Novel Solution for Multi-connectivity 5G-mmW Positioning

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***Abstract*—The forthcoming fifth generation (5G) systems with high beamforming gain antenna units, millimeter-wave (mmWave) frequency bands together with massive Multiple Input Multiple Output (MIMO) techniques are key components for accurate positioning methods. In this paper, we propose the positioning technique that is relying on the sparsity in the MIMO-OFDM channel in time and spatial domains, together with effective beamforming methods. We will study the proposed solution in a multi-connectivity context, which has been considered so far for the purpose of improving the user equipment (UE) communication data rate. We utilize the multi-connectivity for positioning, in order to improve robustness to measurement errors and increase positioning service continuity. In particular, we show that when a UE that has connectivity to more base stations, the total power and delay needed for positioning can be reduced.**

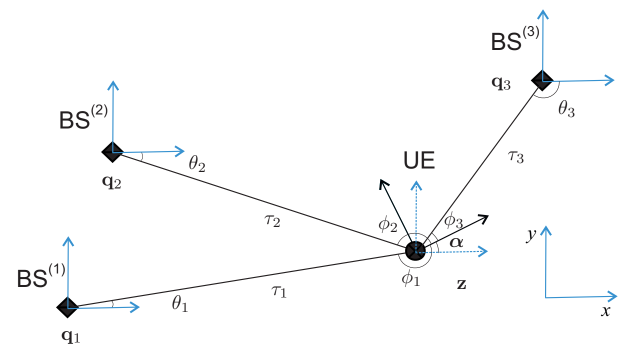

Fig. 1. Communication model showing 3 transmitters (gNB) at location $\mathbf{q_i}$ and receiver (UE) at location $\mathbf{z}$ with LOS delays denoted by τ_i and angles AoA ϕ_i, AoD θ_i, and the rotation α of the receiver.

I. Introduction

5G millimeter-wave (mmWave) signals are characterized by large bandwidths and will be sent and received over large arrays. Combined, this leads to high potential for distance and angle estimation [1]. Applications include vehicular positioning [2] and location-aided communications [3]. An important benefit of mmWave is the reduced requirements on anchor deployment, as localization is possible with only few [4] or even a single anchor [5].

A property of mmWave communication is the use of few radio frequency (RF) chains, relying on analog or hybrid precoders and combiners to establish a high-SNR link [6]. This implies that mmWave localization must account for this hardware limitation in the design of signals and algorithms. For instance, [7] derived the optimal beamforming solution for a given scenario that minimizes the Cramér Rao lower bound (CRLB) for a multicarrier mmWave system in terms of the CRLB characterizing angle-of-arrival (AoA) and delay estimation. In order to design signals to can cover a large angular uncertainty, [8] proposed a 5G mmWave user positioning method by means of beamformed downlink reference signals, while [9] formulated an optimization problem to optimize power allocation across subcarriers for a fixed a priori position uncertainty of the user, given a certain a posteriori requirement on the user uncertainty.

In this paper, we employ a similar formulation as [9] and [7], whereby we aim to find the optimal power allocation for different beam pairs in a multi base station (gNB) scenario. In particular, we are interested in gaining understanding in (i) to what extent it is beneficial to use more than one base station; (ii) how does the total allocated power vary based on the localization requirement, optimization criterion, and number of base stations; (iii) how do power and delay trade off when using more than one base station?

II. System Model

We consider a two-dimensional scenario with a single user (UE) and N_{bs} base stations (gNBs). The user's position and orientation[1], respectively denoted by $\mathbf{z} \in \mathbb{R}^2$ and α, are unknown and yet to be determined. Furthermore, each gNB as well as the user have multiple antennas for beamforming and for simplicity, a single radio frequency (RF) chain transceiver architecture is considered. More specifically, we denote the b-th gNB's location $\mathbf{q}_b$ and we shall assume that all gNBs' antenna comprises N elements, whereas UE's antenna has M elements.

[1]The orientation of the user is measured with respect to a global reference system.

At the time-slot n, the received signal at the UE is given by the superposition of N_{bs} orthogonal reference signals, *i.e.*,

$$y_n(t) = \sum_{b=1}^{N_{bs}} \sqrt{p_{nb}} h_b \mathbf{w}_{nb}^{\mathrm{H}} \mathbf{a}_M(\theta_b) \mathbf{a}_N^{\mathrm{H}}(\phi_b) \mathbf{f}_{nb} x_b(t-\tau_b) + \mathbf{w}_{nb}^{\mathrm{H}} \mathbf{n}_{nb}(t), \quad (1)$$

where $h_b \in \mathbb{C}$, τ_b ϕ_b and θ_b are the complex channel gain, path-delay, AoA and angle-of-departure (AoD) of the line-of-sight (LOS) link between the b-th gNB and the UE, $\mathbf{f}_{nb} \in \mathcal{C}_b$ and $\mathbf{w}_{nb} \in \mathcal{C}_u$ are the transmit-receive unit-norm beamforming pair used for (n,b)-th reference signal transmission; $\mathcal{C}_b \subset \mathbb{C}^N$ and $\mathcal{C}_u \subset \mathbb{C}^M$ are the codebook of the b-th gNB and UE, respectively. In addition, $\mathbf{n}_{nb}(t)$ is the Additive White Gaussian Noise (AWGN) with power spectral density (PSD) N_0, $x_b(t)$ is the reference signal transmitted by the b-th gNB with bandwidth B, duration T_{sym} and unit power, *i.e.*, $1/T_{\mathrm{sym}} \int_0^{T_{\mathrm{sym}}} |x(t)|^2 \mathrm{d}t = 1$. Finally, we denote by $\mathbf{a}_N(x) \in \mathbb{C}^N$ and $\mathbf{a}_M(x) \in \mathbb{C}^M$, the transmit and receive array response vectors of the gNB b and UE, respectively.

Positioning is performed by the joint processing of N_p transmissions, *i.e.*, based on the receiving vector $\mathbf{y}(t) \in \mathbb{C}^{N_p}$. The objective of this work is to develop an power-allocation strategy that minimizes the total transmit power (over all beam pairs and all gNBs) subject to a constraint of the user localization uncertainty. More specifically, our optimization problem is defined as follows:

$$\min_{\mathbf{P}} \quad \mathcal{P}(\mathbf{P}) \quad (2a)$$

$$\text{s.t.} \quad \text{positioning constraint} \quad (2b)$$

$$\mathbf{p}_b \succeq \mathbf{0} \ \forall b, \quad (2c)$$

where $\mathcal{P}$ is a power allocation cost function, $\mathbf{P} \triangleq [\mathbf{p}_1, \cdots, \mathbf{p}_{N_{bs}}]$, $\mathbf{p}_b \in \mathbb{R}^{N_p}$ is the beam-power allocation vector at the b-th gNB, and the positioning constraint ensures that good quality of positioning. This quality will be described through the Fisher information and the Cramér-Rao Lower Bound (CRLB), described next.

III. Optimization Formulation

A. FIM Definitions

In this section, we briefly describe the main FIM concepts. The FIM of $\boldsymbol{\eta}_b \triangleq [\tau_b, \theta_b, \phi_b, \Re(h_b), \Im(h_b)]$ is given by $\mathbf{J}(\boldsymbol{\eta}_b) \in \mathbb{R}^{5\times5}$ and the FIM of $\tilde{\boldsymbol{\eta}}_b \triangleq [\mathbf{z}^{\mathrm{T}}, \alpha, \Re(h_b), \Im(h_b)]$ as $\mathbf{J}(\tilde{\boldsymbol{\eta}}_b) \in \mathbb{R}^{5\times5}$ [5]. These are related by $\mathbf{J}(\tilde{\boldsymbol{\eta}}_b) = \mathbf{T}_b^{\mathrm{T}} \mathbf{J}(\boldsymbol{\eta}_b) \mathbf{T}_b$, where $\mathbf{T}_b \in \mathbf{R}^{5\times5}$ is $\mathbf{T}_b \triangleq (\partial \boldsymbol{\eta}_b^T)/(\partial \tilde{\boldsymbol{\eta}}_b)$. The Equivalent Fisher Information Matrix (EFIM) $\mathbf{J}_{e,b}(\mathbf{z}) \in \mathbb{R}^{2\times2}$ is defined as the inverse of the first 2×2 block of $\mathbf{J}_{\tilde{\boldsymbol{\eta}}_b}^{-1}$. The information from different gNBs is additive so that the total EFIM is

$$\mathbf{J}_e(\mathbf{z}) = \sum_{b=1}^{N_{bs}} \mathbf{J}_{e,b}(\mathbf{z}). \quad (3)$$

Additional information on the expressions of the FIM and EFIM can be found in [5], [10]. The inverse of the EFIM serves as a lower bound on the localization error covariance.

Remark 1. Note that FIMs $\mathbf{J}(\tilde{\boldsymbol{\eta}}_b)$ cannot be added since are defined over different parameters (individual h_b). Instead one can define a FIM over $\tilde{\boldsymbol{\eta}} \triangleq \left[\mathbf{z}^{\mathrm{T}}, \alpha, [\Re(h_b), \Im(h_b)]_{b=1}^{N_{bs}}\right] \in \mathbb{R}^{3+2N_{bs}}$.

B. FIM-constrained Optimization Problems

Given a selection of beams $\mathbf{f}_{nb}$ from gNB b and corresponding combiners $\mathbf{w}_{nb}$, then the FIM and EFIM are additive, i.e.,

$$\mathbf{J}_{e,b}(\mathbf{z}) = \sum_{\substack{\mathbf{w}_{nb} \in \mathcal{C}_u \\ \mathbf{f}_{nb} \in \mathcal{C}_b}} p_{bn} \mathbf{J}_{e,b}(\mathbf{w}_{nb}, \mathbf{f}_{nb}; \mathbf{z}), \quad (4)$$

in which we have explicitly extracted the power p_{bn}, so that $\mathbf{J}_{e,b}(\mathbf{w}_{nb}, \mathbf{f}_{nb}; \mathbf{z})$ should be interpreted as the EFIM of $\mathbf{z}$ given $\mathbf{w}_{nb}, \mathbf{f}_{nb}$ and unit power.

A meaningful optimization is then

$$\min_{\mathbf{p}} \quad \|\mathbf{p}\|_\alpha \quad (5a)$$

$$\text{s.t.} \quad \mathbf{J}_e^{-1}(\mathbf{z}) \preceq \frac{\gamma_e}{2} \mathbf{I}_2, \quad (5b)$$

$$\mathbf{p} \succeq \mathbf{0}, \quad (5c)$$

where $\|\cdot\|_\alpha$ denotes a ℓ_α matrix norm, $\mathbf{p} \in \mathbb{R}^{N_{bs}N_p}$ is the vectorized form of $\mathbf{P}$ and α can be $\{1, 2, \infty\}$. More specifically, $\alpha = 1$ is used to seek the minimum number of beams, $\alpha = 2$ is used to minimize the average power and $\alpha = \infty$ is used to minimize a constant power. Moreover, $\mathbf{J}_e(\mathbf{z})$ is given by (3) and (4). The constraint $\mathbf{J}_e^{-1}(\mathbf{z}) \preceq \gamma_e/2\mathbf{I}_2$ ensures that the location error variance is less than $\gamma_e/2$ in each dimension. We note that the widely used metric Position Error Bound (PEB) is given by $\sqrt{\gamma_e}$. We can express the optimization problem equivalently using a positive semi-definite matrix constraint as

$$\min_{\mathbf{p}} \quad \|\mathbf{p}\|_\alpha \quad (6a)$$

$$\text{s.t.} \quad \begin{bmatrix} \frac{\gamma_e}{2}\mathbf{I}_2 & \mathbf{I}_2 \\ \mathbf{I}_2 & \mathbf{J}_e(\mathbf{z}) \end{bmatrix} \succeq 0. \quad (6b)$$

$$\mathbf{p} \succeq \mathbf{0}, \quad (6c)$$

which is a convex optimization problem and thus amenable for efficient numerical solving. Note that additional constraints (e.g., a power constraint per gNB are straightforward to include).

Remark 2. An alternative optimization can be formulated by determining the FIM of $\tilde{\boldsymbol{\eta}}$ and enforcing $\mathbf{J}^{-1}(\tilde{\boldsymbol{\eta}}) \preceq \boldsymbol{\gamma}_e$, where $\boldsymbol{\gamma}_e \in \mathbb{R}^{3+2N_{bs}}$ is a diagonal matrix comprising the limits on the error variance of each component. The same approach can then be used.

IV. Simulation Results

In this section, we consider a single-user multi-base station scenario and compare three power allocation strategies, hereafter referred to as: 1) minimun number of beams (ℓ_1-norm based), 2) minimum average power (ℓ_2-norm based) and 3) minimum constant power (ℓ_∞-norm based).

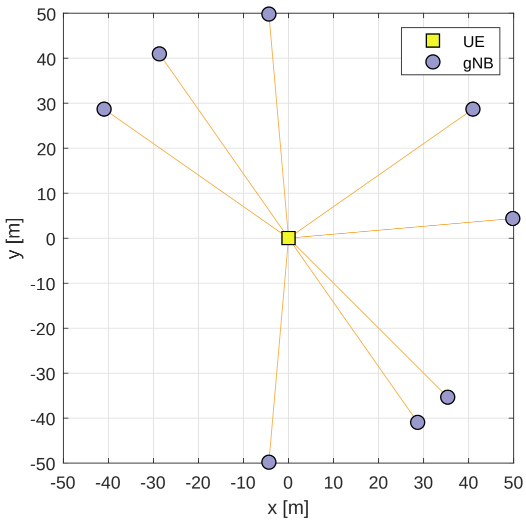

Fig. 2. Illustration of simulation scenario with 8 randomly placed gNBs around the UE. Distance from each gNB to UE is constant $d_b = \|\mathbf{z} - \mathbf{q}_b\| = 50$ m $\forall b$, and AoA $\theta_b \sim \mathcal{U}(0, 2\pi)\ \forall b$.

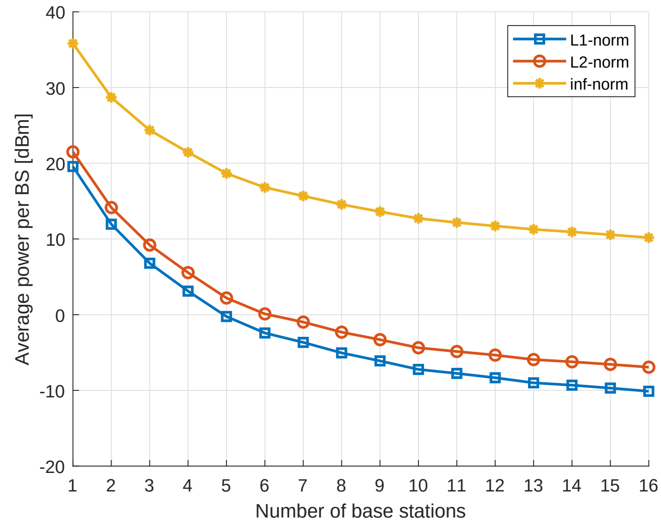

Fig. 3. Required total transmission power over all gNBs and all beam pairs to achieve target PEB $= 2.5$ cm, for ℓ_1, ℓ_2 and ℓ_∞ -norms. Average power is total power over all gNBs and beam pairs divided by number of gNBs available in scenario.

A. Simulation Scenario

In all simulation scenarios, UE's coordinate vector is $\mathbf{z} = [0,\, 0]^{\mathsf{T}}$ and N_{bs} gNBs are placed randomly on a circle of radius d centred at the UE. For instance, in Fig. 2, a typical scenario with $N_{bs} = 8$ and $d = 50$ m is illustrated. We assume a downlink orthogonal frequency-division multiplexing (OFDM) communication at 28 GHz with subcarrier spacing $\Delta_f = 120$ kHz and 127 subcarriers. Both UE and gNB have uniform linear array (ULA) antennas, respectively, with 8 and 16 elements. Beamforming is generated in the RF domain, and for simplicity, we consider a single RF chain and Discrete Fourier Transform (DFT) type codebook.

Positioning measurements (angle and ranging) are obtained from a sequential beam scanning, which takes at most 128^2 slots[3], but might be lower based on the selected power-allocation strategy.

Finally, we shall consider the following metrics: $i)$ the average total transmit power per gNB to look into overall power consumption of the positioning measurement process, $ii)$ the average number of beams to evaluate the time-efficiency of the measurement process and, $iii)$ the achievable PEB to quantify the effectiveness of power allocation strategy to achieve a target localization accuracy.

B. Results and Discussion

Fig. 3 shows the average power per gNB in the network to achieve a target accuracy $\sqrt{\gamma_e} = 0.025$ m. The average power means total power over the full setup, $i.e.$, all beam-pairs in the configuration, divided equally per gNB. Generally, with all strategies the average power decreases with the increase of the number of gNBs. In other words, if the optimal localization accuracy is desired, then the most energy-effective solution is to use as many gNB as possible. Consequently, this indicates that using more links for positioning is more energy-effective than increasing the power per beam.

Moreover, by concentrating the power in a few number of beams, strategy 1), yields the lowest power consumption, closely followed by strategy 2). Strategy 3) is the most inefficient solution in terms of power usage.

Fig. 4 shows the average number of used beam pairs – a metric directly related to the measurement time – as a function of the number of gNBs. In this counting, only beam pairs with a transmit power larger than a given threshold are considered, $e.g.$ threshold set to -80 dBm. It can be noticed, that ℓ_1-

[2] With the codebook size of UE is $|\mathcal{C}_u| = 8$, and each gNB has $|\mathcal{C}_b| = 16$.

[3] We assume that in one slot UE can simultaneously receive DL signals from multiple gNBs and, per gNB, only one beam-pair can tested.

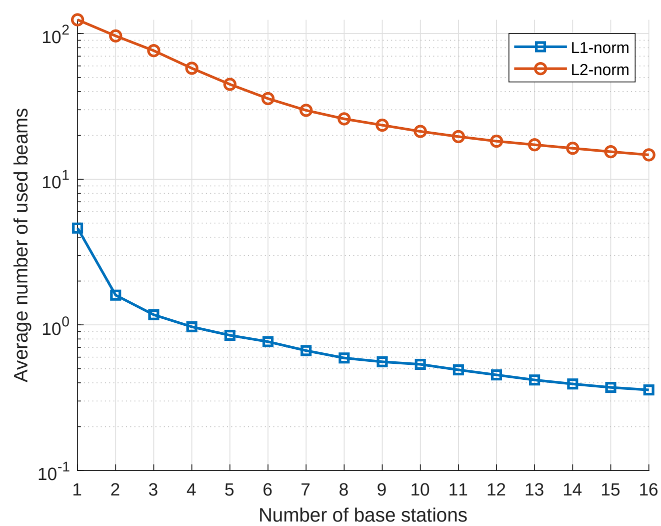

Fig. 4. Average number of used beam pairs (per gNB) as function of number of gNBs in the scenario. ULA antennas used in simulation are 8×1 and 16×1 for UE and for each gNB, respectively.

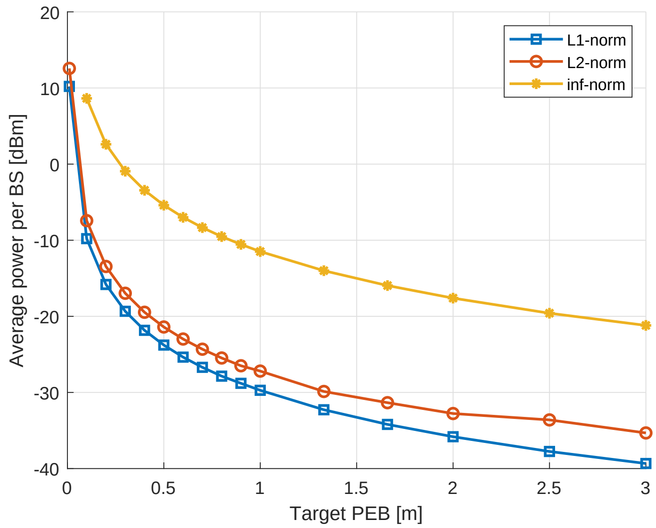

Fig. 5. Total power over gNBs and used beam pairs as function of target PEB. Number of gNBs $N_{bs} = 4$.

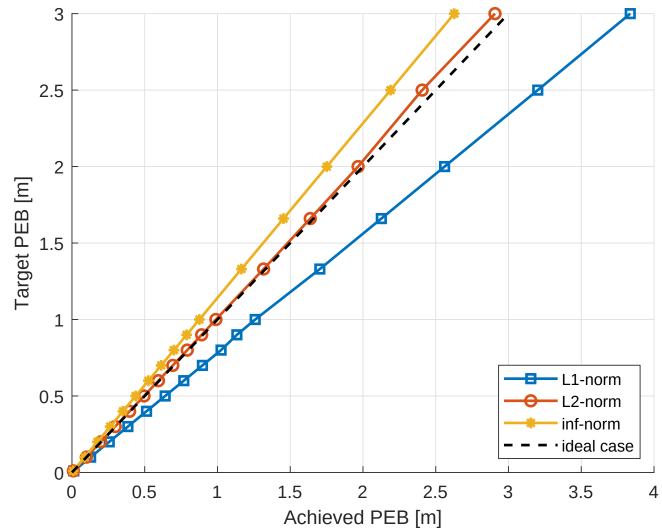

Fig. 6. The performance of the different optimization object functions as a metric of achieved PEB with given target PEB. Black dashed line shows an ideal case. Number of gNBs $N_{bs} = 4$.

norm optimization is again the most effective solution as it yields the shortest delay. When N_{bs} increases, the total delay is reduced, even for the ℓ_2 norm. This can be explained by the limited angular resolution of the codebook, so that few beams from more gNBs is better than many beams from few gNBs. For the ℓ_∞-norm, results are not shown in Fig. 4 as the system always allocates the maximum number of beams.

In Fig. 5, we look into the average total power as a function of target PEB. Generally, a lower target positioning uncertainty leads to a higher power, with a sharp increase for very low values. Finally, in Fig. 6, we consider the realized PEB with respect to the target PEB. Interestingly, the ℓ_1 case leads to a worse PEB than the target, the ℓ_2 case to a PEB close to the target, and the ℓ_∞ to a PEB smaller than the target. These inconsistencies are due to a mismatch between the channels assumed by the optimizer and those generated after the power was allocated.

V. Conclusion

In this paper we considered the problem of finding the optimal power allocation over the multiple beams and multiple base stations on MIMO OFDM wireless network. In particular, we formulate a convex optimization problem to allocate power to beam pairs across different base stations. Simulation results indicate that when more base stations are available and there is an overall power constraint, both total power and delay are reduced. In addition, when using and ℓ_1-norm power minimization, the lowest delay with smallest total power are achieved, while ℓ_2-norm power minimization incurs significantly longer delays.

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