Abstract—We consider beamformer optimization for user equipment (UE) relaying cooperation in heterogeneous cellular networks (HCNs), where the interference from femto cells nearby aggravates the signal-to-interference-plus-noise ratio (SINR) of a macro UE (MUE). A femto UE acts as a relay over device-to-device (D2D) uplink and forward to the MUE, the composite of desired signal and interference to improve the post SINR of the MUE. The beamformers of the UE relay and MUE collaborate to make a balance between the two signals so that the output signal after multistage maximal-ratio combining (MS-MRC) yields a sufficient post SINR for the desired signal. We first consider the case with a single interfering femto access point (FAP) and show that the beamforming for dual-stage MRC can effectively handle the interference. Then, the idea is generalized to the case of two interfering FAPs with a three-stage MRC. A geodesic geometry view allows us to parameterize the BF design with the angles that the involved channel vectors make. This approach makes the optimization of the BF simpler, reduces the feedback overhead, and provides better insight into the problem at hand. Simulations are carried out to validate the performance of the UE relaying cooperation in HCN environments.

Index Terms—Heterogeneous cellular networks (HCNs), UE relaying, D2D uplink, coordinated beamforming, multistage MRC.

I. INTRODUCTION

As the number of wireless devices is rapidly growing, it has put undue burden on the network due to the huge increase of data traffic to deal with. To overcome the problem with congestion and imperfect coverage, small-cell based approach with low power and small coverage area has come into the spotlight. Heterogeneous cellular networks (HCNs) is the term used to describe the resulting networks, where macro cells and small (e.g., femto and pico) cells overlap their coverage for faster and more reliable services to overall users and reduce the shadow areas. Despite these advantages of HCNs, it is feared that they cause significant co-tier and cross-tier interferences [1]–[4]. However, recent study based on stochastic geometry reveals that HCNs are robust to the co-tier and cross-tier interferences [5]–[9], as long as users in HCNs are allowed to access their nearby small-cell access points.

In femto cells, users can connect to any femto access point (FAP) in open subscriber group policy (OSG) or they can connect only to allowed FAPs in closed subscriber group (CSG) policy. In OSG, macro user equipments (UEs) can mitigate the interference from FAPs by switching their associations to the interfering FAPs. With CSG policy, however, macro UEs are not allowed to change the associations so that they are subject to the co-tier and cross-tier interferences when they are approaching the FAPs. In this situation, careful handling of the interference results in better performance of the wireless networks. Up to date, there have been numerous proposals to reduce such interference from coexisting small cells including those in the 3GPP standards [10]–[13]. On the one hand, allocating dedicated radio resources to interfering cells removes the cross-tier interference [2], but it decreases an overall spectral efficiency. On the other hand, controlling the transmit power of FAP is one way for interference coordination [3], [4], but if a macro UE (MUE) comes within the service area of FAP, it may not work due to the severe cross-tier interference.

In recent years, cooperative transmission via relay has been used primarily to improve the overall system capacity or to obtain a diversity gain [14]. Unlike conventional relaying to strengthen the desired signal, the relay can be utilized for forwarding the composite of desired signal plus interference [15], [16], so that the receiver at a victim MUE first decodes the strong interference, subtracts it out, and then decodes the weak desired signal in a balanced way [17]. Note that the interference subtraction approach is well discussed in cellular LTE-HetNet standard [10], [11] to handle the cross-tier interference at UE side. In this paper, we propose the UE relaying cooperation with multi-stage maximal-ratio combining (MS-MRC) to resolve the critical interference issue of the victim MUE in HCNs. We first consider the case of a single interfering FAP and extend to the case of two interfering FAPs to show how the idea can be generalized to the case of multiple interfering FAPs. We assume that the victim MUE is located far from its serving macro base station (MBS) but is approaching the coverage of FAPs which are accessible by the CSG only. The victim MUE connected to the MBS is not in the CSG of a FAP, but there is a UE nearby in

1The CSG policy is a more natural option for femto cells since the femto cells are private devices.
the CSG of the FAP which can help relay the composite signal with amplify-and-forward protocol.\(^2\)

In this scenario, the UEs nearby can utilize D2D communication [21] for the UE relaying. The D2D function here enables the peer UEs to set up the relay link with measured transmit power and channel status. Especially, the UE relaying is realized in conjunction with the M-MRC performed at the victim MUE receiver. The front stages of MS-MRC are performed to decode the strong interference signals sequentially by combining those in two-phase transmissions, one from the FAP and the other from the UE relay. Meanwhile, the final stage of the MS-MRC is to decode the desired signal. Hence, the MS-MRC receiver is like a multi-antenna version of the successive interference cancellation (SIC) based multi-stage receiver [22], [23] for the strong interference channel.

The interference control via distributed relay in the context of interfering multiple peer-to-peer pairs was addressed in [24]–[26]. However, the problem considered herein is different from those since there is a single peer-to-peer link with strong cross-tier interference. When interference exists at the single antenna relay and destination, the performance of cooperative relay transmission was presented in [27]–[29]. Differences in this paper are that we allow UEs to have multiple antennas for the UE relaying and the decoding at the destination is based on the MS-MRC. The beamforming (BF) at UEs helps coordinate the multi-stage SIC operation at the MS-MRC receiver.

The BF for multi-antenna channels in conjunction with the SIC was considered in [30], [31]. However, the BF for the UE relaying and MS-MRC will need to steer the beams, both at the UE relay and victim MUE, in a coordinated manner. Consequently, this coordinated BF design requires extra overhead in computational complexity and feedback information such as the estimation of channels involved, the signal processing for dual-stage MRC receiver, the control signaling for D2D connection, and the BF information exchange in closed-loop mode.\(^3\) In this paper, the BF information feedback is shown to be in trade-off relation with the performance. To facilitate the BF design, we take a geodesic geometry approach [32], [33] to parameterize the BF, based on the angle that the channel vectors from MBS and FAP toward the UE relay and victim MUE make. Similar BF approaches were taken in [34], [35] as well, though in the multi-input multi-output (MIMO) relay network and virtual MIMO context, respectively. This geometry based BF design not only allows a simplified search over the BF space but also provides us with a systematic view of the problem.

The main contributions of this paper are summarized as:

1. First, we design the BF suitable for the UE relaying with dual-stage MRC when there is a single interfering FAP.

2) We design a set of joint BFs in closed-loop mode (i.e., a coordinated manner) both at the UE relay and victim MUE. Here, the victim MUE optimizes the two angles associated with joint BFs at both nodes and informs the UE relay of the angle information through the feedback channel.

3) When the optimization does not provide any feasible solution, and the first stage falls in an outage event, we simply resort to a single stage receiver with Capon beamformers [36], [37].

\(^*\) We then generalize this idea to the case of multiple interfering FAPs where joint BFs are further optimized to facilitate the UE relaying with MS-MRC.

The rest of the paper is organized as follows. In Section II, we describe the system model and problem definition when there is a single interfering FAP. Section III presents the signal model for the UE relaying via D2D uplink, along with the dual-stage MRC receiver. In Section IV, we provide a geometry based BF design and address the issue of feedback channel design. Simulation results are presented in Section V to validate the performance gain offered by the proposed scheme. Finally, the proposed idea is generalized to the case of multiple interfering FAPs in Section VI and concluding remarks are given in Section VII.

**Notations:** The bold lower case letter represents a vector and the bold upper case letter represents a matrix. The notations \(A^{-1}, A', A^H, A^T, Tr[A]\) are the inverse, the transpose, the Hermitian transpose, the pseudo inverse and the trace of a matrix \(A\), respectively. \(I_n\) denotes the identity matrix of size \(a \times a\). \(A^*\) and \(\|a\|\) denote the projection onto the space orthogonal to the columns of \(A\) and the norm of a vector \(\textbf{a}\), respectively. For a complex number \(c, c^*\) denotes the complex conjugate of \(c\). \(|A|\) denotes the cardinality of a set \(A, \text{CN}(0, \textbf{C})\) denotes the complex white Gaussian random vector with zero mean vector \(\textbf{0}\) and the covariance matrix \(\textbf{C}\).

**II. System Model**

In Fig. 1, a picture of HCN is shown where there is a single interfering FAP and the MUE \(MS_2\) approaching the coverage of the FAP suffers from its interference (red channel \(G_2\)). The MBS has \(M_f\) antennas and the FAP has \(M_f\) antennas while each UE is equipped with \(M_m\) antennas. During the downlink transmission, the MBS and FAP share the same spectral resource to serve users in their coverage areas, which causes the MUEs to suffer from the strong interference coming from the FAP nearby. The femto UE \(MS_1\) within its coverage area (and is not necessarily being served by the FAP) overhears the interfering signal and possibly helps the victim MUE \(MS_2\) via D2D uplink \(G_{2,1}\) by forwarding the composite signal toward \(MS_2\). In this way, FAPs can inhabit the macro cell coverage without
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Fig. 1. The downlink of a HCN where the MUE MS2 approaches the coverage of a femto cell area and is experiencing the interference (red channel $G_2$) from the FAP which is using the same spectral resource as the MBS. The femto UE MS1, using D2D communication via the link $\tilde{G}_{2,1}$, helps the victim MUE MS2.

impact much on the macro cell service via UE cooperation for mutual benefit in co-channel environment. The $M_m \times M_b$ matrix channel between the MBS and the $i$-th UE is denoted by $H_i$ and the $M_m \times M_f$ matrix channel between the FAP and the $j$-th UE is denoted by $G_j$. The elements of these channel matrices (including the channel $G_{2,1}$) are independent identically distributed (i.i.d.) $\mathcal{CN}(0,1)$ random variables. The UE relay $M_S1$ in the femto cell uses the D2D uplink resource of a time-division duplex (TDD) frame to relay the overheard composite signal from MBS and FAP. We assume that the amplify-and-forward protocol is used for the UE relaying, and the access to the D2D resource is a priori approved by the network. Note that the D2D resources spatially reuse underutilized macro uplink channels because of the asymmetry existing in uplink and downlink traffics.

Let the precoders at MBS and FAP be $p_b$ and $p_f$ with dimensions $M_b \times 1$ and $M_f \times 1$, respectively. In the downlink transmission, MBS and FAP send the message symbols $x_b$ and $x_f$ ($E[\|x_b\|^2] = P_b$, $E[\|x_f\|^2] = P_f$, $P_b$ and $P_f$ are the power at MBS and FAP, respectively, through their antennas. We assume that the path-loss effect is absorbed in $P_b$ and $P_f$ and that the victim MUE $M_S2$ is much closer to FAP than MBS ($P_f \gg P_b$). The received $M_m \times 1$ vector signals at $M_Sj$, $j \in \{1, 2\}$ is given by

$$y_j = H_j p_b x_b + G_j p_f x_f + n_j$$

where the vector $n_j$ is the $\mathcal{CN}(0, I)$ distributed noise. The UE relay $M_S1$ applies a $M_m \times M_h$ helper beamformer (HBF) $W$ to the received signal in (1) and transmits the product vector $W y_j$ in the uplink transmission. Here, $M_S2$ is assumed to have acquired the channel status information (CSI) with regard to $M_S1$, such as $G_{2,1}$, $H_1$, and $G_1$ through a channel training procedure. From the acquired CSI information, $M_S2$ decides the BF at the nodes and notifies $M_S1$ BF information via a feedback channel in the closed-loop mode. In the downlink transmission, $M_S2$ applies the $M_m \times 1$ reception BF $q_d$ to $y_2$. If $q_d$ is the $M_m \times 1$ reception BF of $M_S2$ in the uplink transmission, the signal received at $M_S2$ in the uplink transmission is

$$r_2^u = q_d^H [G_{2,1} W y_1 + n'_2] = q_d^H G_{2,1} W H_1 p_b x_b + q_d^H G_{2,1} W G_1 p_f x_f + \tilde{n}_2$$

(2)

where $\tilde{n}_2 = q_d^H [G_{2,1} W n_1 + n'_2]$ and the vector $n'_2$ is the $\mathcal{CN}(0,1)$ distributed noise. $M_S2$ uses the dual-stage MRC principle to decode the weak desired signal $x_b$. For this, it first decodes the interference signal $x_f$ and then subtracts out the interference terms from (1) and (2).5

III. HBF (W) AND DUAL-STAGE MRC

A. HBF (W) at UE Relay $M_S1$

Suppose the precoders ($p_b$, $p_f$) and the receive BF ($q_d$) are determined, then we can redefine the channels matrices as

$$h_i = H_i p_b, \quad i = 1, 2$$
$$g_j = G_j p_f, \quad j = 1, 2$$
$$\tilde{G}_{2,1} = \tilde{G}_{2,1}^H q_d.$$ (3)

The signal models in (1) and (2) can equivalently be rewritten, respectively, as

$$y_j = h_j x_b + g_j x_f + n_j$$
$$r_2^u = \tilde{G}_{2,1} W h_1 x_b + \tilde{G}_{2,1} W g_2 x_f + \tilde{n}_2.$$ (4)

Though we will optimize the HBF $W$ for the UE relay $M_S1$, a straightforward approach to design the HBF is to suppress the signal from FAP so that the victim MUE $M_S2$ can decode the message $x_b$ from MBS. If the receiver at $M_S2$ is a single stage and tries to maximize the signal-to-interference-plus-noise ratios (SINRs) for $x_b$, the optimal BF at the UE relay should be the minimum variance distortion-less receiver or the Capon receiver[36], [37]. It is an appropriate approach when $M_S1$ only has the CSI of $h_1$, $g_1$, and $\tilde{g}_{2,1}$. The HBF $W$ based on the Capon receiver can be defined as

$$W_{Capon} = \rho b a^H$$

where $\rho$ is the power scaling factor to be defined later and $a = (R_{1,1})^{-1} h_1 / (h_1^H R_{1,1} h_1)$ with $R_1 = g_1 g_1^H P_f + I_n$. If we use the maximal-ratio transmission for the relay link, then $b$ is the normalized vector of $\tilde{g}_{2,1}$, the channel direction toward $M_S2$.

There are two approaches for the power scaling factor $\rho$ depending on the required channel knowledge at the UE relay [38]–[40]. When the instantaneous channel knowledge is available at the UE relay, the variable gain (VG) factor is found as

$$\rho_{VG} = \sqrt{\frac{P_1}{|a^H h_1|^2 P_b + |a^H g_1|^2 P_f + 1}}$$

4Note that the CSI between the two nearby UEs $G_{2,1}$ is assumed to be acquired for D2D connection while $H_i$ and $G_i$ being estimated by processing the source-relay-destination CSI with the known relay-destination CSI $G_{2,1}$ at $M_S2$, assuming two orthogonal pilot transmissions from MBS and FAP toward $M_S1$.

5The interference from FAP hinders the reception of the MBS transmission though the original MBS transmit power may be stronger than that of FAP.
where \( P_1 \) is the UE relay power. If only the statistical knowledge of the channel is available, the fixed gain (FG) factor is found as

\[
\rho_{FG} = \sqrt{\frac{P_1}{P_b + P_f + 1}}.
\]

B. Dual-Stage MRC at Victim MUE MS\(_2\)

Note that MBS and FAP decide the precoders \((p_b, p_f)\) according to the strategies taken to support multiple users in their cells. Hence, they are a priori given when we consider the cooperative UE relaying over D2D uplink. On the other hand, there are two receive BFs being used by the victim MUE MS\(_2\) for the downlink \(q_d\) and uplink \(q_u\), respectively. The outputs of two BFs provide the diversity reception of the composite signals (direct signal and relayed signal), which incurs about twice complexity compared to single branch reception. The BFs are designed to enhance the interference strength such that the interference subtraction stage at the dual-stage MRC can succeed and pass an interference-free signal to the final stage for data decoding. It is reasonable to use the most strong left eigenvector of \(G_{2,1}\). Fig. 2 shows the receiver structure of MS\(_2\), where two inputs from downlink (1st phase) and uplink (2nd phase) are processed by these BFs with one phase delay operation for downlink transmission and merged into the MRC1 block. The output of the BF \(q_d\) at the lower branch of Fig. 2 is given by

\[
r^d_2 = q^H_d y_2 = q^H_d h_2 x_b + q^H_d g_2 x_f + q^H_d n_2.
\]

The two receiver output statistics \(r^u_2\) in (4) and \(r^d_2\) in (5) are fed into the first stage of dual-stage MRC, where the estimate \(\hat{x}_f\) of the interference signal \(x_f\) is made with the MRC combining weights \(g^H_{2,1} W_1\) and \(q^H_d h_2\), respectively. Then, the first-stage MRC produces the SINR as

\[
SINR_1 = SINR_{u,1} + SINR_{d,1}.
\]

\[
SINR_{u,1} = \frac{|g^H_{2,1} W_1|^2 P_f}{|g^H_{2,1} W_1|^2 P_b + \|W^H g_{2,1}\|^2 + 1},
\]

\[
SINR_{d,1} = \frac{|q^H_d h_2|^2 P_f}{|q^H_d h_2|^2 P_b + 1}.
\]

Based on the decision on \(x_f\) at the first-stage MRC, the SIC stage subtracts out the terms involved with \(x_f\) from (4) and (5). Suppose \(SINR_1\) is strong enough to decode \(x_f\) successfully, then the \(SINR_2\) at the second-stage MRC, where the desired signal \(x_d\) is decoded with the MRC combining weights \(g^H_{1} W_1\) and \(q^H_d h_2\), respectively, is expressed by

\[
SINR_2 = SINR_{u,2} + SINR_{d,2},
\]

\[
SINR_{u,2} = \frac{|g^H_{2,1} W_1|^2 P_b}{\|W^H g_{2,1}\|^2 + 1},
\]

\[
SINR_{d,2} = \frac{|q^H_d h_2|^2 P_b}{|q^H_d h_2|^2 P_b + 1}.
\]

IV. Adaptive Beamformer Control

In this section, we consider the optimization schemes of the beamformers \(q_d\) and \(a\) for the dual-stage MRC receiver. Given that the data rates of \(x_f\) and \(x_d\) are \(w_f\) and \(w_d\), respectively, we can find the required SINRs at MRC1 and MRC2 to decode these signals as \(\eta_1\) and \(\eta_2\), respectively. Recall that the HBF is given by \(W = \rho a h^H\), where \(b\) is the normalized vector of \(g_{2,1}\) and \(\rho\) is the power scaling factor. Therefore, the optimal beamforming can be formulated as

\[
(a, q_d) = \arg \max SINR_2
\]

s.t. \(SINR_1 \geq \eta_1, \|a\| = 1, \|q_d\| = 1\).

Let \(\gamma_2 = \rho^2 \|g_{2,1}\|^2\), then we have the expressions in (10), shown at the bottom of the next page.

A. Open Loop Mode (Optimal \(q_d\) with Fixed \(a\))

Suppose the HBF \(W\) is fixed, for example, as \(W_{\text{Capon}}\), the Capon based beamforming matrix. MS\(_2\) has the channel status knowledge not only of those toward itself \((h_2, g_{2,1})\) but also of those toward MS\(_1\) \((h_1, g_1)\). Let \(\gamma_0 = |a^H h_1|^2\) and \(\gamma_1 = |a^H h_2|^2\), then the optimization in (9) is reformulated as (11), shown at the bottom of the next page, and further simplified as

\[
q_d = \arg \max_{\gamma_2} \frac{\gamma_1 \gamma_2 P_b + (\gamma_2 + 1) |q^H_d h_2|^2 P_b}{\gamma_2 + 1}
\]

s.t. \(\alpha |q^H_d h_2|^2 - |q^H_d h_2|^2 \leq \delta, \|q_d\| = 1\), where

\[
\alpha = (\eta_1 (\gamma_1 P_2 + \gamma_2 + 1) - \gamma_0 \gamma_2 P_f) P_b,
\]

\[
\beta = (\gamma_1 \gamma_2 P_b + \gamma_2 + 1) P_f,
\]

\[
\delta = -\alpha / P_b.
\]
We need to search over the space of complex unit-norm vectors to find an optimal \( \mathbf{q}_d \) in (12). Since the effective channel vectors for \( MS_2 \) are \( \mathbf{h}_2 \) and \( \mathbf{g}_2 \), we can construct \( \mathbf{q}_d \) as shown in Fig. 3, based on the geodesic curve between the two vectors\(^6\) [32], [33]. This way we can avoid searching over the whole complex unit-norm vectors by parameterizing the angle. Since only the magnitude of a BF output is of concern, we consider only the smaller angle \( \Psi \) that the two channel vectors make here. Also, note that the construction of a geodesic geometry based BF is possible only if \( m \geq 2 \). We have \( \| \mathbf{q}_d^H \mathbf{h}_2 \|^2 = \cos^2(\psi) \| \mathbf{h}_2 \|^2 \)

\[
\| \mathbf{q}_d^H \mathbf{g}_2 \|^2 = (\cos(\psi) \cos(\Psi) + \sin(\psi) \sin(\Psi))^2 \| \mathbf{g}_2 \|^2 = \cos^2(\Psi - \psi) \| \mathbf{g}_2 \|^2.
\]

The solid red curve in Fig. 4 shows the trajectory made by \( (\mathbf{q}_d^H \mathbf{h}_2^2, \| \mathbf{g}_2 \|^2) \). The green or blue area is the region where the inequality \( \| \mathbf{q}_d^H \mathbf{g}_2 \|^2 \geq \frac{\alpha}{\beta} \| \mathbf{q}_d^H \mathbf{h}_2 \|^2 - \frac{\beta}{\alpha} \) of (12) holds.

Certainly, the optimal \( \mathbf{q}_d \) is the one maximizing \( \| \mathbf{q}_d^H \mathbf{h}_2 \|^2 \) within the constrained area. Therefore, the optimal \( \mathbf{q}_d \) is the one with the largest \( \| \mathbf{q}_d^H \mathbf{h}_2 \|^2 \) among the points where the red curve and the green or blue line meet. When \( \frac{\beta}{\alpha} < 0 \) (the green line case in Fig. 4), \( \gamma_1 \gamma_2 P_f > \eta_1 (\gamma_1 \gamma_2 P_f + \gamma_2 + 1) \) and the signal from FAP to \( MS_1 \) is strong enough to likely decode \( x_f \). Note that \( \delta = -\alpha/\beta \) and the green line (a) always intersects the \( \| \mathbf{q}_d^H \mathbf{g}_2 \|^2 \) axis with a non-negative value (vice versa for the blue line). The outage event (MRC1 fails to decode \( x_f \) because \( SINR_1 \) is less than \( \eta_1 \)) never happens. When the signal from FAP to \( MS_1 \) is not strong enough (\( \frac{\beta}{\alpha} \geq 0 \), the blue line case in Fig. 4), the blue line always intersects the \( \| \mathbf{q}_d^H \mathbf{g}_2 \|^2 \) axis with a non-negative value. When the red curve is not included in the blue region, the outage event that MRC1 fails to decode \( x_f \) occurs. When the red curve and the blue line meet, the optimal \( \varphi^* \) can be determined as

\[
\alpha \cos^2(\varphi^*) \| \mathbf{h}_2 \|^2 - \beta \cos^2(\Psi - \varphi^*) \| \mathbf{g}_2 \|^2 = \delta, \ \ \ 0 \leq \varphi^* \leq \Psi
\]

which can easily be solved by numerical methods like the bisection search. The optimal \( SINR_2 \) is then derived as

\[
SINR_2 = \frac{\gamma_1 \gamma_2 P_f + (\gamma_2 + 1) \cos^2(\varphi^*) \| \mathbf{h}_2 \|^2 P_b}{\gamma_2 + 1}.
\]

When the solution of (13) is an empty set, we meet an outage event (\( SINR_1 < \eta_1 \)). Then, we ignore the MRC1 and the SIC stages, and pass the received signals on to MRC2 block directly.

\[
SINR_1 = \frac{\gamma_2 \| \mathbf{a}^H \mathbf{g}_1 \|^2 \gamma_2 P_f (\| \mathbf{q}_d^H \mathbf{h}_2 \|^2 P_b + 1) + \| \mathbf{q}_d^H \mathbf{g}_2 \|^2 \| \mathbf{a}^H \mathbf{h}_1 \|^2 P_b + \gamma_2 + 1)}{\gamma_2 \| \mathbf{a}^H \mathbf{h}_1 \|^2 P_b + \gamma_2 + 1} (\| \mathbf{q}_d^H \mathbf{h}_2 \|^2 P_b + 1) \]

\[
SINR_2 = \frac{\gamma_2 \| \mathbf{a}^H \mathbf{h}_1 \|^2 P_b + (\gamma_2 + 1) \| \mathbf{q}_d^H \mathbf{h}_2 \|^2 P_b}{\gamma_2 + 1}.
\]

(10)

\[
\mathbf{q}_d = \arg \max \frac{\gamma_1 \gamma_2 P_f + (\gamma_2 + 1) \| \mathbf{q}_d^H \mathbf{h}_2 \|^2 P_b}{\gamma_2 + 1} \]

s.t. \( \eta_1 (\gamma_1 \gamma_2 P_f + \gamma_2 + 1) (\| \mathbf{q}_d^H \mathbf{h}_2 \|^2 P_b + 1) \leq \left( \gamma_1 \gamma_2 P_f (\| \mathbf{q}_d^H \mathbf{h}_2 \|^2 P_b + 1) + \| \mathbf{q}_d^H \mathbf{g}_2 \|^2 P_f (\gamma_1 \gamma_2 P_f + \gamma_2 + 1) \right), \| \mathbf{q}_d \| = 1.
\]

(11)

---

\(^6\)On the sphere of unit-norm Euclidean space, the geodesic curve is the circular line segment connecting two unit-norm vectors.
to operate in a single stage receiver mode. In this case, we use the Capon BF for the downlink as \( q_d = R_2^{-1} h_2 / (h_2 R_2^{-1} h_2) \), where \( R_2 = g_2 g_2^H P_f + I_{m_u} \). Note that choosing Capon based BFs at the UE relay and victim MUE corresponds to the optimal beamforming for the single stage receiver where the beamformed signals are fed to the final MRC2 block directly. Finally, the outage events occur if the optimal SINR is less than \( \eta_2 \) (i.e., MRC2 fails to decode \( x_b \) even with \( \text{SINR}_{\text{MRC2}} \geq \eta_1 \)) and \( \text{SINR}_{\text{1}} \) is less than \( \eta_2 \) (i.e., MRC2 fails to decode \( x_b \) even with \( \text{SINR}_{\text{1}} < \eta_1 \)).

\[
(a, q_d) = \arg \max_{\gamma_2} \gamma_2 \left| a^H h_1 \right|^2 P_b + (\gamma_2 + 1) \left| q_d^H h_2 \right|^2 P_b
\]

\[
s.t. \quad \alpha(\phi_1) \left| a^H h_2 \right|^2 - \beta(\phi_1) \left| q_d^H g_2 \right|^2 \leq \delta(\phi_1).
\]

\[
\gamma_2 \cos^2(\phi_1) \left| h_1 \right|^2 P_b + (\gamma_2 + 1) \cos^2(\phi) \left| h_2 \right|^2 P_b
\]

\[
\gamma_2 + 1 - \delta(\phi_1), \quad 0 \leq \phi \leq \Psi.
\]

\[
\text{SINR}_2(\phi_1) = \frac{\gamma_2 \cos^2(\phi_1) \left| h_1 \right|^2 P_b + (\gamma_2 + 1) \cos^2(\phi) \left| h_2 \right|^2 P_b}{\gamma_2 + 1}
\]

| \( M_m \times 1 \) received signal at \( MS_1 \) Signal at \( MS_2 \) during the downlink period Signal at \( MS_2 \) during the uplink period | \( y_j, j = 1, 2 \) |
|---|---|---|---|
| BFS message signal (data rate) | \( x_f \) | \( x_f \) |
| Femto message signal (data rate) | \( x_f \) | \( (\delta_f \gamma_1) \) |
| Femto message signals in two FAPs | \( x_f \) | \( x_f \) |
| Angular parameter for \( q_d \) (one FAP) | \( 0 \leq \phi \leq \Psi \) | \( 0 \leq \phi \leq \Psi \) | \( 0 \leq \phi \leq \Psi \) |
| Angular parameter for \( a \) (one FAP) | \( 0 \leq \phi \leq \Psi \) | \( 0 \leq \phi \leq \Psi \) | \( 0 \leq \phi \leq \Psi \) |
| Angular parameter for \( q_d \) (two FAPs) | \( 0 \leq \phi \leq \Psi \) | \( 0 \leq \phi \leq \Psi \) | \( 0 \leq \phi \leq \Psi \) |
| Angular parameter for \( a \) (two FAPs) | \( 0 \leq \phi \leq \Psi \) | \( 0 \leq \phi \leq \Psi \) | \( 0 \leq \phi \leq \Psi \) |

\[
\gamma_0 = \left| a^H g_1 \right|^2 \quad \text{increases} \quad \gamma_1 = \left| a^H h_1 \right|^2. \quad \text{Therefore, decreasing}
\]

\[
\gamma_1 = \cos^2(\phi_1) \left| h_1 \right|^2 \quad \text{reduces} \quad \text{the slope of the constraint equation}
\]

\[
\left| q^H g_2 \right|^2 = \frac{\eta}{\beta} \left| h_2 \right|^2 - \frac{\delta}{\beta}
\]

\[
\text{Also, note that reducing the slope decreases the intersect with the \( \left| q_d^H g_2 \right|^2 \) axis. In summary, we rotate the blue line in Fig. 4 of the constraint equation clockwise (though there is no exact pivot point) as we increase \( \phi_1 \). From Fig. 4, we can see that rotating the slope of blue line (b) clockwise results in a larger \( \left| q_d^H h_2 \right|^2 = \cos^2(\phi) \left| h_2 \right|^2 \) until the line becomes parallel with the horizontal axis where we are given \( \phi = 0 \), \( (q_d = h_2 \) or equivalently \( \alpha(\phi_1) = 0 \)).

\]

The numerator of \( \text{SINR}_2 \) expression in (17) has two terms behaving oppositely and monotonically as we vary \( \phi_1 \). We can reduce the search range of \( \phi_1 \) in the following steps:

- **Step 1:** Starting from \( \phi_1 = 0 \), if \( \alpha(\phi_1) / \beta(\phi_1) < 0 \), go to Step 2. If \( \alpha(\phi_1) / \beta(\phi_1) \geq 0 \), keep using (16) and (18) to find \( \phi_1 \) while increasing \( \phi_1 \). When \( \phi_1 \) reaches \( \Psi_1 \) or (16) results in \( \phi = 0 \) (or equivalently \( \alpha(\phi_1) = 0 \), stop.

- **Step 2:** Choose the argument angle \( \phi = 0 \) and \( \phi_1 = 0 \). Stop.

If we take Step 1, we search part of \( \phi_1 \) ranging from zero angle. When we skip Step 1 and take Step 2, we only investigate a single angle of \( \phi_1 = 0 \). In Table I, we summarize the variables and parameters used for the design of BFs, where \( \gamma_0, \gamma_1, \gamma_2, \) as well as \( h_1 \) and \( g_2 \), are the input parameters and \( \phi_1 \) and \( \phi_2 \) are the output parameters of the algorithm (13) and (18) in closed-loop mode. In open loop mode, \( \phi_1 \) is the only output of (13).

### C. Outage Performance Consideration

The channels considered herein belong to the interference channel with a multi-antenna UE relay. The optimal joint decoding of the desired signals from MBS and FAP is the maximum-likelihood decoding, and hence the proposed SIC based receiver structures are suboptimal. Thus, it is noteworthy that the beamforming schemes in this paper are optimal among only the class of SIC based receivers. It is well known that the SIC based receiver is beneficial when the interfering signal is strong enough to be decoded. The amount of interference intensity required for such receiver is reflected in the constraint \( \text{SINR}_{\text{1}} \geq \eta_1 \). To this end, the proposed schemes attempt to steer the BFs toward the desired signal directions (\( h_1 \) and \( h_2 \)) within...
the constraint $\text{SINR}_1 \geq \eta_1$. However, the constraint forces the BF parameters $\varphi$ and $\varphi_1$ to have non-zero values.

In the green area in Fig. 4, the interference from FAP to MS$_1$ is strong enough so that MRC1 is free of outage and thus we have $\gamma_2 \|g_1\|^2 \cos^2(\Psi_1)P_f > \eta_1 (\gamma_2 \|h_1\|^2 P_b + \gamma_2 + 1)$.

If we set $\varphi = 0$ and $\varphi_1 = 0$, the resulting $\text{SINR}_2$ becomes

$$\text{SINR}_2 = \gamma_2 \|h_1\|^2 P_b + (\gamma_2 + 1) \|h_2\|^2 P_b \frac{\gamma_2 + 1}{\gamma_2 + 1}.$$ (19)

Note that MRC2 outage occurs when $\text{SINR}_2 < \eta_2$ in (19). In the blue area in Fig. 4, MRC1 is trapped into the outage when the line (b) does not meet the red curve. Since the joint optimal BF rotates the blue line until it becomes parallel with the horizontal axis, the outage event occurs when the blue line does not meet the red curve even after $\varphi_1$ reaches $\Psi_1$. Mathematically, this case corresponds to

$$\alpha(\Psi_1) \cos^2(\Psi_1) \|h_2\|^2 - \beta(\Psi_1) \|g_2\|^2 > \delta(\Psi_1).$$ (20)

In general, the decoding of target data is possible when $\text{SINR}_1 \geq \eta_1$ and $\text{SINR}_2 \geq \eta_2$. However, note that there is a possibility of MRC2 decoding the message even with MRC1 in outage, where the UE relay and victim MUE are using the Capon BFs with the single stage receiver mode. Through simulations, we observe marginal outage gains with this receiver mode.

V. RESULTS

Simulation results are presented for the proposed beamforming methods with UE relaying cooperation in the HCN environment and assuming a single interfering FAP, the parameters of which are summarized in Table II. We consider the distance geometry where the UE relay $M$S$_1$ is at the boundary of a femto cell coverage (15 m) and the victim MUE is located at the distance 20 m to 50 m from FAP, as it approaches the femto cell coverage. Here, we assume that a femto cell is the home eNodeB (HeNB) proposed in the LTE-A standard document with propagation path loss and transmit power parameters in [41]. The heterogeneous path losses and transmit powers of the HCN follow from [42]. For illustration, we set the target spectral efficiencies of MBS and FAP to $w_p = w_f = w$.

The decoding success probability is evaluated at the victim MUE $M$S$_2$ for the proposed closed-loop multi-stage receiver (MSR), cooperative Capon based scheme (C-Capon) and non-cooperative Capon based scheme (NC-Capon) to show that the problem of victim MUE can effectively be resolved. Here, the C-Capon scheme refers to the one which applies the Capon BFs both at the UE relay and victim MUE, whereas the NC-Capon scheme refers to the one that applies the Capon BF at the victim MUE only without UE relaying cooperation. Note that these two schemes (NC-Capon and C-Capon) use the single stage receiver without SIC.

Fig. 5 shows the decoding success probability of the UE relaying based MSR, C-Capon and NC-Capon schemes versus the target spectral efficiency $w$ when the victim MUE is 20 meters away from the FAP and all the terminals involved use two antennas. Here, MSR(b) denotes the MSR scheme with $b$ bits feedback.
Fig. 6. The decoding success probability of MSR, C-Capon and NC-Capon schemes versus the target spectral efficiency \( w \) when the victim MUE is 20 meters or 50 meters away from FAP and all terminals involved use two antennas.

(\( W_{\text{Capon}} \)) while \( q_d \) is found from \( \varphi \) satisfying (13). The BF optimization with MSR at the victim MUE provides more than 0.5 bps/Hz gain over C-Capon at the success probability of 0.9. The gain of MSR depends on the number of feedback bits (closed-loop mode) though the effective gain saturates as the number of bits \( b \) approaches 4. The additional gain from this closed-loop optimization exceeds 1.0 bps/Hz at the success probability of 0.9.

In Fig. 6, the performances of various schemes according to the FAP-to-victim MUE distance are plotted. As the victim MUE approaches the FAP, more performance gain is achieved as the interference from FAP becomes more dominant. Also, note that NC-Capon scheme shows a limitation in handling the strong interference as it suffers more severely when the victim MUE is closer to the FAP, which suggests that the proposed UE relaying with MSR schemes is an effective remedy against the growing interference near the FAP.

Fig. 7 plots the effect of number of antennas used at the nodes, which demonstrates that a large number of antennas can be combined with MSR schemes in boosting the performance. Since two and four antennas are the most common and practical configurations in academia and industry standard (e.g., LTE), we consider only those cases for a single interfering FAP. Finally, the effect of the relay gain control (VG and FG) is shown in Fig. 8. The results strongly advocate the use of FG control since the performance advantage of using the UE relaying with VG is so marginal while the complexity gain at the UE relay and victim MUE (for the BF search) is obvious.

VI. EXTENSION TO TWO INTERFERING FAPs

Since FAPs are typically deployed by the subscribers not by the operators, the deployment pattern is quite random and the coverage of more than two FAPs may overlap. Or in rare cases, the FAP may support multiple UEs. In these cases, a MUE may be subject to the interference from multiple FAPs or multiple streams from a FAP. By focusing on the case of two interfering FAPs of interest in practice, we shed light on how the proposed idea can be generalized to handle the case of multiple interfering FAPs.

A. System and Signal Model

Suppose there, in Fig. 1, exists another FAP nearby, and it generates interference to \( MS_1 \) and \( MS_2 \) as well. Let the channel matrices from this FAP to \( MS_1 \) and \( MS_2 \) be \( F_1 \) and \( F_2 \), respectively and the precoded channel vectors be \( f_1 \) and \( f_2 \).

7We can assume that the multiuser interference can be suppressed by the precoding at the MBS when multiple users are supported by the MBS. Therefore, we can treat such case with the proposed scheme in the previous sections.
respectively. Let the first FAP be this newly added one and the second FAP be the one in the previous sections. The transmission powers at the first and second FAPs are given by $P_{f,1}$ and $P_{f,2} (< P_{f,1})$, respectively. Let $x_{f,1}$ and $x_{f,2}$ be the desired signals at the first and second FAPs, respectively, with the data rates $w_{f,1}$ and $w_{f,2}$.

At the UE relay $M_S$, the HBF $W$ can be constructed as before except for the scaling factor $\rho$, which is given for the VG and FG by

$$
\rho_{VG} = \frac{P_1}{|a^Hh_1|^2P_b + |a^Hf_1|^2P_{f,1} + |a^Hg_1|^2P_{f,2} + 1},
$$

$$
\rho_{FG} = \sqrt{P_b + P_{f,1} + P_{f,2} + 1}.
$$

At the victim MUE, a three-stage MRC is applied as shown in Fig. 9, where the same two-branch structure of Fig. 2 is preserved and the first two stages of MRCs subtract out the interference from two FAPs sequentially. The uplink and downlink receive BF $q_u$ and $q_d$ should be adapted according to the interference from two FAPs. Similarly as in Section II and Section III, the signal models of $r_u^d$ and $r_d^2$ can be rewritten as

$$
r_u^d = q_u^H(h_2x_b + f_2x_{f,2} + g_2x_{f,2} + n_2),
$$

$$
r_d^2 = q_d^H(W_1h_1x_b + f_1x_{f,1} + g_1x_{f,2} + n_2),
$$

where

$$
SINR_{d,1} = SINR_{u,d,1} + SINR_{d',1},
$$

$$
SINR_{2} = SINR_{u,d,2} + SINR_{d',2},
$$

$$
SINR_{3} = SINR_{u,d,3} + SINR_{d',3}
$$

and hence the combiner weights at each MRC unit can be similarly applied as before. The SINR values after MRC stages are given, respectively, by (22) and (23). Each SIC and the corresponding MRC stage are skipped if the SINR for the stage is less than the threshold of the stage, and then the received signals are passed on to the next stage as in Section III. Hence the number of stages in operation at the victim MUE varies as in Section III, where there are two cases (single and double stages) depending on the value of $\eta_1$. Here, we need to consider four cases depending on the values of $SINR_1$ and $SINR_2$ against $\eta_1$ and $\eta_2$, respectively.

B. The Beamformer Optimization

1. Open Loop BF: Similar to the previous sections, an optimization strategy for the case of two interfering FAPs can be formulated as

$$
(a, q_d) = \arg \max \quad SINR_3
$$

s.t. $SINR_1 \geq \eta_1, \quad SINR_2 \geq \eta_2, \quad ||a|| = 1, \quad ||q_d|| = 1.
$$

A new definition $\gamma_3 = |a^Hf_1|^2$ allows us to rewrite (24) as

$$
q_d = \arg \max \frac{\gamma_1(\gamma_2 P_b + (\gamma_2 + 1)|q_d^H h_2|^2P_b)}{\gamma_2 + 1}
$$

s.t. $\alpha_1|q_d^H h_2|^2 + \alpha_2|q_d^H g_2|^2P_{f,2} - \alpha_1|q_d^H f_2|^2 \leq -\frac{\alpha_1}{P_b}$,

$$
\alpha_2|q_d^H h_2|^2 - \beta_2|q_d^H g_2|^2 \leq \delta_2, \quad ||q_d|| = 1
$$

where

$$
\alpha_1 = (\eta_1(\gamma_1 P_b + \gamma_2 P_{f,2} + \gamma_2 + 1) - \gamma_2 \gamma_3 P_{f,1}) P_b,
$$

$$
\alpha_2 = (\eta_1(\gamma_1 P_b + \gamma_2 P_{f,2} + \gamma_2 + 1) - \gamma_2 \gamma_3 P_{f,1}) P_b,
$$

$$
\beta_2 = (\gamma_1 P_b + \gamma_2 + 1) P_{f,2},
$$

$$
\delta_2 = -\alpha_2/\beta_2.
$$

Note that the relations between $\alpha_2, \beta_2$ and $\delta_2$ are the same as those of $\alpha, \beta$ and $\delta$ in (12) except that $P_{f,2}$ is used instead of $P_f$.

If $M_m \geq 3$, we can construct the victim MUE downlink BF $q_u$ using the geodesic geometry based angles, as we have done for the case of two interfering FAPs. Since there are three channel vectors $(h_2, g_2$ and $f_2)$ involved at the victim MUE, we, with the two vectors $h_2$ and $g_2$ from the previous sections, find the third vector $f_2$ to form three orthonormal vectors.

When $H = [h_2, g_2]$, $f_2$ is the normalized vector of the vector $f_2 = (I_{M_m} - H(H^H H)^{-1}H^H) f_2$, the projection of $f_2$ onto the orthogonal space of $H$. With the angle definition $\Psi$ as before,
we need a new angle definition $\Omega = \sin^{-1}(\|f_2^\perp\|/\|f_2\|)$ to be the angle between $f_2$ and the plane spanned by $h_2$ and $g_2$. We can form the victim MUE downlink BF as

$$q_d = \cos(\omega) \cos(\phi) \chi^*(\phi) h_2$$

$$+ \cos(\omega) \sin(\phi) \chi^*(\phi) g_2,$$

with $0 \leq \phi \leq \Psi$, $0 \leq \omega \leq \Omega$.  \hfill (26)

Here, the phase correction factor $\chi(\phi)$ is given by $\chi(\phi) = (\cos(\phi) h_2^\perp + \sin(\phi) g_2^\perp)^H f_2$. In this way, $q_d$ can cover the spherical triangle region made by the three geodesic curves between $h_2$, $g_2$, and $f_2$. Note that $|q^H_d h_2|^2 = \cos^2(\omega) \cos^2(\phi) \|h_2\|^2$, $|q^H_d g_2|^2 = \cos^2(\omega) \cos^2(\Psi - \phi) \|g_2\|^2$ and $|q^H_d f_2|^2 = \cos^2(\Omega - \omega) \cos^2(\phi) \|f_2\|^2$.

Since the relations between $\alpha_2$, $\beta_2$ and $\delta_2$ are preserved as in (12), the plane made by $|q^H_d h_2|^2$ and $|q^H_d g_2|^2$ can be depicted as in Fig. 10 depending on the polarity of $\alpha_2/\beta_2$. The green lines are determined by the second constraint of (25) while the first constraint decides the blue lines, which results in the shaded wedge areas of the domains of the given problem. The blue lines meet the vertical axis when $|q^H_d g_2|^2 = \frac{\sigma_1|q^H_d f_2|^2 P_b}{\alpha_1 P_f^2} - \frac{1}{r_f^2}$ and meet the horizontal axis when $|q^H_d h_2|^2 = \frac{\sigma_1|q^H_d f_2|^2 P_b}{\alpha_1 P_f^2} - \frac{1}{r_f^2}$.

Thus, with a fixed, it is tempting to increase $|q^H_d f_2|^2$ by raising $\omega$ in (26) and lift the blue lines and the green lines toward the dashed lines to merge the segments of the red curve into the shaded areas. However, increasing $\omega$ contracts the trajectories (red curves) of $\cos^2(\omega) |q^H_d h_2|^2$, $\cos^2(\omega) |q^H_d g_2|^2$, which leads to the degraded $\text{SINR}_3$ as shown in (25).

When the interference from FAP2 is weak (the case (a) in Fig. 10), the optimal $\omega$ and $\varphi$ are determined when the red curve, the blue line, and the green line meet on a point. Thus, the optimal $\omega^*$ and $\varphi^*$ satisfy the two equations in (27), which can be solved, for example, by the two-dimensional bisection method. If a solution set for (27) is found, the SIC1 and the SIC2 stages can remove the interference, and the resulting optimal $\text{SINR}_3$ is given by

$$\text{SINR}_3 = \frac{(\gamma_1 \gamma_2 + (\gamma_2 + 1)) \cos^2(\omega^*) \cos^2(\varphi^*) \|h_2\|^2}{\gamma_2 + 1}.$$  \hfill (28)

For the case when the interference from FAP2 is strong (the case (b) in Fig. 10), the optimal $\omega$ and $\varphi$ are determined when the red curve and the blue line meet on a point in the horizontal axis (i.e., $\varphi^* = 0$). We only need to find the optimal $\omega^*$ from (29).

$$\text{SINR}_3 = \frac{(\gamma_1 \gamma_2 P_b + (\gamma_2 + 1) \cos^2(\omega) \cos^2(\varphi) \|h_2\|^2}{\gamma_2 + 1}.$$  \hfill (29)

When no solution of (27) or (29) exists in $0 \leq \omega \leq \Omega$, $0 \leq \varphi \leq \Psi$, outage events occur. Then, we skip some of MRC and SIC pairs and reduce the number of stages of the victim MUE receiver. If no solution of (27) exists, we turn the two FAP interfering model into the single FAP interfering model, and apply the method of Section IV-A. This is done by zero-forcing the interference components from a FAP at the UE relay and victim MUE. We can first zero-force the interference components from the first FAP ($f_1$ and $f_2$) as

$$r_2^d = q^H_d (l_m + f_2^H f_2/(|f_2^H f_2|))^{-1} y_2,$n

$$r_2^u = q^H_d (l_m + f_1^H f_1/(|f_1^H f_1|))^{-1} y_1.$$  \hfill (30)

If this model fails to identify the solution of (13) as well, we can similarly zero-force the interference components from the second FAP ($g_1$ and $g_2$) and test the solution of (13). Finally, if the second model fails as well, then we can reduce the victim MUE receiver to the single stage mode with Capon BF at the UE relay and victim MUE. In this case, the Capon
BFs are constructed with \( \mathbf{R}_1 = f_1 f_1 H P_{f,1} + g_1 g_1 H P_{f,2} + I_M \) and \( \mathbf{R}_2 = f_2 f_2 H P_{f,1} + g_2 g_2 H P_{f,2} + I_M \), respectively. In the case of Fig. 10(b), we try to zero-force the first FAP interference with the model of (30) if (29) does not render a solution. If this model fails to produce a solution, then we try the Capon based BFs.

**Observations:** Before going into the discussion on closed-loop BF, there are several points to note for the case where more than two FAPs (or, more than two streams from a FAP) are interfering.

- First, the victim MUE BF can be constructed by applying the geodesic geometric angles iteratively, as was done in (26).
- Second, the number of total victim MUE receiver stages needed is one more than the number of interfering FAPs while the number of constraint equations is the same as the number of interfering FAPs.
- Third, note that the first constraint of (25) is new and the second one is the same as the one in (12). As one more FAP is added to the signal model such as (21), the first constraint equation takes the form as the first one of (25) while the other constraint equations remain. Hence, the trajectory (i.e., the red curve) of \((|q_1^H h_2|^2, |q_2^H g_2|^2)\) shrinks and the other constraint lines are lifted as we steer the beam \( q_d \) toward the newly added interference vector direction.
- Finally, since the trajectory of \((|q_1^H h_2|^2, |q_2^H g_2|^2)\) is shrinking as more FAPs are added to the signal model, it becomes more difficult to decode the desired signal \( x_b \) though the beamforming at the victim MUE tries to enlarge the domain of the optimization by lifting the constraint lines. Reducing the number of stages by skipping some of MRC-SIC pairs may improve the situation and result in better performance.

2) **Closed-Loop BF:** Similarly as we have done in (26), we can form the UE relay BF vector \( \mathbf{a} \) as

\[
\mathbf{a} = \cos(\omega_1) \cos(\varphi_1) \chi_1^\dagger(\varphi_1) \tilde{\mathbf{h}}_1^1 + \cos(\omega_1) \sin(\varphi_1) \chi_1^\dagger(\varphi_1) \tilde{\mathbf{h}}_1^2 + \sin(\omega_1) \tilde{\mathbf{f}}_1^1,
\]

where the vectors \( \tilde{\mathbf{h}}_1^1, \tilde{\mathbf{f}}_1^1, \chi_1(\varphi_1), \xi_1 \) and angles \( \omega_1, \varphi_1 \) are defined similarly as before. We can rewrite (21) as (32), shown at the bottom of the page. Here, \( \alpha_1(\omega_1, \varphi_1), \sigma_1(\varphi_1), \alpha_2(\varphi_1), \beta_2(\varphi_1) \) and \( \delta_2(\varphi_1) \) are defined similarly as in Subsection IV-B to form the constraint inequalities. The optimal \( \mathbf{q}_d(\omega^*(\omega_1, \varphi_1), \varphi^*(\omega_1, \varphi_1)) \) for given \( \omega_1, \varphi_1 \) (hence for a given \( \mathbf{a} \)) can be found using (27). When the solution for \( (\omega, \varphi) \) in (27) is an empty set for given \( \omega_1, \varphi_1 \), we meet the outage event \( \text{SINR}_1 < \eta_1 \) and \( \text{SINR}_2 < \eta_2 \) and then \( \text{SINR}_3(\omega_1, \varphi_1) = 0 \). Note that \( \omega_1 \) does not appear on the right-hand side of \( \text{SINR}_3 \) expression in (33), shown at the bottom of the page, since it affects \( \alpha_1 \) (hence the first constraint) through \( \gamma_3 = |a^H h_1|^2 \).

For \( 0 \leq \omega_1 \leq \Omega_1 \) and \( 0 \leq \varphi_1 \leq \Psi_1 \), we find \((\omega^*(\omega_1, \varphi_1), \varphi^*(\omega_1, \varphi_1))\) and \( \text{SINR}_3(\omega_1, \varphi_1) \) using (27) and (33), respectively, where the optimal \( (\omega_1, \varphi_1) \) is computed from

\[
(\omega_1^*, \varphi_1^*) = \arg \max_{0 \leq \omega_1 \leq \Omega_1, 0 \leq \varphi_1 \leq \Psi_1} \text{SINR}_3(\omega_1, \varphi_1)
\]

for the optimal \( \text{SINR}_3(\omega_1^*, \varphi_1^*) \). Finally, the outage event occurs if the optimal \( \text{SINR}_3(\omega_1^*, \varphi_1^*) \) is less than \( \eta_3 \) (MRC3 fails to decode \( x_b \)). For the UE relaying with FG, we learned in Subsection IV-B that the search for the joint optimal \( \varphi_1 \) can be simplified by rotating the constraint line. The search range of \( \varphi_1 \) can be reduced if we embed Step 1 and Step 2 in the search over \( 0 \leq \omega_1 \leq \Omega_1 \) and \( 0 \leq \varphi_1 \leq \Psi_1 \).
C. Further Results

Fig. 11 shows the outage performance of the UE relaying with MSR when there are two interfering FAPs, one is 20 meters away from the victim MUE and the other is 30 meters away from the victim MUE. The target spectral efficiencies are set to $w_{f} = w_{f1} = w_{f2}$ and three antennas are used at each of the involved node. Note that the numbers of feedback bits are doubled since two angles among three channel vectors are involved in (31) and the number of antennas at nodes should be $M_{n} \geq 3$ to remove the interference from two FAPs. With two interferers, it is hard to imagine that the MSR can pass through the stages so that it can avoid the outage in decoding $x_{b}$ at the final stage. Surprisingly, Fig. 11 shows that the beamforming at the victim MUE and UE relay makes the MSR still effective for improving the outage performance compared to those of NC-Capon and C-Capon. Here, a similar behavior as we have seen in Fig. 5 for the case of a single interfering FAP is observed, and thus the use of MSR with two stages is advocated.

VII. CONCLUSION

We have proposed the UE relaying scheme with multiple antennas coordinated beamforming to resolve the issue of victim MUE in heterogeneous cellular networks with D2D communication between peer UEs nearby. In this case we expect the UE relay close by the interfering FAPs to help the victim MUE strengthen the interference signal for subsequent SIC and then decode the weak desired signal at the final stage. Toward this, the proposed UE relaying cooperation effectively realizes the MS-MRC for signal and interference combining that results in improved decoding performance at the victim MUE. Further, additional performance gain of the proposed scheme can be achieved by realizing a closed-loop beamformer control for both VG and FG control at the UE relay. The proposed scheme becomes more effective when the victim MUE approaches the FAPs and suffers from more severe interference by those FAPs.

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Abstract—We consider beamformer optimization for user equipment (UE) relaying cooperation in heterogeneous cellular networks (HCNs), where the interference from femto cells nearby aggravates the signal-to-interference-plus-noise ratio (SINR) of a macro UE (MUE). A femto UE acts as a relay over device-to-device (D2D) uplink and forward to the MUE, the composite of desired signal and interference to improve the post SINR of the MUE. The beamformers of the UE relay and MUE collaborate to make a balance between the two signals so that the output signal after multistage maximal-ratio combining (MS-MRC) yields a sufficient post SINR for the desired signal. We first consider the case with a single interfering femto access point (FAP) and show that the beamforming for dual-stage MRC can effectively handle the interference. Then, the idea is generalized to the case of two interfering FAPs with a three-stage MRC. A geodesic geometry view allows us to parameterize the BF design with the angles that the involved channel vectors make. This approach makes the optimization of the BF simpler, reduces the feedback overhead, and provides better insight into the problem at hand. Simulations are carried out to validate the performance of the UE relaying cooperation in HCN environments.

Index Terms—Heterogeneous cellular networks (HCNs), UE relaying, D2D uplink, coordinated beamforming, multistage MRC.

I. INTRODUCTION

As the number of wireless devices is rapidly growing, it has put undue burden on the network due to the huge increase of data traffic to deal with. To overcome the problem with congestion and imperfect coverage, small-cell based approach with low power and small coverage area has come into the spotlight. Heterogeneous cellular networks (HCNs) is the term used to describe the resulting networks, where macro cells and small (e.g., femto and pico) cells overlap their coverage for faster and more reliable services to overall users and reduce the shadow areas. Despite these advantages of HCNs, it is feared that they cause significant co-tier and cross-tier interferences [1]–[4]. However, recent study based on stochastic geometry reveals that HCNs are robust to the co-tier and cross-tier interferences [5]–[9], as long as users in HCNs are allowed to access their nearby small-cell access points.

In femto cells, users can connect to any femto access point (FAP) in open subscriber group policy (OSG) or they can connect only to allowed FAPs in closed subscriber group (CSG) policy. In OSG, macro user equipments (UEs) can mitigate the interference from FAPs by switching their associations to the interfering FAPs. With CSG policy, however, macro UEs are not allowed to change the associations so that they are subject to the co-tier and cross-tier interferences when they are approaching the FAPs. In this situation, careful handling of the interference results in better performance of the wireless networks. Up to date, there have been numerous proposals to reduce such interference from coexisting small cells including those in the 3GPP standards [10]–[13]. On the one hand, allocating dedicated radio resources to interfering cells removes the cross-tier interference [2], but it decreases an overall spectral efficiency. On the other hand, controlling the transmit power of FAP is one way for interference coordination [3], [4], but if a macro UE (MUE) comes within the service area of FAP, it may not work due to the severe cross-tier interference.

In recent years, cooperative transmission via relay has been used primarily to improve the overall system capacity or to obtain a diversity gain [14]. Unlike conventional relaying to strengthen the desired signal, the relay can be utilized for forwarding the composite of desired signal plus interference [15], [16], so that the receiver at a victim MUE first decodes the strong interference, subtracts it out, and then decodes the weak desired signal in a balanced way [17]. Note that the interference subtraction approach is well discussed in cellular LTE-HetNet standard [10], [11] to handle the cross-tier interference at UE side. In this paper, we propose the UE relaying cooperation with multi-stage maximal-ratio combining (MS-MRC) to resolve the critical interference issue of the victim MUE in HCNs. We first consider the case of a single interfering FAP and extend to the case of two interfering FAPs to show how the idea can be generalized to the case of multiple interfering FAPs. We assume that the victim MUE is located far from its serving macro base station (MBS) but is approaching the coverage of FAPs which are accessible by the CSG only. The victim MUE connected to the MBS is not in the CSG of a FAP, but there is a UE nearby in

1The CSG policy is a more natural option for femto cells since the femto cells are private devices.
the CSG of the FAP which can help relay the composite signal
with amplify-and-forward protocol.\(^2\)

In this scenario, the UEs nearby can utilize D2D communication [21] for the UE relaying. The D2D function here enables the peer UEs to set up the relay link with measured transmit power and channel status. Especially, the UE relaying is realized in conjunction with the MS-MRC performed at the victim MUE receiver. The front stages of MS-MRC are performed to decode the strong interference signals sequentially by combining those in two-phase transmissions, one from the FAP and the other from the UE relay. Meanwhile, the final stage of the MS-MRC is to decode the desired signal. Hence, the MS-MRC receiver is like a multi-antenna version of the successive interference cancellation (SIC) based multi-stage receiver [22], [23] for the strong interference channel.

The interference control via distributed relay in the context of interfering multiple peer-to-peer pairs was addressed in [24]–[26]. However, the problem considered herein is different from those since there is a single peer-to-peer link with strong cross-tier interference. When interference exists at the single antenna relay and destination, the performance of cooperative relay transmission was presented in [27]–[29]. Differences in this paper are that we allow UEs to have multiple antennas for the UE relaying and the decoding at the destination is based on the MS-MRC. The beamforming (BF) at UEs helps coordinate the multi-stage SIC operation at the MS-MRC receiver.

The BF for multi-antenna channels in conjunction with the SIC was considered in [30], [31]. However, the BF for the UE relaying and MS-MRC will need to steer the beams both at the UE relay and victim MUE, in a coordinated manner. Consequently this coordinated BF design requires extra overhead in computational complexity and feedback information such as the estimation of channels involved, the signal processing for dual-stage MRC receiver, the control signaling for D2D connection, and the BF information exchange in closed-loop mode.\(^3\) In this paper, the BF information feedback is shown to be in trade-off relation with the performance. To facilitate the BF design, we take a geodesic geometry approach [32], [33] to parameterize the BF, based on the angle that the channel vectors from MBS and FAP toward the UE relay and victim MUE make. Similar BF approaches were taken in [34], [35] as well, though in the multi-input multi-output (MIMO) relay network and virtual MIMO context, respectively. This geometry based BF design not only allows a simplified search over the BF space but also provides us with a systematic view of the problem.

The main contributions of this paper are summarized as:

- First, we design the BF suitable for the UE relaying with dual-stage MRC when there is a single interfering FAP.

1) We design a victim MUE BF when the UE relay
BF is fixed and operated in open loop mode. From

\(^2\)In 3GPP standard [18], UE relaying through the device-to-device (D2D) channel [19] has been considered. Energy harvesting based relaying [20] is an approach to justify the UE cooperation in such a way that UE relays can exploit the harvested energy for the cooperation and save the batteries for their own sustainability. As for the benefit, femtocell coverage can be increased by virtue of UE cooperation in HCNs.

\(^3\)Note that the intercell interference coordination (ICIC) based on SIC, employed for the interference mitigation in HCNs (e.g., LTE-HetNet), requires a similar processing overhead and time for implementation [10], [11].

the BF design based on the two channel vectors from MBS and FAP toward the victim MUE, we find the trajectory of the victim MUE BF on the plane made by the magnitude squares of these channel vectors. With the dual-stage MRC employed, the search turns out to be an angle search.

2) We design a set of joint BFs in closed-loop mode (i.e., a coordinated manner) both at the UE relay and victim MUE. Here, the victim MUE optimizes the two angles associated with joint BFs at both nodes and informs the UE relay of the angle information through the feedback channel.

3) When the optimization does not provide any feasible solution, and the first stage falls in an outage event, we simply resort to a single stage receiver with Capon beamformers [36], [37].

- We then generalize this idea to the case of multiple interfering FAPs where joint BFs are further optimized to facilitate the UE relaying with MS-MRC.

The rest of the paper is organized as follows. In Section II, we describe the system model and problem definition when there is a single interfering FAP. Section III presents the signal model for the UE relaying via D2D uplink, along with the dual-stage MRC receiver. In Section IV, we provide a geometry based BF design and address the issue of feedback channel design. Simulation results are presented in Section V to validate the performance gain offered by the proposed scheme. Finally, the proposed idea is generalized to the case of multiple interfering FAPs in Section VI and concluding remarks are given in Section VII.

**Notations:** The bold lower case letter represents a vector and the bold upper case letter represents a matrix. The notations \(A^{-1}, A', A^{H}, A^T\) and \(Tr[A]\) are the inverse, the transpose, the Hermitian transpose, the pseudo inverse and the trace of a matrix \(A\), respectively. \(I_n\) denotes the identity matrix of size \(a \times a\). \(A^+\) and \(|a|\) denote the projection onto the space orthogonal to the columns of \(A\) and the norm of a vector \(a\), respectively. For a complex number \(e^{j\theta}\) denotes the complex conjugate of \(c\). \(|A|\) denotes the cardinality of a set \(A\). \(CN(0, \mathbf{C})\) denotes the complex white Gaussian random vector with zero mean vector \(\mathbf{0}\) and the covariance matrix \(\mathbf{C}\).

**II. System Model**

In Fig. 1, a picture of HCN is shown where there is a single interfering FAP and the MUE \(M_{S2}\) approaching the coverage of the FAP suffers from its interference (red channel \(G_2\)). The MBS has \(M_{b}\) antennas and the FAP has \(M_{f}\) antennas while each UE is equipped with \(M_{m}\) antennas. During the downlink transmission, the MBS and FAP share the same spectral resource to serve users in their coverage areas, which causes the MUEs to suffer from the strong interference coming from the FAP nearby. The femto UE \(M_{S1}\) within its coverage area (and is not necessarily being served by the FAP) overhears the interfering signal and possibly helps the victim MUE \(M_{S2}\) via D2D uplink \(G_{2,1}\) by forwarding the composite signal toward \(M_{S2}\). In this way, FAPs can inhabit the macro cell coverage without...
is given by a reception BF matrix channel between the FAP and the P

\[ y_2 = q_2^H [G_{2,1} W y_1 + n'_2] \]

\[ = q_2^H \tilde{G}_{2,1} \tilde{W} H \tilde{p}_b \tilde{x}_b + q_2^H \tilde{G}_{2,1} \tilde{W} G_1 \tilde{p}_f \tilde{x}_f + \tilde{n}_2 \]  

(2)

where \( \tilde{n}_2 = q^2_2 [G_{2,1} W n_1 + n'_2] \) and the vector \( n'_2 \) is the \( \mathbb{C} \mathbf{N}(0, 1) \) distributed noise. The UE uses the dual-stage MRC principle to decode the weak desired signal \( x_b \). For this, it first decodes the interference signal \( x_f \) and then subtracts out the interference terms from (1) and (2).

III. HBF (W) AND DUAL-STAGE MRC

A. HBF (W) at UE Relay \( M\text{S}_1 \)

Suppose the precoders \( (p_b, p_f) \) and the receive BF \( (q_b) \) are determined, then we can redefine the channels matrices as

\[ h_i = H_i p_b, \quad i = 1, 2 \]

\[ g_j = G_j p_f, \quad j = 1, 2 \]

\[ \tilde{G}_{2,1} = \tilde{G}_{2,1}^H q_b. \]

(3)

The signal models in (1) and (2) can equivalently be rewritten, respectively, as

\[ y_j = h_j x_b + g_j x_f + n_j \]

\[ r'_2 = \tilde{g}_{2,1} \tilde{W} h_1 x_b + \tilde{g}_{2,1} \tilde{W} g_1 x_f + \tilde{n}_2. \]

(4)

Though we will optimize the HBF \( W \) for the UE relay \( M\text{S}_1 \), a straightforward approach to design the HBF is to suppress the signal from FAP so that the victim MUE \( M\text{S}_2 \) can decode the message \( x_b \) from MBS. If the receiver at \( M\text{S}_2 \) is a single stage and tries to maximize the signal-to-interference-plus-noise ratios (SINRs) for \( x_b \), the optimal BF at the UE relay should be the minimum variance distortion-less receiver or the Capon receiver[36], [37]. It is an appropriate approach when \( M\text{S}_1 \) only has the CSI of \( h_1, g_1 \) and \( \tilde{g}_{2,1} \). The HBF \( W \) based on the Capon receiver can be defined as

\[ W_{\text{Capon}} = \rho b a^H \]

where \( \rho \) is the power scaling factor to be defined later and \( a = (R_1)^{-1} h_1 + (R_1)^{-1} h_1 \) with \( R_1 = g_1 g_1^H + P_f I_{M_n} \). If we use the maximal-ratio transmission for the relay link, then \( b \) is the normalized vector of \( \tilde{g}_{2,1} \), the channel direction toward \( M\text{S}_2 \).

There are two approaches for the power scaling factor \( \rho \) depending on the required channel knowledge at the UE relay [38]–[40]. When the instantaneous channel knowledge is available at the UE relay, the variable gain (VG) factor is found as

\[ \rho_{\text{VG}} = \sqrt{\frac{P_1}{|a^H h_1|^2 P_b + |a^H g_1|^2 P_f + 1}} \]

The interference from FAP hinders the reception of the MBS transmission though the original MBS transmit power may be stronger than that of FAP.
where \( P_1 \) is the UE relay power. If only the statistical knowl-
edge of the channel is available, the fixed gain (FG) factor is
found as

\[
\rho_{FG} = \frac{P_1}{\sqrt{P_b + P_f + 1}}
\]

which, without causing much performance loss, can be approx-
imated as

\[
\rho_{FG} = \sqrt{\frac{P_1}{P_b + P_f + 1}}.
\]

### B. Dual-Stage MRC at Victim MUE MS_2

Note that MBS and FAP decide the precoders \((p_b, p_f)\)
according to the strategies taken to support multiple users in
their cells. Hence, they are \textit{a priori} given when we consider the
cooperative UE relaying over D2D uplink. On the other hand,
there are two receive BFIs being used by the victim MUE MS_2
for the downlink \((q_d)\) and uplink \((q_u)\), respectively. The outputs
of two BFIs provide the diversity reception of the composite sig-
als (direct signal and relayed signal), which incurs about twice
the complexity compared to single branch reception. The BFIs
are designed to enhance the interference strength such that the
interference subtraction stage at the dual-stage MRC can suc-
ceed and pass an interference-free signal to the final stage for
data decoding. It is reasonable for \( q_d \) to be the most strong left
eigenvector of \( \tilde{G}_2.1 \). Fig. 2 shows the receiver structure of MS_2,
where two inputs from downlink (1st phase) and uplink (2nd
phase) are processed by these BFIs with one phase delay oper-
ation for downlink transmission and merged into the MRC1
block. The output of the BF \( q_d \) at the lower branch of Fig. 2
is given by

\[
r_d = q_d^H y_2 = q_d^H h_2 x_b + q_d^H g_2 x_f + q_d^H n_2.
\]

The two receiver output statistics \( r_d^u \) in (4) and \( r_d^d \) in (5) are fed
into the first stage of dual-stage MRC, where the estimate \( \hat{x}_f \)
of the interference signal \( x_f \) is made with the MRC combining
weights \( g_2^H W g_1 \) and \( q_d^H g_2 \), respectively. Then, the first-stage
MRC produces the SINR as

\[
SINR_1 = SINR_{u,1} + SINR_{d,1}.
\]

\[
SINR_{u,1} = \frac{|\tilde{g}_2^H Wh_1|^2 P_f}{|\tilde{g}_2^H Wh_1|^2 P_f + \|WH g_2.1\|^2 + 1},
\]

\[
SINR_{d,1} = \frac{|q_d^H h_2|^2 P_f}{|q_d^H h_2|^2 P_f + 1}.
\]

Based on the decision on \( x_f \) at the first-stage MRC, the SIC
stage subtracts out the terms involved with \( x_f \) from (4) and (5).
Suppose \( SINR_1 \) is strong enough to decode \( x_f \) successfully, then
the \( SINR_2 \) at the second-stage MRC, where the desired signal
\( x_2 \) is decoded with the MRC combining weights \( \tilde{g}_{2,1}^H Wh_1 \) and
\( q_d^H h_2 \), respectively, is expressed by

\[
SINR_2 = SINR_{u,2} + SINR_{d,2},
\]

\[
SINR_{u,2} = \frac{|\tilde{g}_{2,1}^H Wh_1|^2 P_f}{\|WH g_{2,1}\|^2 + 1},
\]

\[
SINR_{d,2} = |q_d^H h_2|^2 P_f.
\]

When \( SINR_1 \) is not strong enough to decode \( x_f \), the first stage
MRC1 and SIC are skipped and the received signals \( r_d^2 \) and \( r_d^d \)
are passed on to the final MRC2 block, where the final decision for \( x_f \) is made by the single stage of MRC2 receiver. The SINR
expression for this case (with the interference not subtracted
out) is given by

\[
SINR_{11} = SINR_{u,11} + SINR_{d,11},
\]

\[
SINR_{u,11} = \frac{|\tilde{g}_{2,1}^H Wh_1|^2 P_f}{\|WH g_{2,1}\|^2 + 1},
\]

\[
SINR_{d,11} = \frac{|q_d^H h_2|^2 P_f}{\|q_d^H g_2|^2 P_f + 1}.
\]

### V. Adaptive Beamformer Control

In this section, we consider the optimization schemes of the beamformers \( q_d \) and \( a \) for the dual-stage MRC receiver. Given that the data rates of \( x_f \) and \( x_b \) are \( w_f \) and \( w_b \), respectively, we can find the required SINRs at MRC1 and MRC2 to decode these signals as \( \eta_1 \) and \( \eta_2 \), respectively. Recall that the HBF is given by \( W = \rho a h^H \), where \( b \) is the normalized vector of \( g_{2,1} \) and \( \rho \) is the power scaling factor. Therefore, the optimal beamforming can be formulated as

\[
(a, q_d) = \arg \max \, SINR_2
\]

s.t.  
(9)

Let \( \gamma_2 = \rho^2 \|g_{2,1}\|^2 \), then we have the expressions in (10),
shown at the bottom of the next page.

### A. Open Loop Mode (Optimal \( q_d \) with Fixed \( a \))

Suppose the HBF \( W \) is fixed, for example, as \( W_{\text{Capon}} \), the Capon based beamforming matrix. \( M_{S_2} \) has the channel sta-
tus knowledge not only of those toward itself \((h_2, g_2, g_{2,1})\) but
also of those toward \( M_{S_1} \) \((h_1, g_1)\). Let \( \gamma_0 = |a^H h_1|^2 \) and \( \gamma_1 = |a^H h_2|^2 \), then the optimization in (9) is reformulated as (11),
shown at the bottom of the next page, and further simplified as

\[
\begin{align*}
q_d &= \arg \max_{q_d} \gamma_1 \gamma_2 P_b + (\gamma_2 + 1) |a^H h_2|^2 P_b \\
&\quad \text{s.t.} \quad \alpha |q_d^H h_2|^2 - \beta |q_d h_2|^2 \leq \delta, \quad \|q_d\| = 1,
\end{align*}
\]

where \( \alpha = (\eta_1 \gamma_1 \gamma_2 P_b + \gamma_2 + 1) - \eta_0 \gamma_2 P_b \),
\( \beta = (\gamma_1 \gamma_2 P_b + \gamma_2 + 1) P_f \),
\( \delta = -\alpha / P_b \).
We need to search over the space of complex unit-norm vectors to find an optimal \( \mathbf{q}_d \) in (12). Since the effective channel vectors for \( MS_2 \) are \( \mathbf{h}_2 \) and \( \mathbf{g}_2 \), we can construct \( \mathbf{q}_d \) as shown in Fig. 3, based on the geodesic curve between the two vectors\(^6\) [32], [33]. This way we can avoid searching over the whole complex unit-norm vectors by parameterizing the angle. Since only the magnitude of a BF output is of concern, we consider only the smaller angle \( \Psi \) that the two channel vectors make here. Also, note that the construction of a geodesic geometry based BF is possible only if \( M_m \geq 2 \). We have \( |\mathbf{q}_d^H \mathbf{h}_2|^2 = \cos^2(\varphi) ||\mathbf{h}_2||^2 \) and \( |\mathbf{q}_d^H \mathbf{g}_2|^2 = (\cos(\varphi)\cos(\Psi) + \sin(\varphi)\sin(\Psi))||\mathbf{g}_2||^2 = \cos^2(\Psi - \varphi)||\mathbf{g}_2||^2 \). The solid red curve in Fig. 4 shows the trajectory made by \( (|\mathbf{q}_d^H \mathbf{h}_2|^2, |\mathbf{q}_d^H \mathbf{g}_2|^2) \). The green or blue area is the region where the inequality \( |\mathbf{q}_d^H \mathbf{g}_2|^2 \geq \frac{\alpha}{\beta} |\mathbf{q}_d^H \mathbf{h}_2|^2 - \frac{\delta}{\beta} \) of (12) holds.

Certainly, the optimal \( \mathbf{q}_d \) is the one maximizing \( |\mathbf{q}_d^H \mathbf{h}_2|^2 \) within the constrained area. Therefore, the optimal \( \mathbf{q}_d \) is the one with the largest \( |\mathbf{q}_d^H \mathbf{h}_2|^2 \) among the points where the red curve and the green or blue line meet. When \( \frac{\delta}{\beta} < 0 \) (the green line case in Fig. 4), \( \gamma_1\gamma_2P_b > \eta_1(\gamma_1\gamma_2P_b + \gamma_2 + 1) \) and the signal from FAP to \( MS_1 \) is strong enough to likely decode \( x_f \). Note that \( \delta = -\alpha/P_b \) and the green line (a) always intersects the \( |\mathbf{q}_d^H \mathbf{g}_2|^2 \) axis with a non-positive value (vice versa for the blue line). The outage event (MRC1 fails to decode \( x_f \) because \( SINR_1 \) is less than \( \eta_1 \)) never happens. When the signal from FAP to \( MS_1 \) is not strong enough (\( \frac{\delta}{\beta} \geq 0 \), the blue line case in Fig. 4), the blue line always intersects the \( |\mathbf{q}_d^H \mathbf{g}_2|^2 \) axis with a non-negative value. When the red curve is not included in the blue region, the outage event that MRC1 fails to decode \( x_f \) occurs. When the red curve and the blue line meet, the optimal \( \varphi^* \) can be determined as

\[
\alpha \cos^2(\varphi^*)||\mathbf{h}_2||^2 - \beta \cos^2(\Psi - \varphi^*)||\mathbf{g}_2||^2 = \delta, \quad 0 \leq \varphi^* \leq \Psi
\]

which can easily be solved by numerical methods like the bisection search. The optimal \( SINR_2 \) is then derived as

\[
SINR_2^r = \frac{\gamma_1\gamma_2P_b + (\gamma_2 + 1)\cos^2(\varphi^*)||\mathbf{h}_2||^2P_b}{\gamma_2 + 1}
\]  

When the solution of (13) is an empty set, we meet an outage event (\( SINR_1 < \eta_1 \)). Then, we ignore the MRC1 and the SIC stages, and pass the received signals on to MRC2 block directly

---

\[SINR_1 = \frac{\gamma_2|\mathbf{a}^H \mathbf{g}_1|^2P_f(|\mathbf{q}_d^H \mathbf{h}_2|^2P_b + 1) + |\mathbf{q}_d^H \mathbf{g}_2|^2P_f(\gamma_2|\mathbf{a}^H \mathbf{h}_1|^2P_b + \gamma_2 + 1)}{(\gamma_2|\mathbf{a}^H \mathbf{h}_1|^2P_b + \gamma_2 + 1)(|\mathbf{q}_d^H \mathbf{h}_2|^2P_b + 1)} \]

\[SINR_2 = \frac{\gamma_2|\mathbf{a}^H \mathbf{h}_1|^2P_b + (\gamma_2 + 1)|\mathbf{q}_d^H \mathbf{h}_2|^2P_b}{\gamma_2 + 1} \]

\[\mathbf{q}_d = \arg \max_{\gamma_1\gamma_2P_b + (\gamma_2 + 1)|\mathbf{q}_d^H \mathbf{h}_2|^2P_b} \frac{\gamma_1\gamma_2P_b + (\gamma_2 + 1)|\mathbf{q}_d^H \mathbf{g}_2|^2P_b}{\gamma_2 + 1} \]

s.t. \( \eta_1(\gamma_1\gamma_2P_b + \gamma_2 + 1)(|\mathbf{q}_d^H \mathbf{h}_2|^2P_b + 1) \leq \left( \gamma_1\gamma_2P_f(|\mathbf{q}_d^H \mathbf{h}_2|^2P_b + 1) + |\mathbf{q}_d^H \mathbf{g}_2|^2P_f(\gamma_1\gamma_2P_b + \gamma_2 + 1) \right), ||\mathbf{q}_d|| = 1. \]
to operate in a single stage receiver mode. In this case, we use
the Capon BF for the downlink as \( q_d = R_2^\perp h_2 / (h_2^H R_2^\perp h_2) \),
where \( R_2 = g_2 g_2^H P_f + I_{M_u} \). Note that choosing Capon based
BFs at the UE relay and victim MUE corresponds to the optimal
beamforming for the single stage receiver where the beam-
formed signals are fed to the final MRC block directly. Finally,
the outage events occur if the optimal \( SINR_2^2 \) is less than \( \eta_2 \)
(i.e., MRC2 fails to decode \( x_b \) even with \( SINR_1 \geq \eta_1 \)) and
\( SINR_{11} \) is less than \( \eta_2 \) (i.e., MRC2 fails to decode \( x_b \) even with
\( SINR_1 < \eta_1 \)).

\[
(a, q_d) = \arg \max_{\gamma_2} \gamma_2 |a^H h_1|^2 P_b + (\gamma_2 + 1) |q_d^H h_2|^2 P_b
\]
\[\text{s.t. } \alpha(\psi) |q_d^H h_2|^2 - \beta(\psi) |q_d^H g_2|^2 \leq \delta(\psi). \tag{15}\]

\[
\alpha(\psi) \cos^2(\psi^*) \| h_2 \|^2 - \beta(\psi) \cos^2(\Psi - \psi^*) \| g_2 \|^2
\]
\[= \delta(\psi), \quad 0 \leq \psi^* \leq \Psi. \tag{16}\]

\[
SINR_2(\psi_1) = \frac{\gamma_2 \cos^2(\psi_1) \| h_1 \|^2 P_b + (\gamma_2 + 1) \cos^2(\psi) \| h_2 \|^2 P_b}{\gamma_2 + 1} \tag{17}\]

\section*{B. Closed-Loop Mode (Joint Optimal BF)}

When the HBF \( a \) is not fixed, we find an optimal set of the UE
relay and victim MUE BF \( s \), jointly (i.e., in a coordinated man-
ner). The UE relay beamformer information computed at \( M_{S_2} \)
is feedback to the UE relay \( M_{S_1} \) via D2D uplink. Depending on
the type of the relay gain, the joint optimal BF \( s \) appear slightly
different forms.

1) VG relaying: Similarly as we have done in Fig. 3, we can
form \( a = \cos(\psi_1) \xi_1^1 + \sin(\psi_1) \xi_2^1, \quad 0 \leq \psi_1 \leq \Psi_1 \), where the
vector \( \xi_1^1 \) is the normalized vector of \( \{I_{M_u} - h_1 h_1^H / h_1^H h_1 \} g_1 \),
\( \xi_1 \) is similarly defined as in Fig. 3, and \( \psi_1 \) is the smaller
angle that \( h_1 \) and \( g_1 \) make. Substituting \( \gamma_0 = |a^H h_1|^2 \) and \( \gamma_1 =
|a^H g_1|^2 \) in (9) yields us (15). Here, \( \alpha(\psi_1), \beta(\psi_1) \) and \( \delta(\psi_1) \) are
similarly defined as in subsection IV-A.

Since \( \psi_1 \) defines the constraint inequality, we can find the
optimal \( q_d (\phi^*(\psi_1)) \) for a given \( \psi_1 \) (hence for a given \( a \)) from
(16). Then, \( SINR_2(\psi_1) \) is given in (17). When the solution for
\( \psi_1 \) in (16) is an empty set for a given \( \psi_1 \), we meet the out-
age event for the first stage \( (SINR_1 < \eta_1) \), and then \( SINR_2(\psi_1) \)
should be calculated using (8) and based on the Capon BF. For
\( 0 \leq \psi_1 \leq \Psi_1 \), we find \( \phi^*(\psi_1) \) and \( SINR_2(\psi_1) \) using (16) and
(17), respectively, where the optimal \( \psi_1 \) is computed from

\[
\psi^*_1 = \arg \max_{0 \leq \psi_1 \leq \Psi_1} SINR_2(\psi_1) \tag{18}\]

for the optimal \( SINR_2(\psi_1) \). Finally, the outage event occurs
if the optimal \( SINR_2(\psi_1) \) is less than \( \eta_2 \) (MRC2 fails to
decode \( x_b \)).

2) FG relaying: The search for joint optimal \( \phi_1 \) can
be further simplified since the relay gain factor \( \rho \) is not
dependent on \( \psi_1 \) for the FG control. Note that \( \alpha/\beta = \eta_1 P_b / P_f - \gamma_0 / \gamma_2 / \gamma_1 / \gamma_2 P_b + \gamma_2 + 1 \), and thus decreasing
\( \gamma_0 = |a^H g_1|^2 \) increases \( \gamma_1 = |a^H h_1|^2 \). Therefore, decreasing
\( \gamma_1 = \cos^2(\phi_1) \| h_1 \|^2 \) reduces the slope of the constraint equation
\( \| h_2 \|^2 = \rho (\| h_2 \|^2 - \| g_2 \|^2) \). Also, note that reducing the slope
decreases the intersects with the \( |g_2^H g_2|^2 \) axis. In sum-
mary, we rotate the blue line in Fig. 4 of the constraint equation
clockwise (though there is no exact pivot point) as we increase
\( \phi_1 \). From Fig. 4, we can see that rotating the slope of blue line
(b) clockwise results in a larger \( |q_d^H h_2|^2 = \cos^2(\psi) \| h_2 \|^2 \) until
the line becomes parallel with the horizontal axis where we are
given \( \psi = 0 \) (\( q_d = h_2 \) or equivalently \( \alpha(\psi_1) = 0 \)).

The numerator of \( SINR_2 \) expression in (17) has two terms
behaving oppositely and monotonically as we vary \( \phi_1 \). We can
reduce the search range of \( \phi_1 \) in the following steps:

- **Step 1**: Starting from \( \phi_1 = 0 \), if \( \alpha(\phi_1)/\beta(\phi_1) < 0 \), go to
  **Step 2**. If \( \alpha(\phi_1)/\beta(\phi_1) \geq 0 \), keep using (16) and (18)
to find \( \phi^*_1 \) while increasing \( \phi_1 \). When \( \phi_1 \) reaches \( \Psi_1 \) or (16)
results in \( \phi = 0 \) (or equivalently \( \alpha(\phi_1) = 0 \), stop.

- **Step 2**: Choose the argument angle \( \phi = 0 \) and \( \phi_1 = 0 \). Stop.

If we take **Step 1**, we search part of \( \phi_1 \) ranging from zero
angle. When we skip **Step 1** and take **Step 2**, we only inves-
tigate a single angle of \( \phi_1 = 0 \). In Table I, we summarize the
variables and parameters used for the design of BF, where
\( \gamma_0, \gamma_1, \phi_1, \phi_2, \) and \( \phi_2 \), as well as \( h_1 \) and \( g_2 \), are the input parameters
and \( \phi_1 \) and \( \phi_2 \) are the output parameters of the algorithm (15)
and (18) in closed-loop mode. In open loop mode, \( \phi \) is the only
output of (13).

\section*{C. Outage Performance Consideration}

The channels considered herein belong to the interference
channel with a multi-antenna UE relay. The optimal joint
decoding of the desired signals from MBS and FAP is the
maximum-likelihood decoding, and hence the proposed SIC
based receiver structures are suboptimal. Thus, it is noteworthy
that the beamforming schemes in this paper are optimal among
only the class of SIC based receivers. It is well known that the
SIC based receiver is beneficial when the interfering sig-
nal is strong enough to be decoded. The amount of interference
intensity required for such receiver is reflected in the constraint
\( SINR_1 \geq \eta_1 \). To this end, the proposed schemes attempt to steer
the BF towards the desired signal directions (\( h_1 \) and \( h_2 \) within

\begin{table}[h]
\centering
\caption{Variables and Parameters for the Design of BF}
\begin{tabular}{|c|c|c|}
\hline
\textbf{Signal at M}_{S_1} \text{ during the downlink period} & \textbf{Signal at M}_{S_2} \text{ during the uplink period} & \textbf{BFs (data rate)} \\
\textbf{M}_m \times 1 \text{ received signal at M}_{S_j} & \textbf{M}_s \times 1 \text{ received signal at M}_{S_j} & \textbf{F} \text{ BF message signal (data rate)} \\
\hline
\textbf{\text{\text{Signal at M}_{S_1} \text{ during the downlink period}}} & \textbf{x}_j (0) & \textbf{x}_j (0) \\
\hline
\textbf{F} \text{ BF message signal (data rate)} & \textbf{x}_j (0) & \textbf{x}_j (0) \\
\hline
\textbf{\text{Signal at M}_{S_2} \text{ during the uplink period}} & \textbf{y}_j, j = \{1, 2\} & \textbf{S} \text{ BF message signal (data rate)} \\
\hline
\textbf{\text{F} \text{ BF message signal (data rate)}} & \textbf{x}_j (0) & \textbf{x}_j (0) \\
\hline
\textbf{\text{Angular parameter for q}_d \text{ (one FAP)}} & \textbf{x}_j (0) & \textbf{x}_j (0) \\
\hline
\hline
\end{tabular}
\end{table}
the constraint $\text{SINR}_1 \geq \eta_1$. However, the constraint forces the BF parameters $\psi$ and $\varphi_1$ to have non-zero values.

In the green area in Fig. 4, the interference from FAP to $MS_1$ is strong enough so that MRC1 is free of outage and thus we have $\gamma_2 \|b_1\|^2 \cos^2(\psi_1)P_f > \eta_1 (\gamma_2 \|b_1\|^2 P_b + \gamma_2 + 1)$.

If we set $\varphi = 0$ and $\varphi_1 = 0$, the resulting $\text{SINR}_2$ becomes

$$\text{SINR}_2 = \frac{\gamma_2 \|b_1\|^2 P_b + (\gamma_2 + 1) \|b_2\|^2 P_b}{\gamma_2 + 1}.$$  (19)

Note that MRC2 outage occurs when $\text{SINR}_2 < \eta_2$ in (19). In the blue area in Fig. 4, MRC1 is trapped into the outage when the line (b) does not meet the red curve. Since the joint optimal BF rotates the blue line until it becomes parallel with the horizontal axis, the outage event occurs when the blue line does not meet the red curve even after $\varphi_1$ reaches $\psi_1$. Mathematically, this case corresponds to

$$\alpha(\psi_1) \cos^2(\psi_1)\|b_2\|^2 - \beta(\psi_1)\|b_2\|^2 > \delta(\psi_1).$$  (20)

In general, the decoding of target data is possible when $\text{SINR}_1 \geq \eta_1$ and $\text{SINR}_2 \geq \eta_2$. However, note that there is a possibility of MRC2 decoding the message even with MRC1 in outage, where the UE relay and victim MUE are using the Capon BFs with the single stage receiver mode. Through simulations, we observe marginal outage gains with this receiver mode.

### V. Results

Simulation results are presented for the proposed beamforming methods with UE relaying cooperation in the HCN environment and assuming a single interfering FAP, the parameters of which are summarized in Table II. We consider the distance geometry where the UE relay $MS_1$ is at the boundary of a femto cell coverage (15 m) and the victim MUE is located at the distance 20 m to 50 m from FAP, as it approaches the femto cell coverage. Here, we assume that a femto cell is the home eNodeB (HeNB) proposed in the LTE-A standard document with propagation path loss and transmit power parameters in [41]. The heterogeneous path losses and transmit powers of the HCN follow from [42]. For illustration, we set the target spectral efficiencies of MBS and FAP to $w_0 = w_f = w$.

The decoding success probability is evaluated at the victim MUE $MS_2$ for the proposed closed-loop multi-stage receiver.

**TABLE II**

<table>
<thead>
<tr>
<th>System Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>MBS-to-victim MUE distance</td>
</tr>
<tr>
<td>FAP-to-UE relay distance</td>
</tr>
<tr>
<td>Required spectral efficiency</td>
</tr>
<tr>
<td>MBS / FAP / UE Tx power</td>
</tr>
<tr>
<td>Noise power</td>
</tr>
<tr>
<td>MBS / FAP / UE antenna numbers</td>
</tr>
<tr>
<td>Channel model</td>
</tr>
<tr>
<td>Macrocell path loss model (NLOS)</td>
</tr>
<tr>
<td>HeNB path loss model (NLOS)</td>
</tr>
<tr>
<td>MBS / UE Ant. height</td>
</tr>
<tr>
<td>Carrier frequency</td>
</tr>
</tbody>
</table>

![Fig. 5. The decoding success probability of MSR, C-Capon and NC-Capon schemes versus the target spectral efficiency $w$ when the victim MUE is 20 meters away from the FAP and all the terminals involved use two antennas. Here, MSR(b) denotes the MSR scheme with $b$ bits feedback.](image)

(MSR), cooperative Capon based scheme (C-Capon) and non-cooperative Capon based scheme (NC-Capon) to show that the problem of victim MUE can effectively be resolved. Here, the C-Capon scheme refers to the one which applies the Capon BFs both at the UE relay and victim MUE, whereas the NC-Capon scheme refers to the one that applies the Capon BF at the victim MUE only without UE relaying cooperation. Note that these two schemes (NC-Capon and C-Capon) use the single stage receiver without SIC.

Fig. 5 shows the decoding success probability of the UE relaying based MSR, C-Capon and NC-Capon schemes versus $w$. For MSR schemes, we can directly quantize $\varphi_1$ uniformly. Note that NC-Capon uses a single phase transmission while MSR and C-Capon use two-phase transmissions, one of which is from the D2D spatial reuse with minimal local transmit power of the peer UEs. With the two-branch MRC operation through the cooperation, C-Capon scheme improves the outage performance of NC-Capon scheme. The UE relaying with MSR provides further performance gain over C-Capon and NC-Capon. In MSR schemes, the zero-bit feedback (open loop mode) means that the UE relay uses the Capon based HBF.
Fig. 6. The decoding success probability of MSR, C-Capon and NC-Capon schemes versus the target spectral efficiency $w$ when the victim MUE is 20 meters or 50 meters away from FAP and all terminals involved use two antennas.

(WCapon) while $q_d$ is found from $\phi$ satisfying (13). The BF optimization with MSR at the victim MUE provides more than 0.5 bps/Hz gain over C-Capon at the success probability of 0.9. The gain of MSR depends on the number of feedback bits (closed-loop mode) though the effective gain saturates as the number of bits $b$ approaches 4. The additional gain from this closed-loop optimization exceeds 1.0 bps/Hz at the success probability of 0.9.

In Fig. 6, the performances of various schemes according to the FAP-to-victim MUE distance are plotted. As the victim MUE approaches the FAP, more performance gain is achieved as the interference from FAP becomes more dominant. Also, note that NC-Capon scheme shows a limitation in handling the strong interference as it suffers more severely when the victim MUE is closer to the FAP, which suggests that the proposed UE relaying with MSR schemes is an effective remedy against the growing interference near the FAP. Fig. 7 plots the effect of number of antennas used at the nodes, which demonstrates that a large number of antennas can be combined with MSR schemes in boosting the performance. Since two and four antennas are the most common and practical configurations in academia and industry standard (e.g., LTE), we consider only those cases for a single interfering FAP. Finally, the effect of the relay gain control (VG and FG) is shown in Fig. 8. The results strongly advocate the use of FG control since the performance advantage of using the UE relaying with VG is so marginal while the complexity gain at the UE relay and victim MUE (for the BF search) is obvious.

VI. EXTENSION TO TWO INTERFERING FAPs

Since FAPs are typically deployed by the subscribers not by the operators, the deployment pattern is quite random and the coverage of more than two FAPs may overlap. Or in rare cases, the FAP may support multiple UEs. In these cases, the MUE may be subject to the interference from multiple FAPs or multiple streams from a FAP.\(^7\) By focusing on the case of two interfering FAPs of interest in practice, we shed light on how the proposed idea can be generalized to handle the case of multiple interfering FAPs.

A. System and Signal Model

Suppose there, in Fig. 1, exists another FAP nearby, and it generates interference to $M S_1$ and $M S_2$ as well. Let the channel matrices from this FAP to $M S_1$ and $M S_2$ be $F_1$ and $F_2$, respectively and the precoded channel vectors be $f_1$ and $f_2$, respectively.

\(^7\)We can assume that the multiuser interference can be suppressed by the precoding at the MBS when multiple users are supported by the MBS. Therefore, we can treat such case with the proposed scheme in the previous sections.
Let the first FAP be this newly added one and the second FAP be the one in the previous sections. The transmission powers at the first and second FAPs are given by $P_{f,1}$ and $P_{f,2}$, respectively. Let $x_{f,1}$ and $x_{f,2}$ be the desired signals at the first and second FAPs, respectively, with the data rates $w_{f,1}$ and $w_{f,2}$.

At the UE relay $M_{S,1}$, the HBF $W$ can be constructed as before except for the scaling factor $\rho$, which is given for the VG and FG by

$$\rho_{VG} = \frac{P_1}{|a^H b_1|^2 P_b + |a^H f_1|^2 P_{f,1} + |a^H g_1|^2 P_{f,2} + 1}.$$  

$$\rho_{FG} = \frac{P_1}{P_b + P_{f,1} + P_{f,2} + 1}.$$  

At the victim MUE, a three-stage MRC is applied as shown in Fig. 9, where the same two-branch structure of Fig. 2 is preserved and the first two stages of MRCs subtract out the interference from two FAPs sequentially. The same uplink receive BF $q_d$ is used as in the case of a single interfering FAP while the downlink receive BF $q_d$ should be adapted according to the interference from two FAPs. Similarly as in Section II and Section III, the signal models of $q_d^2$ and $r_2^2$ can be rewritten as

$$r_2^d = q_d^H (h_{2,1} x_b + f_2 x_{f,1} + g_2 x_{f,2} + n_2),$$  

$$r_3^d = g_2^H W (h_{2,1} x_b + f_2 x_{f,1} + g_2 x_{f,2} + n_2).$$  

(21)

$$SINR_1 = SINR_{d,1} + SINR_{d,1},$$  

$$SINR_2 = SINR_{d,2} + SINR_{d,2},$$  

$$SINR_3 = SINR_{d,3} + SINR_{d,3}.$$  

(22)

where

$$SINR_{d,1} = \frac{|g_1^H W f_2|^2 P_{f,1}}{|g_1^H W f_1|^2 P_b + |g_1^H W g_1|^2 P_{f,2} + \|W g_{2,1}\|^2 + 1},$$  

$$SINR_{d,1} = \frac{|q_d^H f_2|^2 P_{f,1}}{|q_d^H h_2|^2 P_b + |q_d^H g_2|^2 P_{f,2} + 1},$$  

$$SINR_{d,2} = \frac{|g_2^H W f_1|^2 P_{f,2}}{|g_2^H W f_1|^2 P_b + \|W g_{2,1}\|^2 + 1},$$  

$$SINR_{d,3} = \frac{|q_d^H g_1|^2 P_{f,2}}{|q_d^H h_2|^2 P_b + 1},$$  

$$SINR_{a,2}, SINR_{d,3} = SINR_{d,2}. $$  

(23)

The case when two streams are served by two precoder vectors at a FAP can be covered by the same signal model.

and hence the combiner weights at each MRC unit can be similarly applied as before. The SINR values after MRC stages are given, respectively, by (22) and (23). Each SINC and the corresponding MRC stage are skipped if the SINR for the stage is less than the threshold of the stage, and then the received signals are passed on to the next stage as in Section III. Hence the number of stages in operation at the victim MUE varies as in Section III, where there are two cases (single and double stages) depending on the value of $\gamma_{b,1}$. Here, we need to consider four cases depending on the values of $SINR_1$ and $SINR_2$ against $\eta_1$ and $\eta_2$, respectively.

B. The Beamformer Optimization

1) Open Loop BF: Similar to the previous sections, an optimization strategy for the case of two interfering FAPs can be formulated as:

$$q_d = \arg\max q_d |a| = 1, \|q_d\| = 1.$$  

(24)

A new definition $\gamma_3 = |a^H f_1|^2$ allows us to rewrite (24) as

$$q_d = \arg\max \frac{\gamma_1 \gamma_2 P_b + (\gamma_2 + 1) |q_d^H h_2|^2 P_b}{\gamma_2 + 1},$$  

subject to $|a^H g_2|^2 + |a^H f_2|^2 P_{f,2} - |a^H q_d^H f_1|^2 \leq -\frac{\alpha_1}{P_b},$  

$$\alpha_2 = |a^H h_2|^2 - \beta_2 |q_d^H g_2|^2 \leq \delta_2, \|q_d\| = 1$$

where $\alpha_1 = (1 (\gamma_1 \gamma_2 P_b + \gamma_2 P_{f,2} + \gamma_2 + 1) - \gamma_2 \gamma_3 P_{f,1}) P_b,$  

$\alpha_1 = (\gamma_1 \gamma_2 P_b + \gamma_2 P_{f,2} + \gamma_2 + 1) P_{f,1},$  

$\alpha_2 = (1 (\gamma_1 \gamma_2 P_b + \gamma_2 P_{f,2} + \gamma_2 + 1) - \gamma_2 \gamma_3 P_{f,1}) P_b,$  

$$\beta_2 = (\gamma_1 \gamma_2 P_b + \gamma_2 + 1) P_{f,2},$$  

$$\delta_2 = -\alpha_2 / P_b.$$  

(25)

Note that the relations between $\alpha_2, \beta_2$ and $\delta_2$ are the same as those of $\alpha, \beta$ and $\delta$ in (12) except that $P_{f,2}$ is used instead of $P_f$.

If $M_m \geq 3$, we can construct the victim MUE downlink BF $q_u$ using the geodesic geometry based angles, as we have done for the case of two interfering FAPs. Since there are three channel vectors ($h_2, g_2$ and $f_2$) involved at the victim MUE, we, with the two vectors $h_2$ and $g_2^H$ from the previous sections, find the third vector $f_{1,2}^H$ to form three orthonormal vectors.

When $H = [h_2, g_2]$, $f_{1,2}^H$ is the normalized vector of the vector $f_{1,2}^H = (I_{M_m} - H (H^H H)^{-1} H^H) f_2$, the projection of $f_2$ onto the orthogonal space of $H$. With the angle definition $\Psi$ as before,
we need a new angel definition $\Omega = \sin^{-1}(|\langle f_2, f_2 \rangle|/|f_2|)$ to be the angle between $f_2$ and the plane spanned by $h_2$ and $g_2$. We can form the victim MUE downlink BF as

$$q_d = \cos(\omega) \cos(\phi) \chi(\phi) \xi^\ast h_2 + \cos(\omega) \sin(\phi) \chi(\phi) g_2^\ast + \sin(\omega) f_2^\ast,$$

with $0 \leq \omega \leq \Psi$, $0 \leq \omega \leq \Omega$. \hfill (26)

Here, the phase correction factor $\chi(\phi)$ is given by $\chi(\phi) = (\cos(\phi) \xi^\ast h_2 + \sin(\phi) g_2^\ast)^\ast f_2$. In this way, $q_d$ can cover the spherical triangle region made by the three geodesic curves between $h_2$, $g_2$, and $f_2$. Note that $|q_d^H h_2|^2 = \cos^2(\omega) \cos^2(\phi) \|h_2\|^2$, $|q_d^H g_2|^2 = \cos^2(\omega) \cos^2(\Psi - \phi) \|g_2\|^2$ and $|q_d^H f_2|^2 = \cos^2(\Omega - \omega) \cos^2(\phi) \|f_2\|^2$.

Since the relations between $\alpha_2$, $\beta_2$, and $\delta_2$ are preserved as in (12), the plane made by $|q_d^H h_2|^2$ and $|q_d^H g_2|^2$ can be depicted as in Fig. 10 depending on the polarity of $\alpha_2/\beta_2$. The green lines are determined when the red curve and the blue lines, which results in the shaded areas. However, increasing $\omega$ contracts the trajectories (red curves) of $\cos^2(\omega)|q_d^H h_2|^2$, $\cos^2(\omega)|q_d^H g_2|^2$, which leads to the degraded SINR as shown in (25).

When the interference from FAP2 is weak (the case (a) in Fig. 10), the optimal $\omega$ and $\phi$ are determined when the red curve, the blue line, and the green line meet on a point. Thus, the optimal $\omega^*$ and $\phi^*$ satisfy the two equations in (27), which can be solved, for example, by the two-dimensional bisection method. If a solution set for (27) is found, the SIC1 and the SIC2 stages can remove the interference, and the resulting optimal SINR$^3$ is given by

$$\text{SINR}^3 = \frac{\gamma \gamma_2 P_b + (\gamma_2 + 1) \cos^2(\omega^*) \cos^2(\phi^*) \|h_2\|^2}{\gamma_2 + 1} P_b.$$

\hfill (28)

For the case when the interference from FAP2 is strong (the case (b) in Fig. 10), the optimal $\omega$ and $\phi$ are determined when the red curve and the blue line meet on a point in the horizontal axis (i.e., $\phi^* = 0$). We only need to find the optimal $\omega^*$ from (29).

When no solution of (27) or (29) exists in $0 \leq \omega \leq \Omega$, $0 \leq \phi \leq \Psi$, outage events occur. Then, we skip some of MRC and SIC pairs and reduce the number of stages of the victim MUE receiver. If no solution of (27) exists, we turn the two FAP interfering model into the single FAP interfering model, and apply the method of Section IV-A. This is done by zero-forcing the interference components from a FAP at the UE relay and victim MUE. We can first zero-force the interference components from the first FAP ($f_1$ and $f_2$) as

$$r_1^d = q_d^H (l_m + f_2 f_2^H / (f_1 f_2^H))^{-1} y_2,$$

$$r_1^u = q_d^H W(l_m + f_1 f_1^H / (f_1 f_1^H))^{-1} y_1. \hfill (30)$$

If this model fails to identify the solution of (13) as well, we can similarly zero-force the interference components from the second FAP ($g_1$ and $g_2$) and test the solution of (13). Finally, if the second model fails as well, then we can reduce the victim MUE receiver to the single stage mode with Capon BF at the UE relay and victim MUE. In this case, the Capon
BXs are constructed with $\mathbf{R}_1 = f_1^T P_{f,1} + g_1 \mathbf{g}_1^H P_{f,2} + I_M$ and $\mathbf{R}_2 = f_2^T P_{f,1} + g_2 \mathbf{g}_2^H P_{f,2} + I_M$, respectively. In the case of Fig. 10(b), we try to zero-force the first FAP interference with the model of (30) if (29) does not render a solution. If this model fails to produce a solution, then we try the Capon based BFs.

**Observations:** Before going into the discussion on closed-loop BF, there are several points to note for the case where more than two FAPs (or, more than two streams from a FAP) are interfering.

- First, the victim MUE BF can be constructed by applying the geodesic geometric angles iteratively, as was done in (26).
- Second, the number of total victim MUE receiver stages needed is one more than the number of interfering FAPs while the number of constraint equations is the same as the number of interfering FAPs.
- Third, note that the first constraint of (25) is new and similarly as we have done in (26), the solution for $s = 0$. Note that $\mathbf{g}$ is less than $\mathbf{f}$ and $\delta_2$ is an empty set for given $\eta$. Finally, the outage event occurs if the optimal $\eta_3$ is less than $\eta_3$ (MRC3 fails to decode $x_b$). For the UE relaying with FG, we learned in Subsection IV-B that the search for the joint optimal $\varphi_1$ can be simplified by rotating the constraint line. The search range of $\varphi_1$ can be reduced if we embed Step 1 and Step 2 in the search over $0 \leq \varphi_1 \leq \Omega_1$ and $0 \leq \varphi_1 \leq \Psi_1$. Similarly as in Subsection IV-B to form the constraint inequalities. The optimal $\eta_3(x_b, \varphi_1, \varphi_1^*)$ is given for $\omega_1, \varphi_1$ (hence for a given $\mathbf{a}$) can be found using (27). When the solution for $x_b$ in (27) is an empty set for given $\omega_1, \varphi_1$, we meet the outage event ($\text{SINR}_1 < \eta_1$ and $\text{SINR}_2 < \eta_2$) and then $\text{SINR}_3(\omega_1, \varphi_1) = 0$. Note that $\omega_1$ does not appear on the right-hand side of $\text{SINR}_3$ expression in (33), shown at the bottom of the page, since it affects $\alpha_1$ (hence the first constraint) through $\gamma_3 = |\mathbf{a}^H \mathbf{h}_1|^2$.

\begin{align}
\varphi_1^* = \arg \max_{0 \leq \varphi_1 \leq \Omega_1, 0 \leq \varphi_1 \leq \Psi_1} \text{SINR}_3(\omega_1, \varphi_1) \quad (34)
\end{align}

for the optimal $\text{SINR}_3(\omega_1^*, \varphi_1^*)$. Finally, the outage event occurs if the optimal $\text{SINR}_3(\omega_1^*, \varphi_1^*)$ is less than $\eta_3$ (MRC3 fails to decode $x_b$). For the UE relaying with FG, we learned in Subsection IV-B that the search for the joint optimal $\varphi_1$ can be simplified by rotating the constraint line. The search range of $\varphi_1$ can be reduced if we embed Step 1 and Step 2 in the search over $0 \leq \varphi_1 \leq \Omega_1$ and $0 \leq \varphi_1 \leq \Psi_1$. Similarly as in Subsection IV-B to form the constraint inequalities. The optimal $\eta_3(x_b, \varphi_1, \varphi_1^*)$ is given for $\omega_1, \varphi_1$ (hence for a given $\mathbf{a}$) can be found using (27). When the solution for $x_b$ in (27) is an empty set for given $\omega_1, \varphi_1$, we meet the outage event ($\text{SINR}_1 < \eta_1$ and $\text{SINR}_2 < \eta_2$) and then $\text{SINR}_3(\omega_1, \varphi_1) = 0$. Note that $\omega_1$ does not appear on the right-hand side of $\text{SINR}_3$ expression in (33), shown at the bottom of the page, since it affects $\alpha_1$ (hence the first constraint) through $\gamma_3 = |\mathbf{a}^H \mathbf{h}_1|^2$.

\begin{align}
\varphi_1^* = \arg \max_{0 \leq \varphi_1 \leq \Omega_1, 0 \leq \varphi_1 \leq \Psi_1} \text{SINR}_3(\omega_1, \varphi_1) \quad (34)
\end{align}

Fig. 11. The decoding success probability of MSR, C-Capon and NC-Capon schemes versus the target spectral efficiency $w$ when the victim MUE is 20 meters away from the first FAP, 30 meters away from the second FAP and all terminals involved use three antennas.
C. Further Results

Fig. 11 shows the outage performance of the UE relaying with MSR when there are two interfering FAPs, one is 20 meters away from the victim MUE and the other is 30 meters away from the victim MUE. The target spectral efficiencies are set to \( W_2 = W.f.1 = W . f.w \) and three antennas are used at each of the involved node. Note that the numbers of feedback bits are doubled since two angles among three channel vectors are involved in (31) and the number of antennas at nodes should be \( M_n \geq 3 \) to remove the interference from two FAPs. With two interferers, it is hard to imagine that the MSR can pass through the stages so that it can avoid the outage in decoding \( x_0 \) at the final stage. Surprisingly, Fig. 11 shows that the beamforming at the victim MUE and UE relay makes the MSR still effective for improving the outage performance compared to those of NC-Capon and C-Capon. Here, a similar behavior as we have seen in Fig. 5 for the case of a single interfering FAP is observed, and thus the use of MSR with two stages is advocated.

VII. CONCLUSION

We have proposed the UE relaying scheme with multiple antennas coordinated beamforming to resolve the issue of victim MUE in heterogeneous cellular networks with D2D communication between peer UEs nearby. In this case we expect the UE relay close by the interfering FAPs to help the victim MUE strengthen the interference signal for subsequent SIC and then decode the weak desired signal at the final stage. Toward this, the proposed UE relaying cooperation effectively realizes the MS-MRC for signal and interference combining that results in improved decoding performance at the victim MUE. Further, additional performance gain of the proposed scheme can be achieved by realizing a closed-loop beamformer control for both VG and FG control at the UE relay. The proposed scheme becomes more effective when the victim MUE approaches the FAPs and suffers from more severe interference by those FAPs.

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