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Interference Utilization Precoding in Multi-Cluster IoT Networks

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In Internet-of-Things, downlink multi-device interference has long been considered as a harmful element deteriorating system performance, and thus the principle of the classic interference-mitigation based precoding is to suppress the multi-device interference by exploiting the spatial orthogonality. In recent years, a judicious interference utilization precoding has been developed, which is capable of exploiting multi-device interference as a beneficial element for improving device's reception performance, thus reducing downlink communication latency. In this review paper, we aim to review the emerging interference utilization precoding techniques. We first briefly introduce the concept of constructive interference, and then we present two generic downlink interference-utilization optimizations, which utilizes the multi-device interference for enhancing system performance. Afterwards, the application of interference utilization precoding is discussed in multi-cluster scenario. Finally, some open challenges and future research topics are envisaged.

Keywords: interference utilization, multi-device interference, multi-cluster, precoding design, Internet-of-Things

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1 INTRODUCTION

Downlink precoding has been regarded as a key technology in multi-user multiple-input and multiple-output (MIMO) communications. With the channel state information (CSI) available at the base station, the multi-user interference can be calculated prior to transmission. In this way, the interference mitigation (IM)-based precoder techniques have been extensively investigated to strictly suppress the interference. The dirty-paper coding (DPC) scheme was proposed in Costa (1983) by pre-subtracting the interference prior to transmission for achieving capacity, which however assumes infinite alphabet input and incurs high computational cost. Although the Tomlinson-Harashima precoding (THP) Sun and Lei (2013) and vector perturbation (VP) Hochwald et al. (2005) precoders aim to reduce the computational complexity over the DPC approach, they still need a sophisticated sphere-search algorithm for algorithm implementation. Hence, low-complexity linear precoders, such as zero-forcing (ZF) and minimum mean squared error (MMSE) Tse and Viswanath (2005), Peel et al. (2005), have attracted much attention in practices due to their low-complexity. On the other hand, optimization-based precoding has been a popular research topic. For example, signal-to-interference-plus-noise ratio (SINR) balancing aims to maximize the minimum SINR subject to a total power constraint (Wiesel et al., 2006); transmission power minimization problem aims to reduce the transmission power at the base station, subject to user's minimum SINR requirements (Schubert and Boche, 2004).

The above designs treat the input as infinite Gaussian signal. Hence, they only exploit the channel correlation for the precoding design. In practice, modulation size is finite, and the input is not Gaussian signal. In this case, there is scope to jointly exploit the correlation among the channels and transmitted data, so that the multi-user interference is possible to make constructive at each receiver, termed as interference utilization (IE) precoding (Masouros and Alsusa, 2007). The concept of constructive interference (CI) has been applied for anonymous communications (Wei et al., 2021a), cognitive radio (Law and Masouros, 2018), large-scale MIMO (Amadori and Masouros, 2016, 2017b), constant envelope (Amadori and Masouros, 2017a; Liu et al., 2017), hybrid beamforming (Hegde et al., 2019), multi-cell coordination (Wei et al., 2020b), rate-splitting (Salem et al., 2019), physical layer security (Khandaker et al., 2019; Wei et al., 2020a; Wei and Masouros, 2020), directional modulation (Wei et al., 2021b), and integrated sensing and communication systems (Liu et al., 2018). In the following section, we briefly discuss the IE-based precoder design.

2 IE-BASED PRECODER DESIGN

For comparison, let us first consider a classic power minimization problem subject to per-device's signal-to-interference-plus-noise ratio (SINR) requirement. Assume that the transmitter is equipped with N antennas for serving K devices ($N \geq K$). Define $\boldsymbol{w}_i \in \mathbb{C}^{(N\times 1)}$ as the precoder vector for the i-th device's intended signal s_i. Write the transmitted symbol vector $\boldsymbol{s} = [s_1, \ldots, s_K]^{\mathbf{T}} \in \mathbb{C}^{(K\times 1)}$, the signal received by the i-th user can be written as

$$y_i = \boldsymbol{h}_i[\boldsymbol{w}_1, \ldots, \boldsymbol{w}_K]\boldsymbol{s} + n_i \tag{1}$$

where $\boldsymbol{h}_i \in \mathbb{C}^{(1\times N)}$is the multiple-input and single-output (MISO) channel spanning from the transmitter to the i-th device, while n_i denotes the receiver's noise, following a Gaussian distribution $\mathbb{CN}(0, \sigma^2)$. A generic power minimization problem can be formulated as

$$\begin{aligned} &\text{P1:}\ \min_{\boldsymbol{w}_1,\ldots,\boldsymbol{w}_K} \sum_{i=1}^{K} \|\omega_i\|^2, \\ &\text{s.t. (C1):}\ \frac{|h_i\omega_i|^2}{\sum_{j\neq i}|h_i\omega_j|^2 + \sigma^2} \geq \Gamma_i, \quad \forall i \in K, \end{aligned} \tag{2}$$

where Γ_i is the i-th device's SINR requirement. The problem P1 represents a non-convex second-order cone programming (SOCP) exercise. By defining $\boldsymbol{W}_i = \boldsymbol{w}_i\boldsymbol{w}_i^H \in \mathbb{C}^{N\times N}$, P1 can be equivalently transformed into

$$\begin{aligned} &\text{P2:}\ \min_{\boldsymbol{w}_1,\ldots,\boldsymbol{w}_K} \sum_{i=1}^{K} \operatorname{tr}(\boldsymbol{W}_i), \\ &\text{s.t. (C1)}: \boldsymbol{h}_i\boldsymbol{W}_i\boldsymbol{h}_i^H \geq \Gamma_i\left(\sum_{j\neq i}\boldsymbol{h}_i\boldsymbol{W}_j\boldsymbol{h}_i^H\right) + \sigma^2, \forall i \in K, \\ &\text{(C2)}: \boldsymbol{W}_i \succeq \mathbf{0}, \forall i \in K, \\ &\text{(C3)}: \operatorname{rank}(\boldsymbol{W}_{\mathrm{i}}) = 1, \forall i \in K, \end{aligned} \tag{3}$$

which can be readily solved as a standard convex semi-definite programming (SDP) problem after dropping constraint (C3).

Different from IM-based precoding that needs to strictly suppress interference, the IE-based precoder is able to exploit the multi-device interference as a constructive element. Multi-device interference can be achieved by exploiting geometrical interpretation shown in **Figure 1**. Explicitly, we first rotate the signal y_i by the angle of $\angle s_i$, and then the rotated signal can be mapped onto real axis and imaginary axis respectively. As can be seen, the received signal falls into a constructive region (in **Figure 1B**) if and only if the trigonometry below is ensured

$$\left(\operatorname{Re}(y_i s_i^*) - \sigma\sqrt{\Gamma}\right)\cdot \tan\left(\frac{\pi}{M}\right) \geq \left|\operatorname{Im}(y_i s_i^*)\right|, \forall k \in K, \tag{4}$$

where M represents constellation size. s_i^* denotes the conjugate of s_i, where s_i is the intended symbol for the i-th user. In particular, Γ physically represents the Euclidean distance in the signal constellation between the constructive region and the decision thresholds, which also directly relates to SINR performance of the received signal. The above discussion can be extended into any order M-PSK and multi-level modulations Kabir et al. (2018). Now, we are able to give the interference utilization-based power minimization precoder such as

$$\begin{aligned} &\text{P1}:\ \min_{\boldsymbol{w}_1,\ldots,\boldsymbol{w}_K} \sum_{i=1}^{K} \|\boldsymbol{w}_i\|^2, \\ &\text{s.t. (Cl)}: \left(\operatorname{Re}(\boldsymbol{h}_i[\boldsymbol{w}_1,\ldots,\boldsymbol{w}_K]\boldsymbol{s}s_i^*) - \sigma\sqrt{\Gamma}\right)\cdot \\ &\tan\left(\frac{\pi}{M}\right) \geq \left|\operatorname{Im}(\boldsymbol{h}_i[\boldsymbol{w}_1,\ldots,\boldsymbol{w}_K]\boldsymbol{s}s_i^*)\right|, \forall k \in K. \end{aligned} \tag{5}$$

Evidently, the precoder optimization is convex in nature, which can be solved directly. Then, we further discuss the IE-based precoder for SINR balancing optimization. When formulating SINR balancing for IE precoder, its problem formulation can be written as

$$\begin{aligned} &\text{P2}:\ \min_{\boldsymbol{w}_1,\ldots,\boldsymbol{w}_K} \sum_{i=1}^{K} \|\boldsymbol{w}_i\|^2, \\ &\text{s.t. (C1)}: \left(\operatorname{Re}(\boldsymbol{h}_i[\boldsymbol{w}_1,\ldots,\boldsymbol{w}_K]\boldsymbol{s}s_i^*) - \sigma\sqrt{\Gamma}\right)\cdot \\ &\tan\left(\frac{\pi}{M}\right) \geq \left|\operatorname{Im}(\boldsymbol{h}_i[\boldsymbol{w}_1,\ldots,\boldsymbol{w}_K]\boldsymbol{s}s_i^*)\right|, \forall k \in K, \\ &\text{(C2)}: \|[\boldsymbol{w}_1,\ldots,\boldsymbol{w}_K]\boldsymbol{s}\|^2 \leq P_{\max}, \end{aligned} \tag{6}$$

where $P_{\max}$ denotes the power budget. It has been proved in Li and Masouros (2018) that, the closed-form of such an IE-based precoder is given as

$$\boldsymbol{W} = \frac{1}{K}\boldsymbol{H}^H(\boldsymbol{H}\boldsymbol{H}^H)^{-1}\operatorname{diag}(\boldsymbol{\Lambda})\boldsymbol{s}\hat{\boldsymbol{s}}, \tag{7}$$

where $\hat{\boldsymbol{s}}$ is given as $\hat{\boldsymbol{s}} = [\frac{1}{S_1}, \frac{1}{S_2}, \ldots, \frac{1}{S_k}]$. $\boldsymbol{\Lambda}$ is an auxiliary matrix, whose value can be calculated by a low-complexity iterative algorithm in Li and Masouros (2018). It can be seen that regardless of power minimization or SINR balancing IE-based precoders, they always have linear structure and can be solved directly, without the need of calling SDP optimization.

Here, we illustrate BER performance of the IE-based precoder, compared against the ZF and MMSE designs as shown in

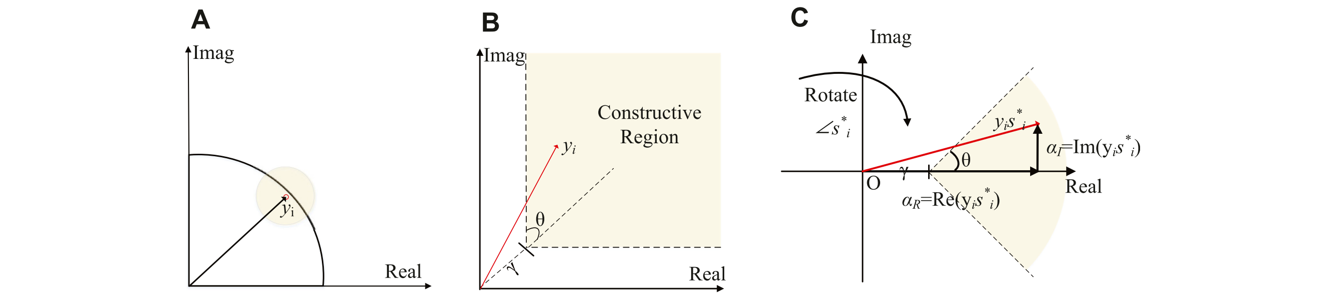

FIGURE 1 | The geometrical interpretation of IE precoding, where the intended symbol is $1 + i/\sqrt{2}$ with QPSK modulation for illustration.

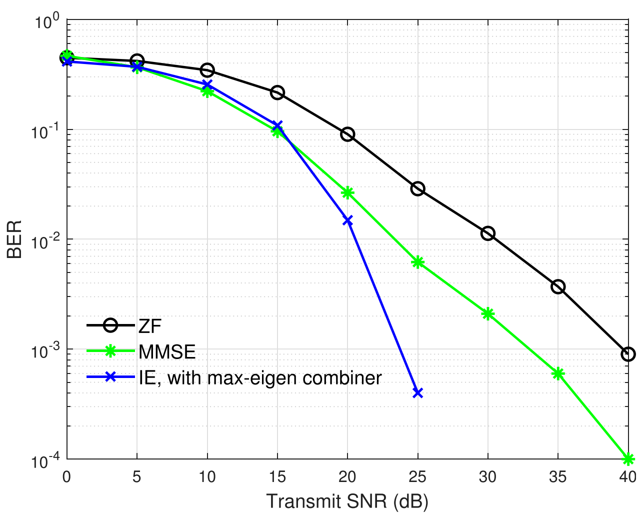

FIGURE 2 | The impact of the SNR on BER performance, where the BS is equipped with 10 transmit antennas for serving $K = 10$ users. The ZF and MMSE are selected as benchmarks.

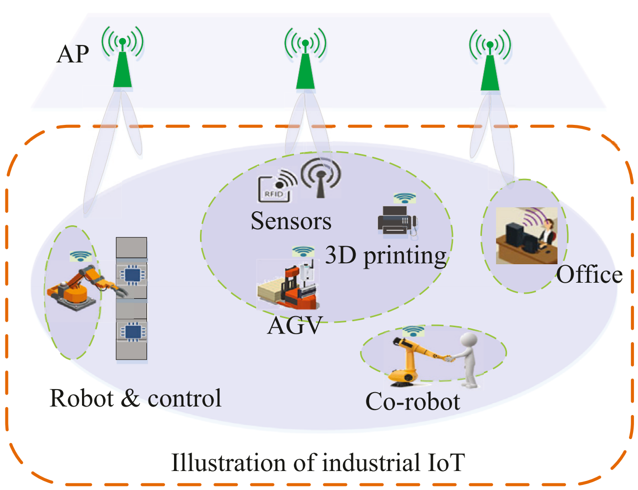

FIGURE 3 | Illustration of multi-cluster IoT systems.

Figure 2. It is observed that as the SNR increases, the BER performance of the IE-based precoder shows rapid improvement. Furthermore, the performance of the IE-based precoder is always superior to the conventional ZF, and outperforms the MMSE at moderate/high SNR regions, which is in line with the analysis of this section.

3 INTERFERENCE MITIGATION BASED PREOCODER IN MULTI-CLUSTER IOT NETWORKS

In multi-cluster IoT systems shown in **Figure 3**, the APs are connected with high-speed optical fiber for joint signal processing. Generally, there are two different coordination mechanisms, i.e., partially-coordinated IE and fully-coordinated IE -based precoder designs. By the former design, the APs only share CSI with others for inter-cluster interference suppression. Since transmission data is not shared among the APs, each AP only serves its associated users, and at the same time suppresses inter-cluster interference. Assume there are M APs for corporation. Define y_{im} and n_{im} as the received signal and noise at the i-th device belonging to the m-th cluster. $h_{im} \in \mathbb{C}^{(1\times N)}$is the MISO channel spanning from the m-th AP to the i-th device. $\mathbf{W_m}$ and $\mathbf{s_m}$ denote the precoder matrix and transmitted symbol vector at the m-th AP, respectively. The received signal can be calculated as

$$y_{im} = \mathbf{h}_{im}\mathbf{W}_{\mathbf{m}}\mathbf{s}_{\mathbf{m}} + \sum_{m'\neq m}\mathbf{h}_{im'}\mathbf{W}_{\mathbf{m'}}\mathbf{s}_{\mathbf{m'}} + n_{im}. \quad (8)$$

When formulating the optimization for the partially-coordinated IE precoder, the CI constraint is rewritten as

$$\left(\mathrm{Re}\left(y_{im}s_{im}^*\right) - \sqrt{(\sigma^2+\Delta_{im})\Gamma}\right)\cdot \tan\left(\frac{\pi}{M}\right) \geq \left|\mathrm{Im}\left(y_{im}s_{im}^*\right)\right|, \forall k \in K. \quad (9)$$

In particular, the term Δ_{im} represents the inter-cluster interference at the i-th user, which needs to be carefully suppressed. The IE-based power minimization problem is re-formulated as

$$\begin{aligned} \text{P3: } & \min_{W_1,\ldots,W_M} \sum_{m=1}^{M} \|W_m\|^2, \\ \text{s.t. (C1): } & \left(\mathrm{Re}\left(y_{im}s_{im}^*\right) - \left(\sigma^2 + \Delta_{im}\right)\Gamma\right)\cdot \\ & \tan\left(\frac{\pi}{M}\right) \ge \left|\mathrm{Im}\left(y_{im}s_{im}^* s_i^*\right)\right|, \forall k \in K, \\ \text{(C2): } & \Delta_{im} \ge \sum\nolimits_{m' \ne m} \|h_{im}, W_m s_m\|^2. \end{aligned} \tag{10}$$

In a similar vein, the IE-based SINR balancing precoder in multi-cluster scenario can be formulated as

$$\begin{aligned} \text{P4: } & \max_{w_1,\ldots,w_K} \Gamma, \\ \text{s.t. (C1): } & \left(\mathrm{Re}\left(y_{im}s_{im}^*\right) - \left(\sigma^2 + \Delta_{im}\right)\Gamma\right)\cdot \\ & \tan\left(\frac{\pi}{M}\right) \ge \left|\mathrm{Im}\left(y_{im}s_i^*\right)\right|, \forall k \in K, \\ \text{(C2): } & \Delta_{im} \ge \sum_{m' \ne m} \left\|h_{im'}, W_{m'} s_{m'}\right\|^2, \forall i \text{ and } m, \\ \text{(C3): } & \|W_m s_m\|^2 \le P_{\max}, \forall m. \end{aligned} \tag{11}$$

By contrast, the fully-coordinated IE design shares both the CSI and the data to be transmitted among the APs, where the APs jointly serve the downlink users in a similar vein of distributed antenna systems. In fact, the fully-coordinated IE makes no much difference compared to the classic IE-based precoder, as the distributed APs can be seen as a virtual multiple transmission antennas.

4 OPEN CHALLENGES AND FUTURE RESEARCH

The topic of the IE-based precoder is still broadly open for research and could be extended in many interesting directions:

4.1 IE-Based Precoder in High Reliability and Low Latency Applications

Some emerging ultra-reliability and low-latency (URLLC) applications require short packet transmission, which indeed has been considered as a key technique in the 5G URLLC scenario Sharma and Wang (2019). For example, one notable observation in these applications is that the transmitting signal is control (command) type information (e.g., start/stop, move left/right, speed up/down, and rotate/shift) or sensing information (e.g., temperature, pressure, moisture, and gas density) (Wang Y. et al., 2021). Hence, the amount of information is delivered in short packets. Evidently, the joint design of IE-based precoder, reliability, and latency may be difficult. How to utilize the concept of IE for achieving high reliability and low latency at an acceptable degree of overhead, remains an open challenge.

4.2 IE-Based Precoder for Millimeter-Wave MIMO Systems

The millimeter-wave (mmWave) MIMO system is a promising technology to achieve gigabit-per-second data rates for future communications, where the number of radio-frequency (RF) chains in mmWave MIMO systems can be tens-to-hundreds of antennas (Wei et al., 2015, Wei et al., 2016). In this context, the large number of RF chains has two major issues in practice, i.e., high complexity for acquiring an optimal full-digital precoder and the hybrid precoder design (Wang J. et al., 2021). Hence, the tradeoff of IE-based Precoder design between low complexity and high reliability should be considered to suit the next-generation mmWave MIMO system.

4.3 IE-Based Precoder for Secure Communications

The essential feature of future communications is that of supporting massive access in IoT, and therefore, the privacy and security requirements are intended to be more complicated and diversified due to the limited number of physical resources (Wang et al., 2020). For example, the public broadcast may have a low privacy requirement, while some personal information requires high confidentiality (Chen et al., 2020). A possible solution is to classify security rank and employ appropriate techniques of physical layer security (PHY) to meet the customized demand of different users. Hence, it is demanding to fundamental analysis and new metrics for designing and evaluating the overall system PHY security performance, especially under the perspective of the IE-based secure Communications (Wei et al., 2021c).

5 CONCLUSION

In this review paper, we have briefly introduced the concept of IE-based precoding, two generic optimizations, i.e., power minimization and SINR balancing optimizations, are formulated. Then, we have examined the IE-based precoder design in multi-cluster IoT scenario. Furthermore, open challenges related to emerging applications are present, where the gap between theory and implementations should be bridged. In a nutshell, there are still essential works for the research of the IE-based precoder, which holds the promise of exciting research in the years to come.

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All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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SUPPLEMENTARY MATERIAL

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