq 1. \end{aligned} \quad (2)$$

In the objective function of (2), the parameter  $\alpha$  emphasize that the secondary transceivers use the channel only  $\alpha$  fraction of the time. The first and second constraints limit the total powers consumed<sup>1</sup> in the primary and secondary subframes, to the corresponding peak powers  $P_p$  and  $P_s$ . The third constraint in (2) is to ensure that the smallest *average* rate of the two primary transceivers are above a given threshold  $\eta$ , while taking into account that these two transceivers are communicating  $(1-\alpha)$  fraction of the time. The threshold  $\eta$  is measured bits per channel use (b/cu). The factor  $\frac{1}{2}$  used in the objective as well as in the primary QoS constraint in (2), implies that the transceivers operate in a half-duplex mode. One can easily show that the primary network QoS inequality constraint becomes equality, otherwise we can choose a larger value for  $\alpha$  than its optimal value such that this constraint is met with equality. However, the new value of  $\alpha$  results in larger value for the objective function. This contradicts the optimality. Hence, we can write  $\alpha = 1 - \frac{2\eta}{\min(R_1(p_2, \mathbf{w}_1), R_2(p_1, \mathbf{w}_1))}$ . It is worth mentioning tha satisfying the constraint  $0 \leq \alpha \leq 1$  leads us to  $\min(R_1(p_2, \mathbf{w}_1), R_2(p_1, \mathbf{w}_1)) \geq 2\eta$ . Replacing the so-obtained  $\alpha$  in the objective function of the optimization problem (2) leads us to the following maximization problem:

$$\begin{aligned} & \underset{\{p_i\}_{i=1}^4, \mathbf{w}_1, \mathbf{w}_2}{\text{maximize}} \quad \frac{1}{2} \left(1 - \frac{2\eta}{\min(R_1(p_2, \mathbf{w}_1), R_2(p_1, \mathbf{w}_1))}\right) \times \\ & \quad \min(R_3(p_4, \mathbf{w}_2), R_4(p_3, \mathbf{w}_2)) \\ & \text{subject to} \quad p_p(p_1, p_2, \mathbf{w}_1) \leq P_p, \quad p_s(p_3, p_4, \mathbf{w}_2) \leq P_s \\ & \quad \min(R_1(p_2, \mathbf{w}_1), R_2(p_1, \mathbf{w}_1)) \geq 2\eta. \end{aligned} \quad (3)$$

Since the constraints as well as the objective function in (3) depend on two mutually exclusive sets of parameters, the optimization problem (3) could be split into the following two separate sub-problems:

#### Sub-Problem 1

$$\begin{aligned} & \underset{p_1, p_2, \mathbf{w}_1}{\text{maximize}} \quad \min(R_1(p_2, \mathbf{w}_1), R_2(p_1, \mathbf{w}_1)) \\ & \text{subject to} \quad p_p(p_1, p_2, \mathbf{w}_1) \leq P_p \\ & \quad \min(R_1(p_2, \mathbf{w}_1), R_2(p_1, \mathbf{w}_1)) \geq 2\eta \end{aligned} \quad (4)$$

#### Sub-Problem 2

$$\begin{aligned} & \underset{p_3, p_4, \mathbf{w}_2}{\text{maximize}} \quad \min(R_3(p_4, \mathbf{w}_2), R_4(p_3, \mathbf{w}_2)) \\ & \text{subject to} \quad p_s(p_3, p_4, \mathbf{w}_2) \leq P_s \end{aligned} \quad (5)$$

The last constraint in Sub-Problem 1 is a feasibility check constraint. We can ignore this constraint, solve the remaining problem, and check if this constraint holds true or not. It has been proven in [3] the problems stated in (4) and (5) lead to SNR balancing. Using the following definitions,  $\Phi(x, y) = 2x\mathbf{D}_1 + (y - 2x)\mathbf{D}_2 + \mathbf{I}$  and  $\Psi(x, y) = 2x\mathbf{E}_1 + (y - 2x)\mathbf{E}_2 + \mathbf{I}$ , it can be shown that the optimal values of the primary and the secondary network parameters are given as

<sup>1</sup>The total power constraint is widely used in the literature [1, 3].

#### Solution to Sub-Problem 1

$$p_1^\circ = \arg \max_{0 \leq p_1 \leq \frac{P_p}{2}} p_1(P_p - 2p_1) \mathbf{h}_p^H \Phi^{-1}(p_1, P_p) \mathbf{h}_p \quad (6)$$

$$p_2^\circ = \frac{1}{2} P_p - p_1^\circ(P_p) \quad (7)$$

$$\mathbf{w}_1^\circ = \kappa(P_p) \sqrt{p_2^\circ(P_p)} \Phi^{-1}(p_1^\circ(P_p), P_p) \mathbf{h}_p. \quad (8)$$

#### Solution to Sub-Problem 2

$$p_3^\circ = \arg \max_{0 \leq p_3 \leq \frac{P_s}{2}} p_3(P_s - 2p_3) \mathbf{h}_s^H \Psi^{-1}(p_3, P_s) \mathbf{h}_s \quad (9)$$

$$p_4^\circ = \frac{1}{2} P_s - p_3^\circ(P_s) \quad (10)$$

$$\mathbf{w}_2^\circ = \mu(P_s) \sqrt{p_4^\circ(P_s)} \Psi^{-1}(p_3^\circ(P_s), P_s) \mathbf{h}_s. \quad (11)$$

where  $\kappa = (\mathbf{h}_p^H (2p_1^\circ \mathbf{D}_1 + \mathbf{I}) \Phi^{-2}(p_1^\circ, P_p) \mathbf{h}_p)^{-\frac{1}{2}}$  and  $\mu = (\mathbf{h}_s^H (2p_3^\circ \mathbf{E}_1 + \mathbf{I}) \Psi^{-2}(p_3^\circ, P_s) \mathbf{h}_s)^{-\frac{1}{2}}$ . It has been proven in [1] and [3] that the maximization problems (6) and (9) are convex in terms of  $p_1$  and  $p_3$ , respectively. We can thus use efficient algorithms, such as interior point methods, in order to solve (6) and (9). Furthermore, the optimum primary and secondary transceivers' instantaneous rates as well as the optimal value of the time sharing factor are, respectively, given by

$$f \triangleq R_1(p_2^\circ, \mathbf{w}_1^\circ) = R_2(p_1^\circ, \mathbf{w}_1^\circ) \quad (12)$$

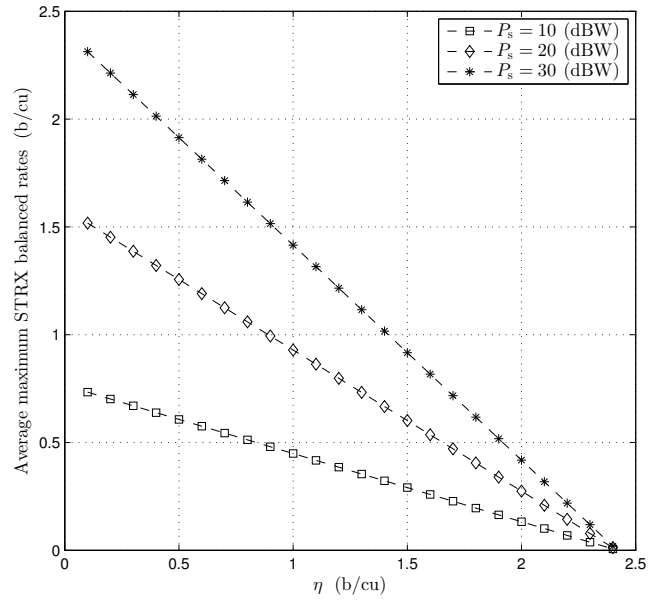
$$g \triangleq R_3(p_4^\circ, \mathbf{w}_2^\circ) = R_4(p_3^\circ, \mathbf{w}_2^\circ) \quad (13)$$

$$\alpha^\circ = 1 - \frac{2\eta}{f}. \quad (14)$$

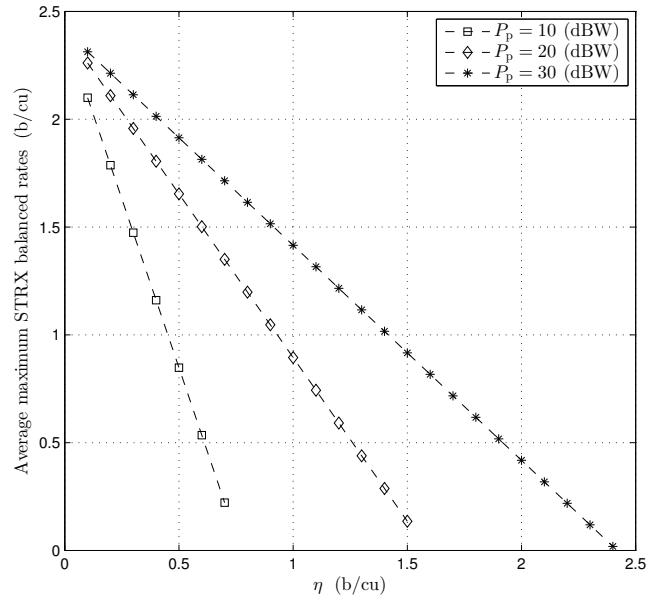
As shown above, the optimization problem (2) can be split into two disjoint sub-problems, hence the primary transceivers do not need to know the secondary CSI to calculate the optimal time sharing factor,  $\alpha^\circ$ . Moreover, the control channel can be employed to broadcast the information that the relays and the secondary transceiver need to set up the connection between themselves. In the first step, the primary transceivers calculate the optimal value of  $\alpha^\circ$  as in (14), and send this value to both secondary transceivers as well as to all the relay nodes. Then, the primary (secondary) transceivers broadcast the following two scalar quantities,  $\kappa$  and  $p_1^\circ$  ( $\mu$  and  $p_3^\circ$ ), in order to allow each relay to calculate its own beamforming coefficient.

## 4. SIMULATION RESULTS

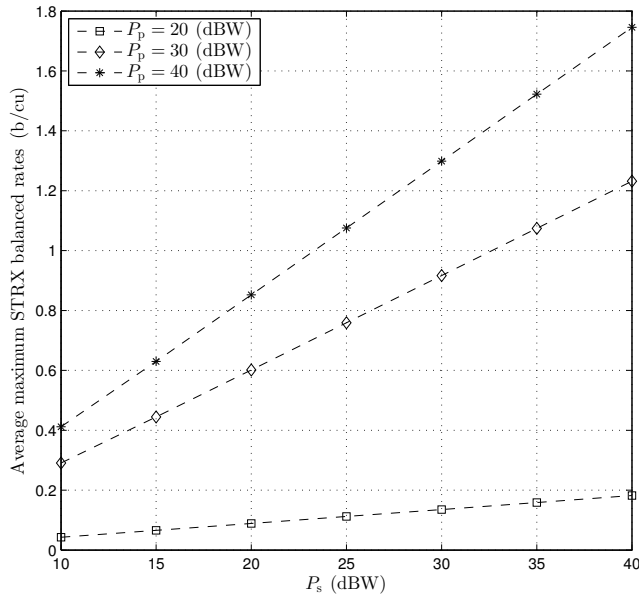
We assume  $n_r = 10$  distributed relays and two transceiver pairs. The channel coefficient between each transceiver and each relay is drawn from a complex Gaussian random distribution with zero-mean and unit variance. Fig. 2 illustrates the average maximum balanced rate of the secondary transceivers versus  $\eta$ , for different values of  $P_s$ , where  $P_p = 30$  (dBW) is chosen. We can see that the average maximum balanced rates of the secondary transceivers decrease linearly when the primary demand  $\eta$  increases. This is in agreement with (3). Moreover, we see that for large values of  $\eta$ , the design problem becomes infeasible. For sufficiently small values of  $\eta$ , the design problem is always feasible, meaning that the primary pair is served with its rate demand equal to  $\eta$  and the secondary transceivers communicate with the largest possible average balanced rates. Furthermore, we can see from Fig. 2 that as  $P_s$  increases, the secondary transceivers achieve higher balanced rates.



**Fig. 2.** Average maximum balanced rates of the secondary transceivers versus  $\eta$  for different values of  $P_s$  when  $P_p = 30$  (dBW)



**Fig. 3.** Average maximum balanced rates of the secondary transceivers versus  $\eta$  for different values of  $P_p$  when  $P_s = 30$  (dBW).



**Fig. 4.** Average maximum balanced rates of the secondary transceivers versus  $P_s$  for different values of  $P_p$  when  $\eta = 1.5$  (b/cu).

In Fig. 3, we plot the average maximum balanced rates of the secondary pair versus  $\eta$  for different values of  $P_p$ , when  $P_s = 30$  (dBW). One can see from this figure that as  $P_p$  is increased, the design problem can satisfy higher primary pair demand  $\eta$ . It is worth mentioning that, when  $P_s$  is fixed, as  $\eta$  approaches zero, all the spectral and temporal resources are allocated to the secondary transceivers, thereby increasing the average maximum secondary transceiver balanced rates to a value which is independent of  $P_p$ .

Fig. 4 illustrates the average maximum balanced rates of the secondary transceivers versus  $P_s$ , for different values of  $P_p$ , when  $\eta = 1.5$  (b/cu). It is obvious that when the design problem is feasible, increasing  $P_s$  leads to a higher value for the average maximum balanced rates of the secondary transceivers. These results are in agreement with the studies of [1, 3, 13].

## 5. CONCLUSIONS

We studied the problem of optimal resource sharing between two pairs of transceivers with the help of a network of  $n_r$  relays. We considered a communication framework where the primary pair leases a portion of its radio frequency spectrum to the secondary pair, in exchange for exploiting the relays to guarantee a minimum data rate for the primary transceivers. We formulated an optimization problem in order to optimally calculate the corresponding design parameters and provide a semi-closed form solution. We presented the solution to this optimization in a closed form.

## 6. REFERENCES

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