Interference Recycling: Exploiting Interfering Signals to Enhance Data Transmission

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Abstract—With the rapid development of wireless communication technologies, the demand for higher data rate and more concurrent transmissions has been continually increasing. Due to the widespread deployment of various wireless technologies, interference has become a key roadblock to the improvement of network performance. Interference has long been known to be harmful, leading to development of numerous interference management (IM) mechanisms based on resource segmentation or signal processing to mitigate or suppress interference. Since a desired signal can be distorted by interference, and thus be incorrectly decoded at the destination, we argue that interference can also be transformed intentionally to extract the desired data from interfering signal(s). Based on this observation, we propose Interference Recycling (IRC). Under IRC, a recycling signal is generated with the interference a victim receiver (Rx) is subjected to, and then sent by the Rx’s associated transmitter (Tx). Under the influence of the recycling signal, the desired data of the victim Tx–Rx pair can be recovered from the interference at the victim Rx. That is, by exploiting the interactions among multiple signals, i.e., recycling signal and interference, useful data information can be extracted from interference, or the unintended data carried in interference can be artificially converted to the desired one. Our theoretical analysis and numerical evaluation have shown that the proposed IRC can fully exploit interference, and hence can significantly improve the spectral efficiency (SE) of the victim Rx compared to the other existing IM methods.

I. INTRODUCTION

With the rapid development of wireless communication technologies, various types of communication systems have been deployed, providing diverse user services. Along with the evolution of hierarchical and heterogeneous network architecture, as well as the proposal of numerous dynamic spectrum sharing mechanisms, interference has become a key impediment to the improvement of network performance. Interference has long been regarded as harmful to data transmission, and is thus eliminated or suppressed by using resource segmentation, such as time division multiple access (TDMA), frequency division multiple access (FDMA) and code division multiple access (CDMA), or signal processing methods, such as zero-forcing (ZF) reception, interference cancellation (IC), interference alignment (IA) and zero-forcing beamforming (ZFBF). Of these signal processing methods, IA and ZFBF attempt to actively adjust the interference features at the interfering source so as to manage the negative effects of the interference, while ZF reception and IC are realized by the victim Rx that suffers from disturbance from other unintended Tx(s), which can be classified as passive interference management (IM).

Besides the above-mentioned methods, researchers have been exploring new ways to manage interference. A physical-layer network coding (PNC) was first proposed in [1]. By utilizing the known interference information in data encoding, disturbance to unintended Rxs can be mitigated effectively, hence improving the transmission efficiency. PNC suggests making use of interference instead of simply treating it as a nuisance. The authors of [2] designed a new PNC scheme via lattice partitions in a relay network. Using this method, each relay maps an interfering signal to an XOR combination of simultaneously transmitted codewords, so that the throughput of a two-way relay channel is doubled compared to the traditional transmission schemes. [3] presented an interference neutralization (IN) scheme. By sending a neutralizing signal with the same strength and the opposite phase with respect to the disturbance, the interference propagated through the wireless channel is canceled out by the neutralizing signal at the target receiver, thereby achieving interference-free reception of the desired signal. In essence, IN exploits both the propagation feature of, and the data information carried by, the interference, so that the interfering signal’s energy is neutralized. By taking into account the power overhead of IN, dynamic interference neutralization (DIN) was proposed in [4]. DIN can balance the benefits brought by and power cost of interference neutralization by optimally distributing the transmit power used for the desired signal’s transmission and the neutralizing signal. By exploiting the fact that interference can not only be mitigated but also be modified, an interference steering (IS) mechanism was proposed in [5]. IS employs a steering signal based on the interference information similarly to IN/DIN, and then by exploiting the interactions among multiple wireless signals, the interference perceived by the victim Rx is adjusted to a direction orthogonal to the desired signal. Therefore, interference-free transmission of the desired signal is achieved.

Although PNC, IN/DIN and IS attempt to make use of interference in IM, their focus is still on the elimination of interference energy. Nevertheless, further utilization of interference remains unaddressed. One may naturally raise a question: “is it possible to convert the interference’s en-
ergy to the useful one so as to enhance the desired data transmission?” One may come up with the wireless energy harvesting (EH) technology [6–9] with which wireless nodes can harvest energy from the environment. The authors of [7] considered a third-party cognitive small cell with wireless powered secondary user equipments (SUEs) that offload data traffic to a primary macrocell. SUEs realize wireless power supply by harvesting energy from radio-frequency (RF) signals sent by the macrocell UE(s) (MUE) as well as RF signals transmitted by the small cell base station (SBS). [8] considered a spectrum sharing scenario where a secondary transmitter communicates with its destination via a decode-and-forward secondary relay (SR) in the presence of interference from multiple primary Txs. The SR harvests energy from received RF signals that include primary interference and uses it to forward the information to the secondary destination, so that secondary user’s average throughput is improved. The authors of [9] provided a comprehensive survey of the studies of exploiting interference for wireless EH, and argued that the redundant resource of interference can be utilized by using EH so as to provide power for wireless nodes. However, these methods [7–9] focus on the use of extra acquired energy rather than acquiring it. Moreover, the information carried by the interference was not utilized.

To mitigate/overcome the above-mentioned deficiencies, we propose a new concept of interference recycling (IRC). Let us illustrate the intuition behind IRC using a well-known communication phenomenon. When a receiver demodulates its desired signal affected by noise, interference and other disturbances during signal propagation, the recovered data will deviate from the true transmitted data. Such a deviation is usually captured by the gap between two constellation points. In case of a strong influence of noise, interference, etc., the receiver won’t be able to decode the transmitted data correctly. Since a signal, while acting as disturbance to an unintended receiver, is always desired signal to its intended receiver, i.e., interfering signal also carries the data symbol, one can naturally ask “if a desired signal can be distorted by an interference resulting in erroneous data, can the interference also be affected likewise so that desired data is erroneously recovered from the true interference?” To answer this question, we first consider the mutual representation of data symbols, i.e., a data symbol can be expressed in terms of the other symbol. Then, we employ a recycling signal sent by the Tx associated with the victim Rx. By exploiting the inter-plays among wireless signals, the victim Rx can recover its desired data from the combination of the interference and the recycling signal, thus achieving the goal of IRC.

This paper makes three main contributions:

- Proposal of a novel data transmission scheme called interference recycling (IRC). By designing and using a recycling signal, the desired data is recovered from the interference and the victim Rx’s spectral efficiency (SE) is improved significantly. We also provide an analysis of IRC from an information theory perspective.
- Development of various IRC implementations. We show that the victim user’s SE with IRC can be further optimized by properly distributing the transmit power used for the desired signal’s transmission and the recycling signal.
- Extension of IRC to general cases with variable numbers of interferences and desired signals, thus generalizing IRC.

The rest of this paper is organized as follows. Section II describes the system model, while Section III details the interference recycling (IRC). Section IV presents various implementations of IRC and Section V analyzes IRC from an information-theoretic perspective. Section VI discusses the generalization of IRC and Section VII evaluates the performance of IRC. Finally, Section VIII concludes the paper.

Throughout this paper, we use the following notations. The set of complex numbers is denoted as $\mathbb{C}$, while vectors/matrices are represented by bold lower-case or upper-case letters. Let $X^T$, $X^H$ and $X^{-1}$ be the transpose, Hermitian and inverse of matrix $X$, respectively. $\lVert \cdot \rVert$ and $\lvert \cdot \rvert$ represent the Euclidean norm and the absolute value, respectively. $\mathbb{E}(\cdot)$ denotes statistical expectation and $(a, b)$ represents the inner product of two vectors.

## II. System Model

We consider downlink transmission in heterogeneous cellular networks (HCNs) composed of overlapping macro and pico cells. As shown in Fig. 1, macro and pico base stations (MBS and PBS) are equipped with $N_{T_1}$ and $N_{T_0}$ antennas, whereas macro user equipment (MUE) and pico user equipment (PUE) are equipped with $N_{R_1}$ and $N_{R_0}$ antennas, respectively. We use $P_{T_1}$ and $P_{T_0}$ to denote the transmit power of MBS and PBS. Let $\mathbf{h}_0 \in \mathbb{C}^{N_{R_0} \times N_{T_0}}$ and $\mathbf{h}_1 \in \mathbb{C}^{N_{R_1} \times N_{T_1}}$ be the channel matrices from PBS to PUE and from MBS to MUE, respectively, while channel state information (CSI) from MBS to PUE is denoted as $\mathbf{h}_{10} \in \mathbb{C}^{N_{R_0} \times N_{T_1}}$. We adopt a spatially uncorrelated Rayleigh flat fading channel model to model the elements of the above matrices as independent and identically distributed zero-mean unit-variance complex Gaussian random variables. We assume that all users experience block fading, i.e., channel parameters remain constant in a block consisting of several successive time slots and vary randomly between successive blocks. Each user can accurately estimate CSI with respect to its intended and unintended Txs and feed it back to the associated BS via a low-rate error-free link (e.g., X2 interface [10]). We assume reliable links for the delivery of CSI and signaling. The delivery delay is negligible relative to the time scale at which the channel state varies [11,12]. Let $\mathbf{x}_1$ and $\mathbf{x}_0$ denote the desired data vectors from MBS and PBS to their serving subscribers. $\mathbb{E}(\lVert \mathbf{x}_0 \rVert^2) = \mathbb{E}(\lVert \mathbf{x}_1 \rVert^2) = 1$ holds. For clarity of exposition, we begin with the assumption of beamforming (BF), i.e., only one data stream is sent from MBS to MUE and from PBS to PUE, respectively. Then, $\mathbf{x}_1$ and $\mathbf{x}_0$ become scalars $x_1$ and $x_0$. We will generalize this design to multiple data streams sent from MBS and PBS in Section VI.
III. DESIGN OF INTERFERENCE RECYCLING

For clarity of exposition, we assume that BF is adopted. However, the following discussion under a simplified parameter setting and the use of BF for transmissions in pico- and macro-cells can be extended to more general settings.

A. Theoretical Basis

The received signal at PUE is expressed as:

\[ y_0 = \sqrt{P_{T1}} h_{10} p_1 x_1 + \sqrt{P_{T0}} h_0 p_{RC} x_{RC} + z_0 \]  

(1)

where \( p_1 \) represents the precoding vector for \( x_1 \) at MBS, \( p_{RC} \) is the precoder for \( x_{RC} \) at MBS, and \( x_{RC} \) is the data symbol carried by the recycling signal. The first term on the right hand side (RHS) of Eq. (1) denotes the interference from MBS and the second term is the IRC signal sent from PBS, \( x_0 \) represents for the additive white Gaussian noise (AWGN) vector whose elements have zero-mean and variance \( \sigma_n^2 \). Note that in Eq. (1), PBS sends an IRC signal instead of its desired signal.

PUE employs a filter vector \( f_0 \) to obtain the estimated signal \( \hat{y}_0 \) as:

\[ \hat{y}_0 = f_0^H (\sqrt{P_{T1}} h_{10} p_1 x_1 + \sqrt{P_{T0}} h_0 p_{RC} x_{RC} + f_0^H z_0). \]  

(2)

To recover the desired data, say \( x_0 \), at PUE, the first term on the RHS of Eq. (2) should satisfy:

\[ f_0^H (\sqrt{P_{T1}} h_{10} p_1 x_1 + \sqrt{P_{T0}} h_0 p_{RC} x_{RC}) = \alpha x_0. \]  

(3)

That is, the post-processed signal at PUE denoted by the term on the left hand side (LHS) of Eq. (3) is PUE’s desired data scaled by a coefficient \( \alpha \). We define \( x_0 = \alpha x_0 \) where \( \alpha \) is a real number, i.e., the phase of \( x_0 \) is either identical (\( \alpha \) is positive) or opposite (\( \alpha \) is negative) to that of \( x_0 \). From Eq. (3), the IRC signal can be determined as elaborated in the next subsection.

Before delving into details, we first illustrate the feasibility of IRC. Fig. 2 shows a simulated example of IRC using BPSK/QPSK [14]. Figs. (a), (b) and (c) each displays a scatterplot of the values that are sampled during the transmission, in the complex plane. The difference between plots (a) and (b) is that symbols “0” and “1” are mapped into phases \( \frac{\pi}{2} \) and \( -\frac{\pi}{2} \) in (a) whereas in (b) they are mapped into 0 and \( \pi \), respectively. Plots (a) and (b) show symbols received under the influence of noise in the constellations of \( S_1 \) and \( S_2 \), and in (c) we see the joint constellation consisting of four clusters for the four possible values sent by \( S_1 \) and \( S_2 \). Without loss of generality, we let plot (a) denote the data symbols carried by the interfering signal from MBS to PUE, while (b) represents the symbols of the IRC signal. Then, by properly determining the recycling symbols \( x_{RC} \) from the constellation points shown in Fig. 2(b), the interfering data (plot (a)) can be converted to the desired data (plot (c)). That is, by employing an IRC signal sent from PBS, PUE can recover its desired data from the interference, i.e., interference recycling is accomplished.

B. Determination of the IRC signal

We exploit the inter-relationship among multiple signals so as to determine the parameters for generating the IRC signal. According to Eq. (3), the maximum gain is achieved when the precoder and the receiving filter match the transmission
channel. Let us consider singular value decomposition (SVD) based pre- and post-processing as an example, i.e., apply SVD to \( h_0 \) to obtain \( h_0 = U_0 \lambda_0 V_0^H \) and adopt \( p_{RC} = v_0^{(1)} \) and \( f_0 = u_0^{(1)} \) at PBS and PUE, respectively, where \( v_0^{(1)} \) and \( u_0^{(1)} \) represent the first column vectors of the right and left singular matrices \( V_0 \) and \( U_0 \). Since an arbitrary symbol can be represented by its magnitude and phase, the desired, interfering and recycling data symbols carried by their associated signals can be expressed as \( x_0 = \rho_0 e^{j \theta_0} \), \( x_1 = \rho_1 e^{j \theta_1} \), and \( x_{RC} = \rho_{RC} e^{j \theta_{RC}} \). Then, Eq. (3) can be rewritten as:

\[
\sqrt{P_{T_0}} \beta_0 e^{j \theta_1} + \sqrt{P_{T_0}} \lambda_0^{(1)} \rho_{RC} e^{j \theta_{RC}} = \rho_0 e^{j \theta_0} \tag{4}
\]

where \( \beta = [u_0^{(1)}]^H h_0 p_1 \) is a complex number. \( \lambda_0^{(1)} \) is the largest singular value of \( h_0 \), indicating the amplitude gain of the principal eigenmode (or spatial sub-channel) of \( h_0 \).

In Eq. (4), \( \alpha, \rho_{RC} \) and \( \theta_{RC} \) are variables, of which \( \rho_{RC} \) and \( \theta_{RC} \) determine the IRC signal. Using different values of \( \rho_{RC} \) and \( \theta_{RC} \), various signals satisfying Eq. (4) can be obtained to realize IRC, but the amplitude gains, i.e., \( |\alpha| \), may vary. In order to maximize the desired signal’s power (or amplitude gain) and make full use of transmit power \( P_{T_0} \) at PBS, the optimal value of \( \rho_{RC} \) should be adopted so as to maximize \( |\alpha| \). After obtaining the optimal \( \rho_{RC} \) and corresponding \( \alpha \), we can compute \( \theta_{RC} \) (see Eq. (13)) and thus construct the IRC signal.

For clarity of presentation, we define \( \varepsilon = \sqrt{P_{T_0}/P_{T_0}} \) By replacing the complex number in Eq. (4) with the sum of its real and imaginary parts, and expressing the complex exponentials in terms of Euler’s formula, we can get Eq. (5) as below. Then, by writing equations based on the real and imaginary parts of Eq. (5), respectively, Eq. (5) can be decomposed into an equation set given by Eq. (6). We define two variables \( A = \varepsilon \rho_1 [\text{Re}(\beta) \cos \theta_1 - \text{Im}(\beta) \sin \theta_1] \) and \( B = \varepsilon \rho_1 [\text{Re}(\beta) \sin \theta_1 + \text{Im}(\beta) \cos \theta_1] \) to simplify Eq. (6) as:

\[
\begin{align}
\lambda_0^{(1)} \rho_{RC} \cos \theta_{RC} &= \frac{1}{\sqrt{P_{T_0}}} \alpha_0 \rho_0 \cos \theta_0 - A \\
\lambda_0^{(1)} \rho_{RC} \sin \theta_{RC} &= \frac{1}{\sqrt{P_{T_0}}} \alpha_0 \rho_0 \sin \theta_0 - B 
\end{align}
\tag{7}
\]

Since \( \rho_{RC} \) is the amplitude of the data symbol carried by the IRC signal, which is sent by PBS. In order to satisfy the power constraint of PBS, the following inequality should hold:

\[
0 < \rho_{RC} \leq 1. \tag{8}
\]

According to Eq. (4), when \( \rho_{RC} \) varies from 0 to 1, the relationship of the post-processed signals at PUE will be one of the following three situations as plotted in Fig. 3, where \( \bar{x}_1 = \varepsilon \sqrt{P_{T_0}} \beta_1 e^{j \theta_1}, \bar{x}_{RC} = \varepsilon \sqrt{P_{T_0}} \lambda_0^{(1)} \rho_{RC} e^{j \theta_{RC}}, \) and \( \bar{x}_0 = \alpha_0 \rho_0 e^{j \theta_0} \). Based on the definitions of \( \bar{x}_1, \bar{x}_{RC} \) and \( \bar{x}_0 \), Eq. (4) becomes \( x_1 + \bar{x}_{RC} = x_0 \). Therefore, as Fig. 3 shows, the vector indicating the post-processed IRC signal \( \bar{x}_{RC} \) should start from the end point (marked as \( O' \)) of the vector representing the filtered interference \( \bar{x}_1 \) (vector \( OO' \)), and the amplitude of \( \bar{x}_{RC} \) is \( |\bar{x}_{RC}| = |\bar{x}_{RC}| = \sqrt{P_{T_0}} \lambda_0^{(1)} \rho_{RC} \). Since \( \rho_{RC} \) ranges from 0 to 1, the radius of the circle with center \( O' \) is \( |\bar{x}_{RC}| = (0, \sqrt{P_{T_0}} \lambda_0^{(1)} \rho_{RC}) \). So, the end point of the vector of post-processed IRC signal is located on the circle with center \( O' \) and of radius \( |\bar{x}_{RC}| \). Then, the recycled desired signal at PUE, i.e., \( x_0 \), can be determined by the intersection of the circle with center \( O' \) and the green dotted line passing through the origin on which the desired data \( x_1 \) lies.

In the case of Fig. 3(a), there is no intersection between the circle and the green dashed line, and hence given \( P_{T_0} \), no IRC signal exists to extract desired data from interference. In Fig. 3(b), the green dotted line is tangent to the bottom of the circle when and only when \( \rho_{RC} = 1 \), and thus IRC signal with transmit power \( P_{T_0} \) can convert interference to the desired signal. As for Fig. 3(c), when \( \rho_{RC} < \rho_{min} \) where \( \rho_{min} < 1 \), no IRC solution exists, while given \( \rho_{RC} = \rho_{min} \), only one solution for IRC signal exists. As \( \rho_{RC} \) varies from \( \rho_{min} \) to 1, there are two intersection points between the circle and the green dashed line, i.e., two IRC solutions, denoted by \( \bar{x}_{RC} \) and \( \bar{x}_{RC} \) exist to yield the recycled desired signal \( \bar{x}_0 \) and \( \bar{x}_0 \), respectively. Moreover, if \( \bar{x}_{RC} \) is adopted as the IRC solution, the modulus of vector denoting \( \bar{x}_0 \), i.e., \( |\bar{x}_{RC}| \), is the difference of the modulus values of projections of interference and recycling signal on the desired signal, \( |\bar{x}_{RC}| = |\bar{x}_{RC}| - |\bar{x}_{RC}| \), and hence \( \bar{x}_1 \) and \( \bar{x}_{RC} \) cancel each other. As a comparison, when \( \bar{x}_{RC} \) is adopted, \( |\bar{x}_{RC}| = |\bar{x}_{RC}| = |\bar{x}_{RC}| + |\bar{x}_{RC}| \), and hence \( \bar{x}_1 \) and \( \bar{x}_{RC} \) construct with each other. Therefore, \( \bar{x}_0 \), incurred by \( \bar{x}_{RC} \), indicates a stronger desired signal power at the PUE.
That is, in order to maximize the output of IRC, the solution of \( \bar{x}_{RC}^+ \) is preferred. Moreover, as can be seen from Fig. 3(c), in order to maximize the amplitude of \( \bar{x}_{RC}^+ \), \( \rho_{RC} \) should be set to 1 so as to obtain a maximum \( |\bar{x}_{RC}| \).

By applying the triangle formula to Eq. (7), we can get Eq. (9) as below, which can be rewritten as Eq. (10). Next, we will solve \( \alpha \) from Eq. (10) under \( \rho_{RC} = 1 \), and then determine \( \theta_{RC} \) based on Eq. (7), so that the IRC signal can be constructed.

By substituting \( \rho_{RC} = 1 \) into Eq. (10) and defining \( D = \rho_0^2 \)

\[
E = -2\sqrt{P_{Tx\rho_0}(A\cos\theta_0 + B\sin\theta_0)} \quad \text{and} \quad F = P_{Ty}(A^2+B^2-[\lambda_0^{(1)}]^2),
\]

Eq. (10) can be simplified to:

\[
D\alpha^2 + E\alpha + F = 0.
\] (11)

The solution for the above quadratic equation with one unknown can be obtained as:

\[
\alpha_{\pm} = \frac{-E \pm \sqrt{E^2 - 4DF}}{2D}.
\] (12)

Let \( \Delta = E^2 - 4DF \), when \( \Delta < 0 \) and \( \Delta > 0 \), there will be one and two solutions for \( \alpha \), respectively. Otherwise, when \( \Delta < 0 \), no solution for \( \alpha \) exists. When there are two solutions for \( \alpha \), we should adopt \( \alpha = \left\{ \begin{array}{l} \alpha_+, \quad |\alpha_+| \geq |\alpha_-| \\ \alpha_-, \quad |\alpha_+| < |\alpha_-| \end{array} \right\} \) so as to maximize the magnitude of \( \bar{x}_0 \).

Based on the above discussion, we set \( \rho_{RC} = 1 \) to determine the parameters of recycling signal. If there is no solution for \( \alpha \), the transmit power of PBS is not sufficient for IRC, needless to say \( \rho_{RC} \in (0,1) \). This is because according to the power constraint of PBS, non-existence of solution for \( \alpha \) means that even PBS utilizes all its power budget, i.e., sets \( \rho_{RC} = 1 \), there is still not enough power for recovering the desired data from the interference. Therefore, when \( \rho_{RC} < 1 \), the power for generating IRC signal decreases, so that \( \alpha \) is still unavailable and hence IRC is inapplicable.

After obtaining \( \alpha \), we can calculate \( \theta_{RC} \) following Eq. (13) as:

\[
\tan\theta_{RC} = \frac{1}{\sqrt{P_{Tx}\rho_0 \cos\theta_0 - A}} \cdot \frac{1}{\sqrt{P_{Tx}\rho_0 \cos\theta_0 - B}}.
\] (13)

With \( \rho_{RC} = 1 \), \( \alpha \) and \( \theta_{RC} \), an IRC signal can be constructed.

Fig. 4 uses Monte Carlo simulation to plot the variation of \( |\alpha| \) with \( \rho_{RC} \) for a randomly selected channel realization. Here, we use \( |\alpha| \) instead of \( \alpha \) because in practice, a negative value of \( \alpha \) may result. We set 10\( \log(P_{Ty}/\sigma_n^2) \) = 1dB and 10\( \log(P_{Ty}/\rho_0^2) \) = 10dB, i.e., \( \varepsilon = 10^{0.9} \). The BPSK modulation is employed to generate \( x_1 \) and \( x_2 \). The numbers of simulated symbols of \( x_1 \) and \( x_2 \) are set to \( 10^5 \). As the figure shows, when \( \rho_{RC} \) is too small, the power of IRC signal is not sufficient for recovering the desired data from the interference, and hence no solution for \( \alpha \). So, \( |\alpha| \) is recorded as 0. As \( \rho_{RC} \) increases, \( |\alpha| \) grows accordingly. When \( \rho_{RC} = 1 \), we get the maximum \( |\alpha| \).

Based on the design of IRC, PUE needs the information of \( \alpha \) to decode its desired data correctly. Otherwise, if \( \alpha \) is unavailable at PUE and the desired data contains amplitude modulation, PUE will not be able to get correct desired data from \( \bar{x}_0 \). But, if the desired data only contains phase modulation, e.g., multiple phase shift keying (MPSK), only the polarity of \( \alpha \) is required at PUE for correct decoding. Specifically, if \( \alpha > 0 \), the desired data \( x_0 \) and the recycled desired signal \( \bar{x}_0 \) are in the same phase; otherwise, if \( \alpha < 0 \), \( x_0 \) and \( \bar{x}_0 \) are in the opposite phase. Therefore, with the polarity of \( \alpha \), \( x_0 \) can be recovered from \( \bar{x}_0 \). In such a case, less overhead will be incurred than delivering the value of \( \alpha \), thus facilitating the use of IRC.

IV. VARIOUS IMPLEMENTATIONS OF IRC

In Section III, we presented the design of IRC under the assumption that PBS only sends the recycling signal under the constraint on \( P_{Tx} \), i.e., all transmit power is used to generate the IRC signal. However, PBS can also send the desired data directly to the PUE. Therefore, one may naturally raise a question “Is it necessary to allocate all the transmit power to the IRC signal?” To answer this question, we will discuss various implementations of IRC.

Fig. 5 illustrates four IRC implementations. Without loss of generality, we employ SVD-based pre- and post-processing at PBS and PUE. Similarly to Fig. 3, the post-processed interference \( \bar{x}_1 \) is denoted by vector \( \bar{O}\bar{D} \), while the recycled desired signal at PUE, \( \bar{x}_{0} \), is represented by a green vector \( \bar{O}\bar{D} \). The angle between \( \bar{O}\bar{D} \) and \( \bar{O}\bar{D} \) is denoted by \( \theta \). As the figure shows, with mode I, PBS allocates all the transmit power \( P_{Tx} \) to the IRC signal \( \bar{x}_{RC} \), \( \bar{O}\bar{D} \) (hence \( |\bar{x}_{RC}|^2 = P_{Tx}[\lambda_0^{(1)}]^2 \) so as to obtain the recycled desired signal \( \bar{x}_{0} \) from the interference \( \bar{x}_1 \)). In such a case, no power is allocated to
the direct transmission of desired signal, denoted by $\tilde{x}_0^T$, and hence $\tilde{x}_0^T = 0$. For a fair comparison, we let the other three IRC implementations, indexed by II, III and IV, respectively, yield an identical target desired signal $\tilde{D}$. We also define the angle $\theta^I$ which is the function of $\tilde{x}_1$, $\tilde{x}_0$ and $P_{T_0}$, and is thus expressed as $\theta^I = f(\tilde{x}_1, \tilde{x}_0, P_{T_0})$.

As for mode II, the powers of post-processed IRC signal $\tilde{x}_{RC}^I$ ($O'A$) and desired signal $\tilde{x}_0^I$ ($A\tilde{D}$) are $|\tilde{x}_{RC}^I|^2$ and $|\tilde{x}_0^I|^2$, respectively. Hence, the total power consumption is $(|\tilde{x}_{RC}^I|^2 + |\tilde{x}_0^I|^2)/|\lambda_0^{(1)}|^2$. Let $O'A$ denote the recyled desired signal. The amplitude of the combination of the recycled and directly transmitted desired signal components is then $|O'A + A\tilde{D}| = |\tilde{D}|$. In mode II, the interference is not fully exploited on that only part of the projection of interference on the desired signal, i.e., $O'A$ out of $O\tilde{B}$, is recycled. Moreover, by the cosine law, $|\tilde{x}_{RC}^I|^2 = |\tilde{x}_{RC}^I|^2 + |\tilde{x}_0^I|^2 - 2|\tilde{x}_{RC}^I||\tilde{x}_0^I|\cos(\pi - \theta^II)$ holds. Since $\cos(\pi - \theta^II) > 0$, we have $|\tilde{x}_{RC}^I|^2 + |\tilde{x}_0^I|^2 > |\tilde{x}_{RC}^I|^2$. Therefore, the total transmit power of mode II is greater than that of scheme I, $P_{T_0}$, so mode II is inferior to mode I's power efficiency [15]. As the triangular shadow area determined by $OO'$, $O\tilde{B}$ and $O'B$ shows, where angle $\theta^II \in (\pi/2, \pi - \theta)$, the mode II implementation falls in this region.

In mode III, the filtered IRC signal $\tilde{x}_{RC}^II$ ($O'B$) and desired signal $\tilde{x}_0^II$ ($B\tilde{D}$) have power $|\tilde{x}_{RC}^II|^2$ and $|\tilde{x}_0^II|^2$, respectively, are obtained by PUE simultaneously. $\theta^III = \frac{\pi}{2}$, and hence mode III makes full use of the interference. The combined desired signal at PUE is $(\tilde{x}_1 + \tilde{x}_{RC}^II) + \tilde{x}_0^II = O\tilde{B} + B\tilde{D} = O\tilde{D}$. According to the Pythagorean theorem, $|\tilde{x}_{RC}^II|^2 + |\tilde{x}_0^II|^2 = |\tilde{x}_{RC}^II|^2$ holds. So, modes III and I yield the same magnitude of desired signal ($|O\tilde{D}|$) with an identical power consumption, i.e., $P_{T_0}$.

In mode IV, the filtered IRC signal $\tilde{x}_{RC}^IV$ ($O'C$) and desired signal $\tilde{x}_0^IV$ ($C\tilde{D}$) have power $|\tilde{x}_{RC}^IV|^2$ and $|\tilde{x}_0^IV|^2$, respectively. The combined desired signal at the PUE is $(\tilde{x}_1 + \tilde{x}_{RC}^IV) + \tilde{x}_0^IV = O\tilde{D}$. Edges $O'B$, $O'D$ and $BD\tilde{D}$ enclose the region of mode IV where $\theta^IV \in (\theta^I, \pi)$. According to the cosine law, we have $|\tilde{x}_{RC}^IV|^2 = |\tilde{x}_{RC}^IV|^2 + |\tilde{x}_0^IV|^2 - 2|\tilde{x}_{RC}^IV||\tilde{x}_0^IV|\cos(\pi - \theta^IV)$, then, since $|\tilde{x}_{RC}^IV|^2 + |\tilde{x}_0^IV|^2 = |\tilde{x}_{RC}^IV|^2$ and $\cos(\pi - \theta^IV) < 0$, the inequality $|\tilde{x}_{RC}^IV|^2 + |\tilde{x}_0^IV|^2 < |\tilde{x}_{RC}^IV|^2 + |\tilde{x}_0^IV|^2$ holds. Therefore, to obtain the same magnitude of desired signal at PUE ($|O\tilde{D}|$), mode IV consumes less power than III. In summary, mode IV outperforms the other three implementations in power efficiency.

Table I summarizes the above discussion.

<table>
<thead>
<tr>
<th>Mode index</th>
<th>$\theta^M$</th>
<th>Tx power consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>$\theta^I = f(\tilde{x}_1, \tilde{x}<em>0, P</em>{T_0})$</td>
<td>$P_{T_0}$</td>
</tr>
<tr>
<td>II</td>
<td>$\theta^II \in (\pi/2, \pi - \theta)$</td>
<td>$P_{T_0}$</td>
</tr>
<tr>
<td>III</td>
<td>$\theta^III = \frac{\pi}{2}$</td>
<td>$P_{T_0}$</td>
</tr>
<tr>
<td>IV</td>
<td>$\theta^IV \in (\theta^I, \pi)$</td>
<td>$&lt; P_{T_0}$</td>
</tr>
</tbody>
</table>

Table I compares different IRC implementations under the constraint that the amplitude of desired signal composed of the recycled and the directly transmitted parts (for mode I, however, the directly transmitted part is 0) should be the same. $\theta^M$ where $M \in \{I, II, III, IV\}$ indicates the angle between the filtered IRC signal and the recycled desired signal with IRC mode $M$. As can be inferred from the table, given the same transmit power budget, mode IV is advantageous over the others in spectral efficiency (SE), while mode I and III rank the second, mode II yields the lowest SE. Moreover, it should be noted that in mode IV, there also exist various implementations under different IRC signal power values, $|\tilde{x}_{RC}^IV|^2/|\lambda_0^{(1)}|^2$. Thus, by allocating the optimal amount of power $|\tilde{x}_{RC}^IV|^2/|\lambda_0^{(1)}|^2$ to the IRC signal, the performance of the IRC mode IV can be optimized further.

V. PERFORMANCE ANALYSIS OF IRC FROM AN INFORMATION-THEORETIC PERSPECTIVE

We now analyze the performance of IRC from the perspective of information theory, based on which the spectral efficiency (SE) of IRC is derived.

Let $X_0$ and $Y_0$ represent the finite input and output symbol sets with respect to a discrete memoryless channel with additive interference and noise. The transmitter sends symbol $\tilde{x}_0 \in X_0$. Since there is additive interference $\tilde{x}_1 \in X_1$ and noise $\tilde{z}_0 \in Z_0$, where $X_1$ and $Z_0$ are discrete spaces, the output of the channel is:

$$\tilde{y}_0 = \tilde{x}_0 + \tilde{x}_1 + \tilde{z}_0$$

where $\tilde{y}_0 \in Y_0$, $\tilde{x}_0$, $\tilde{x}_1$ and $\tilde{z}_0$ are statistically independent from each other, following the Gaussian distributions $\mathcal{N}(0, \sigma^2_0)$, $\mathcal{N}(0, \sigma^2_1)$ and $\mathcal{N}(0, \sigma^2_n)$, respectively.

Then, the channel capacity can be obtained as:

$$C_0 = \frac{1}{2} \log_2 \left(1 + \frac{\sigma^2_0}{\sigma^2_1 + \sigma^2_n} \right).$$

Before delving into the performance analysis of IRC, we first apply the above result to obtain the channel capacity of the pico transmission-pair, i.e., PBS and PUE, without interference management. Based on the system model given in Fig. 1, we let PBS and MBS send data $x_0$ and $x_1$ to PUE and MUE through their principal eigenmodes, respectively. PUE suffers interference from the transmission of $x_1$. Then, the estimated signal post-processed by filter $f_0$ at PUE is:

$$\tilde{y}_0 = f_0^H \sqrt{P_{T_0}} h_0 d_0 x_0 + f_0^H \sqrt{P_{T_1}} h_1 d_1 x_1 + f_0^H z_0$$

where $x_0 = \bar{x}_0 + \bar{x}_1 + \bar{z}_0$. (16)
where $p_0$ and $p_1$ are the precoders at PBS and MBS, respectively. Taking SVD-based signal processing as an example, we employ $\mathbf{p}_0 = \mathbf{v}_{0}^{(1)}$ and $\mathbf{f}_0 = \mathbf{u}_{0}^{(1)}$ where $\mathbf{v}_{0}^{(1)}$ and $\mathbf{u}_{0}^{(1)}$ are the first columns of the right and left singular matrices $\mathbf{V}_0$ and $\mathbf{U}_0$, respectively, obtained from $\mathbf{h}_0 = \mathbf{U}_0\mathbf{A}_0\mathbf{V}_0^\dagger$ (see Section III for details). The post-processed desired signal, interference and noise are expressed as $\bar{x}_0 = \mathbf{f}_0^H \sqrt{P_{T_0}} \mathbf{h}_0 \mathbf{p}_0 x_0 = \sqrt{P_{T_0}} \lambda_0^{(1)} x_0$, $\bar{x}_1 = \mathbf{f}_1^H \sqrt{P_{T_1}} \mathbf{h}_{10} \mathbf{p}_1 x_1$, and $\bar{z}_0 = \mathbf{f}_0^H \mathbf{z}_0$, respectively. Note that in such a case, $\mathbf{f}_0$ is designed to match the desired signal while the interference is not intentionally managed. Then, from Eq. (15), we can get the channel capacity of pico transmission-pair without IM as:

$$C_0^{Non-IM} = \frac{1}{2} \log_2 \left(1 + \frac{\sigma_x^2}{\sigma_z^2 + \sigma_n^2} \right)$$

(17)

where $\sigma_x^2 = P_{T_0} |\lambda_0^{(1)}|^2$.

With IRC, the estimated signal at PUE is given by Eq. (2). Comparing with Eq. (14), Eq. (2) can be rewritten as:

$$\bar{y}_0 = \bar{x}_1 + \bar{x}_{RC} + \bar{z}_0 = \bar{x}_0 + \bar{z}_0.$$  

(18)

Note that $\bar{x}_0$ and $\bar{y}_0$ in Eq. (16) are different from those in Eq. (18), and hence, to avoid ambiguity, we will use $\bar{x}_0^\dagger$ and $\bar{y}_0^\dagger$ as well as $\bar{x}_1^\dagger$ and $\bar{y}_0^\dagger$ to replace $\bar{x}_0$ and $\bar{y}_0$ in Eq. (16) and Eq. (18), respectively. According to Eq. (16), since $\mathcal{X}_0^\dagger$ ($\bar{x}_0^\dagger \in \mathcal{X}_0^\dagger$) and $\mathcal{Z}_0$ are independent of each other and obey the Gaussian distribution of $\mathcal{N}(0, \sigma_x^2)$ and $\mathcal{N}(0, \sigma_n^2)$, and $\bar{x}_1^\dagger = \sqrt{P_{T_1}} \lambda_0^{(1)} x_0^\dagger$, the distribution of $x_0$ follows $\mathcal{N} \left(0, \frac{\sigma_x^2}{P_{T_0} |\lambda_0^{(1)}|^2} \right)$. In the case of Eq. (18), the distribution of PUE’s desired data symbol (i.e., $x_0$) still follows $\mathcal{N} \left(0, \frac{\sigma_x^2}{P_{T_0} |\lambda_0^{(1)}|^2} \right)$. Then, since with IRC, we have $\mathcal{X}_0^\dagger = \alpha x_0$, we can get the distribution of $\bar{x}_0^\dagger$ as $\mathcal{N} \left(0, \frac{\alpha^2 \sigma_x^2}{P_{T_0} |\lambda_0^{(1)}|^2} \right)$. Similarly to the derivation of Eq. (15), the channel capacity of pico transmission-pair with IRC can be obtained as:

$$C_0^{IRC} = \frac{1}{2} \log_2 \left(1 + \frac{\alpha^2 \sigma_x^2}{P_{T_0} |\lambda_0^{(1)}|^2} \sigma_n^2 \right).$$

(19)

By comparing $C_0^{Non-IM}$ and $C_0^{IRC}$, given by Eqs. (17) and (19), respectively, we can find that the power of interference, i.e., $\sigma_x^2$, is in the denominator of the expression of $C_0^{Non-IM}$, while with IRC, the interference is converted to the positive factor $\left(\frac{\alpha^2 \sigma_x^2}{P_{T_0} |\lambda_0^{(1)}|^2} \right)$ in the numerator of the expression of $C_0^{IRC}$. Although $\left(\frac{\alpha^2 \sigma_x^2}{P_{T_0} |\lambda_0^{(1)}|^2} \right)$ in Eq. (19) appears as the desired signal term, PBS doesn’t send desired signal at all. In other words, with IRC, PBS can exploit the interference to realize its desired data transmission.

Based on the above analysis, the average SE of PUE with IRC and Non-IM can be calculated as:

$$\mathbb{E}(C_0^{IRC}) = \mathbb{E} \left\{ \log_2 \left(1 + \frac{\alpha^2 |x_0|^2}{\sigma_n^2} \right) \right\}$$

(20)

and

$$\mathbb{E}(C_0^{Non-IM}) = \mathbb{E} \left\{ \log_2 \left(1 + \frac{P_{T_0} |\lambda_0^{(1)}|^2 |x_0|^2}{\chi + \sigma_n^2} \right) \right\},$$

(21)

where $\chi = P_{T_1} (\mathbf{h}_{10}^H \mathbf{p}_1 x_1) (\mathbf{h}_{10}^H \mathbf{p}_1 x_1)^H$ denotes the strength of interference at PUE.

VI. GENERALIZATION OF IRC

So far, we have assumed that both MBS and PBS employ BF to transmit a single desired data stream to MUE and PUE, respectively, hence imposing only one interference from MBS on the PUE. Here we extend IRC to general cases with variable numbers of interferences and desired data streams with respect to the pico transmission-pair, i.e., PBS and PUE.

A. Arbitrary Number of Interferences

When multiple desired signals come from a MBS, the proposed IRC can be extended as follows. Since picocells are deployed within the coverage of a macrocell, interferences from other MBSs are negligible. For clarity of presentation, we let the number of desired signals from PBS to PUE be 1. For $N > 1$ interferences, i.e., the transmit data vector of MBS is $\mathbf{x}_1 = [x_1^{(1)}, \ldots, x_1^{(N)}]^T$, the received signal at the victim PUE with IRC can be expressed as:

$$y_0 = \sum_{n=1}^{N} \sqrt{P_{T_1}} \mathbf{h}_{10} \mathbf{p}_1^{(n)} x_1^{(n)} + \sqrt{P_{T_0}} \mathbf{h}_0 \mathbf{p}_{RC} x_{RC} + \mathbf{z}_0.$$  

(22)

The transmission of $x_1^{(n)}$ causes the interference $\sqrt{P_{T_1}} \mathbf{h}_{10} \mathbf{p}_1^{(n)} x_1^{(n)}$ where $P_{T_1}$ is the transmit power for $x_1^{(n)}$. $\sum_{n=1}^{N} P_{T_1} = P_{T_1}$ holds. $\mathbf{p}_1^{(n)}$ denotes the precoding vector of $x_1^{(n)}$. By exploiting interplays among the interferences, multiple interference components can be equivalent to one effective interference [16]. Then, the design of IRC given in Section III can be directly applied.

B. Arbitrary Number of Desired Data Streams

We now generalize the number of desired signals, denoted by $M$, that PBS intends to transmit to PUE, i.e., the desired data vector of PUE is $x_0 = [x_0^{(1)}, \ldots, x_0^{(M)}]^T$. For simplicity, we assume MBS sends a single signal to MUE, hence imposing one interference on the PUE.

For $M > 1$ desired data streams of the PUE, $\min(N_{T_0}, N_{R_0}) \geq M$ should hold. That is, there are $M$ decoupled spatial sub-channels available free from mutual interference between PBS and PUE. Then, we consider the projection of the interference on each sub-channel to which IRC is applied. The recycling signal and such a projection component to be recycled are within the same sub-channel, hence guaranteeing orthogonality among multiple IRC signals. Therefore, with $M$ IRC signals via $M$ spatial sub-channels, $M$ independent desired data streams may be recovered at the PUE, respectively.

Based on the above discussion, the received signal at the PUE can be expressed as:

$$y_0 = \sqrt{P_{T_1}} \mathbf{h}_{10} x_1 + \sum_{m=1}^{M} \sqrt{P_{T_0}^{(m)}} \mathbf{h}_0 \mathbf{p}_1^{(m)} x_1^{(m)} + \mathbf{z}_0.$$  

(23)
where $\mathbf{x}_{RC} = \left[ x_{RC}^{(1)} \cdots x_{RC}^{(m)} \cdots x_{RC}^{(M)} \right]^T$ is the transmit IRC data vector of PBS. $P_t^{(m)}$ is the transmit power for $x_{RC}^{(m)}$. $\sum_{m=1}^{M} P_t^{(m)} = P_t$ holds. $p_{RC}^{(m)}$ denotes the precoding vector of $x_{RC}^{(m)}$.

In summary, regardless of the numbers of interferences and desired data streams with respect to the pico transmission-pair, the overall interference recycling problem can be decomposed into multiple independent single-desired-signal single-interference recycling problems, so that the proposed IRC can be readily applied.

VII. Evaluation

We now evaluate the performance of the proposed mechanism using MATLAB. Besides IRC, IN [3,4], IS [5], ZF reception, p2pMIMO and Non-IM are also simulated for comparison. Note that IRC, IN, IS and ZF reception are victim Tx/Rx side implementations, while the interfering Tx–Rx pair does not modify its transmission for the victim. Therefore, we investigate the spectral efficiency (SE) of PUE with various IM schemes. As for ZFBF and IA, since they are interfering Tx-side implementations, PUE’s SE is the same as that of p2pMIMO, i.e., interference to PUE is avoided by MBS-side pre-processing.

We set $N_{T_1} = N_{R_1} = 2$ where $i = 0, 1$. Both macro and pico transmissions employ beamforming and BPSK modulation. Although in practice $P_{T_1} > P_t$, by considering path loss, and since picocells are usually deployed in the edge area of a macrocell for a shorter distance from PBS to PUE than that from MBS to PUE, the post-processed $\tilde{x}_{RC}$ may be strong relative to $\tilde{x}_1$ so that the desired data $x_0$ can be recovered. Therefore, similarly to the discussion in [4,5], we consider the influence of the transmit power of MBS and PBS incorporated with the path loss perceived by PUE, denoted by $P_{T_1}$ and $P_{T_0}$, respectively. Then, we define $\zeta = 10 \log \left( P_{T_1} / \sigma_n^2 \right)$ and $\bar{\varepsilon} = \sqrt{P_{T_1} / P_t}$, and adopt $\zeta \in [0, 20]$ dB and $\bar{\varepsilon} \in [0, 3, 3]$ in our simulation. Although the evaluation is done with some specific parameter settings, a similar conclusion can be drawn for more general cases. In the following simulation, when IRC, IN or IS are inapplicable due to insufficient Tx power budget, we simply switch off the method and adopt Non-IM.

Fig. 6 plots the PUE’s SE along with $\bar{\varepsilon}$ for different IM schemes where $\bar{\varepsilon} \in [0, 3, 3]$. As $\bar{\varepsilon}$ increases, $P_{T_0}$ is shown to become smaller than $P_{T_1}$, decreasing PUE’s SE for all schemes. The proposed IRC (Mode I as illustrated in Fig. 5) outputs the highest SE of all mechanisms, because such an IRC implementation can make full use of interference. Note that p2pMIMO is realized by letting PBS transmit to PUE in accordance with their own transmission channel $h_{01}$ without interference. In such a case, SE of p2pMIMO is the product of power $P_{T_0}$. As for the IRC, PBS sends a recycling signal with power $P_{T_0}$ and exploits the interference power at the victim PUE, and thus SE of IRC is the output of power larger than $P_{T_0}$. Therefore, IRC significantly outperforms p2pMIMO in SE. In Fig. 6(a), when $\zeta$ is small, the interference is weak relative to noise. In such a case, noise dominates the SE performance, so the contribution of IM to SE is limited, incurring ZF and IN inferior to Non-IM.

Fig. 6(b) shows the case when the interference is relatively stronger than noise ($\zeta = 10$ dB). In such a case, IM contributes more to SE enhancement, yielding higher SE than Non-IM, especially for ZF and IS for small $\bar{\varepsilon}$. Given fixed $\zeta$, the interference perceived by PUE determined by $P_{T_1}$, becomes strong relative to $P_{T_0}$ as $\bar{\varepsilon}$ increases, reducing IRC’s feasible probability. Therefore, SE of IRC approaches that of p2pMIMO as $\bar{\varepsilon}$ becomes very large (see Fig. 3). That is, as the interference strength $[O0']$ grows, a larger IRC signal’s magnitude, indicated by the radius of circle with center $O'$, may be required to recover the desired data, i.e., enable the existence of intersection between the circle and the green dotted line on which the desired data $x_0$ lies.

Fig. 7 shows PUE’s SE of different IM methods along with $\zeta$ where $\zeta \in [0, 20]$ dB. Given fixed $\bar{\varepsilon}$, both $P_{T_0}$ and $P_{T_1}$ increase as $\zeta$ grows, thus making more power available at PBS and increasing the SE of all schemes with an increase of $\zeta$. Fig. 7(a) shows IRC to provide the best SE among all the schemes. p2pMIMO is the second while IS is the third. Given a relatively strong interference, i.e., $\zeta > 3$ dB, ZF outperforms IN and Non-IM, while Non-IM yields the lowest SE. The reason can be found in the discussion of Fig. 6. Given $\bar{\varepsilon} = 0.5$, PBS has sufficient power for desired signal’s transmission and interference management such as IS, IN and IRC, thus yielding higher SE than that in Fig. 7(b) under $\bar{\varepsilon} = 2$. In Fig. 7(b), $P_{T_1}$ is strong relative to $P_{T_0}$, but, when $\zeta$ is small, interference at PUE is weak, and hence the feasibility of IRC is high enough, yielding better SE than p2pMIMO. As $\zeta$ increases further, the feasible probability of IRC drops, thus yielding inferior SE to that of p2pMIMO. However, IRC still outperforms IS, IN, ZF and Non-IM.

Fig. 8 plots PUE’s SE with various IRC implementations. The SE of all schemes is shown to decrease as $\bar{\varepsilon}$ grows which is consistent with the results provided in Fig. 6. Since Modes III and I are equivalent in power efficiency measured in bps/W, they yield the same SE as analyzed in Section IV. Because the realization of Modes II and IV are within the right and left triangle areas of Fig. 5, we simulate the average SE over these two areas, respectively. Moreover, as Mode II under-utilizes interference while the other three fully exploit the interference, Mode II outputs the lowest SE, even lower than p2pMIMO when the interference is strong. As discussed in Section IV, Mode IV is the most power-efficient of the four modes, so we also simulate Mode IV with the optimal Tx power allocation to the direct desired data transmission and recycling signal denoted as Optimal, which provides the maximum PUE’s SE.

In summary, the proposed IRC not only outperforms existing victim-side IM schemes such as ZF, IN and IS, but also outperforms ZFBF and IA which are implemented at the interfering Tx to achieve high SE of the victim transmission-pair (PBS and PUE in this paper) as long as $\bar{\varepsilon}$ or/and $\zeta$ are not too large.


