Full-Duplex Millimeter-Wave Communication

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Abstract

The potential of doubling the spectrum efficiency of full-duplex (FD) transmission motivates us to investigate FD millimeter-wave (FD-mmWave) communication. To realize FD transmission in the mmWave band, we first introduce possible antenna configurations for FD-mmWave transmission. It is shown that, different from the cases in micro-wave band FD communications, the configuration with separate Tx/Rx antenna arrays appears more flexible in self-interference (SI) suppression while it may increase some cost and area versus that with the same array. We then model the mmWave SI channel with separate Tx/Rx arrays, where a near-field propagation model is adopted for the line-of-sight (LOS) path, and it is found that the established LOS-SI channel with separate Tx/Rx arrays also shows spatial sparsity. Based on the SI channel, we further explore approaches to mitigate SI by signal processing, and we focus on a new cancellation approach in FD-mmWave communication, i.e., beamforming cancellation. Centered on the constant-amplitude (CA) constraint of the beamforming vectors, we propose several candidate solutions. Lastly, we consider an FD-mmWave multi-user scenario, and show that even if there are no FD users in an FD-mmWave cellular system, the FD benefit can still be exploited in the FD base station. Candidate solutions are also discussed to mitigate both SI and multi-user interference (MUI) simultaneously.

Index Terms

Millimeter wave, mmWave, full duplex, FD, beamforming, SI channel, SI cancellation.

I. INTRODUCTION

MILLIMETER-WAVE (mmWave) communication is a promising technology for next-generation wireless communication [1]–[4] owing to its abundant frequency spectrum resource, which promises a much higher capacity than the existing micro-wave band wireless

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local area networks (WLANs) and cellular mobile communications. In order to bridge the link budget gap due to the extremely high path loss in the mmWave band, beamforming with large antenna arrays are generally required. Subject to expensive radio-frequency (RF) chains, mmWave communication adopts particular beamforming structures, i.e., analog beamforming/combining is usually preferred for one-stream transmission, where all the antennas share a single RF chain and have constant-amplitude (CA) constraint on their weights [1], [4]. Meanwhile, hybrid analog/digital precoding/combining has also been proposed to realize multi-stream/multi-user transmission [2], [3], where a small number of RF chains are used together with a large antenna array with much more number of antenna elements.

On the other hand, when applying mmWave communication in practice, its benefit may be offset by the conventional time division duplex (TDD) or frequency division duplex (FDD). In particular, with TDD sufficient Tx/Rx switching guard time should be reserved to make sure the Tx/Rx circuits work normally. Moreover, when considering multiple access, there may be significant protocol overhead [5]. Even for bi-directional point-to-point transmission, there is still a lot of handshaking overhead [5]. While with FDD a large guard band should be arranged to make sure the interference leakage is small enough. In brief, the conventional TDD/FDD may reduce the effective capacity of mmWave communications. For this reason, we explore full duplex (FD) for mmWave communications in this paper. FD has received significant interest in the past decade. Different from TDD/FDD, transmission and reception occur in the same time/frequency resource block in FD communication, which may double the spectrum efficiency [6], [7]. Moreover, FD provides more efficient and flexible access strategies for multiple access [7], and may not need handshaking for bi-directional point-to-point transmission, which can further increase the practical efficiency of mmWave communication.

However, FD-mmWave communication faces particular challenges. Naturally, the most critical issue in FD-mmWave is also self-interference (SI), which is the transmitted signal received by the local receiver at the same node and needs to be cancelled. The SI itself as well as SI cancellation in FD-mmWave communication has its own features. Firstly, unlike the micro-wave band communications, large antenna arrays are generally required in mmWave communication, which means that specific antenna settings are required to enable FD-mmWave transmission. This is studied in Section II, where we show that the configuration with separate Tx/Rx arrays appears more flexible in SI suppression, while it may increase some cost and area. As using antenna Tx/Rx arrays leads to a matrix SI channel, we then model the line-of-sight (LOS)

(a) Tx/Rx share the same antenna array   (b) Tx/Rx have separate antenna arrays

Fig. 1. Possible antenna configurations of an FD-mmWave node.

component of the SI channel by exploiting a near field signal propagation model in Section III, and we show that the LOS-SI channel also demonstrates spatial sparsity when the number of antenna elements is large. Based on the SI channel, we next explore signal processing schemes to mitigate SI in Section IV, where the spatial sparsity of the SI channel is exploited. In particular, we propose a new SI cancellation method termed as beamforming cancellation, which utilizes the beamforming functions of the Tx and Rx antenna arrays. In Section V, we further consider FD-mmWave communication in a multi-user scenario, and show that the FD benefit can be exploited in the FD base station even if there is no FD user. We also discuss possible solutions to mitigate both SI and multi-user interference (MUI) at the same time. Lastly, we conclude the paper in Section VI.

II. ANTENNA CONFIGURATION

The first issue that we need to address is antenna configuration for FD-mmWave communication. In the mmWave band, the high power consumption of mixed signal components and expensive radio-frequency (RF) chains make it difficult to realize digital baseband beamforming as used in the conventional multiple-input multiple-output (MIMO) systems. Consequently, an analog beamforming/combining structure [1], [4] is generally adopted[1]. Hence, to enable FD transmission in the mmWave band, we introduce two possible antenna configurations as shown

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[1]A hybrid analog/digital precoding/combining structure [2], [3] is also frequently used for multi-stream/multi-user transmission.

in Fig. 1. There are one Tx RF chain and one Rx RF chain in both configurations. In Fig. 1–(a) Tx/Rx share the same antenna array by using circulators. The function of the circulator is to separate the Tx signal path from the Rx signal path, and meanwhile let the Tx/Rx signals be transmitted/received through the antenna connecting to it. In Fig. 1–(b) Tx/Rx are equipped with separate antenna arrays. We compare these two configurations as follows.

Firstly, we compare the capability of SI suppression between the two configurations. For the configuration of sharing the same antenna array in Fig. 1–(a), SI is suppressed by a circulator. The isolation of a circulator is dependent on the quality of the circulator. In the mmWave band, the isolation is still limited in general and needs further improvement. For instance, the isolation of the circulator designed in [8] is only 18 dB, less than that in the micro-wave band in general. On the other hand, even if the circulator is good enough, the signal transmitted from an arbitrary antenna element will also result in significant SI to its neighbor antenna elements, because the distances between these antenna elements are quite small, basically at a level of the wavelength of the carrier. In contrast, with separate antennas as that in Fig. 1–(b), SI can be suppressed by blocking the signals between Tx/Rx antenna arrays and/or locating the Tx/Rx antennas far away from each other. Moreover, with separate arrays, the parameters of Tx/Rx array positioning may also be exploited as additional degrees of freedom to mitigate SI and optimize the system performance, as will be discussed in detail later.

Then, we compare the cost and area of the two configurations. It is clear that the configuration with separate Tx/Rx arrays requires an additional array, while it does not need circulators. It is hard to say whether an antenna array or the circulators have higher cost. Even if an antenna array has higher cost, it is affordable in general because it is only a small part of the total cost of the whole transceiver. In addition to cost, area is also important for an FD device, especially for portable devices. Note that in the micro-wave band the size of a micro-wave antenna is relatively large [6]. Hence, using sperate Tx/Rx antennas will double the antenna area, which may be unfavored for small devices, while sharing the same antennas can save a large area. In contrast, in the mmWave band the size of a mmWave antenna is small; thus an additional antenna array may occupy only a small area. For instance, for a 4×4 uniform planar array (UPA) with half wavelength spacing at 30 GHz, the required area is only about 2×2 cm^2. However, when the number of the antenna elements is too large, the required area may be also large.

In summary, the configuration with separate Tx/Rx arrays appears more flexible in SI suppression over the one sharing the same array for FD-mmWave communication, while it may

increase some cost and area for an FD-mmWave device. In the rest of this paper, we will use the configuration with separate Tx/Rx arrays for FD-mmWave communication, while the one with the same array can be seen as a particular case of the separate arrays from the signaling viewpoint, i.e., the two arrays completely coincide with each other.

III. SI CHANNEL MODELING

An mmWave SI channel refers to the channel from the local Tx array to the local Rx array at the same node. It is different from a mmWave communication channel between two different nodes. For comparison, we briefly introduce a mmWave communication channel, which is expected to have limited scattering, and multi-path components (MPCs) are mainly generated by a few reflections, i.e., a mmWave communication channel has spatial sparsity. Different MPCs have different angles of departure (AoDs) and angles of arrival (AoAs) [2], [3]. In particular, the communication channel from Node 1 to Node 2 can be expressed as $\mathbf{H}_{\mathrm{CM}} = \sum_{\ell=1}^{L} \lambda_\ell \mathbf{a}(N_{\mathrm{AN2}}, \Omega_\ell) \mathbf{a}(N_{\mathrm{AN1}}, \psi_\ell)^{\mathrm{H}}$, where λ_ℓ is the complex coefficient of the ℓ-th path, L is the number of MPCs, $\mathbf{a}(\cdot)$ is the *steering vector function*, N_{AN1} and N_{AN2} are the numbers of antennas at Node 1 and Node 2, respectively, Ω_ℓ and ψ_ℓ are cos(AoD) and cos(AoA) (called AoA or AoD in the remaining of this paper) of the ℓ-th path, respectively. $\mathbf{a}(\cdot)$ depends on the antenna array at Tx/Rx, and if uniform linear arrays (ULAs) with half wavelength spacing are adopted, it can be defined as $\mathbf{a}(N, \Omega) = \frac{1}{\sqrt{N}}[e^{\mathrm{j}\pi 0\Omega}, \ e^{\mathrm{j}\pi 1\Omega}, ..., e^{\mathrm{j}\pi(N-1)\Omega}]^{\mathrm{T}}$, where N is the number of antennas at the Tx or Rx, Ω is AoD or AoA. This model implicitly assumes that the distance of the two nodes is far greater than the wavelength of the carrier, such that a far-field model is adopted.

In contrast, the far-field range condition, i.e., $R \geq 2D^2/\lambda$ [9], does not hold in general for the LOS component of mmWave SI, where R is the distance between Tx and Rx arrays, D is the diameter of the antenna aperture, λ is the wavelength of the carrier. For instance, considering a half-wavelength spaced ULA with 32 elements, the far-field range should satisfy $R \geq 2(16\lambda)^2/\lambda = 1024\lambda$, which is basically too large for small-size devices like mobile phones or laptops even at the mmWave band. Thus, the SI channel may have to use the near-field model, which has a spherical wavefront [9]. In such a case, the LOS path of the SI channel is highly dependent on the structures and relative positions of the Tx/Rx antenna arrays.

In addition to the LOS component, there are also non-LOS (NLOS) components for the mmWave SI channel, due to the possible reflectors near the mmWave device (see Fig. 2), i.e., $\mathbf{H}_{\mathrm{SI}} = \mathbf{H}_{\mathrm{SI,L}} + \mathbf{H}_{\mathrm{SI,N}}$. Different from the LOS component, where the direct path between Tx/Rx

Fig. 2. An illustration of Tx/Rx array positioning.

antennas is short, the propagation distances via the NLOS paths are much longer, and can satisfy the far-field range condition in general [10]. Hence, the NLOS components may adopt the same model as the mmWave communication channel as above introduced. Moreover, compared with the LOS components, the NLOS components experience much higher propagation loss as well as additional reflection loss. Hence, the strength of the NLOS components is much weaker than that of the LOS component. For these reasons, we put more attention to the LOS component of the mmWave SI channel.

Without loss of generality, we consider an antenna placement as shown in Fig. 2. The distance between the first elements of the two arrays is d, and the angle between these two ULAs is ω. With this antenna placement, the channel gain between the n-th receive antenna and the m-th Tx antenna, i.e., the coefficient corresponding to the n-th row and the m-th column of $\mathbf{H}_{\mathrm{SI,L}}$ (the SI channel matrix with a near-field model) is [11], [12] $[\mathbf{H}_{\mathrm{SI,L}}]_{nm} = h_{nm} = \frac{\rho}{r_{nm}} \exp\left(-j2\pi \frac{r_{nm}}{\lambda}\right)$, where r_{nm} is the distance between the m-th element of the transmit array and the n-th element of the receive array, and ρ is a constant for power normalization.

Interestingly, although the LOS-SI channel exploits the near-field model, from our model we find that when the number of antenna elements is large, the LOS-SI channel also shows spatial sparsity, which is similar to the mmWave communication channel. To show this feature, we set the Tx/Rx antenna weight vectors (AWVs) as steering vectors with (cosine) steering angles from -1 to 1, and obtain the beamforming gains $|\mathbf{a}(N, \alpha)^{\mathrm{H}} \mathbf{H}_{\mathrm{SI,L}} \mathbf{a}(N, \beta)|$ with these angle combinations. Fig. 3 shows the results, where we can find that when the number of antenna elements is larger, the angle area, in which the beamforming gain is significant w.r.t. the largest

Fig. 3. Spatial feature of the mmWave LOS-SI channel, where $\omega = 0$. The number of antenna elements is 8 for both the Tx/Rx arrays in the left hand side figure, while 32 for the right hand side figure.

beamforming gain, is smaller. When the number of elements is 32, as shown in the right hand side figure, the LOS-SI channel shows distinct spatial sparsity. In particular, the beamforming gain is significant only when $\beta - \alpha \approx \omega$, the angle of the Tx/Rx arrays; otherwise it is small. This result implies that most of the SI power is distributed along only a few Tx/Rx steering angle pairs. Hence, by steering the Tx/Rx AWVs to other angle pairs, the SI can be efficiently mitigated provided the number of antennas is sufficiently large, and the parameters, e.g., ω, can also be optimized for SI cancellation as will be shown later.

As we can see, a mmWave SI channel can be very complicated, which includes both LOS component with a near-field propagation model and NLOS components with a far-field propagation model. Fortunately, due to the packaging of a portable FD-mmWave device, the propagation circumstances within the device are basically stable. For instance, a mobile phone can be packaged with a metal shell, which can block the reflected mmWave signals from the back of the mobile phone and thus prevents the outside objects, e.g., hands, from affecting the SI channel. Hence, in general a mmWave SI channel can be seen slow-varying. As a consequence, we usually have enough time to make an accurate mmWave SI channel estimation.

IV. SI CANCELLATION

A. SI Cancellation in FD-mmWave Communication

As SI is still significant in FD-mmWave communication even with separate Tx/Rx antenna arrays, we need to mitigate it as much as possible. In the existing micro-wave band FD systems, antenna cancellation, which suppresses signals between Tx/Rx antennas, RF cancellation, which subtracts SI in the RF domain, and baseband cancellation, which mitigates residual SI in the baseband, are three typical methods to cancel SI, and a combination of them usually achieves better performance [6], [7].

For FD-mmWave communication, SI cancellation has its particular challenges. Due to the high frequency and wide band signals, the RF impairments are usually more significant than those in the micro-wave band, including power amplifier (PA) nonlinearity, in phase-quadrature (IQ) mismatch, phase noise, etc. These RF impairments will be embedded in SI and can only be effectively mitigated in RF and antenna cancellations [7], since to cancel these impairments in the baseband is difficult due to the unknown impairment parameters. Unfortunately, in mmWave communications, RF design faces particular challenges due to the high frequency and wide band signals, which means that the parameter design for RF cancellation may be inaccurate, and thus probably only a small part of SI can be reduced by RF cancellation. Moreover, within a small portable devices Tx/Rx antenna cancellation can also only mitigate limited SI. Hence, FD-mmWave communication must seek for other efficient SI cancellation methods.

Fortunately, in addition to the three typical SI cancellation methods, the inherent beamforming structure of mmWave communication enables another important approach to mitigate SI, i.e., beamforming cancellation. In fact, without considering the CA constraint of mmWave communication, the beamforming technology can even completely cancel SI, including Tx RF impairments, by using the zero-forcing (ZF) filtering. In [13] it is shown that with unconstrained beamforming, FD-mmWave communication can achieve promising performance. However, under the CA constraint, the SI may not be completely mitigated, and it becomes a challenge for FD-mmWave communication to mitigate SI under the CA constraint. We focus on this issue in the following subsections.

B. Constant-Amplitude Beamforming Cancellation

Subject to the CA constraint, in regular mmWave communication analog beamforming/combining is generally realized by steering the Tx AWV and Rx AWV to the AoD and AoA of the strongest

MPC, such that high array gain can be achieved. However, this method may not be viable in FD-mmWave communication, where strong SI may exist. In other words, the conventional Tx/Rx AWV settings may not be able to effectively reduce SI, although they can achieve a higher array gain. As a result, the overall signal-to-interference plus noise power ratio (SINR) may be not high, as pointed out in [10]. Hence, in FD-mmWave communication SI driven beamforming/combining must be considered. The problem of CA beamforming cancellation (CA-BFC) is challenging, because the objective function, e.g., the achievable sum rate (ASR) of the two nodes in an FD link, is usually complicated and non-concave due to the SI. Moreover, the CA constraints of the Tx/Rx AWVs are also non-concave/convex.

While it is difficult to find an optimal solution of CA-BFC, it is interesting and with significance to find suboptimal solutions with low computational complexity. Here we discuss some preliminary solutions. Intuitively, as there are only phase uncertainty for each element of the Tx/Rx AWVs under the CA constraints, we may search from 0 to 2π for each element. Theoretically, provided small enough step size, an optimal solution can be found. However, as the numbers of antennas are large in general, the exhaustive search method is basically infeasible due to exhibitively high computational complexity. Hence, we propose the following two candidate methods:

- **Method 1:** To restrict the Tx/Rx AWVs to the steering vector space, i.e., we assume that the Tx/Rx AWVs are all steering vectors and have uncertainty only on the steering angles. Under this assumption, we can search over the steering angle spaces of the Tx/Rx AWVs and find the best steering angles for them to optimize the object. This method is viable just because that the mmWave SI channel also has spatial sparsity, as shown in Section III.

- **Method 2:** To first find AWVs by solving the CA-BFC problem without considering the CA constraints, and then find AWVs that satisfy the CA constraints and have the minimal Euclidean distances from the already found AWVs.

The left hand side figure of Fig. 4 shows ASR comparison between different schemes in an FD-mmWave communication system. The upper bound is obtained by assuming that SI is zero and there are no CA constraints. The "Beam Steering" method is to simply set Tx/Rx AWVs to steer along a strong MPC without considering the SI, which is a typical beamforming method used for regular mmWave communication. "Angle Search" refers to Method 1. To use Method 2, we adopt ZF-Matched Filter (ZF-MF) to obtain the beamforming vectors, and then add the CA

Fig. 4. **Left:** Achievable sum rate comparison between different beamforming schemes in an FD-mmWave communication system, where for each scheme the numbers of Tx and Rx antennas are 16 and 8, respectively, $\omega = \pi$ and $d/\lambda = 5$. **Right:** Achievable sum rate comparison of Angle Search with varying ω, where the number of Tx and Rx antennas is 16 at both nodes, $d/\lambda = 1$. In both figures the signal/noise powers are the same at the two nodes, and the SI is 25 dB w.r.t. the signal power.

constraints according to Method 2. ZF-MF is a linear beamforming algorithm which performs MF at the Tx first and then performs ZF at the Rx.

From the left hand side figure of Fig. 4 we can observe that a conventional beamforming approach (Beam Steering) which does not take SI into account cannot achieve a satisfactory performance. In addition, although the simple Angle Search and ZF-MF with CA methods are viable, there is a significant performance gap from the upper bound, which means that these two methods may better work in low SI cases; when SI is strong (as shown in the figure), these two methods need to work together with other SI cancellation methods, like antenna cancellation or baseband cancellation. Meanwhile, more efficient methods are in demand to deal with the SI under the CA constraint. In fact, it is just the CA constraint that limits the performance of Method 2. Without the CA constraint, ZF-MF can achieve a performance close to the upper bound.

On the other hand, we've mentioned in Section III that the SI channel also has spatial sparsity, which can be exploited to design methods to mitigate SI, e.g., the Angle Search method. As we can expect, the Tx/Rx array positions may significantly affect the performance of this category of methods. The right hand side figure of Fig. 4 shows the ASR comparison of Angle Search

with varying ω. It is clear that ω can dramatically affect the performance, and thus may be considered as another degree of freedom to optimize the ASR. It is noteworthy that different methods may favor different ω.

C. Beamforming Cancellation with Double RF Chains

We've seen that the CA constraints greatly limit the performance of beamforming cancellation. If we can find an approach to remove or avoid the CA constraints, beamforming cancellation can become very promising even without the need to work together with other SI cancellation methods [13]. Fortunately, the work in [14] provides a great opportunity to realize this. It is shown in [14] that an arbitrary vector $\mathbf{v}$ can be expressed as the linear combination of two CA vectors, i.e., $\mathbf{v} = \beta_1 \mathbf{v}_1 + \beta_2 \mathbf{v}_2$, where β_1 and β_2 are coefficients, $\mathbf{v}_1$ and $\mathbf{v}_2$ are CA vectors[2]. This result implies that by doubling the number of Tx/Rx RF chains, although CA constraint holds on each RF chain, the equivalent beamforming vector $\mathbf{v}$ does not exhibit the CA constraint any more, and thus ZF-MF without CA in the left hand side figure of Fig. 4 can be realized.

The left hand side figure of Fig. 5 shows the structure with double Tx/Rx RF chains in an FD-mmWave node with separate Tx/Rx arrays. The Tx/Rx arrays are driven by the two independent Tx/Rx RF chains with CA AWVs. An additional Tx/Rx RF chain increases an additional degree of freedom to control the AWV, and thus the CA constraint does not appear or is circumvented in the beamforming cancellation, according to the result achieved in [14]. On the other hand, doubling the Tx/Rx RF chains may also increase the cost and power consumptions of an FD-mmWave node. Fortunately, as shown in the figure, the two Tx/Rx RF chains can share the same up/down-convertor, power amplifiers (PAs), and low-noise amplifiers (LNAs); hence the cost and power consumptions may not increase much.

V. MULTI-USER SCENARIO

A. Benefit of FD Transmission

In the previous section we mainly discuss point-to-point FD-mmWave transmission, which can be used for wireless backhaul link where bi-directional high data rate is required. In this section, we discuss the benefit of FD-mmWave communication in a multi-user scenario, where a base

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[2]In fact, this result can be extended to multi-stream transmission, i.e., an equivalent fully-digital N-stream precoding can be realized provided $2N$ RF chains with CA constraints in mmWave communications [14].

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Fig. 5. **Left**: FD-mmWave communication with double Tx/Rx RF chains. **Right**: An FD hybrid precoding structure for the BS.

station (BS) serves multiple users. Apparently, with FD transmission the multi-user capacity can be greatly improved, because the achievable rate of each user can be almost doubled. In practice, however, this benefit may be offset, since in some cases one user does not need to transmit and receive simultaneously. For instance, when we make a call, we basically do not speak much when we are listening. Fortunately, with multiple users the BS can still sufficiently exploit the FD benefit most of the time, by receiving from some users while transmitting to some other users at the same time.

The left hand side figure of Fig. 6 shows a typical FD-mmWave multi-user scenario, where an FD BS serves multiple users simultaneously. It is noteworthy that within these users, there are FD users, like User 2, as well as half-duplex (HD) users, like User 1 and User 3. An FD user has the antenna setting shown in Fig. 1, while an HD user can only perform conventional mmWave beamforming, either Tx or Rx, but cannot perform FD Tx/Rx beamforming. In a conventional mmWave multi-user scenario, a mmWave BS usually exploits a hybrid precoding structure [15] to serve multiple users with spatial division multiple access (SDMA). Thus, in an FD-mmWave multi-user scenario, an FD-mmWave BS needs to exploit an FD hybrid precoding structure shown in the right hand side figure of Fig. 5, where M_{RF} Tx RF chains share the same Tx array and N_{RF} Rx RF chains share the same Rx array. With this structure, the BS can transmit data to M_{RF} parallel users and meanwhile receives data from N_{RF} parallel users by using both SDMA and FD transmission.

Fig. 6. **Left**: An FD-mmWave multi-user scenario, where an FD-mmWave BS serves multiple users, including FD users and half-duplex (HD) users. **Right**: Achievable sum rate comparison under a multi-user FD-mmWave scenario, where one BS serves K FD users. For all the users and the BS, the number of Tx and Rx antennas is 16. $\omega = \pi/8$, $d/\lambda = 5$, and the SI is 20 dB w.r.t. the signal power.

As shown in the left hand side figure of Fig. 6, at the same time and the same frequency band, the BS can serve the three users simultaneously. In particular, the BS transmits data to Users 1 and 2, and distinguishes them by SDMA, meanwhile the BS receives data from Users 2 and 3, and also distinguishes them by SDMA. From this scenario we can find that even if there is no FD users in practice, the FD-mmWave BS can still exploit the FD benefit by transmitting data to some users (like User 1) while at the same time receiving data from some other users (like User 3).

B. Interference Mitigation

The FD-mmWave multi-user communication does not achieve the FD benefit for no cost. Instead, the FD-mmWave BS must face more complicated interference management. It is known that in conventional mmWave multi-user systems hybrid precoding must be exploited to mitigate multi-user interference (MUI) and meanwhile achieve array gains for multiple users [15]. In an FD-mmWave multi-user system, the BS must deal with both MUI and SI and meanwhile achieve array gains, which is called FD hybrid precoding in this paper.

Firstly, let us see the SI at the FD-mmWave BS. Unlike the point-to-point case discussed in the previous section and shown in Fig. 1, where the SI only contains one single Tx data stream, under the multi-user scenario, the SI may include multiple independent Tx data streams

for multiple downlink users, which means that the SI becomes multi-dimensional. Appropriate Tx/Rx AWVs must be designed to handle the multi-dimensional SI in addition to the MUI.

On the other hand, subject to the particular antenna structure in the FD-mmWave BS, the precoding matrix (also the combining matrix) has to be decomposed into the product of a digital matrix and an analog matrix, which correspond to digital precoding and analog precoding, respectively [15]. The analog matrix has the CA constraints, which challenges the interference mitigation. In fact, in a conventional mmWave multi-user scenario, where there is only MUI but no SI, the CA constraints already make the mitigation of MUI difficult. For instance, in [15] an approach was proposed to first perform BS-user analog beamforming one by one without considering MUI in analog precoding, and then try to mitigate MUI in digital precoding where there is no CA constraint. This approach can achieve good performance, because the BS-user analog beamforming basically induces little MUI due to the spatial sparsity of the mmWave channel. For this reason, this approach may be also used for the FD hybrid precoding here. In particular, we may first perform BS-user analog beamforming by exploiting Method 1 or Method 2 in the previous section, and then design digital precoding and combining matrices to mitigate MUI and the residual SI. In fact, considering that the SI channel also has the property of spatial sparsity, as introduced in Section III, the spatially sparse precoding [2], which formulates the hybrid precoding problem as a sparse reconstruction problem and solves it with the principle of basis pursuit, can be also exploited to solve the FD hybrid precoding problem.

In addition, in the case that the system complexity is affordable, the method to double the number of Tx/Rx RF chains to remove the CA constraints in the previous section can be also applied in the FD-mmWave BS. In particular, the FD-mmWave BS may be equipped with $2N_{\mathrm{RF}}$ Rx RF chains and $2M_{\mathrm{RF}}$ Tx RF chains to serve N_{RF} uplink users and M_{RF} downlink users simultaneously. In such a case, the CA constraints will not appear in the beamforming cancellation according to the results in [14], and we can perform fully digital precoding/combining to mitigate SI and MUI, which is much more flexible than the hybrid precoding/combining. In the case when the system complexity is limited that the BS can only be equipped with M_{RF} Tx RF chains (and N_{RF} Rx RF chains), there is a tradeoff between using these RF chains to serve M_{RF} downlink users with CA constraints and serving $M_{\mathrm{RF}}/2$ downlink users but with the CA constraints circumvented. Channel conditions would determine which one is better.

The right hand side figure of Fig. 6 shows a preliminary comparison of achievable sum rate under a multi-user FD-mmWave scenario, where ZF-MF-Muser refers to the scheme that

uses ZF-MF (cf. Section IV-B) between the BS and each user for SI cancellation, while Angle Search-Muser refers to the scheme that uses Angle Search (cf. Section IV-B) between the BS and each user for SI cancellation. The MUI is simply mitigated by using ZF filtering in the digital beamforming after SI cancellation. From this figure we can see that due to the CA constraint, the SI and MUI may not be completely cancelled, as there are performance floors for both ZF-MF-Muser and Angle Search-Muser at the high SNR regime. Hence, more efficient methods are in demand to deal with the SI and MUI under the CA constraint. When the CA constraint is not considered, the performance can be greatly improved, which indicates that the method of doubling the number of Tx/Rx RF chains is also effective for the multi-user scenario.

VI. CONCLUSIONS

In this paper, we have explored the potential of FD-mmWave communication. We have first designed antenna configurations for FD-mmWave transmission, and compared two typical settings, i.e., with separate Tx/Rx arrays or with the same array. It is shown that, different from the cases in the conventional micro-wave band FD communications, the configuration with separate Tx/Rx arrays provides flexibility to mitigate SI with signal processing methods, while it may increase some cost and area versus that with the same array. We then have modeled the mmWave SI channel, where a near-field propagation model was exploited to model the LOS component, and we find that the mmWave LOS-SI path also shows spatial sparsity, which is similar to the mmWave communication channel and can be used for SI mitigation.

Afterwards, as RF cancellation may not achieve satisfactory performance in mmWave communication, we have explored a new approach to mitigate SI by spatial signal processing, i.e., beamforming cancellation. With the structure constraints of mmWave beamforming taken into account, we have proposed several candidate solutions. Results show that the CA constraints lead to a significant performance loss, and thus more efficient algorithms are in demand. Moreover, the CA constraint can be circumvented in the beamforming cancellation by doubling the number of Tx/Rx RF chains, and in such a case beamforming cancellation can achieve much better performance. Lastly, we have considered an FD-mmWave multi-user scenario, and showed that even if there are no FD users in an FD-mmWave cellular system, the FD benefit can still be exploited in the FD BS. However, interference cancellation is more stringent in this scenario, because there are both SI and MUI. We have also proposed two candidate solutions for this scenario, which either to disregard the multi-user interference or the CA constraints first to

simplify the hybrid precoding problem. In addition, the approach of doubling the number of RF chains may be also viable here provided that the complexity is affordable.

REFERENCES

[1] P. Xia, R. W. Heath, and N. Gonzalez-Prelcic, "Robust analog precoding designs for millimeter wave MIMO transceivers with frequency and time division duplexing," *IEEE Transactions on Communications*, vol. 64, no. 11, pp. 4622–4634, Nov 2016.

[2] A. Alkhateeb, J. Mo, N. González-Prelcic, and R. Heath, "MIMO precoding and combining solutions for millimeter-wave systems," *IEEE Communications Magazine*, vol. 52, no. 12, pp. 122–131, Dec. 2014.

[3] S. Sun, T. S. Rappaport, R. Heath, A. Nix, and S. Rangan, "MIMO for millimeter-wave wireless communications: beamforming, spatial multiplexing, or both?" *IEEE Communications Magazine*, vol. 52, no. 12, pp. 110–121, Dec. 2014.

[4] Z. Xiao, T. He, P. Xia, and X.-G. Xia, "Hierarchical codebook design for beamforming training in millimeter-wave communication," *IEEE Transactions on Wireless Communications*, no. 5, pp. 3380–3392, May 2016.

[5] S. K. Yong, P. Xia, and A. Valdes-Garcia, *60GHz Technology for Gbps WLAN and WPAN: from Theory to Practice*. West Sussex, UK: Wiley, 2011.

[6] D. Bharadia, E. McMilin, and S. Katti, "Full duplex radios," in *Special Interest Group on Data Communication (SIGCOMM)*. Hong Kong, China: ACM, 2013.

[7] A. Sabharwal, P. Schniter, D. Guo, D. Bliss, S. Rangarajan, and R. Wichman, "In-band full-duplex wireless: challenges and opportunities," *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 9, pp. 1637–1652, Sept 2014.

[8] T. Kijsanayotin and J. F. Buckwalter, "Millimeter-wave dual-band, bidirectional amplifier and active circulator in a CMOS SOI process," *IEEE Transactions on Microwave Theory and Techniques*, vol. 62, no. 12, pp. 3028–3040, 2014.

[9] A. J. Fenn, "Evaluation of adaptive phased array antenna, far-field nulling performance in the near-field region," *IEEE Transactions on Antennas and Propagation*, vol. 38, no. 2, pp. 173–185, Feb. 1990.

[10] L. Li, K. Josiam, and R. Taori, "Feasibility study on full-duplex wireless millimeter-wave systems," in *2014 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, May 2014, pp. 2769–2773.

[11] Y.-P. Liao, H. Han, and Q. Guo, "Design of robust near-field multi-beam forming based on improved LCMV algorithm," *Journal of Information Hiding and Multimedia Signal Processing*, vol. 6, no. 4, pp. 783–791, July 2015.

[12] J.-r. Lin, Q.-c. Peng, and H.-z. Shao, "Near-field robust adaptive beamforming based on worst-case performance optimization," *International journal of electrical and computer engineering*, vol. 1, no. 6, 2006.

[13] X. Liu, Z. Xiao, L. Bai, J. Choi, P. Xia, and X.-G. Xia, "Beamforming based full-duplex for millimeter-wave communication," *Sensors*, vol. 16, no. 7, pp. 1–22, July 2016.

[14] F. Sohrabi and W. Yu, "Hybrid digital and analog beamforming design for large-scale MIMO systems," in *IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*. South Brisbane, QLD: IEEE, 2015, pp. 2929–2933.

[15] A. Alkhateeb, G. Leus, and R. W. Heath, "Limited feedback hybrid precoding for multi-user millimeter wave systems," *IEEE Transactions on Wireless Communications*, vol. 14, no. 11, pp. 6481–6494, 2015.