

Differential Arrays for Butler Multi-Beam STAR

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Abstract—Simultaneous transmit and receive (STAR) over the same frequency range enables in-band full duplex (IBFD) communication with doubled spectral efficiency. This paper presents an IBFD system that connects an antenna array with a multi-beam former to decrease the impact of the self-interference (SI) existing between the transmitter (Tx) and receiver (Rx) in a multiple input and multiple output (MIMO) system. Physical symmetry is used to cancel near-field coupling. Reflections of the Tx from the surrounding environment usually leak into the receive antennas to cause SI with long delay-bandwidth products that are notoriously hard to remove; the proposed differential array greatly reduces such interference.

Index Terms—Antenna Array, Beamforming, MIMO, IBFD, Isolation, SIC, STAR.

I. INTRODUCTION

The use of simultaneous transmit and receive (STAR) across a given frequency range with full overlap between the Tx and Rx spectra is known as in-band full-duplex (IBFD) wireless communications. The adoption of IBFD-STAR doubles spectral efficiency and also enables the development of new types of communication protocols, joint communication and sensing, and electronic warfare systems [1]. Massive-MIMO is a key technology for future wireless networks as it allows channel capacity to scale linearly with the number of independent channels in the MIMO-based RF access system [2]. Typical massive-MIMO operates in time division duplex (TDD) or frequency division duplex (FDD) modes, which are both forms of half-duplex wireless communications. The ability to combine massive-MIMO with IBFD-STAR communications would open up new possibilities for future wireless networks aimed at 6G/NextG deployments. This paper takes a step in this direction by proposing the use of differential antenna arrays for multi-beam MIMO-STAR.

II. TWIN-ARRAY SIC SOLUTION

STAR solutions typically require the use of multi-level SI cancellation to obtain sufficient Tx-Rx isolation, including at the RF [3], analog, and digital [4] stages. The particular challenge of IBFD-STAR for MIMO is that each antenna is coupled to every other antenna in the wireless system via both direct near-field and far-field terms. Typically, the near-field coupling is far stronger (by dozens of dB) and generates strong, frequency-dependent near-field SI, thus making adequate SI cancellation extremely difficult. Circulator approaches do not solve this issue as circulator-based STAR is fundamentally a single antenna approach. To address this challenge, we propose a multi-antenna STAR solution devoid of circulators. Our “twin-array” approach uses a copy of the Tx-Rx array to model the coupling matrix. Such twin arrays

can effectively cancel 20-30 dB of near-field coupling, which is dominant for MIMO-STAR [5], [6]. The residual far-field SI arises from obstructions, scattering, reflections, and other channel effect and is typically much smaller (by 30-60 dB) than near-field coupling. The problem is that the received signals of interest for IBFD-STAR are typically 100-120 dB below the Tx signal. Therefore, even the relatively small far-field SI can be 40-90 dB larger than the Rx signal.

A. Past Work on Twin-Arrays

In [5], we initially proposed a twin-pair antenna canceller for a single Tx and single Rx case. Later, in [6], we expanded our approach to support multiple antennas, where the twin-array is located inside a shielded RF chamber. Thereafter, the shielded RF chamber was replaced with an open array facing towards the rear of the main array [7]. Notably, in our previous work, the twin-array SIC approaches were aimed toward cancellation of the near-field coupling across a wide bandwidth for arrays having a large number of elements. In this new work, we propose a twin-array solution that not only cancels near-field SI, but also allows a significant reduction of far-field reflections by combining near-field cancellation with far-field beamforming within the twin-array architecture.

III. PROPOSED TWIN BUTLER-MATRIX ARRAYS

A. Mathematical Model of the Twin-Array

Let the transmit signal for N antenna elements be represented by an N -point vector $X_T(s)$. Notably, for the case of a Butler matrix, we define the forward beamforming matrix function of transmit signals as $B_{2,1}(s)$, and the corresponding reverse beamforming matrix function of received signals as $B_{1,2}(s)$. Also, we define the forward (transmit) mutual coupling function of the aperture as $H_{2,1}(s)$, and the corresponding reverse (receive) mutual coupling function as $H_{1,2}(s)$. Finally, the Tx-mode Butler-matrix beamformer function is defined as $Y_T(s) = H_{2,1}(s)B_{2,1}(s)X_T(s)$, where $Y_T(s)$ is the outgoing transmit signal across N -elements, while the corresponding Rx-mode Butler-matrix beamformer function is defined as $Y_S(s) = H_{1,2}(s)B_{1,2}(s)X_R(s)$, where $X_R(s)$ is the incident received signal vector.

In the presence of SI, the combined signal at the receivers is a linear combination of the actual (desired) received signal and scattered and reflected components of the Tx signal, yielding $Y_R(s) = P_{2,1}(s)X_T(s) + P_{1,2}(s)X_R(s)$. Here, $P_{2,1}(s) = H_{2,1}(s)B_{2,1}(s)$ corresponds to the total combined scattering parameters including the Butler matrix and the aperture with mutual coupling effects, as seen by the Tx signals going out from the power amplifiers (PAs). Similarly, $P_{1,2}(s) =$

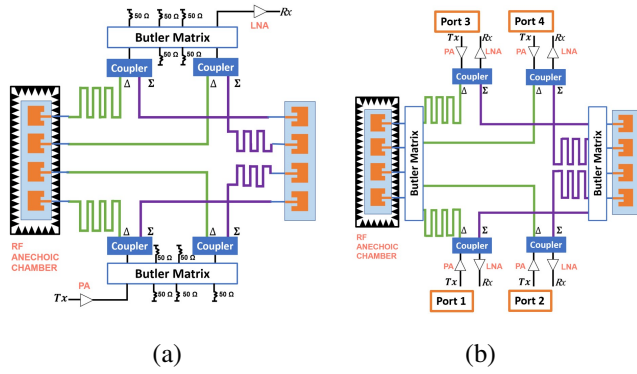


Fig. 1. Two variants of the proposed in-band full-duplex (IBFD) MIMO system. Each array has $N = 4$ elements in this example.

$H_{1,2}(s)B_{1,2}(s)$ is the total combined scattering parameters including the Butler matrix and the aperture with mutual coupling effects, as seen by the incident Rx signals. Moving forward, we combine the aperture coupling with Butler matrix beamforming to describe the complete MIMO system using a single set of multi-port S-parameters. The received signals, $X_R(s)$, consist of two components: i) the signal of interest from far-field transmitters, and ii) the interference, including reflected components of the transmit signal, $X_T(s)$, that are the cause of environmental SI. We can model the incident received signals as $X_R(s) = X_S(s) + H_I(s)P_{2,1}(s)X_T(s) + X_I(s)$, where $X_I(s)$ corresponds to the external interference, $X_S(s)$ is the signal of interest, and $H_I(s)$ corresponds to the far-field SI channel matrix.

Let the twin-array have corresponding S-parameter matrices $P'_{2,1}(s) = P_{2,1}(s) + \Delta_{2,1}(s)$ and $P'_{1,2}(s) = P_{1,2}(s) + \Delta_{1,2}(s)$, where $\Delta_{1,2}(s)$ and $\Delta_{2,1}(s)$ are small valued error matrices which become null matrices for an electrically identical pair of arrays. From Fig. 1, we know that the received signal will be modeled by $Y_R(s) = P_{1,2}(s)X_R(s) + P_{2,1}(s)X_T(s) - P'_{2,1}(s)X_T(s)$, which implies that the near-field SI perfectly cancels when $\Delta_{1,2}(s) = 0$. Assuming for a moment that perfectly identical arrays are available, we are left with the received signal vector $Y_R(s) = P_{1,2}(s)X_R(s) = P_{1,2}(s)[X_S(s) + H_I(s)P_{2,1}(s)X_T(s) + X_I(s)]$.

The far-field SI component is $P_{2,1}(s)H_I(s)P_{1,2}(s)X_T(s)$ and the received far-field signal of interest is simply $P_{2,1}(s)X_S(s)$. Therefore $P_{2,1}(s)$ imposes discrete Fourier transform (DFT) receive-mode beamforming, while $P_{1,2}(s)$ imposes DFT transmit-mode beamforming on the Rx and Tx components. The far-field SI undergoes both transmit and receive beamforming together with the scattering channel $H_I(s)$. Therefore, unless $H_I(s)$ represents a retro-reflective surface that reflects the signal along the same direction of incidence, the received SI would be heavily attenuated due to directional selectivity of the transmit and receive beams. The far-field received signal undergoes directional enhancement due to receive mode DFT beamforming, causing an increase in signal-to-noise and interference ratio (SINR) due to passive beamforming in the Butler matrix, provided we select the right beam port for a particular far-field signal of interest.

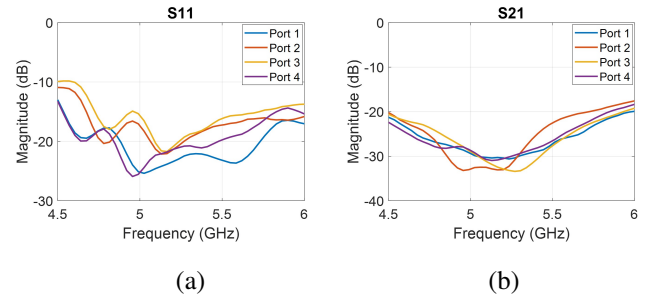


Fig. 2. Measured S-parameters for the proposed system shown in Fig. 1 (b): (a) return loss, and (b) isolation between the Rx and Tx ports.

B. Measurement Results

The proposed method combines a passive multi-beam beam-former matrix realized using passive microwave circuits with the twin-array concept. We propose two variants of the idea, with the Butler matrix appearing in two different locations of the signal flow graph (SFG) as shown in Fig. 1. Fig. 2 shows the measured return loss and isolation between the ports for the second variant (shown in Fig. 1 (b)) using antenna arrays with $N = 4$ elements. The result indicates that the system achieves an isolation between Tx and Rx that is below -30 dB across the entire 5 GHz to 5.5 GHz frequency range.

IV. CONCLUSION

We presented an IBFD approach for MIMO-STAR wireless communication systems. The proposed technique combines physical symmetry with Butler-matrix multi-beam beamforming to cancel both the near-field and far-field coupling of the SI matrix, the latter being for null-directions of the array. Our experimental results show that isolation better than 30 dB is achieved between 4-element Tx and Rx arrays across the bandwidth of interest (5-5.5 GHz).

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