STEER+: Robust Beam Refinement for Full-Duplex Millimeter Wave Communication Systems

(Invited Paper)

Ian P. Roberts*, Yu Zhang†, Tawfik Osman†, and Ahmed Alkhateeb†

*Wireless Lab, Department of Electrical and Computer Engineering, University of California, Los Angeles

†Wireless Intelligence Lab, School of Electrical, Computer and Energy Engineering, Arizona State University

***Abstract*—Recent efforts have highlighted the feasibility of upgrading millimeter wave (mmWave) communication systems with full-duplex capability by harnessing beamforming to cancel self-interference. However, much of this proposed work has been theoretical in nature, has overlooked practical considerations, and has been validated purely through numerical simulation. In contrast, this work introduces a novel beam refinement technique suitable for practical full-duplex mmWave systems, which we experimentally evaluate using off-the-shelf 60 GHz phased arrays. The proposed approach, which we call STEER+, improves upon our prior work with added robustness, allowing a full-duplex mmWave communication system to close the link via traditional beam alignment and simultaneously reduce self-interference to near or even below the noise floor. Experimental results demonstrate the robustness of STEER+ and its ability to more reliably increase SINR, compared to beam selection which purely maximizes SNR or minimizes self-interference.**

I. Introduction

Upgrading millimeter wave (mmWave) base stations (BSs) with full-duplex capability could better utilize radio resources to deliver higher data rates and lower latency, especially in wirelessly backhauled networks, even when users remain as half-duplex devices [1]–[3]. Beyond this, there are applications of full-duplex technology in a variety of emerging areas including joint communication and sensing [4], [5], spectrum sharing [6], and security communications [7]. Even with highly directional beams, however, measurements [8]–[10] have shown that a mmWave communication system incurs prohibitively high self-interference if it attempts to operate in an in-band full-duplex fashion. Recent efforts (e.g., [11]–[14]) have excitedly shown that crafting these beams in just the right way can lead to sufficiently low self-interference and thus unlock full-duplex operation, potentially without the need for additional analog or digital cancellation.

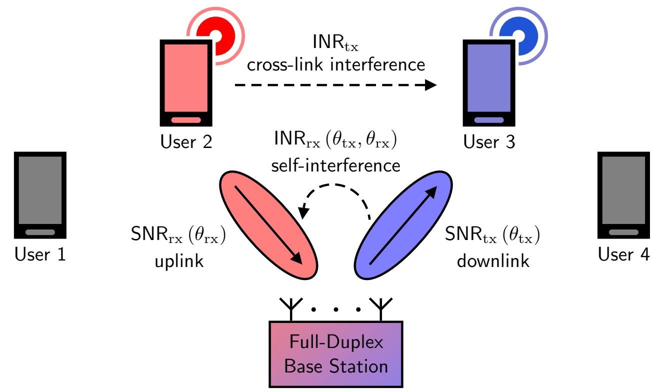
Most existing work developing beamforming-based solutions for full-duplex mmWave systems has been built on theory with impractical assumptions and evaluated through simulation using idealized models. In such works, it has been common to model mmWave self-interference using the spherical-wave multiple-input multiple-output (MIMO) channel model [15] to capture (idealized) near-field propagation between the arrays of a full-duplex transceiver, often in conjunction with a ray-based model to incorporate reflections off the environment [10], [16]–[18]. These channel models have been used to construct and evaluate beamforming designs for full-duplex systems, but their real-world validity has not yet been confirmed. In fact, recent measurements [8] and follow-on modeling [9] suggest that this spherical-wave model [15] is indeed not always observed in practice.

Beyond making use of idealized self-interference channel models, existing beamforming-based full-duplex solutions exhibit a variety of other practical shortcomings. Most work has assumed the ability to estimate the self-interference, downlink, and uplink MIMO channels in real-time, but this is not viable in today's real-world mmWave systems. In 5G and IEEE 802.11ay, for instance, mmWave systems circumvent high-dimensional MIMO channel estimation and instead rely on *beam alignment* to find beams which close the link between a BS and user [19], [20]. Further, existing designs typically ignore the limited resolution of phase shifters, raising questions on how these designs will perform when implemented on actual mmWave transceivers. Recent work [11] addresses many of these practical considerations through the design of STEER, a beam selection methodology for full-duplex mmWave systems, which showed promising results when implemented on 28 GHz phased arrays. It is unclear, however, if STEER will see similar levels of success when implemented on other phased arrays, in real-world environments, and when downlink/uplink performance is measured rather than simulated.

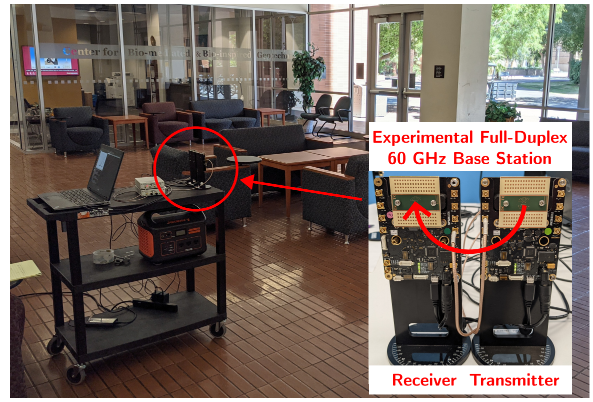
This work introduces STEER+, a novel beam refinement scheme for full-duplex mmWave communication systems that improves upon the recent work of STEER [11] with added robustness. Using off-the-shelf 60 GHz phased arrays, we experimentally evaluate both STEER and STEER+, which to our knowledge, are the first real-world evaluations of their kind, complete with measurements of self-interference, downlink and uplink signal-to-noise ratios (SNRs), and cross-link interference. Experimentally, STEER+ proves to be a more robust solution than STEER and offers higher signal-to-interference-plus-noise ratios (SINRs) and achievable spectral efficiencies.

II. System Model

Consider a full-duplex mmWave BS which transmits downlink to one half-duplex user while simultaneously receiving uplink from another half-duplex user in-band, as portrayed in Fig. 1a. In serving these two users in a full-duplex fashion, the BS incurs self-interference and cross-link interference is inflicted onto the downlink user by the uplink user. It is assumed that the BS employs separate phased arrays for transmission



(a) A full-duplex mmWave BS serving uplink and downlink at once in-band.



(b) Experimental setup using 60 GHz phased arrays.

Fig. 1. As illustrated in (a), we distributed four single-antenna users around our experimental full-duplex BS in the indoor environment shown in (b). Each user can either transmit uplink or receive downlink at any given time. In Section V, we implemented STEER [11] and STEER+ and experimentally evaluated their performance across all downlink-uplink combinations through measurement of self-interference, downlink SNR, uplink SNR, and cross-link interference.

and reception, whereas each user has a single omnidirectional antenna, but this is not a necessary assumption.

Suppose the transmit and receive arrays at the BS are uniform linear arrays oriented horizontally. The transmit array can be electronically steered to produce a beam in some relative azimuth direction θ_{tx} via analog beamforming weights $\mathbf{f}(\theta_{tx}) \in \mathbb{C}^{N_t}$, where N_t is the number of transmit antennas. Likewise, the receive array can be steered toward θ_{rx} via weights $\mathbf{w}(\theta_{rx}) \in \mathbb{C}^{N_r}$, where N_r is the number of receive antennas. When the BS serves a downlink user and an uplink user in a full-duplex fashion, the SINRs of the downlink and uplink can be expressed as

$$\mathsf{SINR}_{tx}(\theta_{tx}) = \frac{\mathsf{SNR}_{tx}(\theta_{tx})}{1 + \mathsf{INR}_{tx}}, \quad (1)$$

$$\mathsf{SINR}_{rx}(\theta_{tx}, \theta_{rx}) = \frac{\mathsf{SNR}_{rx}(\theta_{rx})}{1 + \mathsf{INR}_{rx}(\theta_{tx}, \theta_{rx})}. \quad (2)$$

Here, SNR_{tx} and SNR_{rx} are the downlink and uplink SNRs, while INR_{tx} and INR_{rx} are their interference-to-noise ratios (INRs) due to cross-link interference and self-interference, respectively. These SNRs are respectively functions of the transmit and receive beams and can be written as

$$\mathsf{SNR}_{tx}(\theta_{tx}) = \frac{P_{tx}^{BS} \cdot |\mathbf{h}_{tx}^{*}\mathbf{f}(\theta_{tx})|^2}{P_{noise}^{UE}}, \quad (3)$$

$$\mathsf{SNR}_{rx}(\theta_{rx}) = \frac{P_{tx}^{UE} \cdot |\mathbf{w}(\theta_{rx})^{*}\mathbf{h}_{rx}|^2}{P_{noise}^{BS}}, \quad (4)$$

where P_{tx}^{BS} and P_{tx}^{UE} are the BS and uplink user transmit powers; P_{noise}^{BS} and P_{noise}^{UE} are the BS and downlink user noise powers; and $\mathbf{h}_{tx} \in \mathbb{C}^{N_t}$ and $\mathbf{h}_{rx} \in \mathbb{C}^{N_r}$ are the downlink and uplink channels. When serving downlink and uplink in a full-duplex fashion, self-interference manifests between the transmit and receive arrays of the full-duplex BS. Under a linear model, the INR of the resulting self-interference is a function of the transmit and receive beams and is written as

$$\mathsf{INR}_{rx}(\theta_{tx}, \theta_{rx}) = \frac{P_{tx}^{BS} \cdot |\mathbf{w}(\theta_{rx})^{*}\mathbf{H}\mathbf{f}(\theta_{tx})|^2}{P_{noise}^{BS}}, \quad (5)$$

where $|\mathbf{w}(\theta_{rx})^{*}\mathbf{H}\mathbf{f}(\theta_{tx})|^2$ captures the transmit and receive beam coupling over the self-interference channel $\mathbf{H} \in \mathbb{C}^{N_r \times N_t}$. Cross-link interference can be expressed as $\mathsf{INR}_{tx} = P_{tx}^{UE} \cdot |h|^2 / P_{noise}^{UE}$, which only depends on its channel $h \in \mathbb{C}$, since the users are assumed as single-antenna devices.

A sensible full-duplex design would aim to maximize both the downlink and uplink SINRs in order to offer high achievable spectral efficiencies expressed as

$$R_{tx}(\theta_{tx}) = \log_2(1 + \mathsf{SINR}_{tx}(\theta_{tx})), \quad (6)$$

$$R_{rx}(\theta_{tx}, \theta_{rx}) = \log_2(1 + \mathsf{SINR}_{rx}(\theta_{tx}, \theta_{rx})). \quad (7)$$

In this pursuit, this work primarily focuses on maximizing the downlink and uplink SNRs and minimizing self-interference, since cross-link interference is fixed for a given user pair.

III. STEER: An Existing Full-Duplex Solution

In recent work [11], a beam selection methodology called STEER is proposed to reduce self-interference while delivering high beamforming gain on the downlink and uplink. STEER achieves this by first conducting beam alignment to identify initial steering directions and then slightly shifting these steering directions (on the order of one degree) in search of reduced self-interference. Inspired by the small-scale spatial variability in [8, Fig. 13a], STEER's working principle is that slight shifts of the beams will preserve high SNR on the downlink and uplink and significantly reduce self-interference, yielding SINRs sufficiently high for full-duplex operation.

When serving a downlink user and an uplink user, STEER begins by using beam alignment measurements to solve (or approximately solve) the SNR-maximizations

$$\theta_{tx}^{init} = \underset{\theta_{tx} \in \mathcal{C}_{tx}}{\mathrm{argmax}} \ \mathsf{SNR}_{tx}(\theta_{tx}), \quad (8)$$

$$\theta_{rx}^{init} = \underset{\theta_{rx} \in \mathcal{C}_{rx}}{\mathrm{argmax}} \ \mathsf{SNR}_{rx}(\theta_{rx}), \quad (9)$$

where $\mathcal{C}_{tx}$ and $\mathcal{C}_{rx}$ are beam codebooks used for beam alignment. Note that these codebooks and the methods for conducting beam alignment are not within the scope of STEER, since it can be applied atop any initial beam selections. Conducting beam alignment yields directions in which the BS can steer its beams to deliver high $\mathsf{SNR}_{\rm tx}$ and $\mathsf{SNR}_{\rm rx}$. These are used to initialize STEER. Then, surrounding these initial steering directions, *spatial neighborhoods* are populated as[1]

$$\theta_{\rm tx}^{\rm init} + \mathcal{N}(\Delta\theta_{\rm tx}, \delta\theta_{\rm tx}), \qquad \theta_{\rm rx}^{\rm init} + \mathcal{N}(\Delta\theta_{\rm rx}, \delta\theta_{\rm rx}). \tag{10}$$

Here, a spatial neighborhood of size $\Delta\theta$ and resolution $\delta\theta$ is defined as

$$\mathcal{N}(\Delta\theta, \delta\theta) = \left\{ m \cdot \delta\theta : m \in \left[-\left\lfloor \frac{\Delta\theta}{\delta\theta} \right\rfloor, \left\lfloor \frac{\Delta\theta}{\delta\theta} \right\rfloor \right] \right\}, \tag{11}$$

where $\lfloor \cdot \rfloor$ is the floor operation and $[a, b] \triangleq \{a, a+1, \ldots, b-1, b\}$. An illustration of this concept of a spatial neighborhood can be found in [11, Fig. 3].

To refine its steering directions from the initial ones, the full-duplex BS executes STEER by solving the following.

$$\min_{\theta_{\rm tx},\theta_{\rm rx}} \ \min_{\Delta\vartheta_{\rm tx},\Delta\vartheta_{\rm rx}} \ \Delta\vartheta_{\rm tx}^2 + \Delta\vartheta_{\rm rx}^2 \tag{12a}$$

$$\text{s.t.} \ \ \mathsf{INR}_{\rm rx}(\theta_{\rm tx}, \theta_{\rm rx}) \leq \max\Big(\mathsf{INR}_{\rm rx}^{\rm tgt}, \mathsf{INR}_{\rm rx}^{\rm min}\Big) \tag{12b}$$

$$\theta_{\rm tx} \in \theta_{\rm tx}^{\rm init} + \mathcal{N}(\Delta\vartheta_{\rm tx}, \delta\theta_{\rm tx}) \tag{12c}$$

$$\theta_{\rm rx} \in \theta_{\rm rx}^{\rm init} + \mathcal{N}(\Delta\vartheta_{\rm rx}, \delta\theta_{\rm rx}) \tag{12d}$$

$$0 \leq \Delta\vartheta_{\rm tx} \leq \Delta\theta_{\rm tx}, \ 0 \leq \Delta\vartheta_{\rm rx} \leq \Delta\theta_{\rm rx} \tag{12e}$$

In this problem, STEER aims to find the transmit and receive steering directions $(\theta_{\rm tx}, \theta_{\rm rx})$ that yield self-interference $\mathsf{INR}_{\rm rx}(\theta_{\rm tx}, \theta_{\rm rx})$ below some target $\mathsf{INR}_{\rm rx}^{\rm tgt}$; note that the $\max$ operation in (12b) is simply to ensure the problem is feasible, where $\mathsf{INR}_{\rm rx}^{\rm min}$ is the minimum self-interference over the neighborhood. In an effort to preserve high SNRs, STEER minimizes the deviation of the transmit and receive beams from the initial selections $\left(\theta_{\rm tx}^{\rm init}, \theta_{\rm rx}^{\rm init}\right)$ by minimizing the size of the spatial neighborhoods from which beams are selected, upper-bounded by $\Delta\theta_{\rm tx}$ and $\Delta\theta_{\rm rx}$.

STEER's beam-shifting approach seems sensible based on the small-scale spatial variability observed in [8] and the experimental evaluation in [11]. However, such an approach may not always be reliable in real-world settings. First of all, if the initial beam selections are not well-aligned with the users, slights shifts could lead to prohibitive SNR losses. In addition, shifting a beam's steering direction on the order of one degree is not necessarily straightforward in practical phased arrays due to hardware nonidealities and limitations. This can lead to unexpected losses in downlink/uplink SNR. Additionally, if there is not sufficient spatial variability, STEER may require significant shifting to reduce self-interference, which can degrade downlink and uplink SNRs. As we will see, STEER can also be sensitive to neighborhood size $(\Delta\theta_{\rm tx}, \Delta\theta_{\rm rx})$, a design parameter; a neighborhood size that is too small can restrict STEER from finding low self-interference, whereas one too large may lead to too much SNR degradation. The optimal neighborhood size can vary for different downlink-uplink user pairs, as we will see shortly, making it unclear how to choose a neighborhood size that generalizes well. Nonetheless, STEER does have attractive practical attributes and can be an effective full-duplex solution. In the next section, we extend STEER to overcome its aforementioned practical shortcomings.

IV. STEER+: A MORE ROBUST VERSION OF STEER

We now introduce STEER+, a more robust version of STEER that makes use of downlink and uplink measurements to guarantee their quality does not prohibitively degrade when slightly shifting beams to reduce self-interference. To do this, we modify problem (12) as follows by slightly altering the self-interference constraint as (13b) and introducing a new spectral efficiency constraint (13c).

$$\min_{\theta_{\rm tx},\theta_{\rm rx}} \ \min_{\Delta\vartheta_{\rm tx},\Delta\vartheta_{\rm rx}} \ \Delta\vartheta_{\rm tx}^2 + \Delta\vartheta_{\rm rx}^2 \tag{13a}$$

$$\text{s.t.} \ \ \mathsf{INR}_{\rm rx}(\theta_{\rm tx}, \theta_{\rm rx}) \leq \mathsf{INR}_{\rm rx}^{\rm tgt} \tag{13b}$$

$$R_{\rm sum}(\theta_{\rm tx}, \theta_{\rm rx}) \geq \min\big(R_{\rm sum}^{\rm tgt}, R_{\rm sum}^{\rm max}\big) \tag{13c}$$

$$\theta_{\rm tx} \in \theta_{\rm tx}^{\rm init} + \mathcal{N}(\Delta\vartheta_{\rm tx}, \delta\theta_{\rm tx}) \tag{13d}$$

$$\theta_{\rm rx} \in \theta_{\rm rx}^{\rm init} + \mathcal{N}(\Delta\vartheta_{\rm rx}, \delta\theta_{\rm rx}) \tag{13e}$$

$$0 \leq \Delta\vartheta_{\rm tx} \leq \Delta\theta_{\rm tx}, \ 0 \leq \Delta\vartheta_{\rm rx} \leq \Delta\theta_{\rm rx} \tag{13f}$$

Problem (13) aims to find the beam pair $(\theta_{\rm tx}, \theta_{\rm rx})$ that yields a sum spectral efficiency above some target $R_{\rm sum}^{\rm tgt}$ while minimizing the beam pair's distance from the initial beam selections $\left(\theta_{\rm tx}^{\rm init}, \theta_{\rm rx}^{\rm init}\right)$. In doing so, it is required that self-interference be below some threshold $\mathsf{INR}_{\rm rx}^{\rm tgt}$ and that the beams be within their respective neighborhoods. By including (13c), we can ensure that a certain level of quality is maintained on the downlink and uplink for an appropriately chosen target $R_{\rm sum}^{\rm tgt}$. To outright maximize sum spectral efficiency, one can set $R_{\rm sum}^{\rm tgt} = \infty$. The $\min$ operation in (13c) is to ensure this constraint is feasible, where $R_{\rm sum}^{\rm max}$ is the maximum sum spectral efficiency possible, given the other constraints.

To better understand the motivation behind STEER+, consider the approach to solving its design problem (13) shown in Algorithm 1 and illustrated in Fig. 2, akin to [11, Algorithm 1]. Our algorithm begins by forming spatial neighborhoods around the initial transmit and receive beam selections based on some specified size and resolution. Then, the beam pairs from these neighborhoods are sorted based on their deviation from the initial beam selections. Cross-link interference between the uplink and downlink users is either approximated or directly measured and fed back to the BS. For each beam pair $(\theta_{\rm tx}, \theta_{\rm rx})$ within the set of sorted candidate beam pairs, self-interference $\mathsf{INR}_{\rm rx}(\theta_{\rm tx}, \theta_{\rm rx})$ is measured at the full-duplex BS. If the measured self-interference is below the threshold $\mathsf{INR}_{\rm rx}^{\rm tgt}$, this triggers measurement of the downlink and uplink SNRs. Note that if $\mathsf{SNR}_{\rm tx}(\theta_{\rm tx})$ or $\mathsf{SNR}_{\rm rx}(\theta_{\rm rx})$ has been measured previously, the prior measurement can be referenced to reduce overhead. With these, the downlink and uplink SINRs can be computed, along with the sum spectral efficiency. This process continues for each candidate beam pair until a beam pair offers a sum spectral efficiency greater than or equal to the target $R_{\rm sum}^{\rm tgt}$. If this target is never met, the

[1]Note that our phased arrays are linear arrays, whereas [11] employs planar arrays. As a result, there are minor differences in our presentation of STEER.

Algorithm 1 Executing STEER+ iteratively to reduce the required number of measurements.

Input: $\theta_{\rm tx}^{\rm init}$, $\theta_{\rm rx}^{\rm init}$, $\mathsf{INR}_{\rm rx}^{\rm tgt}$, $R_{\rm sum}^{\rm tgt}$, $\Delta\theta_{\rm tx}$, $\Delta\theta_{\rm rx}$, $\delta\theta_{\rm tx}$, $\delta\theta_{\rm rx}$
  $\mathcal{T}_{\rm tx} = \theta_{\rm tx}^{\rm init} + \mathcal{N}(\Delta\theta_{\rm tx}, \delta\theta_{\rm tx})$
  $\mathcal{T}_{\rm rx} = \theta_{\rm rx}^{\rm init} + \mathcal{N}(\Delta\theta_{\rm rx}, \delta\theta_{\rm rx})$
  $\mathcal{D}_{\rm tx} = \left\{\Delta\vartheta_{\rm tx} = \left|\theta_{\rm tx} - \theta_{\rm tx}^{\rm init}\right| : \theta_{\rm tx} \in \mathcal{T}_{\rm tx}\right\}$
  $\mathcal{D}_{\rm rx} = \left\{\Delta\vartheta_{\rm rx} = \left|\theta_{\rm rx} - \theta_{\rm rx}^{\rm init}\right| : \theta_{\rm rx} \in \mathcal{T}_{\rm rx}\right\}$
  $\mathcal{D} = \left\{\Delta\vartheta_{\rm tx}^2 + \Delta\vartheta_{\rm rx}^2 : \Delta\vartheta_{\rm tx} \in \mathcal{D}_{\rm tx}, \Delta\vartheta_{\rm rx} \in \mathcal{D}_{\rm rx}\right\}$
  $[\sim, \mathcal{J}] = \mathrm{sort}(\mathcal{D}, \mathsf{ascend})$
  Approximate (or measure) cross-link interference $\mathsf{INR}_{\rm tx}$.
  $\theta_{\rm tx}^{\star} = \theta_{\rm tx}^{\rm init}$, $\theta_{\rm rx}^{\star} = \theta_{\rm rx}^{\rm init}$, $R_{\rm sum}^{\rm max} = 0$
  for $(\theta_{\rm tx}, \theta_{\rm rx}) \in [\mathcal{T}_{\rm tx} \times \mathcal{T}_{\rm rx}]_{\mathcal{J}}$ **do**
    Measure (or reference) $\mathsf{INR}_{\rm rx}(\theta_{\rm tx}, \theta_{\rm rx})$.
    if $\mathsf{INR}_{\rm rx}(\theta_{\rm tx}, \theta_{\rm rx}) \leq \mathsf{INR}_{\rm rx}^{\rm tgt}$ **then**
      Measure (or reference) $\mathsf{SNR}_{\rm tx}(\theta_{\rm tx})$ and $\mathsf{SNR}_{\rm rx}(\theta_{\rm rx})$.
      $\mathsf{SINR}_{\rm tx}(\theta_{\rm tx}) = \mathsf{SNR}_{\rm tx}(\theta_{\rm tx})/(1 + \mathsf{INR}_{\rm tx})$
      $\mathsf{SINR}_{\rm rx}(\theta_{\rm tx}, \theta_{\rm rx}) = \mathsf{SNR}_{\rm rx}(\theta_{\rm rx})/(1 + \mathsf{INR}_{\rm rx}(\theta_{\rm tx}, \theta_{\rm rx}))$
      $R_{\rm tx}(\theta_{\rm tx}) = \log_2(1 + \mathsf{SINR}_{\rm tx}(\theta_{\rm tx}))$
      $R_{\rm rx}(\theta_{\rm tx}, \theta_{\rm rx}) = \log_2(1 + \mathsf{SINR}_{\rm rx}(\theta_{\rm tx}, \theta_{\rm rx}))$
      if $R_{\rm tx}(\theta_{\rm tx}) + R_{\rm rx}(\theta_{\rm tx}, \theta_{\rm rx}) > R_{\rm sum}^{\rm max}$ **then**
        $\theta_{\rm tx}^{\star} = \theta_{\rm tx}$, $\theta_{\rm rx}^{\star} = \theta_{\rm rx}$
        $R_{\rm sum}^{\rm max} = R_{\rm tx}(\theta_{\rm tx}) + R_{\rm rx}(\theta_{\rm tx}, \theta_{\rm rx})$
        if $R_{\rm sum}^{\rm max} \geq R_{\rm sum}^{\rm tgt}$ **then**
          Break for-loop; sum spectral efficiency target met.
        end if
      end if
    end if
  end for
Output: $\theta_{\rm tx}^{\star}$, $\theta_{\rm rx}^{\star}$

beam pair offering the maximum sum spectral efficiency will be used; this is the motivation behind including $R_{\rm sum}^{\rm max}$ in (13c). Note that our algorithm handles the case where problem (13) is infeasible by defaulting to the initial steering directions if no beam pair meets the threshold $\mathsf{INR}_{\rm rx}^{\rm tgt}$.

The role of $\mathsf{INR}_{\rm rx}^{\rm tgt}$ in STEER+ is to throttle the consumption of resources used to measure downlink and uplink SNRs. A very low $\mathsf{INR}_{\rm rx}^{\rm tgt}$ will lead to fewer downlink and uplink measurements (saving on overhead) but may prevent STEER+ from locating the beam pair that maximizes spectral efficiency. Therefore, it is essential that $\mathsf{INR}_{\rm rx}^{\rm tgt}$ not be too strict; letting $\mathsf{INR}_{\rm rx}^{\rm tgt} = \infty$ will trigger measurement of $\mathsf{SNR}_{\rm tx}(\theta_{\rm tx})$ for all $\theta_{\rm tx}$ and of $\mathsf{SNR}_{\rm rx}(\theta_{\rm rx})$ for all $\theta_{\rm rx}$ until the target $R_{\rm sum}^{\rm tgt}$ is met—this may be resource-expensive. As we will see, $\mathsf{INR}_{\rm rx}^{\rm tgt} \approx 6$ dB is sufficient in our experimental evaluation of STEER+. In addition, a modest target $R_{\rm sum}^{\rm tgt}$ can reduce the execution time and the number of measurements required by STEER+ but can also restrict it from maximizing spectral efficiency; recall $R_{\rm sum}^{\rm tgt} = \infty$ will maximize spectral efficiency. As the size of the neighborhoods $(\Delta\theta_{\rm tx}, \Delta\theta_{\rm rx})$ increases, the sum spectral efficiency cannot degrade with STEER+, unlike with STEER, as we will see shortly. Keeping the neighborhood size small, however, can reduce the number of measurements required by STEER+, especially when $\mathsf{INR}_{\rm rx}^{\rm tgt}$ and $R_{\rm sum}^{\rm tgt}$ are high.

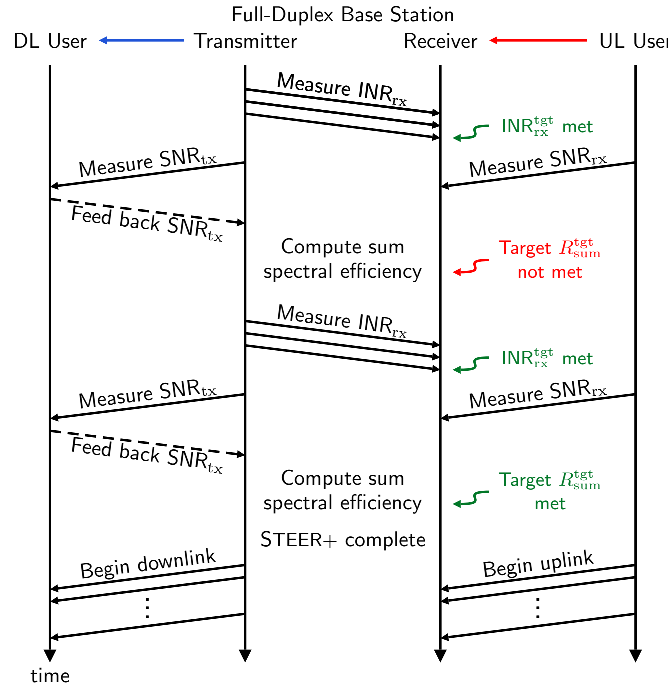


Fig. 2. Solving problem (13) in an iterative fashion using Algorithm 1 to reduce the required number of SNR and INR measurements.

V. Experimental Evaluation of STEER and STEER+

Now, we conduct an experimental evaluation of STEER and STEER+ using off-the-shelf 60 GHz phased arrays. As illustrated in Fig. 1a, we distributed four single-antenna users around our experimental full-duplex BS in the indoor environment shown in Fig. 1b. The transmit and receive arrays at the full-duplex BS were arranged in a side-by-side configuration with the transmit array on right and receive array on left, separated by 10 cm. One of the same phased arrays was used for each user, activating only a single antenna for an omnidirectional pattern. Each user operates in a half-duplex time-division duplexing (TDD) fashion, meaning the full-duplex BS is capable of transmitting downlink to any user while receiving uplink from any of the other three users. In this experimental setup, we can accurately gauge system performance by measuring self-interference, cross-link interference, downlink SNR, and uplink SNR.

For any $(\theta_{\rm tx}, \theta_{\rm rx})$, we can measure the resulting $\mathsf{SINR}_{\rm tx}(\theta_{\rm tx})$ and $\mathsf{SINR}_{\rm rx}(\theta_{\rm tx}, \theta_{\rm rx})$, which can then be used to directly compute achievable spectral efficiencies $R_{\rm tx}(\theta_{\rm tx})$ and $R_{\rm rx}(\theta_{\rm tx}, \theta_{\rm rx})$ as in (6)–(7), with their sum being denoted $R_{\rm sum}(\theta_{\rm tx}, \theta_{\rm rx})$. When running STEER and STEER+, we use a spatial resolution of $\delta\theta_{\rm tx} = \delta\theta_{\rm rx} = 1^\circ$, the same as in [11]. For STEER, we use a self-interference target of $\mathsf{INR}_{\rm rx}^{\rm tgt} = 0$ dB, since this was empirically found to yield best performance. To demonstrate STEER+, we use a target of $\mathsf{INR}_{\rm rx}^{\rm tgt} = R_{\rm sum}^{\rm tgt} = \infty$, which will maximize sum spectral efficiency. In both, for initial beam selection, we execute exhaustive beam alignment using codebooks spanning -60° to 60° with 8° resolution, defined as $\mathcal{C}_{\rm tx} = \mathcal{C}_{\rm rx} = \{-60^\circ, -52^\circ, \ldots, 60^\circ\}$. When pre-

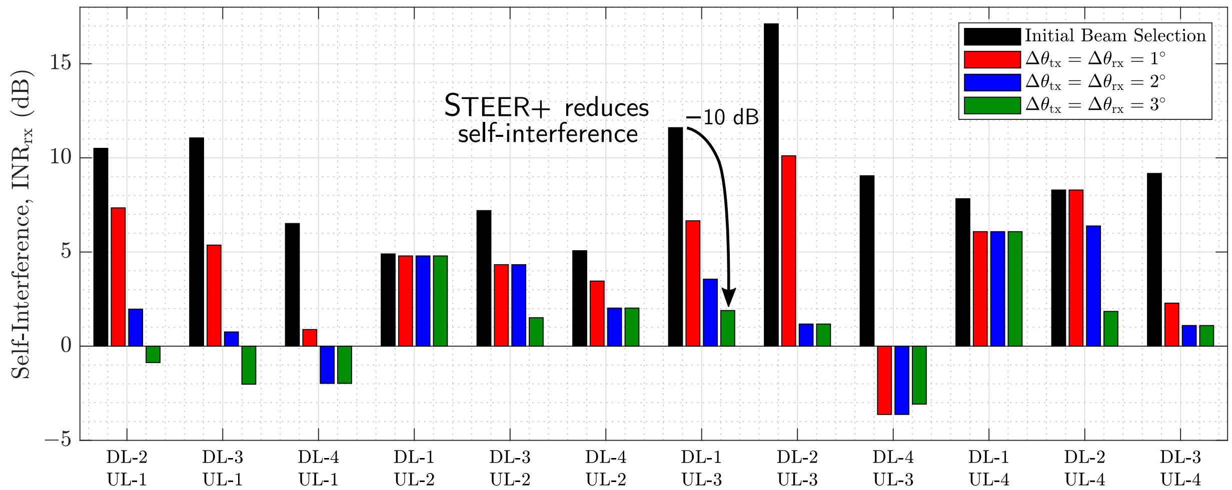
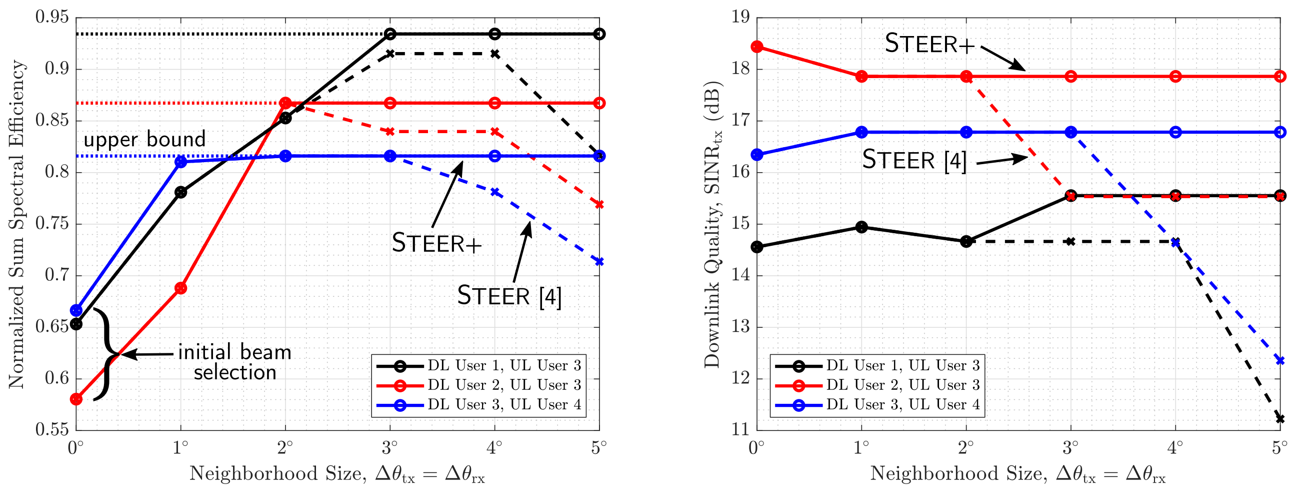


Fig. 3. The self-interference for each downlink-uplink user pair after running STEER+ with various neighborhood sizes $\Delta\theta_{tx} = \Delta\theta_{rx}$. The black bars correspond initial beam selection, before STEER+ is applied. STEER+ is reliably reduces self-interference to near or even below the noise floor.



(a) Sum spectral efficiency.

(b) Downlink quality, SINR_{tx}.

Fig. 4. For STEER [11] (dashed lines) and STEER+ (solid lines), shown is the (a) normalized sum spectral efficiency and (b) downlink SINR as a function of neighborhood size $\Delta\theta_{tx} = \Delta\theta_{rx}$ for three different downlink-uplink user pairs. STEER can be sensitive to neighborhood size, whereas STEER+ maintains performance as the neighborhood size is widened.

senting sum spectral efficiency, we normalize it for illustrative purposes as

$$\underbrace{\frac{R_{sum}(\theta_{tx}, \theta_{rx})}{\log_2\left(1 + \mathsf{SNR}_{tx}(\theta_{tx}^{init})\right) + \log_2\left(1 + \mathsf{SNR}_{rx}(\theta_{rx}^{init})\right)}}_{\text{"codebook capacity"}}, \quad (14)$$

which simply normalizes it to the interference-free full-duplex capacity following beam alignment, which we refer to as the *codebook capacity*. A normalized sum spectral efficiency of 0.5 can be attained by half-duplex operation via TDD, whereas around 1 is approximately best-case performance to expect from a full-duplex solution following beam alignment.

In Fig. 3, we plot the resulting self-interference INR_{rx} for each downlink-uplink user pair after running STEER+ for various $\Delta\theta_{tx} = \Delta\theta_{rx}$. In all three, the black bars correspond to quantities with initial beam selection (i.e., before STEER+ is applied). STEER+'s ability to reduce self-interference is on full display in Fig. 3. Without STEER+, self-interference is typically well above the noise floor, ranging from about 5 dB to around 17 dB above noise. With STEER+, self-interference can be reduced to just above the noise floor or even below with $\Delta\theta_{tx} = \Delta\theta_{rx} = 3°$. For $\Delta\theta_{tx} = \Delta\theta_{rx} = 3°$, we can see from Fig. 3 that an $\mathsf{INR}_{rx}^{tgt} \approx 6$ dB would not prevent STEER+ from maximizing spectral efficiency, allowing it to save on downlink/uplink measurements, since $\mathsf{INR}_{rx} \leq 6$ dB can be attained by all user pairs.

Now, in Fig. 4a, we plot normalized sum spectral efficiency for three user pairs as a function of neighborhood size $\Delta\theta_{tx} = \Delta\theta_{rx}$ for both STEER (dashed lines) and STEER+ (solid lines). The maximum achievable sum spectral efficiency (i.e., R_{sum}^{max} for $\Delta\theta_{tx} = \Delta\theta_{rx} = \infty°$) for each user pair is shown as the dotted lines. With the initial beam selections, all three user pairs marginally exceed 0.5. When activating STEER and STEER+ with $\Delta\theta_{\mathrm{tx}} = \Delta\theta_{\mathrm{rx}} = 2^\circ$, noteworthy increases in spectral efficiency are enjoyed. STEER, however, degrades as neighborhood size increases beyond a certain point for all three user pairs, and notice that the point of degradation differs across user pairs. This degradation is due to the simple fact that STEER does not take into account $\mathsf{SNR}_{\mathrm{tx}}$ or $\mathsf{SNR}_{\mathrm{rx}}$ but rather aims to purely minimize self-interference $\mathsf{INR}_{\mathrm{rx}}$. As such, if permitted to deviate too far, STEER may select beam pairs that do not maintain high SNR on the downlink and uplink. This highlights STEER's sensitivity to the selection of neighborhood size (a design parameter). Choosing $\Delta\theta_{\mathrm{tx}} = \Delta\theta_{\mathrm{rx}} = 2^\circ$ yields performance better than initial beam selection but is not optimal for all users. STEER+, on the other hand, can actually obtain the maximum sum spectral efficiency possible in all three cases with a neighborhood size of at least 3°; we found this to be true across all twelve user pairs.

To better explore the discrepancy between STEER and STEER+, consider Fig. 4b showing downlink SINR for each of the same three user pairs as in Fig. 4a. Following beam alignment, downlink SINR is expectedly quite high, given the fairly modest cross-link interference levels we observed. STEER and STEER+ closely follow each other for small neighborhoods but diverge beyond a certain point. In its effort to purely minimize self-interference, STEER sacrifices downlink SNR by selecting a beam pair prohibitively far from the initial beam selection when allocated a larger neighborhood. STEER+, on the other hand, strategically trades off downlink SINR for self-interference reduction only when it improves sum spectral efficiency. In fact, by doing this, STEER+ can actually *improve* downlink SINR by refining its beam selection following beam alignment, as seen in the blue and black lines. The improvements offered by STEER+ over STEER highlight the impact that downlink and uplink measurements can have on a design's performance and overall robustness.

VI. Conclusion

In this work, we introduced STEER+, a more robust version of our recent work called STEER [11]. STEER+ is a beam refinement mechanism for full-duplex mmWave systems, which uses slight shifts of the transmit and receive beams to reduce self-interference while maintaining high SNR. Using off-the-shelf 60 GHz phased arrays, we experimentally evaluated both STEER and STEER+ to demonstrate how they both can be effective solutions, but the latter proves to offer better performance and more robustness. STEER+ is capable of reducing self-interference to near or even below the noise floor while making small sacrifices in SNR, allowing it to approach the interference-free upper bound on achievable spectral efficiency. In terms of future work, the development and experimental evaluation of other beamforming-based solutions would be valuable strides toward practical full-duplex mmWave systems; perhaps machine learning could be a useful tool in this regard. Working toward a measurement-backed self-interference MIMO channel model would also be a worthwhile endeavor to enable better design and numerical evaluation of beamforming-based full-duplex solutions, especially for those without access to phased array platforms.

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