On The Inherent Self-Interference Suppression of Full-Duplex Phased Arrays

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***Abstract*—This paper quantitatively investigates the inherent self-interference (SI) suppression property of dual-polarized full-duplex (FD) linear phased array antennas. The amount of systemic SI suppression is derived for an $N \times 1$ array as a function of the phase taper applied on it. The systemic SI suppression occurs due to the destructive interference of signals in different phased array channels. Results indicate more than 10-15 dB SI suppression for most beam directions, and around 2 dB SI suppression for the normal beam direction.**

***Index Terms*—Self-interference, full-duplex, phased arrays**

I. Introduction

Transmission and reception at the same time/frequency resource, i.e. in-band full-duplex (FD) operation, has been a promising candidate for next generation mobile communication systems. Its main advantage is potentially doubling the spectral efficiency, but FD also helps reduce the network latency and enables new capabilities for terminals such as collision detection [1]. The bottleneck of FD radio is the self-interference (SI), the unwanted coupling of the transmitted signal to its own receiver. Mitigating the SI requires the combination of cancellation and suppression techniques in antenna/propagation, analog/RF, and digital/baseband domains. Various techniques have been reported for SI mitigation [1], [2].

In addition to FD, the phased array antenna is another candidate for improved wireless communications [3]. Phased arrays provide additional antenna gain as well as beam steering and spatial interference rejection capabilities. As mm-wave frequencies are envisioned for next generation mobile communications, phased arrays are even more promising, as the antenna dimensions get smaller and large phased arrays become feasible.

Several work has focused combining FD operation with phased arrays. Half of the 32 antennas are used for TX and the other half for RX in [3]. A single channel FD mm-wave link using phased arrays is demonstrated in [4]. Recently, an 8x8 cross-polarized array is reported in [5] for FD operation. The SI suppression of a single cross-polarized antenna for FD operation is discussed in [6]. A full-duplex massive MIMO system is investigated in [7], in terms of inter-user interference. Finally, [8] reviews the mutual couplings in phased array, but discusses only the spatial interference suppression of arrays by adjusting the beam nulls. No work in the literature has focused on the inherent SI suppression of phased arrays.

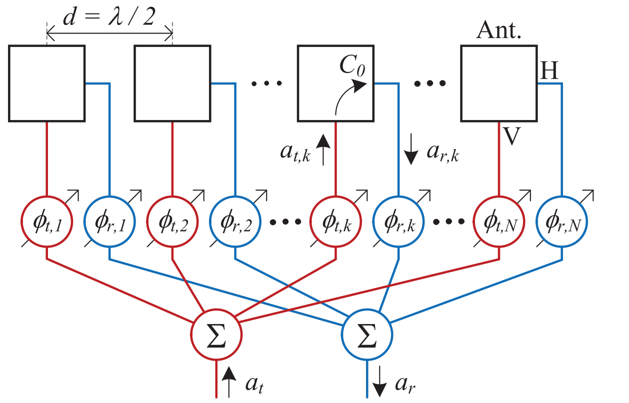

Fig. 1. $N \times 1$ element, full-duplex phased array with separate phase shifters for TX and RX. Full-duplex operation is obtained via dual polarized antennas.

In this work, we analyze a FD linear phased array of size $N \times 1$ and quantify its SI suppression performance in the presence of no additional SI suppression/cancellation circuitry. Theoretical results demonstrate more than 10-15 dB systemic SI suppression for most beam directions, and around 2 dB SI suppression for the normal beam. The limit of the SI suppression for the normal beam is also derived for large arrays.

II. SI Suppression in FD Phased Arrays

Consider a linear phased array of size $N \times 1$ as shown in Fig. 1. Dual polarized antennas are used for simultaneous transmission (TX) and reception (RX), and we take their finite isolation into account. The array employs a separate phase shifter for TX and RX paths with continuous phase control, an ideal 1-to-N power divider/combiner (lossless and matched), and no dedicated SI cancellation circuitry.

In the following discussion we make use of normalized voltage waves, a_t and a_r, for the transmitted and received signals, respectively. If the total transmitter input of the array is a_t, the transmitted signal from the antenna k is

$$a_{t,k} = \frac{a_t}{\sqrt{N}} e^{-j\phi_{t,k}} \tag{1}$$

where $\phi_{t,k}$ denotes the phase shift introduced in the transmitter

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channel k. Then, the received SI signal at antenna l becomes

$$a_{r,l} = \sum_{k=1}^{N} a_{t,k} C_{lk} \tag{2}$$

where C_{lk} denotes the complex coupling coefficient from the transmit port of antenna k to the receive port of antenna l. The combined received SI signal is

$$a_r = \frac{1}{\sqrt{N}} \sum_{l=1}^{N} a_{r,l} e^{-j\phi_{r,l}} \tag{3}$$

where $e^{-j\phi_{r,l}}$ is the phase shift introduced in the receiver channel l. Combining (1)-(3), the received SI signal can be found as

$$a_r = \frac{a_t}{N} \sum_{l=1}^{N} \sum_{k=1}^{N} C_{lk} e^{-j(\phi_{t,k}+\phi_{r,l})} \tag{4}$$

Assuming a reciprocal coupling between antennas and that the coupling is mainly determined by the distance between antennas, we can define $C_{lk} = C_{kl} = C_{k-l}$. In this notation, C_0 is the coupling from a transmitter to its own receiver, C_1 is the coupling to the adjacent receivers, and so on. Let's also define $\phi_{t,k} + \phi_{r,l} = \phi_{kl}$, that is the combined phase shift introduced by the path composed of transmitter k and receiver l. Furthermore, we assume a continuous phase taper, $\Delta\phi$ between the antennas, i.e.

$$\phi_{t,1} = \phi_{t,2} - \Delta\phi = \phi_{t,3} - 2\Delta\phi = \cdots = \phi_{t,N} - (N-1)\Delta\phi \tag{5}$$

$$\phi_{r,1} = \phi_{r,2} - \Delta\phi = \phi_{r,3} - 2\Delta\phi = \cdots = \phi_{r,N} - (N-1)\Delta\phi \tag{6}$$

In our new notation, this linear phase taper condition can be expressed as

$$\phi_{kl} = \phi_{11} + (k+l-2)\Delta\phi \tag{7}$$

Using these definitions, (4) can be rewritten as (8). Combining the terms further results in (9), where $f(n)$ is defined as (10).

$$a_r = \frac{a_t}{N} e^{-j\phi_{11}} \left[C_0 \sum_{m=0}^{N-1} e^{-j2m\Delta\phi} + 2C_1 e^{-j\Delta\phi} \sum_{m=0}^{N-2} e^{-j2m\Delta\phi} + 2C_2 e^{-j2\Delta\phi} \sum_{m=0}^{N-3} e^{-j2m\Delta\phi} + \cdots + 2C_{N-1} e^{-j(N-1)\Delta\phi} \right] \tag{8}$$

$$a_r = \frac{a_t}{N} e^{-j\phi_{11}} \left(C_0 f(0) + 2 \sum_{n=1}^{N-1} C_n f(n) \right) \tag{9}$$

$$f(n) = \sum_{m=0}^{N-n-1} e^{-j(n+2m)\Delta\phi} \tag{10}$$

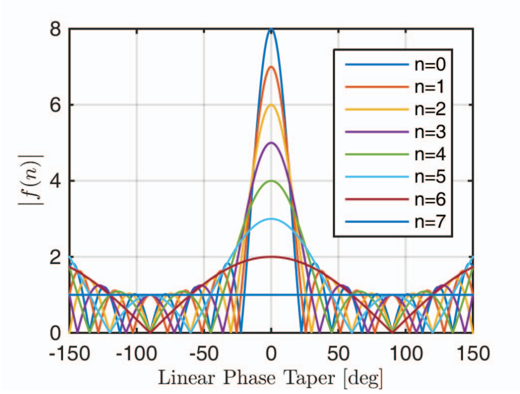

Fig. 2. Magnitude of $f(n)$ given in (10) vs phase taper of an 8-element array.

III. Results and Discussion

Before delving into details of (9) and (10), a few words are needed concerning the phase taper, $\Delta\phi$. Planar antennas used in phased arrays are not omnidirectional. Due to their "element factor", most arrays can scan the beam only up to ±45-60°. If the angle between the steered beam and normal beam is θ, then it can be shown that $\theta = \sin^{-1}(\Delta\phi/\pi)$ for an antenna spacing of $d = \lambda/2$, where λ is the wavelength. Thus, to achieve a beam scanning range of $\theta = \pm 60°$, $\Delta\phi$ has to be in the range of $-150°$ to $+150°$.

Going back to the previous discussion, the magnitude plot of $f(n)$ for $N = 8$ is given in Fig. 2 as a function of the phase taper. Note that the maximum value of $|f(n)|$ is $N - n$, and this occurs only when $\Delta\phi = 0$. Actually, this also occurs when $\Delta\phi = \pm\pi$, but these are outside the useful range of $\Delta\phi$, as explained in the previous paragraph. The sum of complex exponentials in (10) causes a destructive interference when $\Delta\phi$ is not in the vicinity of zero, explaining the behavior in Fig. 2.

Both the first term and the summation in (9) includes the function f. Note that, the first term is due to an antenna's own limited isolation, while the summation is due to mutual antenna couplings. If we neglect the summation and consider the normal beam, (9) reduces simply to $|a_r| = |a_t C_0|$, which is equivalent to the performance of a single antenna. However, since $f(n)$ is much less than its maximum value when the beam is steered (Fig. 2), the array performs an inherent SI suppression.

To qualitatively derive the SI suppression of the array, we need a relation between C_0 and C_n's. This relation can be formulated by assuming that it is dictated by the free space path loss. For an antenna spacing of $d = \lambda/2$ and a path loss of $\mathrm{PL} = (4\pi d/\lambda)^2$ we can derive

$$C_n = C_0 \frac{e^{-j\beta n d}}{4\pi d/\lambda} = C_0 \frac{e^{-j\pi n}}{2\pi n} = (-1)^n C_0 / 2\pi n \tag{11}$$

After substituting (11) into (9), we can plot $|a_r/a_t C_0|$, which is the SI suppression performance of the array; because this magnitude would be unity if we used a single antenna.

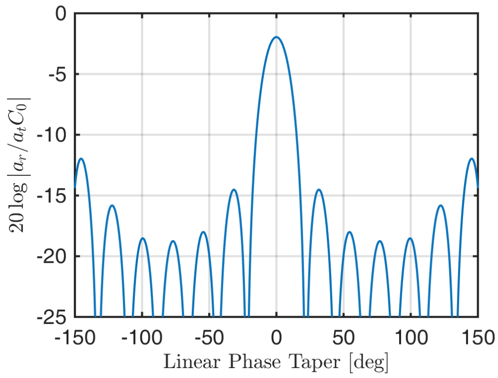

Fig. 3. SI Magnitude of an 8-element array normalized to SI of a single antenna system.

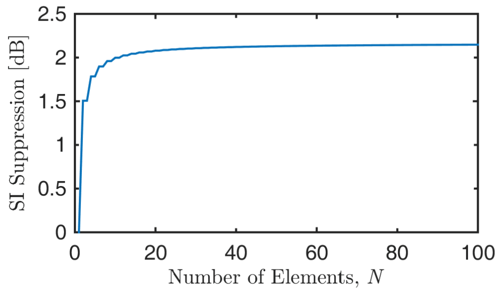

Fig. 4. Inherent SI suppression for normal beam direction vs number of array elements.

Fig. 3 shows this SI suppression in dB as a function of the phase taper. Remarkably, more than 10 dB suppression can be obtained when the phase taper of the array is higher than $+15°$ or lower than $-15°$. For some beam directions, the suppression exceeds 25 dB, but this is not realistic due to many factors. All else being ideal, even the phase shifter quantization errors would limit this performance in case of a digitally controlled phase shifter.

An interesting point is that, the array suppresses the SI, even for the normal beam, approximately by 2 dB for an 8-element array. For larger arrays, the SI suppression of the normal beam approaches exactly -2.16 dB. This can be shown as in (12), by substituting (11) into (9), setting $f(n) = 0$, computing the limit of $|a_r/a_t C_0|$ as $N \to \infty$, and using the fact that the alternating harmonic series is equal to $\ln 2$. Fig. 4 shows the SI suppression of the normal beam as a function of number of antenna elements in the array. The suppression performance increment is marginal for more than 8 elements.

$$\lim_{N\to\infty} \left| \frac{a_r}{a_t C_0} \right| = \lim_{N\to\infty} \left[1 + \frac{1}{\pi} \sum_{n=1}^{N} (-1)^n \left(\frac{1}{n} - \frac{1}{N} \right) \right]$$
$$= 1 + \frac{1}{\pi} \sum_{n=1}^{\infty} \frac{(-1)^n}{n} = 1 + \frac{\ln 2}{\pi} = 0.7794 = -2.16 \text{ dB} \quad (12)$$

IV. Conclusion

We theoretically showed that even without an active SI cancellation circuitry, a full-duplex phased array can provide considerable SI suppression. The SI suppression performance was qualitatively analyzed using a simple full-duplex linear phased array model. The analysis showed more than 10 dB SI suppression for most beam directions. Furthermore, using the simplest free-space path loss model, it was shown that the array provides SI suppression even for the normal beam. It was also shown that the SI suppression limit of the normal beam approaches to -2.16 dB as the array size increases. These preliminary results suggest that full-duplex phased arrays are capable of providing SI suppression in addition to the currently utilized SI suppression/cancellation techniques on antenna/propagation, RF/analog, and digital/baseband domains.

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