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Beamforming Design for In-Band Full-Duplex Multi-Cell Multi-User MIMO LSA Cellular Networks

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ABSTRACT The in-band full-duplex (IBFD) mechanism offers many advantages over standard half duplex (HD) systems: it can potentially double the capacity and increase spectrum utilization efficiency. While IBFD renders many conventional research problems irrelevant, it unearths several new problems that urgently need attention. We focus on a the design of a Licensed Shared Access (LSA) based spectrum sharing framework with IBFD multi-cell multi-user multiple-input multiple-output (MIMO) communication network as the licensee, which operates in the service region of a multi-user MIMO incumbent network. We propose a modified LSA controller framework for the protection zone scenario of LSA, whereby the LSA controller ensures that the licensees always have access to data rates above a given threshold, for which aggregate interference towards the incumbents is also kept at minimum. Accordingly, we propose a hierarchical two-step beamforming framework, where i) the LSA controller first seeks the quality of service (QoS) requirements from the licensee network. Based on the QoS requirements, beamformers are designed to minimize the aggregate interference towards the incumbents. ii) In the second step, the interference minimized in the first step is considered as a constraint for the new beamformer design problem that maximizes the aggregate uplink and downlink throughput of the licensee network. Numerical results demonstrate the precedency of the proposed algorithms for IBFD LSA when compared to baseline HD LSA, whereby we observe i) over 60% improvement in throughput performance for the licensee network and ii) a reduction in interference exposure towards the incumbents from the licensees by at least 6.8315dB.

INDEX TERMS Full-duplex, licensed shared access, licensee, multi-cell, multi-user mimo, spectrum sharing.

I. INTRODUCTION

Early deployments of fifth generation (5G) New Radio (NR) have been classified under two distinct categories of frequency bands within ranges known as FR1 (<7.225 GHz) and FR2 (>24.250 GHz) [1], [2]. While ample amount of spectrum is available in FR2 (mmWave frequencies), the FR1 bands are plagued by spectrum paucity due to spectrum fragmentation and the current static spectrum allocation policy. One promising solution to address this problem and fully deliver on the promise of 5G is to enhance the utilization of available frequency bands by employing cooperation/coordination and cognition among various entities of the communication network [3]–[5]. Furthermore, it allows new types of players in mobile network operators (MNO) who might not otherwise be able to afford or wish to have an exclusive/national-level license to provide service with quality of service (QoS) guarantees to mobile broadband users (MBUs) through a substantially smaller investment.

Based on the above, various spectrum access technologies such as Cognitive Radios (CRs) [6]–[8], Spectrum Access Systems (SAS) [9], [10], Licensed Shared Access (LSA)

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[11]–[17], etc., have been studied in literature. While CRs allow secondary users to access the spectrum of primary users in either underlay, overlay or interweave fashion, SAS and LSA are regularized evolutions of existing CRs. Nevertheless, among the various spectrum access solutions available today, the LSA architecture is the most universally accepted and has advantageous over other techniques (for 5G in particular) in the sense that the LSA controller can be easily deployed through software defined networking (SDN)-based approaches to manage the spectral opportunities dynamically based on the distributed inputs reported from incumbents and heterogeneous nodes of 5G networks [18], [20]. For example, in the US, Qualcomm has proposed the use of LSA/ASA in 3.5 GHz band for LTE deployment [20], [21]. Apart from USA, in Europe, LSA has already been identified by the European Commission (EC) and Conférence Européenne des Postes et des Télécommunications (CEPT) as the common basis for voluntary sharing within existing licenses in general [22], [23], and especially for the implementation of Mobile/Fixed Communication Networks (MFCN) in military bands.

Accordingly, in this paper, we address the specific problem of spectrum scarcity faced by MNOs and propose a framework for LSA for improving the QoS of MBUs through efficient spectrum sharing between LSA incumbents and a mobile cellular network consisting of multiple small cells. At this point, it is worth noting that most spectrum sharing approaches that are currently in practise, including many LSA architectures [15] are passive in nature. For example, CEPT has proposed the following options for LSA in Europe: i) exclusion zones, where no interferers are allowed, ii) restriction zones, where interferers are allowed to transmit with limited power or antenna height, and iii) protection zones, where the incumbents will tolerate interference up to a given threshold. These policies of spectrum access places the entire burden on MNOs to maintain an extremely high confidence level of interference protection towards incumbents by either transmitting in white spaces or not transmitting at all inside predefined exclusion zones. The potential for such conservative approaches is quite limited, which is reflected by their modest progress in becoming a business case for commercial deployment. If the LSA controller, instead of being solely managed by the incumbents, is originally designed with the anticipation of sharing, i.e., prioritize the service requirements (within a specific limit) of the MBUs, then the spectrum paucity can be significantly improved. Unlike in baseline LSA architecture, in this paper we lay out a modified LSA controller architecture for the protection zone scenario, where instead of asking the MNOs to transmit with interference temperature constraints, QoS constraints are maintained with minimal interference towards the incumbents. This shifts the management of the LSA controller towards the licensees, thus providing the MNOs with greater confidence to meet the required QoS requirements of MBUs.

Furthermore, analogous to conventional wireless networks, existing architectures for LSA networks employ half-duplex (HD) radios, which cannot simultaneously utilize the time and frequency resources of a spectrum bandwidth, thereby not only reducing the spectrum efficiency, but also increasing latency in communication. This problem can be mitigated by implementing simultaneous transmit and receive (STAR) radios communicating in in-band full-duplex (IBFD) mode [19], [20]. Recent advances in various self-interference (SI) cancellation techniques in antenna, analog and digital domains [24], [25] invalidate a long-held assumption that transmission and reception cannot happen simultaneously within the same time-frequency band. With separate antennas for transmission/ reception, IBFD-multi-input multi-output (MIMO) radios, can support bidirectional communication, thus improving the QoS of the MBUs further [26]. Since the incorporation of IBFD radios in a modified LSA architecture facilitates the exploration of a unique dimension of improving spectrum utilization efficiency and network throughput, IBFD-LSA requires new designs of network architectures and algorithms. Accordingly, in this article we aim at addressing the paradox between spectrum scarcity and under-utilization by exploring and proposing a modified LSA controller framework, which involves a hierarchical two step beamforming design technique for the desired co-existence.

A. DISTINCTION FROM EXISTING WORK AND CONTRIBUTIONS

Most of the related works on CR and LSA [6] and [20] consider a conservative sharing agreement by allowing licensees to transmit with interference constraints only. Further, many of these works only consider HD transmission, either in time division duplexing mode or frequency division duplexing mode and do not take into consideration the non-ideal nature of hardware components (e.g., oscillators, analog-to-digital converters (ADCs), power amplifiers, digital-to-analog converters (DACs), etc.) at the transmit and receive chains. Additionally, works such as [27]–[31] study the beamformer design of IBFD MIMO CRs but only for single cell set-up. Furthermore, though the authors in [26] and [36] consider IBFD transmission, they do not consider a spectrum sharing sharing (Licensed Shared Access) framework for the protection zone of LSA.

With regards to this paper, the application of the IBFD technology and the modifications in service requirements of the licensee network introduces fundamental new challenges to baseline HD LSA systems. Further, the consideration of multi-cell operation of the licensee network is a practical necessity and requires a non-trivial extension of prior studies. This is since the multi-cell operation of the IBFD enabled licensee network fundamentally impacts the network interference pattern, which not only impacts the incumbents, but also the quality of experience of the MBUs. In particular, the multi-cell operation of IBFD BSs leads to i) additional interference paths among them, ii) interference among the uplink (UL) users and downlink (DL) users of the same cell, known as co-channel interference (CCI), iii) interference among the uplink users and downlink users of adjacent cells, known as inter-cell interference (ICI), and iv) the BSs and UL users' transmissions from all cells collectively add to the interference towards the incumbents, which should now be jointly controlled. The main distinctions of this paper are summarized below.

- We propose a modified LSA controller framework for the protection zone scenario of LSA, whereby the LSA controller ensures that the MBUs always have access to data rates above a given threshold, for which aggregate interference towards the incumbents is also kept at minimum.
- Unlike existing work, this work considers a practical system model, with multiple licensees, involving a multi-cell network and multiple incumbents. Further, the base-stations in each cell of the licensee network is enabled with IBFD radio, serving multiple DL and UL users at the same time and frequency resources, utilizing the spectrum of the incumbents. This is motivated by the idea of achieving higher spectral efficiency, where spectral coexistence is enabled simultaneously not only among the UL, DL MBUs, but also the incumbents.
- While the use of IBFD radio at each BS enhances the QoE of the MBUs, it also induces a higher intensity of interference towards the incumbents. This in turn may violate the baseline LSA architecture requirements. Hence, it is necessary to revisit the requirements for the proposed modified LSA controller. Accordingly, we propose a two-step hierarchical beamforming framework, where:
  - The LSA controller first seeks the QoS requirements from the licensee network. Based on the QoS requirements, an optimization problem is formulated to design beamformers that minimize the aggregate interference towards the incumbents. In order to concretize the treatment of the interference, both interference from the licensee network towards the incumbents and the interference towards the licensee network are jointly considered under the impacts of hardware distortions.
  - In the second step, the interference minimized in the first step is considered as a constraint of the new optimization problem that maximizes the joint uplink and downlink rate of the licensee network. In particular, our method ensures QoS on the best-effort basis for the licensee network, while also ensuring guaranteed interference protection for the incumbent as proposed in baseline LSA architecture.
- The formulated joint beamforming design problems in both the steps are non-convex in nature. By considering a minimum MSE (MMSE) based receiver, we derive the closed form expressions for the transmit beamforming matrices. With the obtained transmit beamforming matrix, we update the receiver beamforming matrices in an alternating manner until convergence is achieved.
- Through numerical results we verify the effectiveness of the IBFD operation along with the proposed hierarchical two-step beamforming approach, both in terms of the improved QoS for the licensees as well as protection for incumbents when compared to baseline HD LSA networks.

In comparison to prior works, the current approach is far-reaching in the sense that it gives the MNOs more confidence to utilize the spectrum of the incumbents.

B. PAPER ORGANIZATION

The rest of the paper is organized as follows. Section II presents the considered LSA system model. The two-step beamforming design for spectrum access is presented in Section III and numerical results are presented in Section IV. The implementation of the modified LSA controller and computational complexity of the algorithms are given in Section V and the paper is concluded in Section VI.

C. NOTATIONS

Lower case and upper case boldface letters represent vectors and matrices, respectively. Scalars are denoted by lower case standard font. $(\cdot)^T$ and $(\cdot)^*$ denote transpose and conjugate, respectively. $\mathbb{E}\{\cdot\}$ is the statistical expectation, and $\mathrm{tr}\{\cdot\}$ is the trace operator. $\mathbf{I}_N$ and $\mathbf{0}_{N\times M}$ denote N by N identity and N by M zero matrices, respectively. $\mathcal{CN}(\mu, \sigma^2)$ represents a complex Gaussian distribution with mean μ and varience σ^2. $\mathbb{R}^{m\times n}$ and $\mathbb{C}^{m\times n}$ are the real and complex matrices, respectively. $\|\mathbf{x}\|_2$ denotes the Euclidean norm of a vector $\mathbf{x}$. $\perp$ and $\otimes$ represent the statistical independence and Kronecker product, respectively.

II. SYSTEM MODEL

We consider a LSA network involving a mobile broadband network (MBN) as the licensee that co-exist in the service range of a multi-user MIMO incumbent (IN) network as shown in Figure 1. The MBN consists of a G-cell multi-user MIMO network, where each BS in a cell, equipped with $2M_B$ antennas (M_B antennas for transmission and M_B antennas for reception) operates in IBFD mode and serves K_g^u UL and K_g^d DL HD users, each equipped with M_u and M_d antennas, respectively. Each of the R INs are equipped with M_T and M_R transmit and receive antennas, respectively.

The channels in the network are defined as follows: $\mathbf{H}_{k_g^d,j} \in \mathbb{C}^{M_d\times M_B}$ denotes the channel between the j-th BS and DL user k_g^d, $\mathbf{H}_{k_g^d,i_j^u} \in \mathbb{C}^{M_d\times M_u}$ denotes the CCI channel between UL user i_j^u and DL user k_g^d, $\mathbf{H}_{g,g} \in \mathbb{C}^{M_B\times M_B}$ represents the SI channel in the g-th BS, $\mathbf{H}_{g,j} \in \mathbb{C}^{M_B\times M_B}$ represents ICI from j-th BS to the g-th BS, $\mathbf{H}_{r,g} \in \mathbb{C}^{M_R\times M_B}$ represents interference channel from BS g to r-th IN, and $\mathbf{H}_{g,i_j^u} \in \mathbb{C}^{M_B\times M_u}$ and $\mathbf{H}_{r,i_j^u} \in \mathbb{C}^{M_R\times M_u}$ represent the channels between UL user i_j^u and BS g and r-th IN, respectively. $\mathbf{H}_{g,r} \in \mathbb{C}^{M_B\times M_T}$ and $\mathbf{H}_{k_g^d,r} \in \mathbb{C}^{M_d\times M_T}$ represent interference channels from incumbents to BS of cell g and k_g^d-th downlink user,

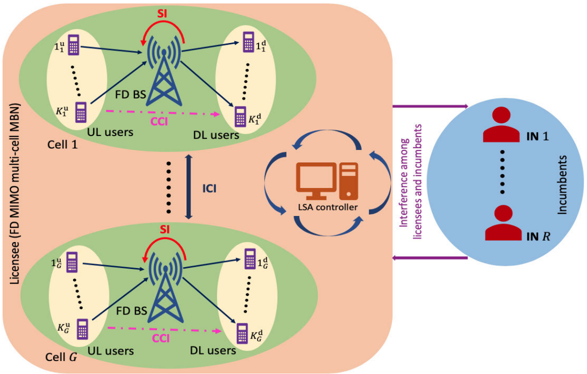


FIGURE 1. An illustration of a modified LSA network involving a IBFD multi-user multi-cell MIMO MBN (licensee) and a multi-user MIMO incumbent network.

respectively. Some of the important notations used throughout the paper are summarized in Table 1.

Further, in this work we focus on residual SI (RSI) cancellation in the digital domain (through the design of digital precoder/ receiver matrices) with the assumption that prior antenna/ analog cancellation has been performed.[1] Accordingly, we take into account the limited dynamic range, which is caused by non-ideal amplifiers, oscillators, ADCs, and digital-to-analog converters (DACs). We adopt the limited dynamic range model in [32], which has also been commonly used in IBFD literature. Particularly, at each receive antenna an additive white Gaussian "receiver distortion" with variance β times the energy of the undistorted received signal on that receive antenna is applied, and at each transmit antenna, an additive white Gaussian "transmitter noise" with variance κ times the energy of the intended transmit signal is applied. This transmitter/ receiver distortion model is valid, since it was shown by hardware measurements in [33] and [34] that the non-ideality of the transmitter and receiver chain can be approximated by an independent Gaussian noise model, respectively.

Now, the signal received by the DL user k_g^d and that received by the BS g can be written as[2]

$$\mathbf{y}_{k_g^d} = \sum_{j=1}^{G}\sum_{i=1}^{K_j^d} \mathbf{H}_{k_g^d,j}\left(\mathbf{V}_{i_j^d}\mathbf{s}_{i_j^d} + \mathbf{c}_{i_j^d}\right) + \sum_{j=1}^{G}\sum_{i=1}^{K_j^u} \mathbf{H}_{k_g^d,i_j^u}\left(\mathbf{V}_{i_j^u}\mathbf{s}_{i_j^u} + \mathbf{c}_{i_j^u}\right) + \mathbf{e}_{k_g^d} + \mathbf{n}_{k_g^d}, \quad (1)$$

[1]Any analog domain SI cancellation technique described in literature can be added as an antecedent block to our architecture to achieve a holistic design.

[2]Since the MBN network cannot differentiate the interference generated by the incumbents from the background thermal noise, the noise vectors $\mathbf{n}_{k_g^d}$ and $\mathbf{n}_g$ in (1) and (2) capture the background thermal noise as well as the interferences $\sum_{r=1}^{R}\sqrt{P_r}\mathbf{H}_{k_g^d,r}\mathbf{s}_r$ and $\sum_{r=1}^{R}\sqrt{P_r}\mathbf{H}_{g,r}\mathbf{s}_r$ generated by the r-th IN towards k_g^d-th user and g-th BS, respectively. Here, $\mathbf{s}_r \in \mathbb{C}^{M_t\times 1}$ and P_r are the transmitted signal power from r-th IN.

TABLE 1. Table of notations.

Notations	Description
G	Total number of cells in the MBN.
$K_g^u(K_g^d)$	Total number of UL (DL) users in cell g of the MBN.
R	Total number of INs in the Incumbent network.
M_B	Number of transmit/receive antennas at the each IBFD BS.
$M_u(M_d)$	Number of antennas at UL (DL) users.
$M_T(M_R)$	Number of transmit (receive) antennas at each IN.
$\mathbf{I}_{r,\text{MBN}}$	Interference from MBN to r-th IN.
$\mathbf{H}_{k_g^d,j}$	Channel between j^{th} BS and k_g^d-th DL user.
$\mathbf{H}_{k_g^d,i_j^u}$	CCI channel between i_j^u-th UL user and k_g^d-th DL user.
$\mathbf{H}_{g,g}$	SI channel in the g^{th} BS.
$\mathbf{H}_{g,j}$	ICI channel between j-th BS and g-th BS.
$\mathbf{H}_{r,g}$	Interference channel between g-th BS and r-th IN.
$\mathbf{H}_{r,i_j^u}$	Interference channel between i_j^u-th UL user and IN.
$\mathbf{H}_{g,i_j^u}$	Channel between i_j^u-th UL user and g-th BS .
$\mathbf{H}_{g,r}$	Channel between r-th IN and g-th BS.
$\mathbf{H}_{k_g^d,r}$	Channel between r-th IN and k_g^d-th downlink user.

$$\mathbf{y}_g = \sum_{j=1}^{G}\sum_{i=1}^{K_j^u} \mathbf{H}_{g,i_j^u}\left(\mathbf{V}_{i_j^u}\mathbf{s}_{i_j^u} + \mathbf{c}_{i_j^u}\right) + \sum_{j=1}^{G}\sum_{i=1}^{K_j^d} \mathbf{H}_{g,j}\left(\mathbf{V}_{i_j^d}\mathbf{s}_{i_j^d} + \mathbf{c}_{i_j^d}\right) + \mathbf{e}_g + \mathbf{n}_g. \quad (2)$$

Here, $\mathbf{s}_{i_j^u} \in \mathbb{C}^{d_{i_j^u}\times 1}$ represents the data transmitted by UL user i in cell j with length $d_{i_j^u}$ and $\mathbb{E}\left[\mathbf{s}_{i_j^u}\mathbf{s}_{i_j^u}^H\right] = \mathbf{I}_{d_{i_j^u}}$ and $\mathbf{s}_{i_j^d} \in \mathbb{C}^{d_{i_j^d}\times 1}$ denotes the data transmitted by j-th BS to i-th DL user in cell j with length $d_{i_j^d}$ and $\mathbb{E}\left[\mathbf{s}_{i_j^d}\mathbf{s}_{i_j^d}^H\right] = \mathbf{I}_{d_{i_j^d}}$. Further, $\mathbf{V}_{i_j^d} \in \mathbb{C}^{M_B\times d_{i_j^d}}$ and $\mathbf{V}_{i_j^u} \in \mathbb{C}^{M_u\times d_{i_j^u}}$ are the transmit beamforming matrices associated with $\mathbf{s}_{i_j^d}$ and $\mathbf{s}_{i_j^u}$, respectively. The terms $\mathbf{n}_{k_g^d} \in \mathbb{C}^{M_d\times 1}$ and $\mathbf{n}_g \in \mathbb{C}^{M_B\times 1}$ denote the additive white Gaussian noise (AWGN) vector with zero-mean and variance σ_U and σ_B at the DL user k_g^d and BS g, respectively. Finally, $\mathbf{c}_{i_j^d} \in \mathbb{C}^{M_B\times 1}$ and $\mathbf{c}_{i_j^u} \in \mathbb{C}^{M_u\times 1}$ denote tramsmit distortion at the BS j and UL user i_j^u, respectively and $\mathbf{e}_{k_j^d} \in \mathbb{C}^{M_d\times 1}$ and $\mathbf{e}_g \in \mathbb{C}^{M_B\times 1}$ denote receiver distortion at the DL user k_g^d and BS g, respectively, which are modelled as [32]

$$\mathbf{c}_{i_j^d} \sim \mathcal{CN}\left(0, \kappa_B \text{diag}\left(\mathbf{V}_{i_j^d}\mathbf{V}_{i_j^d}^H\right)\right), \quad \mathbf{c}_{i_j^d} \perp \mathbf{V}_{i_j^d}\mathbf{s}_{i_j^d}, \quad (3)$$

$$\mathbf{c}_{i_j^u} \sim \mathcal{CN}\left(0, \kappa_U \text{diag}\left(\mathbf{V}_{i_j^u}\mathbf{V}_{i_j^u}^H\right)\right), \quad \mathbf{c}_{i_j^u} \perp \mathbf{V}_{i_j^u}\mathbf{s}_{i_j^u}, \quad (4)$$

with $\kappa_B, \kappa_U \ll 1$, and

$$\mathbf{e}_{k_j^d} \sim \mathcal{CN}\left(0, \beta_U \text{diag}\left(\Phi_{k_j^d}\right)\right), \quad \mathbf{e}_{k_j^d} \perp \mathbf{u}_{k_j^d}, \quad (5)$$

$$\mathbf{e}_g \sim \mathcal{CN}\left(0, \beta_B \text{diag}\left(\Phi_g\right)\right), \quad \mathbf{e}_g \perp \mathbf{u}_g, \quad (6)$$

with $\Phi_{k_j^d} = \text{Cov}\{\mathbf{u}_{k_j^d}\}$, $\Phi_g = \text{Cov}\{\mathbf{u}_g\}$ and $\beta_B, \beta_U \ll 1$. Here, $\mathbf{u}_{k_j^d}$ and $\mathbf{u}_g$ are the undistorted received signal vector at the DL user k_g^d and BS g, respectively. We assume the perfect channel state information (CSI) availability and synchronization at all the nodes through the LSA controller. Since, the BS g knows its own transmitted signal $\sum_{i=1}^{K_g^d} \mathbf{H}_{g,g}\mathbf{V}_{i_g^d}\mathbf{s}_{i_g^d}$, this term can be cancelled out[3] in (2), yielding

$$\tilde{\mathbf{y}}_g = \sum_{j=1}^{G}\sum_{i=1}^{K_j^u} \mathbf{H}_{g,i_j^u}\left(\mathbf{V}_{i_j^u}\mathbf{s}_{i_j^u} + \mathbf{c}_{i_j^u}\right) + \sum_{j=1,j\neq g}^{G}\sum_{i=1}^{K_j^d} \mathbf{H}_{g,j}\left(\mathbf{V}_{i_j^d}\mathbf{s}_{i_j^d} + \mathbf{c}_{i_j^d}\right) + \mathbf{e}_g + \mathbf{n}_g. \quad (7)$$

Using (1)–(7), we can obtain the rate of DL user k_g^d and UL user k_g^u as [35]

$$R_{k_g^d} = \log_2\left|\mathbf{I}_{M_d} + \Sigma_{k_g^d}^{-1}\mathbf{H}_{k_g^d,g}\mathbf{V}_{k_g^d}\mathbf{V}_{k_g^d}^H\mathbf{H}_{k_g^d,g}^H\right|, \quad (8)$$

$$R_{k_g^u} = \log_2\left|\mathbf{I}_{M_B} + \Sigma_{k_g^u}^{-1}\mathbf{H}_{k_g^u,g}\mathbf{V}_{k_g^u}\mathbf{V}_{k_g^u}^H\mathbf{H}_{k_g^u,g}^H\right|, \quad (9)$$

where $\Sigma_{k_g^d}$ and $\Sigma_{k_g^u}$ denote the interference-plus-noise covariance matrices for the DL user k_g^d and UL user k_g^u and are given on the bottom of next page (the detailed derivation is given in Appendix A). Now, the aggregate interference from the IBFD MBN towards the r-th IN can be written as

$$\mathbf{I}_{r,\mathrm{MBN}} = \sum_{j=1}^{G}\sum_{i=1}^{K_j^u} \mathbf{H}_{r,i_j^u}\left(\mathbf{V}_{i_j^u}\mathbf{V}_{i_j^u}^H + \kappa_U \mathrm{diag}\left(\mathbf{V}_{i_j^u}\mathbf{V}_{i_j^u}^H\right)\right)\mathbf{H}_{r,i_j^u}^H + \sum_{j=1}^{G}\sum_{i=1}^{K_j^d} \mathbf{H}_{r,j}\left(\mathbf{V}_{i_j^d}\mathbf{V}_{i_j^d}^H + \kappa_B \mathrm{diag}\left(\mathbf{V}_{i_j^d}\mathbf{V}_{i_j^d}^H\right)\right)\mathbf{H}_{r,j}^H. \quad (12)$$

III. BEAMFORMING DESIGN FOR MODIFIED PROTECTION ZONE

As stated earlier, current spectrum sharing techniques are passive in nature, whose first objective is to protect the incumbents. They are not designed with licensees' requirements in mind. In this paper we propose a beamforming design solution, where the LSA controller aligns with the QoS requirements of the MBN, while still protecting the incumbents. Now, with the QoS constraints from MBN set, we first aim at minimizing the aggregate interference temperature from the MBN towards the INs. Next, we aim at jointly maximizing the UL and DL rates of the IBFD MBN, but constraining it with the minimum interference obtained in the first step.

A. STEP 1: BEAMFORMING DESIGN FOR INTERFERENCE MINIMIZATION TOWARDS INCUMBENTS

The beamforming design problem for minimizing the interference from IBFD MBN towards the incumbent network can be formulated as

$$\mathbf{P1}: \min_{\mathbf{V}} \sum_{r=1}^{R} \mathrm{tr}\left\{\mathbf{I}_{r,\mathrm{MBN}}\right\}$$
$$\text{Subject to } (C.1)\ R_{k_g^u} \geq R_{k_g^u,min}, \quad k = 1,\cdots,K_g^u,\ \forall g,$$
$$(C.2)\ R_{k_g^d} \geq R_{k_g^d,min}, \quad k = 1,\cdots,K_g^d,\ \forall g,$$
$$(C.3)\ \mathrm{tr}\left(\mathbf{V}_{k_g^u}\mathbf{V}_{k_g^u}^H\right) \leq P_{k_g^u},\quad k = 1,\cdots,K_g^u,\ \forall g,$$
$$(C.4)\ \sum_{k=1}^{k_g^d} \mathrm{tr}\left(\mathbf{V}_{k_g^d}\mathbf{V}_{k_g^d}^H\right) \leq P_g, \quad \forall g. \quad (13)$$

The optimization problem **(P1)** is not in a tractable form and cannot be efficiently solved. To that end, in the subsequent part of this section, we attempt to convert the original problem by first converting the rate constraints into equivalent mean squarred error (MSE) constraints and then seek to derive the closed form solutions for the transmit beamforming matrices by keeping the receive beamforiming matrix constant. With the obtained transmit beamforming matrix, we update the receiver beamforming matrices in an alternating manner until convergence is achieved.

1) CONVERSION OF (C.1) AND (C.2)

If we use a MMSE based receiver, MSE based optimization problems become equivalent to SINR based optimization problems. Therefore, the rate based constraints in (C.1) and (C.2) can be transformed into MSE constraints as [36]

$$R_{k_g^u} \simeq -\mathrm{tr}\left\{\mathbf{W}_{k_g^u}\mathbf{E}_{k_g^u}\right\} + \log_2\left|\ln 2\mathbf{W}_{k_g^u}\right| + \frac{d_{k_g^u}}{\ln 2}, \quad (14)$$

$$R_{k_g^d} \simeq -\mathrm{tr}\left\{\mathbf{W}_{k_g^d}\mathbf{E}_{k_g^d}\right\} + \log_2\left|\ln 2\mathbf{W}_{k_g^d}\right| + \frac{d_{k_g^d}}{\ln 2}. \quad (15)$$

where $\mathbf{W}_{k_g^u}$ and $\mathbf{W}_{k_g^d}$ denote weight matrix for the UL user k_g^u and DL user k_g^d. The $\mathbf{E}_{k_g^u}$ and $\mathbf{E}_{k_g^d}$ are MSE matrices of the UL user k_g^u and DL user k_g^d and are given as

$$\mathbf{E}_{k_g^u} = \left(\mathbf{U}_{k_g^u}\mathbf{H}_{g,k_g^u}\mathbf{V}_{k_g^u} - \mathbf{I}_{d_{k_g^u}}\right)\left(\mathbf{U}_{k_g^u}\mathbf{H}_{g,k_g^u}\mathbf{V}_{k_g^u} - \mathbf{I}_{d_{k_g^u}}\right)^H + \mathbf{U}_{k_g^u}\Sigma_{k_g^u}\mathbf{U}_{k_g^u}^H, \quad (16)$$

$$\mathbf{E}_{k_g^d} = \left(\mathbf{U}_{k_g^d}\mathbf{H}_{g,k_g^d}\mathbf{V}_{k_g^d} - \mathbf{I}_{d_{k_g^d}}\right)\left(\mathbf{U}_{k_g^d}\mathbf{H}_{g,k_g^d}\mathbf{V}_{k_g^d} - \mathbf{I}_{d_{k_g^d}}\right)^H + \mathbf{U}_{k_g^d}\Sigma_{k_g^d}\mathbf{U}_{k_g^d}^H, \quad (17)$$

where $\mathbf{U}_{k_g^u} \in \mathbb{C}^{\mathbf{I}_{d_{k_g^u}} \times M_B}$ and $\mathbf{U}_{k_g^d} \in \mathbb{C}^{\mathbf{I}_{d_{k_g^d}} \times M_d}$ are linear receiver matrices at BS g and at the DL user k_g^d. For the given transmit beamforming matrices, the optimal beamforming receiver is the MMSE receive filter at the BS g and at the

[3] The channel state information (CSI) of the SI channel can be acquired by using pilot signals, which in an IBFD node is echoed back to itself. Due to small distances between transmit and receive antennas of an IBFD node, the received power of this echoed-backed pilot signal is very high. As a result, the SI channel can be estimated with high accuracy.

k_g^d DL user, which can be computed as

$$\begin{aligned}\mathbf{U}^{\star}_{k_g^u} &= \arg\min_{\{\mathbf{U}_{k_g^u}\}} \operatorname{tr}\left\{\mathbf{E}_{k_g^u}\right\} \\ &= \mathbf{V}^H_{k_g^u}\mathbf{H}^H_{g,k_g^u}\left(\mathbf{H}_{g,k_g^u}\mathbf{V}_{k_g^u}\mathbf{V}^H_{k_g^u}\mathbf{H}^H_{g,k_g^u}+\Sigma_{k_g^u}\right)^{-1}, \end{aligned} \quad (18)$$

$$\begin{aligned}\mathbf{U}^{*}_{k_g^d} &= \arg\min_{\{\mathbf{U}_{k_g^d}\}} \operatorname{tr}\left\{\mathbf{E}_{k_g^d}\right\} \\ &= \mathbf{V}^H_{k_g^d}\mathbf{H}^H_{g,k_g^d}\left(\mathbf{H}_{g,k_g^d}\mathbf{V}_{k_g^d}\mathbf{V}^H_{k_g^d}\mathbf{H}^H_{g,k_g^d}+\Sigma_{k_g^d}\right)^{-1}. \end{aligned} \quad (19)$$

Now, by decomposing $\mathbf{W}_{k_g^u} = \mathbf{B}^H_{k_g^u}\mathbf{B}^H_{k_g^u}$ and $\mathbf{W}_{k_g^d} = \mathbf{B}^H_{k_g^d}\mathbf{B}_{k_g^d}$, the terms $\operatorname{tr}\left\{\mathbf{W}_{k_g^u}\mathbf{E}_{k_g^u}\right\}$ in (14) and $\operatorname{tr}\left\{\mathbf{W}_{k_g^d}\mathbf{E}_{k_g^d}\right\}$ in (15) can be written as (20) and (21), given on bottom of next page. Now by fixing **U** and **V** and checking the first order optimality conditions for $\mathbf{W} = \left\{\mathbf{W}_{k_g^u}\mathbf{W}_{k_g^d}\right\}$, we get the optimal weights at the BS g and at the k_g^d DL users as

$$\mathbf{W}^*_{k_g^u} = \frac{1}{\ln 2}\mathbf{E}^{-1}_{k_g^u}, \quad \mathbf{W}^*_{k_g^d} = \frac{1}{\ln 2}\mathbf{E}^{-1}_{k_g^d}. \quad (22)$$

Now, by using (8), (9) and expressing the constraints $(C.3)$ and $(C.4)$ in vector forms, the problem (**P1**) in (13) for fixed value of **U** and **W** can be reformulated as

$$\mathbf{P2}: \min_{\mathbf{V}} \sum_{r=1}^{R} \operatorname{tr}\left\{\mathbf{I}_{r,\mathrm{MBN}}\right\}$$

$$\text{Subject to } (C.1)\ \operatorname{tr}\left\{\mathbf{W}_{k_g^u}\mathbf{E}_{k_g^u}\right\} - \log_2\left|\ln 2\mathbf{W}_{k_g^u}\right| - \frac{d_{k_g^u}}{\ln 2} \le -R_{k_g^u,min}, \quad k=1,\cdots,K_g^u,\ \forall g,$$

$$(C.2)\ \operatorname{tr}\left\{\mathbf{W}_{k_g^d}\mathbf{E}_{k_g^d}\right\} - \log_2\left|\ln 2\mathbf{W}_{k_g^d}\right| - \frac{d_{k_g^d}}{\ln 2} \le -R_{k_g^d,min}, \quad k=1,\cdots,K_g^d,\ \forall g,$$

$$(C.3)\ \left\|\operatorname{vec}\left(\mathbf{V}_{k_g^u}\right)\right\|^2 \le P_{k_g^u}, \quad k=1,\cdots,K_g^u,\ \forall g,$$

$$(C.4) \sum_{k=1}^{k_g^d}\left\|\operatorname{vec}\left(\mathbf{V}_{k_g^d}\right)\right\|^2 \le P_g, \quad \forall g. \quad (23)$$

For fixed value of **U** and **W**, the reformulated problem (**P2**) is convex in **V**. The closed form solutions of the UL and DL transmit beamformers are given below in (24) and (25), respectively, the derivations of which are given in Appendix B.

$$\mathbf{V}_{k_g^u} = \left(\mathbf{F}_{k_g^u} + \mu_{k_g^u}\mathbf{I}_{d_{k_g^u}}\right)^{-1}\lambda_{k_g^u}\mathbf{H}^H_{g,k_g^u}\mathbf{U}^H_{k_g^u}\mathbf{W}_{k_g^u}, \quad (24)$$

$$\mathbf{V}_{k_g^d} = \left(\mathbf{F}_{g} + \mu_{g}\mathbf{I}_{d_{k_g^d}}\right)^{-1}\lambda_{k_g^d}\mathbf{H}^H_{k_g^d,g}\mathbf{U}^H_{k_g^d}\mathbf{W}_{k_g^d}. \quad (25)$$

Here, $\mathbf{F}_{k_g^u}$ and $\mathbf{F}_g$ are given in (26) and (27) on the bottom of next page, with

$$\delta'_{j,g} = \begin{cases} 1 & \text{if } j \neq g \\ 0 & \text{otherwise.} \end{cases} \quad (28)$$

In the above, the Lagrange multipliers $\lambda_{k_g^u}$, $\lambda_{k_g^d}$, $\mu_{k_g^u}$, and $\mu_{k_g^d}$ are related with the rate constraints $(C.1)$ and $(C.2)$ and power constraints $(C.3)$ and $(C.4)$, respectively. An iterative algorithm to obtain the minimum interference towards the incumbents through the design of optimal transmit and receive beamforming matrices is shown in Algorithm 1.

$$\begin{aligned}\Sigma_{k_g^d} \approx & \sum_{\substack{j=1\\(i,j\neq k,g)}}^{G}\sum_{i=1}^{K_j^d}\mathbf{H}_{k_g^d,j}\mathbf{V}_{i_j^d}\mathbf{V}^H_{i_j^d}\mathbf{H}^H_{k_g^d,j} + \sum_{j=1}^{G}\sum_{i=1}^{K_j^u}\mathbf{H}_{k_g^d,i_j^u}\mathbf{V}_{i_j^u}\mathbf{V}^H_{i_j^u}\mathbf{H}^H_{k_g^d,i_j^u} + \sum_{j=1}^{G}\sum_{i=1}^{K_j^d}\kappa_B\mathbf{H}_{k_g^d,j}\operatorname{diag}\left(\mathbf{V}_{i_j^d}\mathbf{V}^H_{i_j^d}\right)\mathbf{H}^H_{k_g^d,j} \\ & + \sum_{j=1}^{G}\sum_{i=1}^{K_j^u}\kappa_U\mathbf{H}_{k_g^d,i_j^u}\operatorname{diag}\left(\mathbf{V}_{i_j^u}\mathbf{V}^H_{i_j^u}\right)\mathbf{H}^H_{k_g^d,i_j^u} + \sum_{j=1}^{G}\sum_{i=1}^{K_j^d}\beta_U\operatorname{diag}\left(\mathbf{H}_{k_g^d,j}\mathbf{V}_{i_j^d}\mathbf{V}^H_{i_j^d}\mathbf{H}^H_{k_g^d,j}\right) \\ & + \sum_{j=1}^{G}\sum_{i=1}^{K_j^u}\beta_U\operatorname{diag}\left(\mathbf{H}_{k_g^d,i_j^u}\mathbf{V}_{i_j^u}\mathbf{V}^H_{i_j^u}\mathbf{H}^H_{k_g^d,i_j^u}\right) + \sigma_U^2\mathbf{I}_{M_d}, \end{aligned} \quad (10)$$

$$\begin{aligned}\Sigma_{k_g^u} \approx & \sum_{\substack{j=1\\(i,j\neq k,g)}}^{G}\sum_{i=1}^{K_j^u}\mathbf{H}_{g,i_j^u}\mathbf{V}_{i_j^u}\mathbf{V}^H_{i_j^u}\mathbf{H}^H_{g,i_j^u} + \sum_{j=1,j\neq g}^{G}\sum_{i=1}^{K_j^d}\mathbf{H}_{g,j}\mathbf{V}_{i_j^d}\mathbf{V}^H_{i_j^d}\mathbf{H}^H_{g,j} + \sum_{j=1}^{G}\sum_{i=1}^{K_j^u}\kappa_U\mathbf{H}_{g,i_j^u}\operatorname{diag}\left(\mathbf{V}_{i_j^u}\mathbf{V}^H_{i_j^u}\right)\mathbf{H}^H_{g,i_j^u} \\ & + \sum_{j=1}^{G}\sum_{i=1}^{K_j^d}\kappa_B\mathbf{H}_{g,j}\operatorname{diag}\left(\mathbf{V}_{i_j^d}\mathbf{V}^H_{i_j^d}\right)\mathbf{H}^H_{g,j} + \sum_{j=1}^{G}\sum_{i=1}^{K_j^u}\beta_B\operatorname{diag}\left(\mathbf{H}_{g,i_j^u}\mathbf{V}_{i_j^u}\mathbf{V}^H_{i_j^u}\mathbf{H}^H_{g,i_j^u}\right) \\ & + \sum_{j=1}^{G}\sum_{i=1}^{K_j^d}\beta_B\operatorname{diag}\left(\mathbf{H}_{g,j}\mathbf{V}_{i_j^d}\mathbf{V}^H_{i_j^d}\mathbf{H}^H_{g,j}\right) + \sigma_B^2\mathbf{I}_{M_B} \end{aligned} \quad (11)$$

B. STEP 2: BEAMFORMING DESIGN FOR SUM RATE MAXIMIZATION FOR LICENSEES

After obtaining $I_{\min}$ from Algorithm 1, we maximize the sum rate of the MBN by replacing the existing set of variables $\{\mathbf{V}, \mathbf{U}, \mathbf{W}\}$ with a new set $\{\widehat{\mathbf{V}}, \widehat{\mathbf{U}}, \widehat{\mathbf{W}}\}$, but with same dimension and physical meaning. Accordingly, step 2 of the beamforming design problem can be formulated as

$$\begin{aligned}
\textbf{P3}: \max_{\widehat{\mathbf{V}},\widehat{\mathbf{U}},\widehat{\mathbf{W}}} \quad & \left\{\sum_{j=1}^{G}\sum_{i=1}^{K_j^u} R_{i_j^u} + \sum_{j=1}^{G}\sum_{i=1}^{K_j^d} R_{i_j^d}\right\} \\
\text{Subject to } & (C.1)\ \mathrm{tr}\left(\widehat{\mathbf{V}}_{k_g^u}\widehat{\mathbf{V}}_{k_g^u}^H\right) \le P_{k_g^u}, \\
& k = 1, \cdots, K_g^u,\ \forall g, \\
& (C.2)\ \sum_{k=1}^{K_g^d} \mathrm{tr}\left(\widehat{\mathbf{V}}_{k_g^d}\widehat{\mathbf{V}}_{k_g^d}^H\right) \le P_g, \quad \forall g, \\
& (C.3)\ \sum_{r=1}^{R} \mathrm{tr}\left\{\mathbf{I}_{r,\mathrm{MBN}}\right\} \le I_{\min}.
\end{aligned} \tag{29}$$

Hereinafter, $R_{i_j^u}$, $R_{i_j^d}$ and $\mathbf{I}_{r,\mathrm{MBN}}$ are obtained using the new set of variables $\{\widehat{\mathbf{V}}, \widehat{\mathbf{U}}, \widehat{\mathbf{W}}\}$. Now, by using (14) and (15), we convert the objective function of problem (**P3**) and constraints $(C.1) - (C.3)$ into their MSE equivalents and vector form, respectively. The vector form of $\mathbf{I}_{r,\mathrm{MBN}}$ is given in (30) on the bottom of next page and the problem (**P3**) is reformulated as

$$\begin{aligned}
\textbf{P4}: \min_{\widehat{\mathbf{V}}} \quad & \sum_{j=1}^{G}\sum_{i=1}^{K_j^u} -\mathrm{tr}\left\{\widehat{\mathbf{W}}_{k_g^u}\widehat{\mathbf{E}}_{k_g^u}\right\} + \log_2\left|\ln 2\widehat{\mathbf{W}}_{k_g^u}\right| + \frac{d_{k_g^u}}{\ln 2} \\
& + \sum_{j=1}^{G}\sum_{i=1}^{K_j^d} -\mathrm{tr}\left\{\widehat{\mathbf{W}}_{k_g^d}\widehat{\mathbf{E}}_{k_g^d}\right\} + \log_2\left|\ln 2\widehat{\mathbf{W}}_{k_g^d}\right| + \frac{d_{k_g^d}}{\ln 2} \\
\text{Subject to } & (C.1)\ \left\|\mathrm{vec}\left(\widehat{\mathbf{V}}_{k_g^u}\right)\right\|^2 \le P_{k_g^u}, \\
& k = 1, \cdots, K_g^u,\ \forall g, \\
& (C.2)\ \sum_{k=1}^{K_g^d} \left\|\mathrm{vec}\left(\widehat{\mathbf{V}}_{k_g^d}\right)\right\|^2 \le P_g, \quad \forall g, \\
& (C.3)\ \sum_{r=1}^{R} \left\|\mu_{r,\mathrm{MBN}}\right\|_2^2 \le I_{\min},
\end{aligned} \tag{31}$$

where $\widehat{\mathbf{E}}_{k_g^u}$ and $\widehat{\mathbf{E}}_{k_g^d}$ are computed using $\{\widehat{\mathbf{V}}, \widehat{\mathbf{U}}, \widehat{\mathbf{W}}\}$. Since the problem (**P4**) is convex, we can find the optimal beamformer matrices and weight matrix as depicted in Appendix C. We can use sub-gradient or linear search method [37] to update the Lagrange multipliers, which is calculated in a way similar to the previous case. The convergence to an optimal solution is guaranteed in case of the sub-gradient method for a small step size. Like before, we use an iterative algorithm (shown in Algorithm 2) to obtain the optimal receive and transmit beamforming matrix.

IV. NUMERICAL RESULT

In this section, we numerically investigate the performance of the considered LSA system model by implementing the proposed beamformer design algorithms. The simulations are performed for a center frequency of 2 GHz and bandwidth of

$$\mathrm{tr}\left\{\mathbf{W}_{k_g^u}\mathbf{E}_{k_g^u}\right\} = \mathrm{tr}\left\{\mathbf{B}_{k_g^u}\left(\mathbf{U}_{k_g^u}\mathbf{H}_{g,k_g^u}\mathbf{V}_{k_g^u} - \mathbf{I}_{d_{k_g^u}}\right)\left(\mathbf{U}_{k_g^u}\mathbf{H}_{g,k_g^u}\mathbf{V}_{k_g^u} - \mathbf{I}_{d_{k_g^u}}\right)^H \mathbf{B}_{k_g^u}^H\right\} + \mathrm{tr}\left\{\mathbf{B}_{k_g^u}\mathbf{U}_{k_g^u}\Sigma_{k_g^u}\mathbf{U}_{k_g^u}^H\mathbf{B}_{k_g^u}^H\right\} \tag{20}$$

$$\mathrm{tr}\left\{\mathbf{W}_{k_g^d}\mathbf{E}_{k_g^d}\right\} = \mathrm{tr}\left\{\mathbf{B}_{k_g^d}\left(\mathbf{U}_{k_g^d}\mathbf{H}_{k_g^d,g}\mathbf{V}_{k_g^d} - \mathbf{I}_{d_{k_g^d}}\right)\left(\mathbf{U}_{k_g^d}\mathbf{H}_{k_g^d,g}\mathbf{V}_{k_g^d} - \mathbf{I}_{d_{k_g^d}}\right)^H \mathbf{B}_{k_g^d}^H\right\} + \mathrm{tr}\left\{\mathbf{B}_{k_g^d}\mathbf{U}_{k_g^d}\Sigma_{k_g^d}\mathbf{U}_{k_g^d}^H\mathbf{B}_{k_g^d}^H\right\} \tag{21}$$

$$\begin{aligned}
\mathbf{F}_{k_g^u} = \; & \mathbf{H}_{r,k_g^u}^H\mathbf{H}_{r,k_g^u} + \kappa_U \mathrm{diag}\left(\mathbf{H}_{r,k_g^u}^H\mathbf{H}_{r,k_g^u}\right) + \sum_{j=1}^{G}\sum_{i=1}^{K_j^u} \lambda_{k_g^u}\left[\mathbf{H}_{j,k_g^u}^H\mathbf{U}_{i_j^u}^H\mathbf{W}_{i_j^u}\mathbf{U}_{i_j^u}\mathbf{H}_{j,k_g^u} + \kappa_U \mathrm{diag}\left(\mathbf{H}_{j,k_g^u}^H\mathbf{U}_{i_j^u}^H\mathbf{W}_{i_j^u}\mathbf{U}_{i_j^u}\mathbf{H}_{j,k_g^u}\right)\right. \\
& \left. + \beta_B \mathbf{H}_{j,k_g^u}^H \mathrm{diag}\left(\mathbf{U}_{i_j^u}^H\mathbf{W}_{i_j^u}\mathbf{U}_{i_j^u}\right)\mathbf{H}_{j,k_g^u}\right] + \sum_{j=1}^{G}\sum_{i=1}^{K_j^d} \lambda_{k_g^d}\left[\mathbf{H}_{i_j^d,k_g^u}^H\mathbf{U}_{i_j^d}^H\mathbf{W}_{i_j^d}\mathbf{U}_{i_j^d}\mathbf{H}_{i_j^d,k_g^u}\right. \\
& \left. + \kappa_U \mathrm{diag}\left(\mathbf{H}_{i_j^d,k_g^u}^H\mathbf{U}_{i_j^d}^H\mathbf{W}_{i_j^d}\mathbf{U}_{i_j^d}\mathbf{H}_{i_j^d,k_g^u}\right) + \beta_U \mathbf{H}_{i_j^d,k_g^u}^H \mathrm{diag}\left(\mathbf{U}_{i_j^d}^H\mathbf{W}_{i_j^d}\mathbf{U}_{i_j^d}\right)\mathbf{H}_{i_j^d,k_g^u}\right],
\end{aligned} \tag{26}$$

$$\begin{aligned}
\mathbf{F}_g = \; & \mathrm{H}_{r,g}^H\mathrm{H}_{r,g} + \kappa_B \mathrm{diag}\left(\mathrm{H}_{r,g}^H\mathrm{H}_{r,g}\right) + \sum_{j=1}^{G}\sum_{i=1}^{K_j^d} \lambda_{i_j^d}\left[\mathbf{H}_{i_j^d,g}^H\mathbf{U}_{i_j^d}^H\mathbf{W}_{i_j^d}\mathbf{U}_{i_j^d}\mathbf{H}_{i_j^d,g} + \kappa_B \mathrm{diag}\left(\mathbf{H}_{i_j^d,g}^H\mathbf{U}_{i_j^d}^H\mathbf{W}_{i_j^d}\mathbf{U}_{i_j^d}\mathbf{H}_{i_j^d,g}\right)\right. \\
& \left. + \beta_U \mathbf{H}_{i_j^d,g}^H \mathrm{diag}\left(\mathbf{U}_{i_j^d}^H\mathbf{W}_{i_j^d}\mathbf{U}_{i_j^d}\right)\mathbf{H}_{i_j^d,g}\right] + \sum_{j=1}^{G}\sum_{i=1}^{K_j^u} \lambda_{k_g^u}\left[\delta'_{j,g}\mathbf{H}_{j,g}^H\mathbf{U}_{i_j^u}^H\mathbf{W}_{i_j^u}\mathbf{U}_{i_j^u}\mathbf{H}_{j,g} + \kappa_B \mathrm{diag}\left(\mathbf{H}_{j,g}^H\mathbf{U}_{i_j^u}^H\mathbf{W}_{i_j^u}\mathbf{U}_{i_j^u}\mathbf{H}_{j,g}\right)\right. \\
& \left. + \beta_B \mathbf{H}_{j,g}^H \mathrm{diag}\left(\mathbf{U}_{i_j^u}^H\mathbf{W}_{i_j^u}\mathbf{U}_{i_j^u}\right)\mathbf{H}_{j,g}\right]
\end{aligned} \tag{27}$$

Algorithm 1 Beamforming Design for Aggregate Interference Minimization Towards Incumbents With QoS Constraints for Licensees

Initialize $\mathbf{V}_{k_g^u}$ and $\mathbf{V}_{k_g^d}$.

loop

for $n = 1 : n_{max}$; n_{max} = maximum number of iteration.

a. $n \leftarrow n + 1$. Update $\left(\mathbf{U}_{k_g^u}, \mathbf{U}_{k_g^d}\right)$ using (18) and (19) with fixed $\left(\mathbf{V}_{k_g^u}, \mathbf{V}_{k_g^d}\right)$, $\forall k, g$.

b. Update $\left(\mathbf{W}_{k_g^u}, \mathbf{W}_{k_g^d}\right)$ using (22) for fixed $\left(\mathbf{V}_{k_g^u}, \mathbf{V}_{k_g^d}\right)$ and $\left(\mathbf{U}_{k_g^u}, \mathbf{U}_{k_g^d}\right)$ $\forall k, g$.

c. Update $\left(\mathbf{V}_{k_g^u}, \mathbf{V}_{k_g^d}\right)$ using (24) and (25) with fixed $\{\mathbf{W}_{k_g^u}, \mathbf{W}_{k_g^d}\}$ and $\left(\mathbf{U}_{k_g^u}, \mathbf{U}_{k_g^d}\right)$ $\forall k, g$.

d. Repeat steps **a** to **c** until convergence or $n = n_{max}$.

e. Obtain $I_{\min} = \sum_{r=1}^{R} \operatorname{tr}\left\{\mathbf{I}_{r,\text{MBN}}\right\}$.

end loop

Send $I_{\min}$ to algorithm 2.

Algorithm 2 Beamforming Design for Sum Rate Maximization of Licensees With Interference Constraints Towards Incumbents

Receive minimized $I_{\min}$ from algorithm 1.

Set this minimized $I_{\min}$ as thershold limit in this algorithm.

Initialize $\widehat{\mathbf{V}}_{k_g^u}$ and $\widehat{\mathbf{V}}_{k_g^d}$.

loop

for $n = 1 : n_{max}$, n_{max} = maximum number of iteration.

a. $n \leftarrow n + 1$. Update $\left(\widehat{\mathbf{U}}_{k_g^u}, \widehat{\mathbf{U}}_{k_g^d}\right)$ using using (42) and (43) with fixed $\left(\widehat{\mathbf{V}}_{k_g^u}, \widehat{\mathbf{V}}_{k_g^d}\right)$, $\forall k, g$.

b. Update $\left(\widehat{\mathbf{W}}_{k_g^u}, \widehat{\mathbf{W}}_{k_g^d}\right)$ using (44) for fixed $\left(\widehat{\mathbf{V}}_{k_g^u}, \widehat{\mathbf{V}}_{k_g^d}\right)$ and $\left(\widehat{\mathbf{U}}_{k_g^u}, \widehat{\mathbf{U}}_{k_g^d}\right)$ $\forall k, g$.

c. Update $\left(\widehat{\mathbf{V}}_{k_g^u}, \widehat{\mathbf{V}}_{k_g^d}\right)$ using (3) and (40) with fixed $\{\widehat{\mathbf{W}}_{k_g^u}, \widehat{\mathbf{W}}_{k_g^d}\}$ and $\left(\widehat{\mathbf{U}}_{k_g^u}, \widehat{\mathbf{U}}_{k_g^d}\right)$ $\forall k, g$.

d. Repeat steps **a** to **c** until convergence or $n = n_{max}$.

end loop

Obtain the beamformers that maximizes the sum rate of the licensees.

10 MHz.[4] Small cell are considered as they conform to short distances and low mobility through low power transmission, which is not only suitable for LSA, but also for IBFD radios. Accordingly, each cell of the MBN is randomly distributed within an area of $50 - 150$ m from the incumbents. The radius of each cell is set to 50 m and the minimum distance of each user from the IBFD BS is fixed 10 m. Further, each cell consists of one IBFD BS serving one UL and one DL user, which are distributed randomly with in the circumference of the cell. The channels between a transmitting node and a receiving node follow the path loss model for line-of-sight (LOS) and non-line-of-sight (NLOS) propagation. We follow the 3GPP LTE [40] specifications as given in Table 2. The channels between users and BSs, and vice-versa and from all transmitting nodes of the MBN towards the incumbents are given as $\mathbf{H}_{Rx,Tx} = \sqrt{\gamma}\widehat{\mathbf{H}}_{Rx,Tx}$, where $\widehat{\mathbf{H}}_{Rx,Tx}$ represents small scale fading and is distributed as $\mathcal{CN}(0, 1)$, with $\gamma = 10^{(-PL/10)}$. Here, PL denotes the path loss exponent and the indices Rx and Tx indicate receiving and transmitting nodes. The SI channel is modelled according to Rician distribution [24] as $\mathbf{H}_{g,g} \sim \mathcal{CN}\left(\sqrt{\frac{K}{1+K}}\widehat{\mathbf{H}}_{g,g}, \frac{1}{1+K}\mathbf{I}_{M_B} \otimes \mathbf{I}_{M_B}\right)$, where K is the rician factor and $\widehat{\mathbf{H}}_{g,g}$ is a deterministic matrix. and some of the important parameter settings are presented in Table 2. Unless otherwise stated, rest of the parameters are as follows: $M_u = M_d = N = 2$, $M_B = 4$, $M_T = M_R = 4$, $R_{k_g^u,min}(R_{k_g^d,min}) = 1(2)$bits/sec/Hz, $P_g = P_{k_g^u} = 0$ dB, $\kappa_B(\beta_B) = \kappa_U(\beta_U) = \kappa(\beta) = -70$ dB, and CCI attenuation

[4]The proposed modified LSA controller framework is not limited to any specific frequency band and can be implemented in other bands proposed for sharing around the world without any alteration in the primary system parameters or algorithm design. However, certain alterations in frequency dependent path loss and propagation parameters may be required.

$$
\mathbf{I}_{r,\text{MBN}} = \left\| \begin{array}{c} \left\lfloor \left[\mathbf{I}_{d_{i_j^u}} \otimes \mathbf{H}_{r,i_j^u}\right] vec(\widehat{\mathbf{V}}_{i_j^u}) \right\rfloor_{j=1,\ldots,G,i=1,\ldots,K_j^u} \\ \left\lfloor \sqrt{\kappa_U}\left[\mathbf{I}_{d_{i_j^u}} \otimes \left(\left(\operatorname{diag}\left(\mathbf{H}^H_{r,i_j^u}\mathbf{H}_{r,i_j^u}\right)\right)^{\frac{1}{2}}\right)\right] vec(\widehat{\mathbf{V}}_{i_j^u}) \right\rfloor_{j=1,\ldots,G,i=1,\ldots,K_j^u} \\ \left\lfloor \left[\mathbf{I}_{d_{i_j^d}} \otimes \mathbf{H}_{r,j}\right] vec(\widehat{\mathbf{V}}_{i_j^d}) \right\rfloor_{j=1,\ldots,G,i=1,\ldots,K_j^d} \\ \left\lfloor \sqrt{\kappa_B}\left[\mathbf{I}_{d_{i_j^d}} \otimes \left(\left(\operatorname{diag}\left(\mathbf{H}^H_{r,j}\mathbf{H}_{r,j}\right)\right)^{\frac{1}{2}}\right)\right] vec(\widehat{\mathbf{V}}_{i_j^d}) \right\rfloor_{j=1,\ldots,G,i=1,\ldots,K_j^d} \end{array} \right\|_2^2
$$

$$
= * \left\|\mu_{r,\text{MBN}}\right\|_2^2 \tag{30}
$$

factor[5] $\upsilon = 0.1$. The simulation setup is shown in Fig. 2 and random initialization is used for all the algorithms. For the purpose of comparison, baseline HD LSA framework is also simulated. The tolerance level of the algorithms is set to 10^5, the minimum and maximum number of iterations is set at 100 and 500, respectively, and the results are averaged over 100 independent channel realizations.

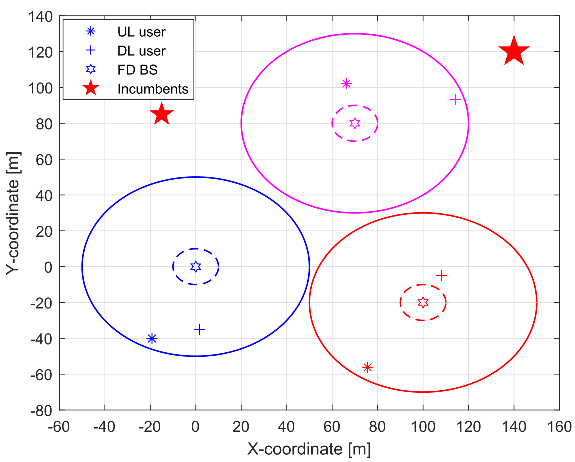


FIGURE 2. Simulation setup.

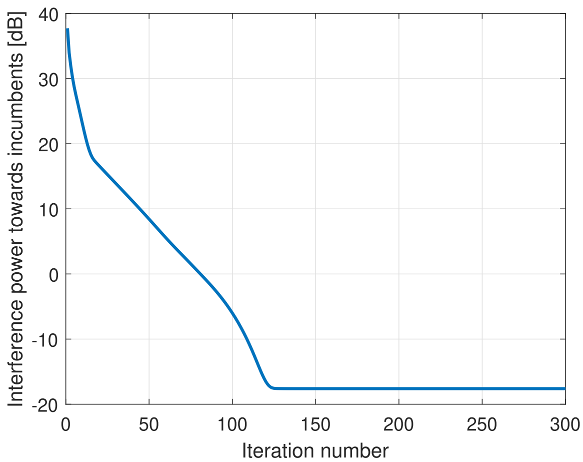


FIGURE 3. Evolution of Algorithm 1.

We begin by showing the evolution of Algorithm 1 in Figure 3. It can be noticed that as number of iteration increases, the cost function (aggregate interference towards the incumbents) decreases monotonically. The algorithm converges in the range of 120-150 iterations thus verifying its feasibility. The convergence of Algorithm 2 follows suit and is omitted here to avoid repetition.

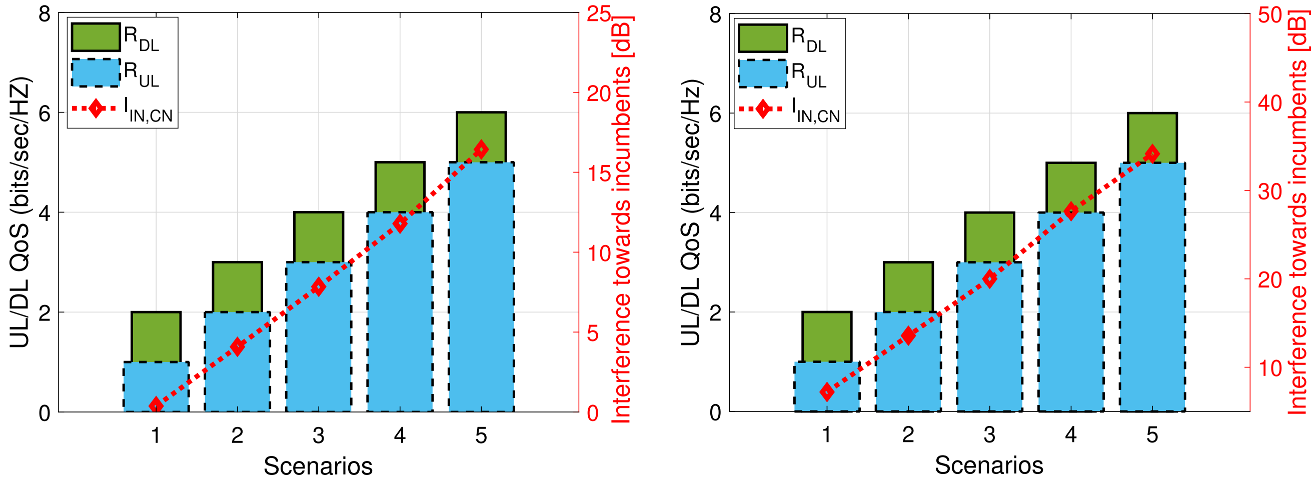
Next, in Figure 4 we present the performance of the LSA network and the corresponding trade-offs when Algorithm 1 is implemented by the LSA controller. The $x-$ axis represents the number of considered scenarios, the left $y-$axis represents the (UL, DL) aggregate QoS requirements for the IBFD licensee network and the right $y-$ axis represents the corresponding minimized interference towards the incumbents. While Figure 4a shows the performance of the IBFD case, Figure 4b shows the HD case. Comparing the two figures it can be seen that to maintain a particular QoS for the licensee network, the incumbent has to suffer through higher interference exposure for the case of HD operation than the IBFD network. For example, for case 1 (i.e. for UL QoS = 1 bits/sec/Hz and DL QoS = 2 bits/sec/Hz), the aggregate interference at incumbents from the HD licensee network is 6.8315 dB more than the IBFD licensee network and this gap further increases when the QoS requirements are increased. This can be explained by the fact that to achieve a specific QoS rate requirement, the IBFD system requires less transmit power than HD system as it is utilizing the full spectral resources unlike the HD case. Accordingly, the IBFD radios generate less interference and is extremely beneficial for LSA scenarios. Nevertheless, the above gains are subject to proper residual SI and CCI suppression, which we will evaluate in the following examples with respect to Algorithm 2.

After obtaining the interference temperature from Algorithm 1, the LSA controller implements Algorithm 2 to jointly maximize the throughput of all the UL and DL users in the MBN. Now, in order to verify that Algorithm 2 does not violate the minimized interference from Algorithm 1, in Figure 5 we show the complementary cumulative distribution (CCD) of the total interference power from the MBN towards incumbents, i.e., $\mathbb{P}\left[\sum_{r=1}^{R} \|\mu_{r,\text{MBN}}\|_2^2 \leq I_{min}\right]$, where $\sum_{r=1}^{R} \|\mu_{r,\text{MBN}}\|_2^2$ is the total interference power from MBN towards incumbents (as shown in C.3 of P4) and I_{min} is the minimized cost function of Algorithm 1. After evaluating Algorithm 1 based on scenario 1 (Figure 4), we have

TABLE 2. Simulation parameters settings.

Notation	Description
Cell radius at the MBN (r)	50 m
Thermal noise density	-174d Bm/Hz
Noise figure	BS: 13 dB, user: 9 dB
Bandwidth (B)	10 MHz
MBN BS to BS pathloss (in dB, D in km)	LOS if $D < 2/3 : 98.4 + 20\log_{10}(D)$ LOS if $D \geq 2/3$: $101.9 + 40\log_{10}(D)$ NLOS : $169.36 + 40\log_{10}(D)$
MBN BS to user pathloss (in dB, D in km)	LOS : $103.8 + 20.9\log_{10}(D)$ NLOS : $145.4 + 37.5\log_{10}(D)$
User to user path loss (in dB, D in km)	if $D \leq 50\text{m} : 98.45 + 20\log_{10}(D)$ if $D > 50\text{m} : 55.78 + 20\log_{10}(D)$
Shadowing standard deviation (in dB)	between cells: 6 between BS and users: LOS: 3, NLOS: 4
LOS probability (D in km)	$0.5 - \min(0.5, 5\exp(-0.156/D))$ $+ \min(0.5, 5\exp(-D/0.003))$

[5]It is important to exploit a smart channel assignment algorithm in a IBFD system prior to beamformer design. This is due to the fact that CCI can be reduced by assigning weaker interference path users into the same channel. The effect of channel assignment is incorporated in our analysis through an attenuation coefficient, υ, on the CCI channels. In particular, υ represents the amount of isolation among UL and DL users.



(a) IBFD LSA network. (b) Baseline HD LSA network.

FIGURE 4. Comparison between FD LSA network and baseline HD LSA network.

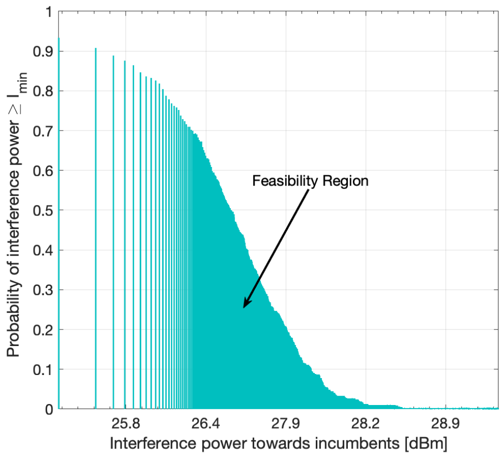


FIGURE 5. Probability of interference from MBN towards incumbents w.r.t maximum allowed minimized interference, I_{min}.

$I_{min} = 1.098\text{W} \approx 30.04\text{dBm}$. Now, it can be seen from the figure that the probability of total interference power from the MBN to the incumbent network is zero when it is close to or higher than $I_{min} \approx 28.9\text{dBm}$. This verifies the operation of Algorithm 2, which ensures that the interference towards the incumbents is always kept below or equal to the interference temperature obtained in Algorithm 1. While achieving equality will ensure maximum throughput for the MBN, the LSA controller ensures that algorithm 2 mainly operates below I_{min} to protect the incumbents, but still providing the users of the MBN with specific throughput, which we in the following analysis. Further, the area under the CCD curve can be contemplated as the region, under which Algorithm 2 is always feasible to enable the modified LSA framework.

Next, in Figure. 6 we show the aggregate throughput[6] performance of the licensee IBFD MBN and compare it with baseline HD LSA MBN with respect to the level of RSI cancellation, which in practise is reflected by the amount of transmit/ receive distortion ($\kappa = \beta$). It can be seen from the figure that at higher RSI cancellation levels the throughput of the MBN is higher. Further, IBFD LSA outperforms baseline HD LSA when the RSI cancellation level is ≥20 dB. To quantify, at a reasonable RSI cancellation level of around −60 dB, IBFD LSA outperforms baseline HD LSA by around 60%.

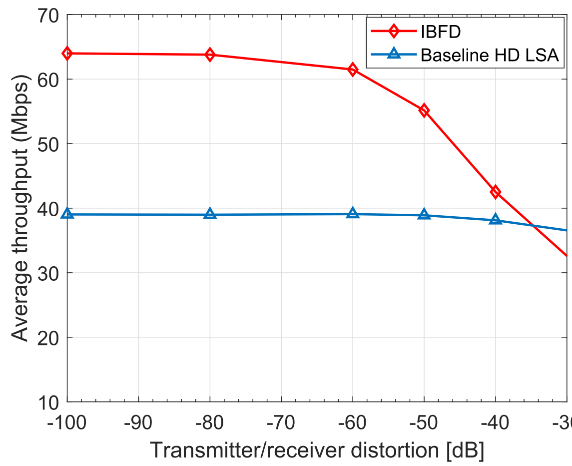


FIGURE 6. Throughput performance of IBFD LSA and baseline HD LSA vs RSI cancellation level reflected by the amount of transmit/ receive distortion ($\kappa = \beta$).

Next, in Figure 7 we show the effect of CCI attenuation on the IBFD LSA system. As stated before, the CCI attenuation is the isolation among UL and DL users. From the figure, it can be observed that as the CCI suppression factor increases, i.e., υ decreases, IBFD LSA system outperforms its corresponding HD counterpart significantly. However, CCI suppression factor does not impact the HD system. This can be explained by the fact that while IBFD uses both the time and frequency resources to simultaneously serve UL and DL users, the HD operation only serves either the UL or DL users at a particular time or frequency. Hence, greater isolation among UL and DL users is desirable for the successful implementation of IBFD system.

[6]The aggregate throughput of the network is calculated as: $B \times \sum_{j=1}^{G} \left\{ \sum_{i=1}^{K_j^u} R_{i_j^u} + \sum_{i=1}^{K_j^d} R_{i_j^d} \right\}$ Mbps.

Lastly, for the sake of comparison, in Fig. 8 we show the comparison between the proposed beamforming design (optimal precoder–MMSE receiver) and baseline schemes i) zero-forcing (ZF) precoder–receiver and ii) maximum-ratio transmission (MRT) precoder–maximum ratio combiner (MRC) receiver with respect to aggregate throughput in the MBN vs residual SI (RSI) cancellation strength. It can be seen from the figure that for reasonable RSI suppression levels (*i.e.,* $\sim[-100, \ldots, -50]$dB the combination of optimal precoder and the corresponding MMSE receiver outperforms ZF–ZF and MRT–MRC by a significant margin. For example, at a RSI cancellation strength of -80dB, the aggregate throughput obtained through the proposed beamforming scheme is approximately 37 and 40 mbps more than ZF–ZF and MRC–MRT, respectively. This is due to the fact that i) though the intra-cell interference is nulled within cells by the ZF-ZF and MRT–MRC schemes, inter-cell interference exists which degrades the throughput performance. ii) Further, the imperfect SI cancellation due to hardware impairments in the IBFD MBN results in distorted interference nulling, thus yielding residual interference at the receivers, which in turn jeopardizes the achievable throughput.

V. CSI ACQUISITION, IMPLEMENTATION AND COMPLEXITY OF THE MODIFIED LSA CONTROLLER

After illustrating the feasibility and advantages of the proposed model, in this section, we provide a holistic elaboration on the implementation and complexity of the beamforming algorithms for the modified LSA controller. The proposed algorithms are implemented in a centralized fashion inside the modified LSA controller, which inadvertently posses a central processing unit with high end computing capabilities.

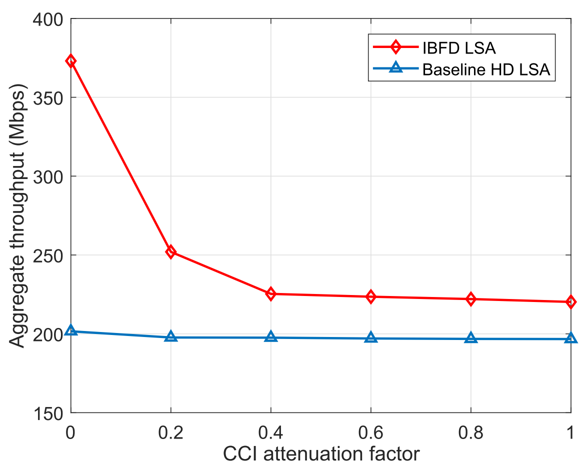


FIGURE 7. Throughput performance of IBFD LSA and baseline HD LSA vs CCI attenuation factor (υ).

A. CSI ACQUISITION

The CSI of the entire LSA network is obtained via the LSA controller with the ability to exchange the CSI between the incumbentss and the licensees. Following the centralized

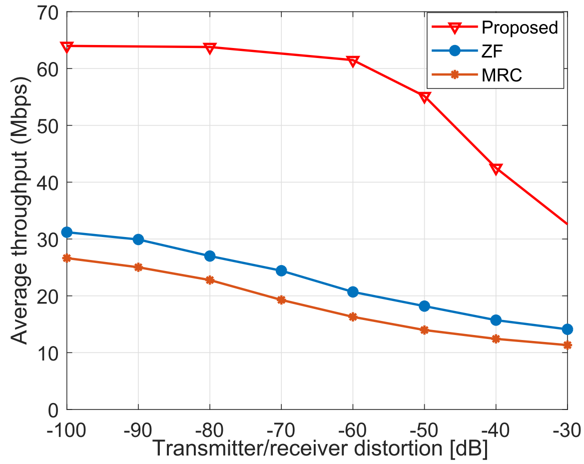


FIGURE 8. Comparison between the proposed precoder–receiver design and baseline ZF–ZF and MRC–MRT.

approach, the LSA controller gathers the all CSI information and $R_{k_j^u}$, and $R_{k_j^d}$ ($I_{\min}$) from the licensees (incumbents), computes all the desired variables and then distributes them to the respective BSs and users. The estimation of CSI matrices in the LSA network follows a similar strategy to that of traditional systems, as the incumbent and MBN cooperate with the LSA controller. This is performed via the exchange of the training sequences and feedback, and the application of usual CSI estimation methods [43], [44].

In particular, such a LSA based spectrum sharing framework between incumbents and MBNs can be envisioned in many domains, most notable of which are: 1) federal incumbents sharing spectrum with federal communication systems (F2F sharing), and 2) federal incumbents sharing spectrum with commercial mobile communication systems (F2M sharing). In F2F sharing, CSI can be acquired by the entities fairly easily as both systems belong to federal authority. In F2M sharing, CSI can be acquired by giving incentives to both the entities, among which are protection from interference from each other and price based incentives to the incumbent. Under both the domains one way to get CSI is that the incumbent network estimates the interference channels based on the training symbols sent by MBN receivers. Another approach is that the incumbent network aids MBN in channel estimation, with the help of a low-power reference signal, and they feed back the estimated channel to incumbent network. Since, incumbent's signal is treated as interference at the MBN, we can characterize the channel as interference channel and refer to information about it as interference-channel state information (ICSI). Furthermore, for the case of F2M sharing, the algorithms should be centrally operated in the LSA controller, whereby the LSA controller acquires the CSI of all the users and the incumbents and then processes the algorithm at its state-of-the-art servers. This will provide access of the incumbent network's CSI to only the licensees, which can be protected through prior agreements between the MNO and the incumbent network.

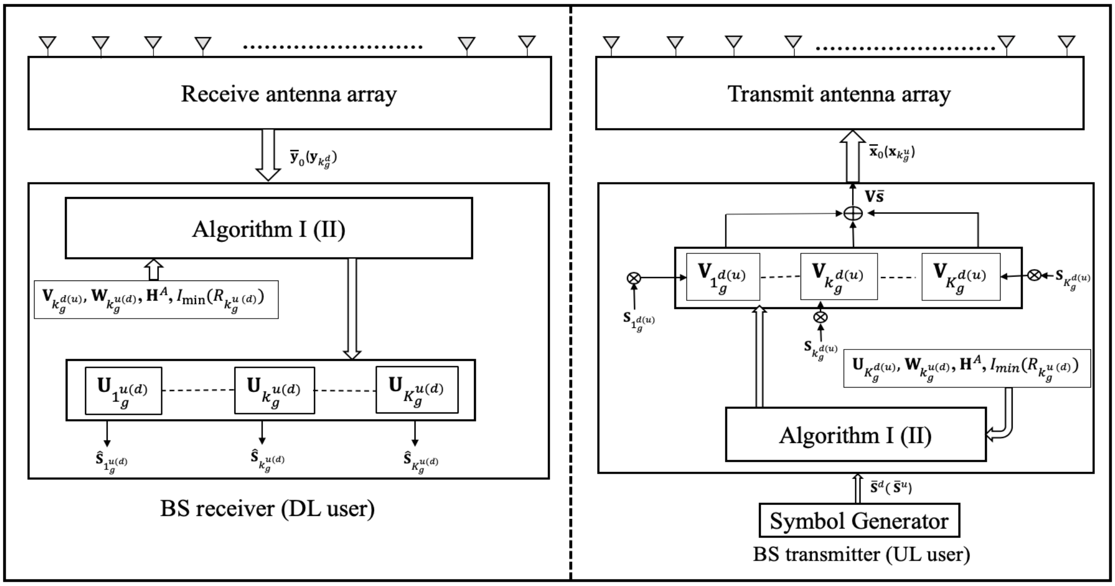


FIGURE 9. An illustration of the modified LSA controller's operation. $\mathbf{H}_A$ represents all the channels in the LSA network, with $A \in \{x, y\}$, where x, y denote the notations for respective channels from Table 1. V, U and W are replaced by $\widehat{\mathbf{V}}$, $\widehat{\mathbf{U}}$ and $\widehat{\mathbf{W}}$ in Algorithm 2.

B. IMPLEMENTATION

For simplification of illustration, we assume the following: $K_g^u = K_g^d = K$, $M_u = M_d = M_B = M_T = M_R = M$ and $d_{i_j^u} = d_{i_j^d} = d$.

For implementing the algorithms, a total of $M^2G^2(K+1)^2 + G(1+K)M^2R$ CSI elements are required at the LSA controller. Then with the available CSI elements, the LSA controller calculates all the transmit beamformers[7] $\mathbf{V}_{k_g^d}$ and $\mathbf{V}_{k_g^u}$ and distributes them to the respective transmitting BSs and users, resulting in $2GKMd$ matrix elements.

A schematic illustration of the implementation is shown in Fig. 9. While the IBFD BSs' perspective is shown here, the UL and DL users follow suit. The symbol generators of the IBFD BSs' transmitters generate the symbols, which are first multiplied by the transmit beamforming matrices and then transmitted through the transmitting antenna array. The transmitted symbols (from the UL users in this case) are received at the receiver of BSs through the receive antenna array which are then multiplied with receive beamforming matrices to obtain the estimated symbols.

C. COMPUTATIONAL COMPLEXITY

To compute all uplink receivers $\mathbf{U}_{k_g^u}$ from (18), we require $\mathcal{O}(14G^2K^2(M^3+M^2d-M^2))$ flops for calculating multiplication terms inside the inverse, $\mathcal{O}(GK(M^3+M^2)$ flops for calculating the inverse term, and $\mathcal{O}(GK(2M^3+2M^2d-M^2))$ flops for multiplying the outside terms with the inverse term [45]. To compute uplink weights $\mathbf{W}_{k_g^u}$, we need to calculate the MSE matrix. Since $\Sigma_{k_g^u}$ is calculated during calculation of $\mathbf{U}_{k_g^u}$, therefore we only need $\mathcal{O}(2GK(M^3+M^2)$ flops to calculate the inverse term and $\mathcal{O}(2G^2K^2(M^3+2M^2d+2d^2M))$ flops for multiplication. To compute UL precoding matrix, $\mathbf{V}_{k_g^u}$, $\mathcal{O}(4G^2K^2(24M^3+11M^2))$ flops are required to calculate $\mathbf{F}_{k_g^u}$, $\mathcal{O}(2GK(M^3+M^2)$ flops to calculate its inverse, and $\mathcal{O}(2GK(6M^3-3M^2)$ flops to calculate multiplication of the inverse term with the outside terms. In a similar way, the number of flops for the downlink case can be calculated.

VI. CONCLUSION

We proposed a modified LSA controller design, whereby a hierarchical two-step beamformer design approach was proposed by taking hardware impairments into consideration with the objective of i) minimizing the interference temperature from the licensee network towards the incumbent network, while maintaining predefined QoS requirements of the MBUs and ii) maximizing the UL/DL throughput of the licensee network while maintaining the minimized interference obtained from Step 1. Numerical results demonstrate that for specific UL and DL QoS requirements and proper RSI and CCI cancellation, the proposed IBFD framework generates less interference towards the incumbents than baseline HD LSA systems, while also providing the licensees with better throughput. Finally we showed how the proposed design can be implemented in practice, which we believe can act as a cornerstone for future development and implementation of modified LSA frameworks that will help us to fully realize the technology's promise.

[7]Note that the two steps use two different sets of beamforming matrices, i.e., **V**, **U** and **W** used in Algorithm 1 are replaced by $\widehat{\mathbf{V}}$, $\widehat{\mathbf{U}}$ and $\widehat{\mathbf{W}}$ in Algorithm 2.

APPENDIX A
DERIVATION OF DL AND UL INTERFERENCE POWER

Using (1), the total residual interference plus noise term at the k_g^d-th DL user can be given as

$$\mathbf{r}_{k_g^d} = \sum_{\substack{j=1 \\ (i,j\neq k,g)}}^{G}\sum_{i=1}^{K_j^d} \mathbf{H}_{k_g^d,j}\mathbf{V}_{i_j^d}\mathbf{s}_{i_j^d} + \sum_{j=1}^{G}\sum_{i=1}^{K_j^d} \mathbf{H}_{k_g^d,j}\mathbf{c}_{i_j^d} + \sum_{j=1}^{G}\sum_{i=1}^{K_j^u} \mathbf{H}_{k_g^d,i_j^u}\left(\mathbf{V}_{i_j^u}\mathbf{s}_{i_j^u} + \mathbf{c}_{i_j^u}\right) + \mathbf{e}_{k_g^d} + \mathbf{n}_{k_g^d}. \quad (32)$$

The covariance matrix of $\mathbf{r}_{k_g^d}$ $\left(i.e.\ \boldsymbol{\Sigma}_{k_g^d}\right)$ can be written as

$$\boldsymbol{\Sigma}_{k_g^d} = \mathbb{E}[\mathbf{r}_{k_g^d}(\mathbf{r}_{k_g^d})^H]. \quad (33)$$

Now, i) using the value of $\mathbf{r}_{k_g^d}$ from (32), ii) using (3)–(6), iii) considering the fact that the covariance of independent and identically distributed (i.i.d.) random variables is zero [41], iv) by making the approximations $\kappa_U \ll 1$ and $\kappa_B \ll 1$, and v) ignoring the product terms $\beta_U(\beta_B)\kappa_B(\kappa_U)$, (33) can be written as (10)

In a similar way by using (2), the covariance matrix of the total residual interference plus noise term for k_g^u-th UL user ($i.e.\ \boldsymbol{\Sigma}_{k_g^u}$) can be derived as (11).

APPENDIX B
DERIVATION OF OPTIMAL UL AND DL PRECODER FOR ALGORITHM 1

The Lagrange dual objective function of (23) is given by (34), as shown in next page.

Next, the differentiation of (34) with respect to $\mathbf{V}_{k_g^u}$ treating all channels, $\mathbf{V}_{i_j^d}$, $\mathbf{W}_{k_g^u}$, $\mathbf{W}_{k_g^d}$, $\mathbf{U}_{k_g^u}$, $\mathbf{U}_{k_g^d}$ as constants and using the properties of derivative of trace of multiplication of matrix [42], can be written as (35), given on the page.

Now setting derivative of (35) as $\frac{\partial \mathcal{L}}{\partial \mathbf{V}_{k_g^u}} = 0$, and rearranging the terms, we obtain the closed form solutions for the optimal UL precoders as (24). In a similar way, we get the optimal DL precoder matrix as (25).

APPENDIX C
OPTIMAL UL AND DL PRECODER FOR ALGORITHM 2

The Lagrange dual objective function of problem P4 is given by (36), as shown on the next page, where λ_c, $\mu_{i_j^d}$ and $\mu_{i_j^u}$ are the Lagrange multipliers associated with the constraints of the problem P4. Next, the differentiation of (36) with respect to $\widehat{\mathbf{V}}_{k_g^u}$ treating $\widehat{\mathbf{V}}_{i_j^d}$, $\widehat{\mathbf{W}}_{k_g^u}$, $\widehat{\mathbf{W}}_{k_g^d}$, $\widehat{\mathbf{U}}_{k_g^u}$ and $\widehat{\mathbf{U}}_{k_g^d}$ as constants and using the properties of derivative of trace of multiplication of matrix, can be written as (37).

Setting the derivative of (37) as $\frac{\partial \widehat{\mathcal{L}}}{\partial \widehat{\mathbf{V}}_{k_g^u}} = 0$, we obtain the closed form solutions for the optimal UL precoder $\left(\widehat{\mathbf{V}}_{k_g^u}\right)$ as

$$\widehat{\mathbf{V}}_{k_g^u} = \left(\widehat{\mathbf{F}}_{k_g^u} + \mu_{k_g^u}\mathbf{I}_{d_{k_g^u}}\right)^{-1}\mathbf{H}_{g,k_g^u}^H\widehat{\mathbf{U}}_{k_g^u}^H\widehat{\mathbf{W}}_{k_g^u}, \quad (38)$$

where $\widehat{\mathbf{F}}_{k_g^u}$ can be written as (39).

In a similar way, we get the optimal DL precoder matrix $\left(\widehat{\mathbf{V}}_{k_g^d}\right)$ as

$$\widehat{\mathbf{V}}_{k_g^d} = \left(\widehat{\mathbf{F}}_{k_g^d} + \mu_{k_g^d}\mathbf{I}_{d_{k_g^d}}\right)^{-1}\mathbf{H}_{k_g^d,g}^H\widehat{\mathbf{U}}_{k_g^d}^H\widehat{\mathbf{W}}_{k_g^d}, \quad (40)$$

where $\widehat{\mathbf{F}}_{k_g^d}$ can be written as (41) shown in next page.

$$\begin{aligned}\mathcal{L} = &\sum_{j=1}^{G}\sum_{i=1}^{K_j^u}\mathbf{H}_{r,i_j^u}\left(\mathbf{V}_{i_j^u}\mathbf{V}_{i_j^u}^H + \kappa_U\mathrm{diag}\left(\mathbf{V}_{i_j^u}\mathbf{V}_{i_j^u}^H\right)\right)\mathbf{H}_{r,i_j^u}^H + \sum_{j=1}^{G}\sum_{i=1}^{K_j^d}\mathbf{H}_{r,j}\left(\mathbf{V}_{i_j^d}\mathbf{V}_{i_j^d}^H + \kappa_B\mathrm{diag}\left(\mathbf{V}_{i_j^d}\mathbf{V}_{i_j^d}^H\right)\right)\mathbf{H}_{r,j}^H \\ &+ \sum_{j=1}^{G}\sum_{i=1}^{K_j^u}\lambda_{i_j^u}\left(\mathrm{tr}\left\{\mathbf{W}_{i_j^u}\mathbf{E}_{i_j^u}\right\} - \log_2\left|\ln 2\mathbf{W}_{i_j^u}\right| - \frac{d_{i_j^u}}{\ln 2} + R_{i_j^u,min}\right) + \sum_{j=1}^{G}\sum_{i=1}^{K_j^u}\mu_{i_j^u}\left(\mathrm{tr}\left(\mathbf{V}_{i_j^u}\mathbf{V}_{i_j^u}^H\right) - P_{i_j^u}\right) \\ &+ \sum_{j=1}^{G}\sum_{i=1}^{K_j^d}\lambda_{i_j^d}\left(\mathrm{tr}\left\{\mathbf{W}_{i_j^d}\mathbf{E}_{i_j^d}\right\} - \log_2\left|\ln 2\mathbf{W}_{i_j^d}\right| - \frac{d_{i_j^d}}{\ln 2} + R_{i_j^d,min}\right) + \sum_{j=1}^{G}\sum_{i=1}^{K_j^d}\mu_{i_j^d}\left(\mathrm{tr}\left(\mathbf{V}_{i_j^d}\mathbf{V}_{i_j^d}^H\right) - P_{i_j^d}\right)\end{aligned} \quad (34)$$

$$\begin{aligned}\frac{\partial \mathcal{L}}{\partial \mathbf{V}_{k_g^u}} = &\ 2\mathbf{H}_{r,k_g^u}^H\mathbf{H}_{r,k_g^u}\mathbf{V}_{k_g^u} + 2\kappa_U\mathrm{diag}\left(\mathbf{H}_{r,k_g^u}^H\mathbf{H}_{r,k_g^u}\right)\mathbf{V}_{k_g^u} + 2\lambda_{k_g^u}\mathbf{H}_{g,k_g^u}^H\mathbf{U}_{k_g^u}^H\mathbf{W}_{k_g^u}\mathbf{U}_{k_g^u}\mathbf{H}_{g,k_g^u}\mathbf{V}_{k_g^u} - 2\lambda_{k_g^u}\mathbf{H}_{g,k_g^u}^H\mathbf{U}_{k_g^u}^H\mathbf{W}_{k_g^u} \\ &+ 2\sum_{\substack{j=1 \\ (i,j\neq k,g)}}^{G}\sum_{i=1}^{K_j^u}\lambda_{i_j^u}\mathbf{H}_{j,i_g^u}^H\mathbf{U}_{i_j^u}^H\mathbf{W}_{i_j^u}\mathbf{U}_{i_j^u}\mathbf{H}_{j,i_j^u}\mathbf{V}_{k_g^u} + 2\kappa_U\sum_{j=1}^{G}\sum_{i=1}^{K_j^u}\lambda_{i_j^u}\mathrm{diag}\left(\mathbf{H}_{j,k_g^u}^H\mathbf{U}_{i_j^u}^H\mathbf{W}_{i_j^u}\mathbf{U}_{i_j^u}\mathbf{H}_{j,k_g^u}\right)\mathbf{V}_{k_g^u} \\ &+ 2\beta_B\sum_{j=1}^{G}\sum_{i=1}^{K_j^u}\lambda_{i_j^u}\mathbf{H}_{j,k_g^u}^H\mathrm{diag}\left(\mathbf{U}_{i_j^u}^H\mathbf{W}_{i_j^u}\mathbf{U}_{i_j^u}\right)\mathbf{H}_{j,k_g^u}\mathbf{V}_{k_g^u} + 2\sum_{j=1}^{G}\sum_{i=1}^{K_j^d}\lambda_{k_g^d}\left[\mathbf{H}_{i_j^d,k_g^u}^H\mathbf{U}_{i_j^u}^H\mathbf{W}_{i_j^d}\mathbf{U}_{i_j^d}\mathbf{H}_{i_j^d,k_g^u}\right. \\ &\left.+\ \kappa_U\mathrm{diag}\left(\mathbf{H}_{i_j^d,k_g^u}^H\mathbf{U}_{i_j^d}^H\mathbf{W}_{i_j^d}\mathbf{U}_{i_j^d}\mathbf{H}_{i_j^d,k_g^u}\right) + \beta_U\mathbf{H}_{i_j^d,k_g^u}^H\mathrm{diag}\left(\mathbf{U}_{i_j^d}^H\mathbf{W}_{i_j^d}\mathbf{U}_{i_j^d}\right)\mathbf{H}_{i_j^d,k_g^u}\right]\mathbf{V}_{k_g^u} + 2\mu_{k_g^u}\mathbf{V}_{k_g^u}\end{aligned} \quad (35)$$

Now, the optimal beamforming receiver at the BS g and at the k_g^d DL user can be computed as

$$\widehat{\mathbf{U}}_{k_g^u} = \widehat{\mathbf{V}}_{k_g^u}^H \mathbf{H}_{g,k_g^u}^H \left(\mathbf{H}_{g,k_g^u} \widehat{\mathbf{V}}_{k_g^u} \widehat{\mathbf{V}}_{k_g^u}^H \mathbf{H}_{g,k_g^u}^H + \widehat{\Sigma}_{k_g^u} \right)^{-1}, \quad (42)$$

$$\widehat{\mathbf{U}}_{k_g^d} = \widehat{\mathbf{V}}_{k_g^d}^H \mathbf{H}_{g,k_g^d}^H \left(\mathbf{H}_{g,k_g^d} \widehat{\mathbf{V}}_{k_g^d} \widehat{\mathbf{V}}_{k_g^d}^H \mathbf{H}_{g,k_g^d}^H + \widehat{\Sigma}_{k_g^d} \right)^{-1}. \quad (43)$$

Further, the optimal weights at the BS g and at the k_g^d users are computed as

$$\widehat{\mathbf{W}}_{k_g^u} = \frac{1}{\ln 2} \widehat{\mathbf{E}}_{k_g^u}^{-1} \left(\widehat{\mathbf{U}}_{k_g^u}, \widehat{\mathbf{V}}_{k_g^u}, \widehat{\Sigma}_{k_g^u} \right), \quad (44)$$

$$\widehat{\mathbf{W}}_{k_g^d} = \frac{1}{\ln 2} \widehat{\mathbf{E}}_{k_g^d}^{-1} \left(\widehat{\mathbf{U}}_{k_g^d}, \widehat{\mathbf{V}}_{k_g^d}, \widehat{\Sigma}_{k_g^d} \right). \quad (45)$$

$$\begin{aligned}
\widehat{\mathcal{L}} = & \sum_{j=1}^{G} \sum_{i=1}^{K_j^u} -\mathrm{tr}\left\{ \widehat{\mathbf{W}}_{i_j^u} \widehat{\mathbf{E}}_{i_j^u} \right\} + \log_2 \left| \ln 2 \widehat{\mathbf{W}}_{i_j^u} \right| + \frac{d_{i_j^u}}{\ln 2} + \sum_{j=1}^{G} \sum_{i=1}^{K_j^d} -\mathrm{tr}\left\{ \widehat{\mathbf{W}}_{i_j^d} \widehat{\mathbf{E}}_{i_j^d} \right\} + \log_2 \left| \ln 2 \widehat{\mathbf{W}}_{i_j^d} \right| + \frac{d_{i_j^d}}{\ln 2} \\
& + \lambda_c \Bigg[\sum_{j=1}^{G} \sum_{i=1}^{K_j^u} \left(\mathbf{H}_{r,i_j^u} \left(\widehat{\mathbf{V}}_{i_j^u} \widehat{\mathbf{V}}_{i_j^u}^H + \kappa_U \mathrm{diag}\left(\widehat{\mathbf{V}}_{i_j^u} \widehat{\mathbf{V}}_{i_j^u}^H \right) \right) \mathbf{H}_{r,i_j^u}^H \right) + \sum_{j=1}^{G} \sum_{i=1}^{K_j^d} \mathbf{H}_{r,j} \left(\widehat{\mathbf{V}}_{i_j^d} \widehat{\mathbf{V}}_{i_j^d}^H \right) \mathbf{H}_{r,j}^H \\
& + \kappa_B \mathbf{H}_{r,j}^H \mathrm{diag}\left(\widehat{\mathbf{V}}_{i_j^d} \widehat{\mathbf{V}}_{i_j^d}^H \right) \mathbf{H}_{r,j}^H - I_{\min} \Bigg] + \sum_{j=1}^{G} \sum_{i=1}^{K_j^d} \mu_{i_j^d} \left(\mathrm{tr}\left(\widehat{\mathbf{V}}_{i_j^d} \widehat{\mathbf{V}}_{i_j^d}^H \right) - P_{i_j^d} \right) \\
& + \sum_{j=1}^{G} \sum_{i=1}^{K_j^u} \mu_{i_j^u} \left(\mathrm{tr}\left(\widehat{\mathbf{V}}_{i_j^u} \widehat{\mathbf{V}}_{i_j^u}^H \right) - P_{i_j^u} \right) \quad (36)
\end{aligned}$$

$$\begin{aligned}
\frac{\partial \widehat{\mathcal{L}}}{\partial \widehat{\mathbf{V}}_{k_g^u}} = & 2\mathbf{H}_{g,k_g^u}^H \widehat{\mathbf{U}}_{k_g^u}^H \widehat{\mathbf{W}}_{k_g^u} \widehat{\mathbf{U}}_{k_g^u} \mathbf{H}_{k_g^u} \mathbf{V}_{k_g^u} - 2\mathbf{H}_{g,k_g^u}^H \widehat{\mathbf{U}}_{k_g^u}^H \widehat{\mathbf{W}}_{k_g^u} + 2 \sum_{\substack{j=1 \\ (i,j \neq k,g)}}^{G} \sum_{i=1}^{K_j^u} \mathbf{H}_{g,i_j^u}^H \widehat{\mathbf{U}}_{i_j^u}^H \widehat{\mathbf{W}}_{i_j^u} \widehat{\mathbf{U}}_{i_j^u} \mathbf{H}_{g,i_j^u} \widehat{\mathbf{V}}_{k_g^u} \\
& + 2\kappa_U \sum_{j=1}^{G} \sum_{i=1}^{K_j^u} \mathrm{diag}\left(\mathbf{H}_{g,i_j^u}^H \widehat{\mathbf{U}}_{i_j^u}^H \widehat{\mathbf{W}}_{i_j^u} \widehat{\mathbf{U}}_{i_j^u} \mathbf{H}_{g,i_j^u} \right) \widehat{\mathbf{V}}_{k_g^u} + 2\beta_B \sum_{j=1}^{G} \sum_{i=1}^{K_j^u} \mathbf{H}_{g,i_j^u}^H \mathrm{diag}\left(\widehat{\mathbf{U}}_{i_j^u}^H \mathbf{W}_{i_j^u} \widehat{\mathbf{U}}_{i_j^u} \right) \mathbf{H}_{g,i_j^u} \widehat{\mathbf{V}}_{k_g^u} \\
& + 2\lambda_c \sum_{j=1}^{G} \sum_{i=1}^{K_j^u} \mathbf{H}_{r,i_j^u}^H \mathbf{H}_{r,i_j^u} \widehat{\mathbf{V}}_{k_g^u} + 2\,\lambda_c \kappa_U \sum_{j=1}^{G} \sum_{i=1}^{K_j^u} \mathrm{diag}\left(\mathbf{H}_{r,i_j^u}^H \mathbf{H}_{r,i_j^u} \right) \widehat{\mathbf{V}}_{k_g^u} + 2\mu_{k_g^u} \widehat{\mathbf{V}}_{k_g^u} \quad (37)
\end{aligned}$$

$$\begin{aligned}
\widehat{\mathbf{F}}_{k_g^u} = & \mathbf{H}_{g,k_g^u}^H \widehat{\mathbf{U}}_{k_g^u}^H \widehat{\mathbf{W}}_{k_g^u} \widehat{\mathbf{U}}_{k_g^u} \mathbf{H}_{k_g^u} + \sum_{\substack{j=1 \\ (i,j \neq k,g)}}^{G} \sum_{i=1}^{K_j^u} \mathbf{H}_{g,i_j^u}^H \widehat{\mathbf{U}}_{i_j^u}^H \widehat{\mathbf{W}}_{i_j^u} \widehat{\mathbf{U}}_{i_j^u} \mathbf{H}_{g,i_j^u} + \kappa_U \sum_{j=1}^{G} \sum_{i=1}^{K_j^u} \mathrm{diag}\left(\mathbf{H}_{g,i_j^u}^H \widehat{\mathbf{U}}_{i_j^u}^H \widehat{\mathbf{W}}_{i_j^u} \widehat{\mathbf{U}}_{i_j^u} \mathbf{H}_{g,i_j^u} \right) \\
& + \beta_B \sum_{j=1}^{G} \sum_{i=1}^{K_j^u} \mathbf{H}_{g,i_j^u}^H \mathrm{diag}\left(\widehat{\mathbf{U}}_{i_j^u}^H \widehat{\mathbf{W}}_{i_j^u} \widehat{\mathbf{U}}_{i_j^u} \right) \mathbf{H}_{g,i_j^u} + \lambda_c \sum_{j=1}^{G} \sum_{i=1}^{K_j^u} \mathbf{H}_{r,i_j^u}^H \mathbf{H}_{r,i_j^u} + \lambda_c \kappa_U \sum_{j=1}^{G} \sum_{i=1}^{K_j^u} \mathrm{diag}\left(\mathbf{H}_{r,i_j^u}^H \mathbf{H}_{r,i_j^u} \right) \quad (39)
\end{aligned}$$

$$\begin{aligned}
\widehat{\mathbf{F}}_{k_g^d} = & \mathbf{H}_{k_g^d,g}^H \widehat{\mathbf{U}}_{k_g^d}^H \widehat{\mathbf{W}}_{k_g^d} \widehat{\mathbf{U}}_{k_g^d} \mathbf{H}_{k_g^d,g} + \sum_{\substack{j=1 \\ (i,j \neq k,g)}}^{G} \sum_{i=1}^{K_j^d} \mathbf{H}_{k_g^d,j}^H \widehat{\mathbf{U}}_{i_j^d}^H \widehat{\mathbf{W}}_{i_j^d} \widehat{\mathbf{U}}_{i_j^d} \mathbf{H}_{k_g^d,j} + \kappa_B \sum_{j=1}^{G} \sum_{i=1}^{K_j^d} \mathrm{diag}\left(\mathbf{H}_{k_g^d,j}^H \widehat{\mathbf{U}}_{i_j^d}^H \widehat{\mathbf{W}}_{i_j^d} \widehat{\mathbf{U}}_{i_j^d} \mathbf{H}_{k_g^d,j} \right) \\
& + \beta_U \sum_{j=1}^{G} \sum_{i=1}^{K_j^d} \mathbf{H}_{k_g^d,j}^H \mathrm{diag}\left(\widehat{\mathbf{U}}_{i_j^d}^H \widehat{\mathbf{W}}_{i_j^d} \widehat{\mathbf{U}}_{i_j^d} \right) \mathbf{H}_{k_g^d,j} + \lambda_c \sum_{j=1}^{G} \sum_{i=1}^{K_j^d} \left[\mathbf{H}_{r,i_j^d} \mathbf{H}_{r,i_j^d}^H + \kappa_B \mathrm{diag}\left(\mathbf{H}_{r,i_j^d} \mathbf{H}_{r,i_j^d}^H \right) \right] \quad (41)
\end{aligned}$$

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