Multi-cell Coordinated Joint Sensing and Communications

Nithin Babu and Christos Masouros

***Abstract*—This paper proposes block-level precoder (BLP) designs for a multi-input single-output (MISO) system that performs joint sensing and communication across multiple cells and users. The Cramer-Rao-Bound for estimating a target's azimuth angle is determined for coordinated beamforming (CBF) and coordinated multi-point (CoMP) scenarios while considering inter-cell communication and sensing links. The formulated optimization problems to minimize the CRB and maximize the minimum-signal-to-interference-plus-noise-ratio (SINR) are non-convex and are represented in the semidefinite relaxed (SDR) form to solve using an alternate optimization algorithm. The proposed solutions show improved performance compared to the baseline scenario that neglects the signal component from neighboring cells.**

***Index Terms*—Integrated Sensing and Communication, Cramer-Rao bound, CoMP, CBF**

I. Introduction

A common property to realize the next-generation wireless network's location-based services, such as connected vehicles and remote healthcare, is the communication network possessing radio sensing capability. A high-resolution sensing requires large bandwidth and multiple antennas, which are expected to be a part of the 5G advanced and 6G networks. Moreover, the high path loss in the proposed higher-frequency bands reduces the coverage area, demanding small-cell deployments that increase the chances of line-of-sight (LoS) links to the users/targets. Hence, the next-generation mobile communication network, hereafter referred to as an Integrated Sensing and Communication (ISAC) system, has the potential to do radio frequency (RF) sensing in addition to serving the users.

The idea of an ISAC system has gained much attention lately from academia [1] and industry [2]. The main challenge in realizing an ISAC system is designing an optimal waveform tailored to both the sensing and communication performance matrices. Numerous works realize an ISAC system by incorporating communication (radar) information into the existing radar (communication) waveforms [3], [4]. Another approach in designing ISAC waveform is to minimize the error with some ideal radar waveform that guarantees a good estimation performance while guaranteeing a set of communication-related constraints [5]. Since such solutions depend on the availability of the ideal radar waveform, the authors of [6] proposed optimal waveforms for point and extended targets that minimize the Cramer-Rao Bound (CRB) while guaranteeing a minimum level of signal-to-interference-plus-noise ratio (SINR) for each user. Other metrics that have been optimized in the context of an ISAC system include SINR, Mutual information (MI), Energy Efficiency, etc. SINR-based optimization takes the SINR of the radar/communication receivers as the primary objective or constraint. The authors of [7] design the radar transmit precoder, the radar subsampling scheme, and the communication transmit covariance matrix to maximize the radar SINR while meeting given communication rate and power constraints. A weighted sum of communication and radar MI maximization is presented in [8]. The work in [9] proposes optimum power allocation schemes to maximize the sum-rate and energy efficiency of an ISAC system while satisfying certain radar target detection and minimum data rate per user requirements.

All the aforementioned works consider a single-cell ISAC system with single/multiple targets and single/multiple users. In practise, there will be more than one ISAC base station (BS) close to each other due to the dense deployment of small cell BSs. This will cause inter-cell interference to the communication users from the neighboring BSs. Additionally, inter-cell reflection (ICR) will be received by a BS from its target due to the signal transmitted from the neighboring BSs. The received power through ICR can degrade the target parameter estimation if the BS is unaware of the data transmitted from the neighboring BS. Conversely, the BSs can coordinate by sharing the data to improve the estimation performance. In this paper, we consider a multi-cell ISAC system and design precoders that minimize the CRB in target angle estimation and maximize the minimum SINR received by users, subject to total power constraint.

II. System Model

We consider a multi-input single-output (MISO) system with J cells and K users per cell; each cell has a target and a BS with a uniform linear array (ULA) of N_t transmit antennas spaced at $\lambda/2$ distance, where λ is the wavelength. The BS is also equipped with a N_r-element receive ULA with a sparse spacing of $N_\mathrm{t}\lambda/2$ antennas. The m^{th} BS transmits a narrowband signal matrix, $\mathbf{X}_m \in \mathcal{C}^{N_\mathrm{t}\times L}$, to the users in the cell, with $L > N_\mathrm{t}$ being the length of the radar pulse/ communication frame. Here, all BSs transmit simultaneously, and a BS receives its echo signal and multiple echo signals from its target due to ICR from the neighboring BSs. As shown in the figure, we select the dominant path among the ICR paths. The resulting echo signal received by the m^{th} BS from the target in its cell is given as

$$\mathbf{Y}_m^{\mathrm{R}} = \mathbf{G}_{mm}\mathbf{X}_m + \sum_{n\neq m}^{J} \mathbf{G}_{nm}\mathbf{X}_n + \mathbf{Z}_m^{\mathrm{R}}, \quad \forall m, \tag{1}$$

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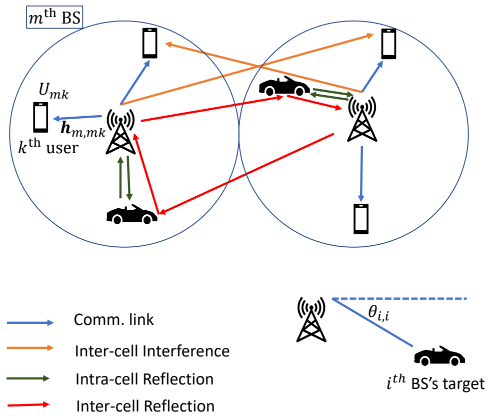

Fig. 1: System setup.

where $\mathbf{G}_{nm} = \alpha_{nm}\mathbf{a}_{mm}\mathbf{v}_{nm}^{\mathrm{T}}\, \forall n = \{1,2,..,J\} \equiv \mathcal{J}$, is the target response matrix at the m^{th} BS due to the transmission from the n^{th} BS in which $\mathbf{a}_{m,m}$ and $\mathbf{v}_{nm}$ are the array response vectors in the directions θ_{mm} and θ_{nm}, respectively, and $()^{\mathrm{T}}$ represents the transpose operation. $\alpha_{n,m}$ represents the complex amplitude of the received signal and $\mathbf{Z}_m^{\mathrm{R}} \in \mathbb{C}^{N_{\mathrm{r}}\times L}$ is an additive white Gaussian noise (AWGN) vector with the variance of each entry being σ_{R}^2. (1) assumes that all the neighboring BSs have a LoS link to the m^{th} BS's target. The transmitted symbol matrix $\mathbf{X}_m = \mathbf{W}_m\mathbf{S}_m$, where $\mathbf{W}_m = [\mathbf{w}_{m1}, \mathbf{w}_{m2}, ..., \mathbf{w}_{mK}]$ for $m \in \{1,2,..,J\}$ are the dual-functional beamforming matrices to be designed. $\mathbf{S}_m \in \mathcal{C}^{K\times L}$ is the orthogonal data stream transmitted to K users of the m^{th} BS: $(1/L)\mathbf{S}_m\mathbf{S}_m^H = \mathbf{I}_K$. The first term on the right-hand side (RHS) of (1) is called intra-cell reflection due to the signal vector from the same BS, whereas the second term represents ICR due to the signals from the remaining BSs.

The received signal at k^{th} user of the m^{th} cell, represented as U_{mk}, is expressed as

$$\mathbf{y}_{mk}^{\mathrm{C}} = \mathbf{h}_{m,mk}^T\mathbf{X}_m + \sum_{n\neq m}^{J} \mathbf{h}_{n,mk}^T\mathbf{X}_n + \mathbf{z}_{mk}^{\mathrm{C}},\ \forall U_{mk}, \tag{2}$$

where $\mathbf{h}_{n,mk} \in \mathbb{C}^{N_{\mathrm{t}}\times 1}$ is the channel from the n^{th} BS to $U_{m,k}$ and $\mathbf{z}_{mk}^{\mathrm{C}}$ is an AWGN noise vector with variance of each entry being σ_{C}^2. The first term in the RHS of (2) contains intra-cell interference from the users of the same cell, whereas the second term represents the inter-cell interference from the neighboring cells.

As explained in [10], a multi-cell system can work either in (a) coordinated beamforming (CBF) mode: each BS has a disjoint set of users to serve with data but selects transmit strategies jointly with all other BSs to reduce inter-cell interference, or (b) coordinated multipoint (CoMP) mode in which all the BSs can serve and coordinate interference to all users. In the following section, we consider the CBF and CoMP modes of BS operations to design an efficient precoder that maximizes both the sensing and communication performances.

A. Sensing and Communication Performance Metrics

We aim to minimize the variance of the error in target parameter estimation. For an unbiased estimator, the error variance is lower bound by the CRB given by the inverse of the Fisher information matrix. We assume each BS estimates its target's angle $\theta_{m,m}$ from the received signal (1). From (1), the received echo signal at the BS is a multi-variate Gaussian random variable with mean $\mu_{m,*}$ and covariance matrix $\mathbf{C}_{m,*}$. Then the $(m,m)^{\text{th}}$ element of the Fisher information matrix (FIM) is given by,

$$\mathrm{F}_{mm} = 2\,\mathrm{Re}\left\{\mathrm{tr}\left(\frac{d\mu_{m,*}^H}{d\theta_{mm}}\mathbf{C}_{m,*}^{-1}\frac{d\mu_{m,*}}{d\theta_{mm}}\right)\right\}. \tag{3}$$

Since we consider only one target parameter estimation per BS, the FIM will be a scalar value given by (3). The entries of the $\mu_{m,*}$ and $\mathbf{C}_{m,*}$ depend on whether the BSs are operating in the CBF or the CoMP mode, whose corresponding expressions are derived in the following sections.

In the communication aspect, we aim to maximize the minimum signal-to-interference-plus-noise-ratio (SINR) value experienced by a user in a cell. Again, the corresponding SINR expressions vary depending on the BSs' operation mode.

B. Coordinated Beamforming

In CBF, as no data is shared between the BSs, the m^{th} BS knows only the data symbol matrix $\mathbf{X}_m$. Therefore, from (1), $\boldsymbol{\mu}_{m,\text{cbf}} = \mathbf{G}_{m,m}\mathbf{X}_m$ and

$$\mathbf{C}_{m,\text{cbf}} = L\sum_{n\neq m}^{J}\mathbf{G}_{n,m}\mathbf{W}_m\mathbf{W}_m^H\mathbf{G}_{n,m}^H + \sigma_{\mathrm{R}}^2\mathbf{I}_{N_r} \tag{4}$$

Using the definitions of $\mathbf{G}_{m,m}$, we have,

$$\begin{aligned}
&\frac{1}{L\alpha_{mm}^2}\mathrm{tr}\left(\frac{d\boldsymbol{\mu}_{m,\text{cbf}}^H}{d\theta_{mm}}\mathbf{C}_{m,\text{cbf}}^{-1}\frac{d\boldsymbol{\mu}_{m,\text{cbf}}}{d\theta_{mm}}\right)\\
&= (\dot{\mathbf{a}}_{mm}^H\mathbf{C}_{m,\text{cbf}}^{-1}\dot{\mathbf{a}}_{mm}) \circ (\mathbf{v}_{mm}^H\mathbf{R}_{\mathbf{X}_m}^*\mathbf{v}_{mm})\\
&+ (\dot{\mathbf{a}}_{mm}^H\mathbf{C}_{m,\text{cbf}}^{-1}\mathbf{a}_{mm}) \circ (\mathbf{v}_{mm}^H\mathbf{R}_{\mathbf{X}_m}^*\dot{\mathbf{v}}_{mm})\\
&+ (\mathbf{a}_{mm}^H\mathbf{C}_{m,\text{cbf}}^{-1}\dot{\mathbf{a}}_{mm}) \circ (\dot{\mathbf{v}}_{mm}^H\mathbf{R}_{\mathbf{X}_m}^*\mathbf{v}_{mm})\\
&+ (\mathbf{a}_{mm}^H\mathbf{C}_{m,\text{cbf}}^{-1}\mathbf{a}_{mm}) \circ (\dot{\mathbf{v}}_{mm}^H\mathbf{R}_{\mathbf{X}_m}^*\dot{\mathbf{v}}_{mm})
\end{aligned} \tag{5}$$

where $\mathbf{R}_{\mathbf{X}_m} = \mathbf{W}_m\mathbf{W}_m^H = \sum_{k=1}^K \mathbf{w}_{mk}\mathbf{w}_{mk}^H = \sum_{k=1}^K \mathbf{W}_{mk}$, and $()^*$ represents the conjugate of the operand. Since we aim to estimate one target parameter per BS, minimizing the CRB is the same as maximizing the Fisher information value $\mathrm{FIM}_{mm}^{\text{cbf}}$ obtained by substituting (5) in (3). Hence, in the CBF mode, for the m^{th} BS, We aim to solve the following optimization problem:

$$\text{(P1)}:\underset{\{\mathbf{w}_{mk}\},\gamma}{\text{maximize}}\ \frac{u}{\mathrm{NF}_{\mathrm{R}}}\,\mathrm{FIM}_{mm}^{\text{cbf}} + \frac{(1-u)}{\mathrm{NF}_{\mathrm{C}}}\gamma$$

$$\frac{|\mathbf{h}_{m,mk}^T\mathbf{w}_{mk}|^2}{\sum_{l\neq k}^K|\mathbf{h}_{m,mk}^T\mathbf{w}_{ml}|^2 + \sum_{n\neq m}^J\sum_{l=1}^K|\mathbf{h}_{n,mk}^T\mathbf{w}_{nl}|^2 + \sigma_{\mathrm{C}}^2} \geq \gamma \tag{6}$$

$$\sum_{k=1}^K \mathrm{tr}\left(\mathbf{w}_{mk}\mathbf{w}_{mk}^H\right) \leq P_t, \tag{7}$$

where u is the weighting factor to select between the communication and the sensing performance matrices; NF_{R} and NF_{C}

are the normalization factors which are obtained by setting $u = 1$ and $u = 0$, respectively. The objective function of (P1) is the maximization (minimization) of the FIM (CRB) and the minimum SINR value among the users of the m^{th} cell. (6) is the SINR constraint whereas, (7) is the total power constraint with P_t being the total available power at the BS. (P1) is difficult to solve because of the non-convex form of $\mathbf{C}_{m,\text{cbf}}$ in (3) and the non-convex multiplication between γ and the interference terms in (6). Using the semidefinite relaxation (SDR) technique, the SINR constraint can be rewritten as,

$$\operatorname{tr}(\mathbf{Q}_{m,mk}\mathbf{W}_{mk}) - \gamma\left(\sum_{l\neq k}^{K}\operatorname{tr}(\mathbf{Q}_{m,mk}\mathbf{W}_{ml})\right) - \gamma\left(\sum_{n\neq m}^{J}\sum_{l=1}^{K}\operatorname{tr}(\mathbf{Q}_{n,mk}\mathbf{W}_{nl})\right) \geq \gamma\sigma_R^2 \ \forall U_{mk}, \tag{8}$$

where $\mathbf{Q}_{m,mk} = \mathbf{h}^*_{m,mk}\mathbf{h}^T_{m,mk}$ and $\mathbf{W}_{ml} = \mathbf{w}_{ml}\mathbf{w}^H_{ml}$. (P1) can be reformulated as,

$$\text{(P1.1):}\underset{\{\mathbf{W}_{mk}\},\gamma}{\text{maximize}} \ \frac{u}{\text{NF}_\text{R}}\,\text{FIM}^{\text{cbf}}_{mm} + \frac{(1-u)}{\text{NF}_\text{C}}\gamma,$$

$$(8), \tag{9}$$

$$\sum_{k=1}^{K}\operatorname{tr}(\mathbf{W}_{mk}) \leq P_t. \tag{10}$$

A workaround to the non-convex SINR constraint is to rewrite it as signal leakage constraints:

$$\sum_{l=1}^{K}\operatorname{tr}(\mathbf{Q}_{m,nk}\mathbf{W}_{ml}) \leq I_{\max}/(J-1) \ \forall U_{n,k} \ \forall n \neq m, \tag{11}$$

$$\sum_{l\neq k}^{K}\operatorname{tr}(\mathbf{Q}_{m,mk}\mathbf{W}_{ml}) \leq I'_{\max} \ \forall U_{m,k}, \tag{12}$$

$$\operatorname{tr}(\mathbf{Q}_{m,mk}\mathbf{W}_{mk}) - \gamma\left(I'_{\max} + I_{\max}\right) \geq \gamma\sigma_R^2 \ \forall U_{mk}. \tag{13}$$

(11) limits the total inter-cell interference experienced by any user to be less than $I_{\max}$ whereas the intracell interference caused is constrained below $I'_{\max}$. Please note that for given $I_{\max}$ and $I'_{\max}$ values, (11)-(13) are all convex constraints of the optimization variable of (P1.1). We tackle the non-convex objective function using an alternating optimization algorithm. In the i^{th} iteration of the algorithm, we solve the following two optimization problems alternatively.

For given $I_{i-1,\max}$, $I'_{i-1,\max}$, $\{\mathbf{W}^{i-1,}_{mk}\}$,

$$\text{(P1.1.A):}\underset{\{\mathbf{W}^i_{mk}\},\gamma}{\text{maximize}} \ \frac{u}{\text{NF}_\text{R}}\,\text{FIM}^{\text{cbf}}_{mm} + \frac{(1-u)}{\text{NF}_\text{C}}\gamma$$

$$(10)-(13), \tag{14}$$

$$\text{rank}(\mathbf{W}^i_{mk}) = 1;\ \mathbf{W}^i_{mk} \geq \mathbf{0} \quad \forall U_{mk} \tag{15}$$

and for an obtained solution of (P1.1.A): γ^* and $\text{FIM}^{*^{\text{cbf}}}_{mm}$,

$$\text{(P1.1.B):}\underset{\{\mathbf{W}^i_{mk}\},I_{\max},I'_{i,\max}}{\text{minimize}} \quad I_{i,\max} + I'_{i,\max}$$

$$\text{FIM}^{\text{cbf}}_{mm} \geq \text{FIM}^{*^{\text{cbf}}}_{mm} \quad \forall m \tag{16}$$

$$\operatorname{tr}\left(\mathbf{Q}_{m,mk}\mathbf{W}^i_{mk}\right) - \gamma^*\left(I'_{i,\max} + I_{i,\max}\right) \geq \gamma^*\sigma_R^2 \ \forall U_{mk}, \tag{17}$$

$$(10)-(12),(15). \tag{18}$$

In the i^{th} iteration, $\mathbf{C}_{m,\text{cbf}}$ is estimated using $\mathbf{W}^{i-1}_{mk}$. This makes the objective function an affine function of $\mathbf{R}_{x_m} = \sum_{k=1}^{K}\mathbf{W}_{mk}$. (P1.1.A) maximizes the weighted combination of the sensing and communication performance metrics for a given inter-cell and intra-cell interference values, whereas (P1.1.B) minimizes the interference values while guaranteeing given sensing and communication performance. Omitting the rank constraint, (P1.1.A) and (P1.1.B) are convex optimization problems solved using MATLAB's CVX solver. The overall procedure is given in Algorithm 1. We can obtain $\mathbf{w}_{m,k}$ from

Algorithm 1: CBF: precoder design

1 **Input**: u, $\{\mathbf{h}_{m,nk}\}$, $\{\mathbf{G}_{mn}\}$, $I_{0,\max}$, $I'_{0,\max}$,$\{\mathbf{W}^0_{mk}\}$, $i = 0$
2 **while** *no convergence* **do**
3 Determine $\mathbf{C}_{m,\text{cbf}}$ using $\{\mathbf{W}^i_{mk}\}$
4 $i = i + 1$
5 Solve (P1.1.A) for each BS: γ^* and $\{\text{FIM}^{*^{\text{cbf}}}_{mm}\}$
6 Solve (P1.1.B) to obtain $I_{i,\max}$, $I'_{i,\max}$,$\{\mathbf{W}^i_{mk}\}$
7 **Output**:$\{\mathbf{W}^i_{mk}\}$.

$\mathbf{W}^i_{mk}$ using Eigen value decomposition technique if the rank of $\mathbf{W}^i_{mk} > 1$

C. Coordinated Multi-point

In a CoMP scenario, the data transmitted to a user is shared among the BSs. Let $\mathbf{X} = [\mathbf{X}_1;\mathbf{X}_2,...;\mathbf{X}_J] \in \mathcal{C}^{N\times L}$ be the concatenated symbol matrix available at each BS with $N = JN_\text{t}$; $\mathbf{D}_m = \text{diag}(\mathbf{0}_{N_\text{t}},..,\mathbf{I}_{N_\text{t}},..,\mathbf{0}_{N_\text{t}}) \in \mathcal{C}^{N\times N}$; $\mathbf{v}'_{mm} = \{\vec{0}_{N_\text{t}},..,\mathbf{v}_{m,m},..,\vec{0}_{N_\text{t}}\} \in \mathcal{C}^{N\times 1}$. Since each BS knows the transmitted symbol matrix of the other BSs, the ICR of (1) aids the target's angle estimation. Consequently, the received echo at the m^{th} BS is a multi-variate Gaussian random variable with mean $\boldsymbol{\mu}_{m,\text{cmp}} = \mathbf{G}'_{m,m}\mathbf{D}_m\mathbf{X} + \sum_{n\neq m}^{J}\mathbf{G}'_{n,m}\mathbf{D}_n\mathbf{X}$ where $\mathbf{G}'_{n,m} = \alpha_{n,m}\mathbf{a}_{m,m}\mathbf{v}'^{\text{T}}_{nm}$ and the covariance matrix $\mathbf{C}_{m,\text{cmp}} = \sigma^2_\text{R}\mathbf{I}_{N_\text{r}}$.

As an indicative example, let us take the case with $J = 2$. Adapting the CRB derivation from [11] to the CoMP case, for $m,n \in \{1,2\}$ and $m \neq n$, we get,

$$\begin{aligned}
&\operatorname{tr}\left\{\frac{d\boldsymbol{\mu}_{\boldsymbol{m},\text{CoMP}}}{d\theta_{mm}}^H\mathbf{C}^{-1}_{m,\text{cmp}}\frac{d\boldsymbol{\mu}_{\boldsymbol{m},\text{CoMP}}}{d\theta_{mm}}\right\} \\
&= L\alpha^2_{m,m}(\dot{\mathbf{a}}^H_{mm}\mathbf{C}^{-1}_{m,\text{cmp}}\dot{\mathbf{a}}_{mm}) \circ (\mathbf{v}'^H_{mm}\mathbf{D}_m\mathbf{R}^*_\mathbf{X}\mathbf{D}^H_m\mathbf{v}'_{mm}) \\
&+ L\alpha^2_{mm}(\dot{\mathbf{a}}^H_{mm}\mathbf{C}^{-1}_{m,\text{cmp}}\mathbf{a}_{mm}) \circ (\mathbf{v}'^H_{mm}\mathbf{D}_m\mathbf{R}^*_\mathbf{X}\mathbf{D}^H_m\dot{\mathbf{v}}'_{mm}) \\
&+ L\alpha^2_{mm}(\mathbf{a}^H_{mm}\mathbf{C}^{-1}_{m,\text{cmp}}\dot{\mathbf{a}}_{mm}) \circ (\dot{\mathbf{v}}'^H_{mm}\mathbf{D}_m\mathbf{R}^*_\mathbf{X}\mathbf{D}^H_m\mathbf{v}'_{mm}) \\
&+ L\alpha^2_{mm}(\mathbf{a}^H_{mm}\mathbf{C}^{-1}_{m,\text{cmp}}\mathbf{a}_{mm}) \circ (\dot{\mathbf{v}}'^H_{mm}\mathbf{D}_m\mathbf{R}^*_\mathbf{X}\mathbf{D}^H_m\dot{\mathbf{v}}'_{mm}) \\
&+ L\alpha_{nm}\alpha_{mm}(\dot{\mathbf{a}}^H_{mm}\mathbf{C}^{-1}_{m,\text{cmp}}\dot{\mathbf{a}}_{mm}) \circ (\mathbf{v}'^H_{nm}\mathbf{D}_n\mathbf{R}^*_\mathbf{X}\mathbf{D}^H_m\mathbf{v}'_{mm}) \\
&+ L\alpha_{nm}\alpha_{mm}(\mathbf{a}^H_{mm}\mathbf{C}^{-1}_{m,\text{cmp}}\dot{\mathbf{a}}_{mm}) \circ (\mathbf{v}'^H_{nm}\mathbf{D}_n\mathbf{R}^*_\mathbf{X}\mathbf{D}^H_m\dot{\mathbf{v}}'_{mm}) \\
&+ L\alpha_{nm}\alpha_{mm}(\dot{\mathbf{a}}^H_{mm}\mathbf{C}^{-1}_{m,\text{cmp}}\dot{\mathbf{a}}_{mm}) \circ (\mathbf{v}'^H_{mm}\mathbf{D}_m\mathbf{R}^*_\mathbf{X}\mathbf{D}^H_n\mathbf{v}'_{nm}) \\
&+ L\alpha_{nm}\alpha_{mm}(\mathbf{a}^H_{mm}\mathbf{C}^{-1}_{m,\text{cmp}}\dot{\mathbf{a}}_{mm}) \circ (\dot{\mathbf{v}}'^H_{mm}\mathbf{D}_m\mathbf{R}^*_\mathbf{X}\mathbf{D}^H_n\mathbf{v}'_{nm}) \\
&+ L\alpha_{nm}\alpha_{mm}(\dot{\mathbf{a}}^H_{mm}\mathbf{C}^{-1}_{m,\text{cmp}}\dot{\mathbf{a}}_{mm}) \circ (\mathbf{v}'^H_{nm}\mathbf{D}_n\mathbf{R}^*_\mathbf{X}\mathbf{D}^H_n\mathbf{v}'_{nm}).
\end{aligned} \tag{19}$$

The FIM values for the two BSs, $\text{FIM}_{mm}^{\text{comp}}$, can be obtained by substituting (19) in (3). Please note that, as in the CBF case, (19) assumes that each BS only estimates its target's angle. Let $\mathbf{h}_k \in \mathcal{C}^{N\times 1}$ be the channel vector from all the BSs to the k^{th} user where $k = \{1, 2, ..., 2K\}$. The corresponding optimization problem in the CoMP scenario can be formulated as,

$$\text{(P2):}\underset{\{\mathbf{W}_k\},\eta,\gamma}{\text{maximize}} \;\; u\, f + (1-u)\gamma,$$

$$\text{FIM}_{mm}^{\text{comp}} \geq f, \quad \forall m, \tag{20}$$

$$\frac{|\mathbf{h}_k^T \mathbf{w}_k|^2}{\sum_{l\neq k}^{2K} |\mathbf{h}_k^T \mathbf{w}_l|^2 + \sigma_{\text{C}}^2} \geq \gamma, \;\; \forall k, \tag{21}$$

$$\sum_{k=1}^{K} \text{tr}\left(\mathbf{D}_m \mathbf{w}_k \mathbf{w}_k^H \mathbf{D}_m^H\right) \leq P_t, \forall m. \tag{22}$$

The objective function of (P2) is to maximize the weighted combination of the minimum FIM and SINR values. (21) and (22) are the SINR and per-BS power constraints, respectively. Using the SDR technique (P2) is reformulated as

$$\text{(P2.1):}\underset{\{\mathbf{W}_k\},f,\gamma}{\text{maximize}} \;\; u\, f + (1-u)\gamma,$$

$$\text{FIM}_{m,m}^{\text{comp}} \geq f, \quad \forall m, \tag{23}$$

$$\text{tr}\left(\mathbf{Q}_k \mathbf{W}_k\right) - \gamma\left(\sum_{l\neq k}^{2K} \text{tr}\left(\mathbf{Q}_k \mathbf{W}_l\right)\right) \geq \gamma\sigma_{\text{C}}^2, \;\; \forall k, \tag{24}$$

$$\sum_{k=1}^{K} \text{tr}\left(\mathbf{D}_m \mathbf{W}_k \mathbf{D}_m^H\right) \leq P_t, \tag{25}$$

$$\mathbf{W}_k \succeq \mathbf{0}\, \forall k, m, \; \text{rank}(\mathbf{W}_k) = 1. \tag{26}$$

where $\mathbf{Q}_k = \mathbf{h}_k \mathbf{h}_k^H \in \mathcal{C}^{N\times N}$ and $\mathbf{W}_l = \mathbf{w}_l \mathbf{w}_l^H \in \mathcal{C}^{N\times N}$. Also, $\mathbf{R}_{\mathbf{X}} = \sum_{l=1}^{2K} \mathbf{w}_l \mathbf{w}_l^H$. The SINR constraint (24) makes (P2.1) a non-convex problem. We adopt a similar approach of CBF to resolve this issue; (24) can be rewritten as,

$$\sum_{l\neq k}^{2K} \text{tr}\left(\mathbf{Q}_k \mathbf{W}_l\right) \leq I_{\max}, \tag{27}$$

$$\text{tr}\left(\mathbf{Q}_k \mathbf{W}_k\right) - \gamma I_{\max} \geq \gamma\sigma_{\text{C}}^2 \;\forall k. \tag{28}$$

We alternatively solve the following two optimization problems until convergence to obtain the optimal precoding vectors. For a given $I_{\max}$,

$$\text{(P2.1.A):}\underset{\{\mathbf{W}_k\},f,\gamma}{\text{maximize}} \;\; u\, f + (1-u)\gamma$$

$$(23), (25) - (28) \tag{29}$$

For given f^* and γ^* values

$$\text{(P2.1.B):}\underset{\{\mathbf{W}_k\},I_{\max}}{\text{minimize}} \quad I_{\max}$$

$$\text{FIM}_{m,m}^{\text{comp}} \geq f^* \quad \forall m = \{1, 2\} \tag{30}$$

$$\text{tr}\left(\mathbf{Q}_k \mathbf{W}_k\right) - \gamma^* I_{\max} \geq \gamma\sigma_{\text{C}}^2 \;\forall k. \tag{31}$$

$$(25) - (27) \tag{32}$$

The overall precoder design procedure is similar to Algorithm 1 without step 3.

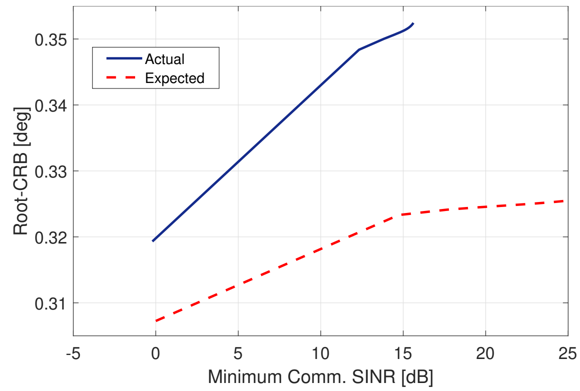

Fig. 2: RCRB performance gap if IC links are neglected, $N_t = 6$, $N_r = 4$.

III. Numerical Evaluation

In this section, we summarize our main findings through numerical evaluation. The simulation parameters are $J = 2$, $K = 3$, $P_t = 40$ dBm; the noise variances $\sigma_{\text{C}}^2 = \sigma_{\text{R}}^2 = 0$ dBm. The targets are located at $\theta_{11} = -50°$, $\theta_{12} = 60°$, $\theta_{22} = 50°$, $\theta_{21} = -60°$.

Fig. 2 shows that neglecting the ICR can decrease the target angle estimation accuracy. Here, we design the precoders of the two BSs independently, neglecting the ICR and interference from the neighboring BS. We estimate the expected and actual root-CRB (RCRB) values using the obtained solution by neglecting and considering the ICR. The performance gap increases more in the high minimum communication SINR regime since the target of the neighboring BS receives more ICR power. This emphasizes the need to consider the reflections from the neighboring BSs while designing the precoders that maximize both sensing and communication performances.

For a better understanding of the beampattern towards the users and the targets, for Fig. 3, we consider LoS channels between the users and the BSs with $N_{\text{t}} = 16$ and $N_{\text{r}} = 4$. The figure shows beampatterns plotted using the precoders obtained for CBF and CoMP using Algorithm 1. In the CoMP mode, the obtained solution radiates power in both the neighboring BS's target's and users' directions since it aids the communication and the sensing performances. Conversely, the CBF solution radiates relatively less power toward the neighboring BS's target and users to minimize interference. Fig. 4 compares the RCRB values obtained for the CBF and CoMP schemes for different numbers of antennas. As seen in the figure, for a given minimum communication SINR, the sensing performance in the CoMP mode outperforms the CBF mode performance because of the additional signal power received through the inter-cell reflection and communication links. The figure shows that in all the cases, the RCRB increases exponentially in the high-SINR regime for a given power budget since a major share of the available power is radiated toward the users to achieve the minimum communication SINR value. Moreover, the sensing performance degrades proportionally to the increase in the minimum communication SINR when the number of antennas is low. This is because the interference towards the users increases because of a

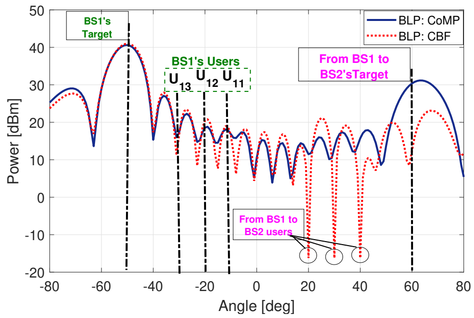

Fig. 3: Beampatterns for CBF and Comp, when γ = 30 dBm, N_{t} = 16, N_{t} = 4.

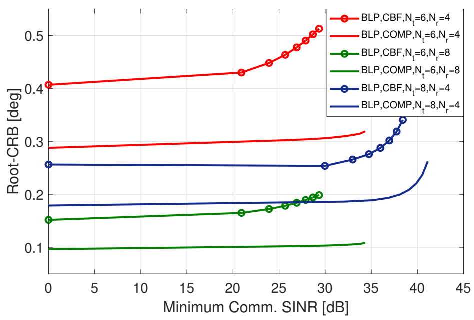

Fig. 4: RCRB Vs Minimum Communication SINR.

high beamwidth value, demanding more power to satisfy the minimum SINR constraint. When the number of antennas increases, the beamforming gain increases, thereby reducing the required power to achieve the communication performance. This keeps the sensing performance stable in the low-SINR regime. Hence, the CoMP mode with many antennas performs best but has an additional overhead of sharing the data and channel state information among the BSs.

IV. Conclusion

This paper considered the effect of inter-cell reflection (ICR) and interference while designing precoders for a multi-cell MISO ISAC system operating in coordinated beamforming (CBF) and coordinated multipoint (CoMP) modes. The considered problem maximizes a weighted combination of sensing and communication performances for a given power budget. The obtained solution suggests that neglecting the inter-cell (IC) links degrades the performance, and the performance can be improved by carefully utilizing the additional IC links.

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