Hierarchical Prior Zero-Forcing for Cognitive Relaying

Feeby Salib and Karim G. Seddik
Electronics Engineering Department, American University in Cairo, AUC Avenue, New Cairo, Egypt.
email: fsalib@aucegypt.edu, kseddik@aucegypt.edu

Abstract—**In this paper, cognitive radio relaying in the physical layer is investigated where the cognitive base station (CBS) relays the PU's signal while transmitting its own signals to its secondary users (SUs). A new and simple linear method for beamforming, based on zero-forcing beamforming, adapted for the different levels of priority that users may possess in a cognitive radio network, is proposed and the special case of two SUs is analytically studied.**

I. Introduction

Cognitive radio is a promising solution for alleviating spectrum scarcity problem by utilizing the available spectrum in a more efficient way so that it can meet the dramatic demand increase in wireless communications [1]. In Cognitive Radio Network (CRN), the primary user (PU) transmission has to be protected from coexisting secondary users (SUs). Cognitive radio can offer assistance to the PU transmission to benefit a higher opportunity for its own transmission; this assistance could be through relaying the PU signal [2].

In [3], the authors proposed a modified zero-forcing (ZF) scheme named prior zero-forcing (PZF) scheme at the cognitive radio base station (CBS), where the PU is given priority by relaying its signal without considering its interference to the transmissions of the SUs in the system, while the SUs transmissions are not permitted to cause any interference to the PU transmission. The performance of the PZF scheme was compared with the conventional zero-forcing (CZF) scheme and the model of a single SU and a PU was studied as a special case. It was proved that when the target rate of the SU is less than 1 bit/sec/HZ, the total required power by the PZF scheme to achieve the target rates for the users is less than that required by the CZF scheme and vice versa [3]. However, besides the priority of the PU, the SUs in a network may have different priorities and each SU may need a different Quality of Service (QoS) requirement.

Nevertheless, most of the research work done in cognitive radio networks treat all SUs equally, while few recent works considered SUs with different priority levels. Moreover, all these works addressed this issue in the multiple access control (MAC) layer only and not in the physical layer, which will be our focus in this paper. In [4], [5], prioritized SUs issue was addressed by developing strategies in the MAC layer for the channel allocation accounting for the different levels of the SUs priorities. For example, in [4] SUs were divided into two levels of priority and "priority-based spectrum handoff" was considered. In [5], a prioritized based allocation scheme was established to consider the different levels of priority for SUs transmissions so that the SUs with higher priority can experience less data transmission delay and channel switches.

In this paper, different priority levels for SUs are achieved by a newly proposed scheme called Hierarchical Priority Zero-Forcing (HPZF) scheme. The proposed HPZF scheme is based on the PZF scheme proposed in [3], and it can be considered as an extension of the latter. Also, it is worth mentioning that the priority levels of the different users are recognized not only from power allocation perspective, but also from the beamforming vectors design.

Notations: Throughout the paper we refer to vectors with bold lower cases such as $\mathbf{g}$. Pseudo-inverse of a matrix $\mathbf{A}$ is denoted by $\mathbf{A}^{\dagger}$. Let $\mathbf{A}^T$, $\mathbf{A}^{\mathcal{H}}$ and $\mathbf{A}^*$ denote the transpose, Hermitian (conjugate) transpose and the conjugate of the matrix $\mathbf{A}$, respectively.

II. System Model

CRN with one primary user and M SUs communicating with one CBS is considered. The PU and all the SUs are equipped with a single receiving antenna while the CBS is equipped with $L \geq M+1$ antennas. When the link between PU transmitter and its receiver is good enough, the CBS can transmit signals to its SUs but without causing any interference to the PU using ZF beamforming. However, when the PU link suffers from a deep fade, the PU can ask the CBS for assistance, hence the CBS will be in charge of transmitting the PU signal along with its SUs signals. The CBS firstly decodes the PU signal, and then relays it at the same time it transmits its own signals to its SUs. The priority of SUs comes after the priority of the PU. After considering the PU as being the user with the highest priority in the CRN, let the priority of the M SUs be sorted such that the 1st SU has the highest priority among the SUs and the M-th SU has the least priority.

We assume that the CBS uses random Gaussian codebooks [3]; therefore, the transmitted signals can be treated as white complex Gaussian processes; let $s_p \sim \mathcal{CN}(0, \sigma_P^2)$ and $s_i \sim \mathcal{CN}(0, \sigma_i^2)$ denote the information symbols to be transmitted to the PU and the i-th SU, respectively. Then, the transmitted signal vector by the CBS can be written as

$$\mathbf{x} = \mathbf{w}_p s_p + \sum_{i=1}^{M} \mathbf{w}_i s_i, \tag{1}$$

where $\mathbf{w}_p$ and $\mathbf{w}_i$ are the beamforming vectors for the PU and the i-th SU, respectively. Then the received signal at the PU and that at the i-th SU can be written, respectively, as

$$y_p = \mathbf{h}_p^T \mathbf{w}_p s_p + \mathbf{h}_p^T \sum_{i=1}^{M} \mathbf{w}_i s_i + n_p, \tag{2}$$

$$y_i = \mathbf{h}_i^T \mathbf{w}_i s_i + \mathbf{h}_i^T \mathbf{w}_p s_p + \mathbf{h}_i^T \sum_{k=1;k\neq i}^{M} \mathbf{w}_k s_k + n_i, \quad (3)$$

where $\mathbf{h}_p$, $\mathbf{h}_i$, n_p and n_i are the $L \times 1$ channel gain between the CBS and PU, the $L \times 1$ channel gain between the CBS and the i-th SU, the noise at the PU and the noise at i-th SU, respectively. We assume that the noise variances are equal, i.e., n_p and $n_i \sim \mathcal{CN}(0, \sigma_n^2)$. Then, the received SINR at the PU and the i-th SU can be given, respectively, by

$$\begin{aligned} \gamma_{pr} &= \frac{|\mathbf{h}_p^T \mathbf{w}_p|^2 \gamma_{pt}}{\sum_{i=1}^{M} |\mathbf{h}_p^T \mathbf{w}_i|^2 \gamma_{it} + 1} \\ \gamma_{ir} &= \frac{|\mathbf{h}_i^T \mathbf{w}_i|^2 \gamma_{it}}{|\mathbf{h}_p^T \mathbf{w}_p|^2 \gamma_{pt} + \sum_{k=1;k\neq i}^{M} |\mathbf{h}_i^T \mathbf{w}_k|^2 \gamma_{kt} + 1}, \end{aligned} \quad (4)$$

where $\gamma_{pt} = E[|s_p|^2]/\sigma_n^2$ and $\gamma_{it} = E[|s_i|^2]/\sigma^2$.

In the following, analysis of the HPZF scheme is considered along with the comparison with both the PZF and CZF schemes. First, we will briefly present the CZF and PZF schemes.

III. Zero-Forcing Beamforming

A. The CZF Scheme

Adopting CZF, all users are treated equally. Beamforming vectors are chosen such that no user induces interference to any other user; that is

$$|\mathbf{h}_k^T \mathbf{w}_j|^2 = \begin{cases} 0 & \forall k \neq j \\ 1 & k = j. \end{cases} \quad (5)$$

The optimal orthogonal beamforming is simply constructed by finding the pseudo-inverse of the channel matrix. Define $\mathbf{H}_c = [\mathbf{h}_1, \mathbf{h}_2, \cdots, \mathbf{h}_i, \cdots, \mathbf{h}_M]$, $\mathbf{H}_i = [\mathbf{h}_1, \cdots, \mathbf{h}_{i-1}, \mathbf{h}_{i+1}, \cdots, \mathbf{h}_M]$, and let $\Phi_{\mathbf{H}_c} = \mathbf{I} - \mathbf{H}_c \mathbf{H}_c^\dagger$ represent the null space of $\mathbf{H}_c$; also, let $\Phi_{\mathbf{h}_p} = \mathbf{I} - \mathbf{h}_p \mathbf{h}_p^\dagger$ and $\Phi_{\mathbf{H}_i} = \mathbf{I} - \mathbf{H}_i \mathbf{H}_i^\dagger$. Then, we can write the beamforming vectors as

$$\mathbf{w}_p^* = \frac{\mathbf{h}_p - \mathtt{Proj}_{\mathbf{H}_c} \mathbf{h}_p}{\|\mathbf{h}_p - \mathtt{Proj}_{\mathbf{H}_c} \mathbf{h}_p\|}, \ \mathbf{w}_i^* = \frac{\mathbf{h}_i - \mathtt{Proj}_{[\mathbf{H}_i, \mathbf{hp}]} \mathbf{h}_i}{\|\mathbf{h}_i - \mathtt{Proj}_{[\mathbf{H}_i, \mathbf{hp}]} \mathbf{h}_i\|}, \quad (6)$$

where $\mathtt{Proj}_{\mathbf{H}_c} \mathbf{h}_p$ denotes the projection of $\mathbf{h}_p$ over the subspace spanned by the columns of $\mathbf{H}_c$. So we will have

$$\gamma_{pr} = |\mathbf{h}_p^T \mathbf{w}_p|^2 \gamma_{pt}, \ \gamma_{ir} = |\mathbf{h}_i^T \mathbf{w}_i|^2 \gamma_{it}. \quad (7)$$

The resulting effective channel gains for the CBS-PU link, G_{pC}, and the CBS-ith SU link, G_{iC}, using the CZF scheme are given, respectively, by

$$\begin{aligned} G_{pC} &= |\mathbf{h}_p^T \mathbf{w}_p|^2 = \|\Phi_{\mathbf{H}_c} \mathbf{h}_p\|^2 \\ G_{iC} &= |\mathbf{h}_i^T \mathbf{w}_i|^2 = \|\mathbf{h}_i - \mathtt{Proj}_{[\mathbf{H}_i, \mathbf{h}_p]} \mathbf{h}_i\|^2 = \mathbf{h}_i^{\mathcal{H}} \Phi_{\mathbf{H}_i} \mathbf{h}_i (1 - \rho_{\mathbf{H}_i}^2), \end{aligned} \quad (8)$$

where $\rho_{\mathbf{H}_i} = \sqrt{\dfrac{|\mathbf{h}_p^{\mathcal{H}} \Phi_{\mathbf{H}_i} \mathbf{h}_i|^2}{\mathbf{h}_p^{\mathcal{H}} \Phi_{\mathbf{H}_i} \mathbf{h}_p \mathbf{h}_i^{\mathcal{H}} \Phi_{\mathbf{H}_i} \mathbf{h}_i}}$ is the correlation coefficient between $\mathbf{h}_i$ and $\mathbf{h}_p$ in the nullspace of $\mathbf{H}_i$.

B. The PZF Scheme

In this case, the beamforming vector for the PU signal can be implemented in any signal direction since the PU relayed transmission does not have any constraint [3] (in the PZF, the PU beamformer does not have to place nulls in the directions of the SUs). The beamforming vector that achieves the largest channel effective gain for the CBS-PU link will be in the same direction of the PU channel, which resembles the maximum ratio transmission (MRT) as $\mathbf{w}_p^* = \frac{\mathbf{h}_p}{\|\mathbf{h}_p\|}$. The effective channel gains of the CBS-PU link and the CBS-ith SU link using PZF can be written, respectively, as

$$G_{pP} = \|\mathbf{h}_p\|^2, \ G_{iP} = |\mathbf{h}_i^T \mathbf{w}_i|^2 = \mathbf{h}_i^{\mathcal{H}} \Phi_{\mathbf{H}_i} \mathbf{h}_i (1 - \rho_{\mathbf{H}_i}^2). \quad (9)$$

Note that the beamforming vectors and the channel effective gains of the SUs in the PZF case are the same as that in CZF case but the PU will cause some interference at the SUs receivers in this case.

IV. The Proposed Hierarchal Prior Zero-Forcing (HPZF) Scheme

In the HPZF scheme, the user with higher priority does not have to place a null in the direction of any other user with lower priority. In HPZF, we aim to find beamforming vectors that maintain the different priorities of the SUs; the received signals at each user can be written as

$$\begin{aligned} y_p &= \mathbf{h}_p^T \mathbf{w}_p s_p + n_p, \\ y_i &= \mathbf{h}_i^T \mathbf{w}_i s_i + \mathbf{h}_i^T \mathbf{w}_p s_p + \mathbf{h}_i^T \sum_{k=1}^{i-1} \mathbf{w}_k s_k + n_i. \end{aligned} \quad (10)$$

Therefore, the SINR at the PU is given by $\gamma_{ir} = |\mathbf{h}_i^T \mathbf{w}_i|^2 \gamma_{it}$, while the SINR at the i-th SU is given by

$$\gamma_{ir} = \frac{|\mathbf{h}_i^T \mathbf{w}_i|^2 \gamma_{it}}{|\mathbf{h}_p^T \mathbf{w}_p|^2 \gamma_{pt} + \sum_{k=1}^{i-1} |\mathbf{h}_i^T \mathbf{w}_k|^2 \gamma_{kt} + 1}. \quad (11)$$

It is obvious that PU does not suffer from any interference, and each SU only suffers from interference from the users with higher priority relative to it.

A. HPZF Beamforming Vectors and Effective Channel Gains

To keep the level of interference on each user in the CRN different depending on its priority, the beamforming vectors in the HPZF scheme are designed as

$$\mathbf{w}_p^* = \frac{\mathbf{h}_p}{\|\mathbf{h}_p\|}, \ \mathbf{w}_i^* = \frac{\mathbf{h}_i - \mathtt{Proj}_{[\mathbf{h}_p, \mathbf{h}_1, \cdots, \mathbf{h}_{i-1}]} \mathbf{h}_i}{\|\mathbf{h}_i - \mathtt{Proj}_{[\mathbf{h}_p, \mathbf{h}_1, \cdots, \mathbf{h}_{i-1}]} \mathbf{h}_i\|}. \quad (12)$$

Note that PZF beamforming vector for the least priority SU is the same as that using CZF or PZF since it needs to place a null in the direction of any other user in the network.

The effective channel gain of the CBS-PU link and the CBS-i-th SU link using HPZF are given, respectively, by $G_{pH} = \|\mathbf{h}_p\|^2$ and

$$G_{iH} = |\mathbf{h}_i^T \mathbf{w}_i|^2 = \left\| \mathbf{h}_i - \mathtt{Proj}_{[\mathbf{h}_p, \mathbf{h}_1, \cdots, \mathbf{h}_{i-1}]} \mathbf{h}_i \right\|^2.$$

It is worth mentioning that in case new SUs demand service from the CBS, HPZF preserves the performance for each user whatever the number of extra new users entering to the network if the new users have lower priority, which is not the case for the CZF and PZF schemes.

B. Required Transmit Power

To study the total required transmit power in the HPZF case, the interference on the users with different priorities is derived. Let I_{ki} denote the interference induced by user k on user i normalized by the noise variance. Let η_p be the SINR target at the PU, while η_i be the SINR target for the i-th SU.

The PU is the only user that does not suffer from interference from any other user in the system due to its first priority, so $I_{kp} = 0,\ \forall k$.

The other users are affected by the users with higher priority. So these interference terms can be drawn up as follows.

$$I_{ki} = |\mathbf{h}_i^T \mathbf{w}_k|^2 \gamma_{ktH},\ k < i. \tag{13}$$

Then, the required transmit power that satisfies the target SINR for the PU and for the i-th SU can be calculated, respectively, as

$$\gamma_{ptH} = \eta_p / G_{pH}, \quad \gamma_{itH} = \frac{\eta_i (1 + I_{pi} + \sum_{k=1}^{i-1} I_{ki})}{G_{iH}}. \tag{14}$$

Note that, in this context, power refers to the power normalized by the noise variance, which is assumed to be the same for all users. Then the total required transmit power using HPZF scheme, γ_{totalH}, can be written as $\gamma_{totalH} = \gamma_{ptH} + \sum_{i=1}^{M} \gamma_{itH}$.

V. Comparison among the Different Schemes

A. Comparison between HPZF and PZF

The total required transmit powers for the HPZF and PZF schemes are compared to find a condition under which HPZF can perform better than PZF from the total required transmit power point of view. The condition for $\gamma_{totalH} < \gamma_{totalP}$ is

$$\gamma_{ptH} + \sum_{i=1}^{M} \gamma_{itH} < \gamma_{ptP} + \sum_{i=1}^{M} \gamma_{itP} \rightarrow$$
$$\sum_{i=1}^{M} \frac{\eta_i (1 + I_{pi} + \sum_{k=1}^{i-1} I_{ki})}{\|\Phi_{[\mathbf{h}_p, \mathbf{h}_p, \cdots, \mathbf{h}_{i-1}]} \mathbf{h}_i\|^2} < \sum_{i=1}^{M} \frac{\eta_i (1 + I_{pi})}{\|\Phi_{\mathbf{H}_i} \mathbf{h}_i\|^2}. \tag{15}$$

It could be seen that the i-th SU effective channel gain using HPZF is greater than that using PZF for all users except the SU of the least priority, i.e., $G_{iH} > G_{iP}\, \forall\, i \leq (M-1)$, but the i-th SU, except for the 1st SU, suffers more interference in HPZF than that in PZF, depending on its level of priority. Therefore, it is not straightforward to claim which scheme would require less total power for achieving the target rates for the different users in the CRN. Equation (15) can be used to decide which scheme results in a lower required transmit power based on the instantaneous channel knowledge.

B. Comparison between HPZF and CZF

The total required transmit powers for the HPZF and CZF cases are compared to find a condition under which HPZF can perform better than CZF, from the total required transmit power point of view, the same way used in the above section. Then the condition for $\gamma_{totalH} < \gamma_{totalC}$ is

$$\frac{\eta_p}{G_{pH}} + \sum_{i=1}^{M} \frac{\eta_i (1 + I_{pi} + \sum_{k=1}^{i-1} I_{ki})}{G_{iH}} < \frac{\eta_p}{G_{pC}} + \sum_{i=1}^{M} \frac{\eta_i}{G_{iC}} \rightarrow$$
$$\frac{\eta_p}{\|\mathbf{h}_p\|^2} + \sum_{i=1}^{M} \frac{\eta_i (1 + I_{pi} + \sum_{k=1}^{i-1} I_{ki})}{\|\Phi_{[\mathbf{h}_p, \mathbf{h}_p, \ldots, \mathbf{h}_{i-1}]} \mathbf{h}_i\|^2} < \frac{\eta_p}{\|\Phi_{\mathbf{H}_c} \mathbf{h}_p\|^2} + \sum_{i=1}^{M} \frac{\eta_i}{\|\Phi_{\mathbf{H}_i} \mathbf{h}_i\|^2}. \tag{16}$$

It could be seen that the i-th SU effective channel gain using HPZF is greater than that using CZF for all users except the SU of the least priority, i.e., $G_{iH} > G_{iC}\ \ \forall i \leq (M-1)$, but in HPZF, the i-th SU suffers from interference induced by the users of higher priority, while in CZF, the i-th SU does not suffer from any interference from any user. Also, it is obvious that the required transmit power for the PU using the HPZF is less than that using the CZF. Therefore, it is not straightforward to claim which scheme would require less total power for achieving the target rates.

C. A Special Case: Two Secondary Users

Now, a special case, where two SUs, i.e., $M = 2$, of different levels of priority are coexisting with the PU, is considered.

The different interference terms can be calculated as

$$I_{pi} = |\mathbf{h}_i^{\mathcal{H}} \mathbf{w}_p^*|^2 \gamma_{ptH} = \frac{|\mathbf{h}_i^{\mathcal{H}} \mathbf{h}_p|^2}{\|\mathbf{h}_p\|^2} \gamma_{ptH} = \frac{|\mathbf{h}_i^{\mathcal{H}} \mathbf{h}_p|^2}{\|\mathbf{h}_p\|^4} \eta_p, \tag{17}$$

$$I_{12} = |\mathbf{h}_2^{\mathcal{H}} \mathbf{w}_1^*|^2 \gamma_{1tH} = \frac{|\mathbf{h}_2^{\mathcal{H}} (\mathbf{h}_1 - \mathbf{h}_p \mathbf{h}_p^{\dagger} \mathbf{h}_1)|^2}{\|\mathbf{h}_1 - \mathbf{h}_p \mathbf{h}_p^{\dagger} \mathbf{h}_1\|^4} \eta_1 \left(1 + \frac{|\mathbf{h}_1^{\mathcal{H}} \mathbf{h}_p|^2}{\|\mathbf{h}_p\|^4} \eta_p\right). \tag{18}$$

Then, the required transmit power for each SU, γ_{itH}, is given by

$$\begin{aligned}
\gamma_{1tH} &= \eta_1 \frac{\left(1 + \frac{|\mathbf{h}_1^{\mathcal{H}} \mathbf{h}_p|^2}{\|\mathbf{h}_p\|^4} \eta_p\right)}{\|\Phi_p \mathbf{h}_1\|^2}, \\
\gamma_{2tH} &= \eta_2 \frac{(1 + I_{p2} + I_{12})}{G_{2H}} \\
&= \frac{\eta_2 \left(1 + \frac{|\mathbf{h}_2^{\mathcal{H}} \mathbf{h}_p|^2}{\|\mathbf{h}_p\|^4} \eta_p + \frac{|\mathbf{h}_2^{\mathcal{H}} \Phi_p \mathbf{h}_1|^2}{\|\Phi_p \mathbf{h}_1\|^4} \eta_1 \left(1 + \frac{|\mathbf{h}_1^{\mathcal{H}} \mathbf{h}_p|^2}{\|\mathbf{h}_p\|^4} \eta_p\right)\right)}{\|\Phi_p \mathbf{h}_1\|^2 \left(1 - \frac{|\mathbf{h}_1^{\mathcal{H}} \Phi_p \mathbf{h}_2|^2}{\|\Phi_p \mathbf{h}_1\|^2 \|\Phi_p \mathbf{h}_2\|^2}\right)},
\end{aligned} \tag{19}$$

while the required transmit power for the PU, $\gamma_{ptH} = \frac{\eta_p}{\|\mathbf{h}_p\|^2}$. Then, the total required transmit power using the HPZF scheme, γ_{totalH}, can be calculated by substituting the above derived power expressions in

$$\gamma_{totalH} = \gamma_{ptH} + \gamma_{1tH} + \gamma_{2tH}, \tag{20}$$

while the total power required using the PZF scheme is given by

$$\begin{aligned}
\gamma_{totalP} &= \gamma_{ptP} + \gamma_{1tP} + \gamma_{2tP} \\
&= \frac{\eta_p}{\|\mathbf{h}_p\|^2} + \eta_1 \frac{\left(1 + \frac{|\mathbf{h}_1^{\mathcal{H}} \mathbf{h}_p|^2}{\|\mathbf{h}_p\|^4} \eta_p\right)}{\|\Phi_p \mathbf{h}_1\|^2 \left(1 - \frac{|\mathbf{h}_1^{\mathcal{H}} \Phi_p \mathbf{h}_2|^2}{\|\Phi_p \mathbf{h}_1\|^2 \|\Phi_p \mathbf{h}_2\|^2}\right)} \\
&+ \eta_2 \frac{\left(1 + \frac{|\mathbf{h}_2^{\mathcal{H}} \mathbf{h}_p|^2}{\|\mathbf{h}_p\|^4} \eta_p\right)}{\|\Phi_p \mathbf{h}_2\|^2 \left(1 - \frac{|\mathbf{h}_1^{\mathcal{H}} \Phi_p \mathbf{h}_2|^2}{\|\Phi_p \mathbf{h}_1\|^2 \|\Phi_p \mathbf{h}_2\|^2}\right)}.
\end{aligned} \tag{21}$$

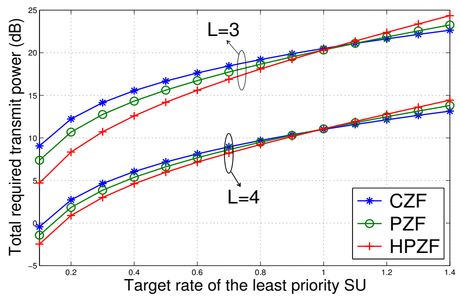

Fig. 1: Comparison of the required transmit power: $M = 2$, $L = 3, 4$, $R_p = R_{s1} = R_{s2}$.

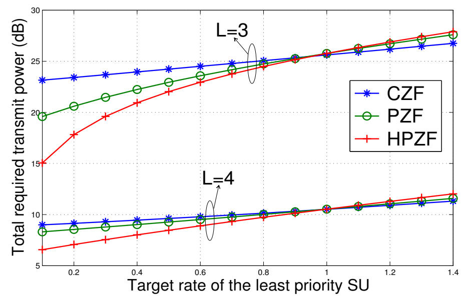

Fig. 2: Comparison of the required transmit power: $M = 2$, $L = 3, 4$, $R_p = 1$, $R_{s1} = R_{s2}$.

1) Comparison between HPZF and PZF for $M = 2$: The total required transmit powers for the HPZF and PZF schemes are compared to find the condition when HPZF is more power efficient than PZF. After some manipulation, the condition for HPZF to be more power efficient than PZF can be shown to be given as $\eta_2 < 1$; when $\eta_2 < 1$ or equivalently the target rate of the 2nd SU is less than 1 bit/sec/Hz, i.e., $R_{s2} < 1$ bit/sec/Hz, HPZF requires less power than PZF to satisfy the target rates for all users. Therefore, the selection between the HPZF and PZF schemes only depends on the target rate of the user of the least priority, which in our case is the target rate of the 2nd SU.

2) Comparison between HPZF and CZF for $M = 2$: Unfortunately, it is too difficult to get a simple condition to determine which scheme performs better. Therefore, we can find the condition for this case numerically; this condition depends on the instantaneous channel values of all the users in the CRN and the target rates.

VI. Simulation Results

In the following simulations, all the links between the CBS and the SUs and the link between CBS and the PU are assumed to be i.i.d. Rayleigh fading with a variance of 1. Fig. 1 shows the results for the case of $M = 2$ where the target rates for the PU and all the SUs were equal, i.e., $R_p = R_{s1} = R_{s2}$. In Fig. 2 the target rates for the PU and 1st SU were set to be 1 bit/sec/HZ. It could be seen that when the target rate of the SU of the least priority is less than 1, i.e., $R_{s2} < 1$ bit/sec/Hz, HPZF requires less total power than the PZF, which is consistent with our analysis. Also it could be deduced from the above figures that with increasing the number of transmit antennas at the CBS, L, the performance gaps between the different schemes decrease (as we have more degrees of freedom with increasing L).

In Fig. 3, the target rates for the PU and the 1st SU were set to be 2 bit/sec/Hz and 1.5 bit/sec/HZ, respectively, with $L = 5$. It can be seen that HPZF outperforms the CZF as long as $R_{s2} \leq 0.73$ bit/sec/Hz, while HPZF outperforms the PZF as long as the target rate for the 2nd SU is less than 1 bit/sec/Hz. Also, Fig. 3 shows that the PZF performs better than the CZF only in a small range, where the target rate for the 2nd SU less than about 0.2.

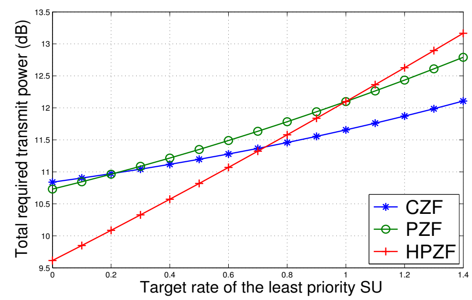

Fig. 3: Comparison of the required transmit power: $M = 2$, $L = 5$, $R_p = 2$,$R_{s1} = 1.5$.

VII. Conclusion

In this paper, we consider CRN relaying in the physical layer where the CBS relays the PU signals while transmitting its own signals to its SUs, which have different priorities, via a new simple linear scheme denoted by hierarchical prior zero-forcing (HPZF) scheme. In HPZF, each user causes interference to only the users that have lower priority and no interference to the higher priority users. The special case of two SUs was analytically studied. We showed that in the two SUs scenario, the HPZF algorithm outperforms the previously proposed PZF scheme in terms of the total power requirement as long as the target rate for the least SU is less than 1 bit/sec/Hz. Also, the conditions, based on the instantaneous channel knowledge and target rates, for which the HPZF scheme outperforms the PZF and the CZF schemes were derived.

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