Full-Duplex in Large-Scale Wireless Systems

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***Abstract*—In this paper, we investigate the combination of full-duplex wireless communication with large-scale multiple-input multiple-output (MIMO) technology, which has the potential for bidirectional wireless communication at high spectral efficiency and low power consumption. In addition, we study its application to cellular (multi-user) systems that could be extended with large antenna arrays, such as 3GPP LTE. In order to solve the fundamental issue of self-interference cancellation in full-duplex cellular communication systems, we propose two schemes that exploit the excess of antennas present at the base-station (BS) of large-scale MIMO systems. We investigate the associated sum-rate and show that by carefully selecting the ratio between number of transmit and receive antennas at the BS, one is able to maximize the system capacity. We furthermore investigate the inter-user interference issue that occurs in multi-user scenarios, as well as the impact of residual transmit-side (TX) radio-frequency (RF) impairments. Our preliminary results show that large-scale MIMO is able to render full-duplex communication more resilient against inter-user interference and helps to mitigate the effects of residual TX-RF impairments.**

I. Introduction

Large-scale multiple-input multiple-output (MIMO) is an emerging wireless communication technology that offers increased spectral efficiency and link reliability compared to conventional (small-scale) MIMO wireless systems [1]–[6]. The idea underlying large-scale MIMO is to serve a small number of users from a base station (BS) that is equipped with hundreds of antennas. The excess of antennas at the BS (in contrast to user antennas) allows fine-grained beamforming to each user terminal, which enables energy-efficient and high-throughput data transmission [4].

Another promising technology that is believed to increase the spectral efficiency (compared to conventional half-duplex systems) is full-duplex wireless communication; this approach aims at transmitting and receiving data at the same time and within the same frequency band [7]. In theory, full-duplex data transmission is capable of doubling the spectral efficiency compared to that of half-duplex systems. In practice, however, the benefits promised by full-duplex technology is limited by the so-called *self-interference*, which refers to the transmitted signals that are directly received at the terminal's receive chain (in addition to the data signals received from other transmitters). To combat the fundamental problem of self-interference, a variety of solutions have been proposed in the literature [7]–[13]. The schemes of [8], [9] rely on RF-level and analog-level cancellation methods. In [10], self-interference is cancelled by careful placement of the transmit and receive antennas at each terminal. Another approach is to cancel interference via baseband processing techniques, e.g., using sophisticated transmit and receive filters (see [7], [11]–[13]). More recently, multi-user interference cancellation schemes have been proposed in, e.g., [14], [15].

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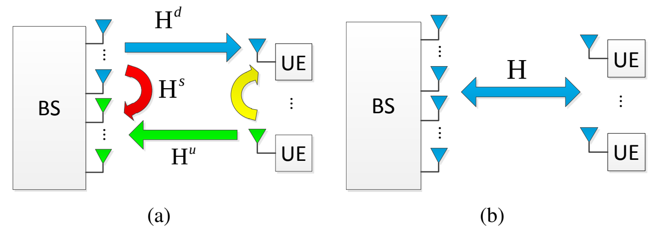

Fig. 1. System overview: (a) full-duplex system; (b) half-duplex system.

Contributions: In this paper, we investigate the application of full-duplex data transmission to cellular (multi-user) communication systems such as 3GPP LTE, by leveraging the benefits of large-scale MIMO. To this end, we propose two self-interference suppression schemes, referred to as extended zero forcing (ZF) precoding and extended regularized channel inversion (RCI), which are capable of jointly exploiting the gains of large-scale MIMO and full-duplex communication. We show that by carefully selecting the ratio between the number of BS transmit and receive antennas, we are able to maximize the sum rate of the communication system. We furthermore demonstrate that full-duplex communication in combination with large-scale MIMO becomes more resilient against (i) user-to-user interference and (ii) residual transmit-RF impairments, which typically limit the performance of full-duplex communication in practical transceiver designs.

II. System Model

The large-scale, full-duplex MIMO wireless system considered in the remainder of this paper is depicted in Fig. 1(a). At the BS, the system is equipped with N_{dl} antennas for the downlink and N_{ul} antennas for the uplink. In addition, there are U user terminals. This part of the system is equivalent to a $N_{dl} \times U$ system in downlink and a $N_{ul} \times U$ system in uplink, where $U < N_{dl}$ and $U < N_{ul}$. As a reference, we also consider a conventional half-duplex $N \times U$ multi-user MIMO system with $N = N_{ul} + N_{dl}$ BS antennas (see Fig. 1(b)).

A. Downlink model

In the downlink, the transmitted (coded) bit stream is mapped to constellation points in the set $\mathcal{O}$. The modulated vector $\mathbf{s}^d = [s_1^d, \ldots, s_U^d]^T$ with $\mathbf{s}^d \in \mathcal{O}^U$, containing the modulated symbols for all U users, is then precoded as

$$\mathbf{u}^d = \mathbf{P}\mathbf{s}^d, \tag{1}$$

where $\mathbf{u}^d = [u_1^d, \ldots, u_{N_{dl}}^d]^T$ corresponds to the precoded vector, and $\mathbf{P}$ is a $N_{dl} \times U$ precoding matrix. The power of the resulting precoded vector is normalized as

$$\mathbf{x}^d = \sqrt{E_\mathrm{s}^d}\frac{\mathbf{u}^d}{\|\mathbf{u}^d\|}. \tag{2}$$

Here, $\mathbf{x}^d = [x_1^d, \ldots, x_{N_{dl}}^d]^T$ is the transmit vector and E_s^d is the downlink transmission power. The power-normalized transmit vector is then transmitted over the wireless channel and the received signal at the i^th user is modeled as follows:

$$y_i^d = \mathbf{h}_i^d\mathbf{x}^d + z_i^d + n_i^d. \tag{3}$$

Here, $\mathbf{h}_i^d \in \mathbb{C}^{1\times N_{dl}}$ is the downlink channel vector generated from WINNER-Phase-2 model [16], z_i^d is the interference generated from the other (transmitting) users, and n_i^d is zero-mean complex Gaussian (ZMCG) noise with variance N_0^d.

B. Uplink model

In the uplink, the transmitted bit stream at each user is encoded and modulated analogously to the downlink. The modulated vector of all U users, denoted by $\mathbf{s}^u = [s_1^u, \ldots, s_U^u]^T$ with $\mathbf{s}^u \in \mathcal{O}^U$, is transmitted over the wireless channel, which is modeled as

$$\mathbf{y}^u = \mathbf{H}^u\mathbf{s}^u + \mathbf{H}^s\mathbf{x}^d + \mathbf{n}^u. \tag{4}$$

Here, $\mathbf{y}^u = [y_1^u, \ldots, y_{N_{ul}}^u]^T$, $\mathbf{H}^u \in \mathbb{C}^{N_{ul}\times U}$ is the (tall and skinny) uplink channel matrix, $\mathbf{H}^s \in \mathbb{C}^{N_{ul}\times N_{dl}}$ is the self-interference channel from the BS transmitters to the BS receivers, and $\mathbf{n}^u \in \mathbb{C}^{N_{ul}}$ models additive noise; $\mathbf{H}^u$ is generated from the WINNER-Phase-2 model [16]; the entries of $\mathbf{H}^s$ are assumed to be i.i.d. ZMCG with variance β [7]; the entries of $\mathbf{n}^u$ are assumed to be i.i.d. ZMCG with variance N_0^u. We furthermore define the uplink transmission power at user i to be $\mathbb{E}\{|s_i|^2\} = E_\mathrm{s}^u/U$.

C. System impairments

To analyze the proposed full-duplex system in a more realistic scenario, we also include one of the key system impairments. In particular, we model residual BS transmit-side (TX) radio-frequency (RF) impairments, which are commonly characterized by the error vector magnitude (EVM). With such residual TX-RF impairments, the transmit vector in (2) can be modeled as follows (see [17] for the details):

$$\mathbf{x}^d \to \mathbf{x}^d + \Delta\mathbf{x}^d. \tag{5}$$

Here, the entries of $\Delta\mathbf{x}^d$ are assumed i.i.d. ZMCG with variance $\varepsilon^2 E_\mathrm{s}^d$, where ε^2 represents the EVM.

III. Self-interference Suppression Schemes

In this section, we develop two self-interference suppression schemes for full-duplex, large-scale MIMO systems. We furthermore characterize the optimal ratio between transmit and receive antennas at the full-duplex BS.

A. Self-interference in large-scale MIMO systems

In large-scale MIMO systems, the precoded downlink signal can be more focused to the receiving antennas as the number of BS transmit antennas increases. As a consequence, one can increase the received SNR at each user [2]. This phenomenon, however, does not necessarily reduce the self-interference power (at the BS). To analyze this behavior, we compute the self-interference power at the i^th BS receiver using (2) and (4) as follows:

$$E_i^s = \|\mathbf{h}_i^s\mathbf{x}^d\|^2 = \mathbb{E}\left\{E_\mathrm{s}^d\,\frac{{\mathbf{s}^d}^H\mathbf{P}^H{\mathbf{h}_i^s}^H\mathbf{h}_i^s\mathbf{P}\mathbf{s}^d}{\|\mathbf{P}\mathbf{s}^d\|^2}\right\}.$$

Here, $\mathbf{h}_i^s \in \mathbb{C}^{1\times N_{dl}}$ is the self-interference channel vector for i^th BS receiver. As the precoding matrix $\mathbf{P}$ is constructed using the matrix $\mathbf{H}^d$, which is assumed to be uncorrelated from $\mathbf{h}_i^s$, the self-interference power corresponds to $E_i^s = \beta^2 E_\mathrm{s}^d$, where β^2 is the variance of each entry in $\mathbf{h}_i^s$. This result indicates the average self-interference power at each BS receiver is constant and does not depend on the number of BS transmit antennas. Hence, self-interference suppression in full-duplex systems is necessary to maintain good transmission performance.

B. Enabling full-duplex for mobile communication

In the typical small-cell systems, such as microcells (with up to 2 km range), the transmission power is around 33 dBm to 40 dBm [18]. By assuming the noise floor is −90 dBm [19], meaning that we need about 123 dB to 130 dB self-interference suppression to enable full-duplex for mobile communication. This requirement significantly exceeds the capabilities of current self-interference suppression techniques, which achieve a reduction of approximately 113 dB [8].

As shown in [2], by maintaining the same received SNR, large-scale MIMO systems can reduce their transmission power at both BS and UE to E_s^d/N_{dl}. This implies that by increasing N_{dl} to, say, 100, the transmission power can be scaled down to the range from 13 dBm to 20 dBm. At this transmission power, we can apply full-duplex transmission to mobile communication in combination with existing self-interference cancellation schemes [8], [20].

However, as we need to cancel the interference from all transmit antennas, a direct application of existing analog and radio frequency domain self-interference suppression methods to a large-scale MIMO BS will result in excessive hardware complexity. As a consequence, we will focus on baseband-level self-interference suppression techniques suitable for massive MIMO base-stations.

C. Self-interference suppression precoding schemes

We propose two self-interference suppression precoding schemes: (i) the extended zero forcing (ZF) precoder and (ii) the extended regularized channel inversion (RCI) precoder. The idea is to form the beams of the downlink signals to the users, while simultaneously form beams to the BS receivers to send all-zero signals, which will avoid self-interference. The extended ZF precoder is designed to minimize the multi-user interference, while the extended RCI is designed to maximize the signal-to-interference-plus-noise ratio (SINR). Both precoders are constructed by extending (1) to

$$\mathbf{u}^d = \mathbf{P}_{ext}\mathbf{s}^d_{ext}, \;\; \mathbf{s}^d_{ext} = \begin{bmatrix} \mathbf{s}^d \\ \mathbf{0}_{N_{ul}\times 1} \end{bmatrix}, \tag{6}$$

where $\mathbf{P}_{ext}$ is the extended precoding matrix and r is the rank of $\mathbf{H}^s$. The vector $\mathbf{0}_{N_{ul}\times 1}$ is the $N_{ul} \times 1$ all-zeros vector to be transmitted to the BS receivers (to suppress self-interference).

1) Extended zero-forcing precoder: To minimize multi-user interference, the conventional ZF precoder used in the downlink of large-scale MIMO systems is constructed as ${\mathbf{H}^d}^H(\mathbf{H}^d{\mathbf{H}^d}^H)^{-1}$ [2], where ${\mathbf{H}^d}^H$ is the Hermitian of $\mathbf{H}^d$. To suppress the self-interference, we extend the ZF precoder to send zeros to the BS receive antennas as

$$\mathbf{P}_{ext} = \mathbf{H}^H_{ext}(\mathbf{H}_{ext}\mathbf{H}^H_{ext})^{-1}, \;\; \mathbf{H}_{ext} = \begin{bmatrix} \mathbf{H}^d \\ \mathbf{H}^s \end{bmatrix}. \tag{7}$$

By applying blockwise matrix inversion, the above extended ZF precoder is equivalent to defining the precoding matrix used for (1) as follows:

$$\begin{aligned} \mathbf{P} =& ({\mathbf{H}^d}^H - {\mathbf{H}^s}^H(\mathbf{H}^s{\mathbf{H}^s}^H)^{-1}\mathbf{H}^s{\mathbf{H}^d}^H) \\ &(\mathbf{H}^d{\mathbf{H}^d}^H - \mathbf{H}^d{\mathbf{H}^s}^H(\mathbf{H}^s{\mathbf{H}^s}^H)^{-1}\mathbf{H}^s{\mathbf{H}^d}^H)^{-1}. \end{aligned} \tag{8}$$

2) Extended regularized channel inversion precoder: Although the ZF precoder can perfectly avoid multi-user interference, the RCI precoder has better performance by maximizing the SINR at each user. The RCI precoder is conventionally defined as ${\mathbf{H}^d}^H(\mathbf{H}^d{\mathbf{H}^d}^H + \alpha\mathbf{I})^{-1}$ with $\alpha = UN^d_0/E^d_\mathrm{s}$ [21]. For a full-duplex system, we extend the RCI precoder to reduce the self-interference as

$$\mathbf{P}_{ext} = \mathbf{H}^H_{ext}(\mathbf{H}_{ext}\mathbf{H}^H_{ext} + \mathbf{R})^{-1}, \;\; \mathbf{R} = \begin{bmatrix} \alpha_1\mathbf{I} & 0 \\ 0 & \alpha_2\mathbf{I} \end{bmatrix}. \tag{9}$$

By following the same derivation as in [21], we set $\alpha_1 = UN^d_0/E^d_\mathrm{s}$ to maximize SINR at each user and $\alpha_2 = 0$ in order to suppress the self-interference at the BS receive antennas. By applying a blockwise matrix inversion, the above extended RCI precoder is equivalent to

$$\begin{aligned} \mathbf{P} =& ({\mathbf{H}^d}^H - {\mathbf{H}^s}^H(\mathbf{H}^s{\mathbf{H}^s}^H)^{-1}\mathbf{H}^s{\mathbf{H}^d}^H) \\ &(\mathbf{H}^d{\mathbf{H}^d}^H + \alpha_1\mathbf{I} - \mathbf{H}^d{\mathbf{H}^s}^H(\mathbf{H}^s{\mathbf{H}^s}^H)^{-1}\mathbf{H}^s{\mathbf{H}^d}^H)^{-1}. \end{aligned} \tag{10}$$

3) Sum-rate optimal antenna ratio: In a large-scale MIMO system, the uplink sum-rate for each user can be approximated [2] as follows:

$$C^u \approx \log_2\left(1 + \frac{N_{ul}}{U}\frac{E^u_s}{N^u_0}\right). \tag{11}$$

Using the same approach, we can also approximate the downlink sum-rate for our proposed extended ZF precoder. In particular, as N_{dl} becomes large, the downlink sum-rate for each user can be approximated as follows:

$$C^d \approx \log_2\left(1 + \frac{(N_{dl} - N_{ul})}{U}\frac{E^d_s}{N^d_0}\right). \tag{12}$$

The expressions in (11) and (12) give rise to the assumption that there is an optimal ratio between BS transmitters and BS receivers to maximize the total sum-rate of both, the downlink and uplink. In particular, by computing $\max_{N_{ul}/N_{dl}}(C^d + C^u)$, the optimal ratio N_{ul}/N_{dl} is achieved by

$$\frac{N_{ul}}{N_{dl}} = \frac{N + \left(U\frac{N^d_0}{E^d_s} - 2U\frac{N^u_0}{E^u_s}\right)}{3N - \left(U\frac{N^d_0}{E^d_s} - 2U\frac{N^u_0}{E^u_s}\right)}, \tag{13}$$

where N is the total number of BS antennas $N = N_{ul} + N_{dl}$. From (13) we see that as E^d_s/N^d_0 and E^u_s/N^u_0 become large, or as N becomes large, one obtains the following sum-rate optimal antenna ratio: $N_{ul}/N_{dl} \approx 1/3$. Hence, by choosing $3\times$ more downlink than uplink antennas, one can maximize the system's total sum rate at high SNRs.

IV. Simulation and Analysis

In this section, we compare the performance of the proposed full-duplex system (i.e., full-duplex BS and user equipment (UE)) using the proposed self-interference suppression schemes at the BS to that of a half-duplex system (i.e., half-duplex BS and UE). At the UE side, we assume the use of the self-interference cancellation techniques from existing work [8], [20]. We further investigate the impact of user-to-user (U2U) interference on the system's performance.

A. System parameters

We assume for the half-duplex system that the downlink and uplink transmissions are carried out in different time slots, which is reasonable for large-scale MIMO systems [1]. For the full-duplex system, downlink and uplink transmissions occur simultaneously. The full-duplex and half-duplex BS are equipped with same number of antennas. Since the hardware complexity of the UE is critical, we assume both the full-duplex UE and half-duplex UE are equipped with 1 transmit and 1 receive chains, which are equivalent to 1 antenna for half-duplex UE and 2 antennas for full-duplex UE. Both systems deploy OFDM transmission with 128 sub-carriers and a carrier frequency of 5.25 GHz.

B. Full-duplex system vs. half-duplex system

We compare the system's sum-rate of the proposed full-duplex and half-duplex system over a period of two OFDM symbol time slots. We fix the number of BS antennas, N, and vary the ratio of BS receive antennas to BS transmit antennas, N_{ul}/N_{dl}. We assume the following parameters:

- The number of UEs, U, is 4.
- The number of BS antennas, N, is 128.
- For the half-duplex system, in both the uplink and the downlink time slot, the system configuration is 128×4.
- For the full-duplex system, the BS has N_{dl} transmitters and N_{ul} receivers and serves 4 UEs simultaneously. In the uplink, the system configuration is $N_{ul} \times 4$; in the downlink, the system configuration is $N_{dl} \times 4$.

The results in Figs. 2(a) and 2(b) show that more receive antennas N_{ul} at the BS result in higher uplink sum-rate, whereas more BS transmit antennas N_{dl} result in higher downlink sum-rate. The results also show that although there

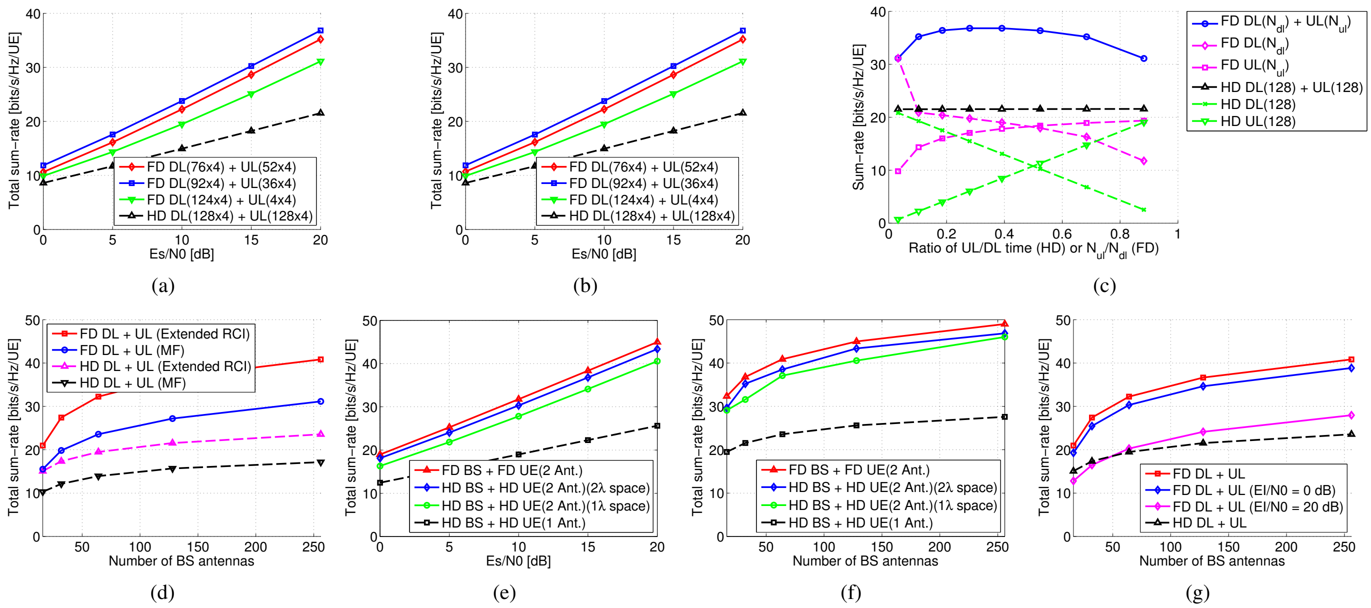

Fig. 2. (a) Extended ZF precoder with different UL/DL antenna ratios ($N = 128$); (b) Extended RCI precoder different UL/DL antenna ratios ($N = 128$); (c) Extended RCI precoder different UL/DL antenna ratios ($N = 128$; $E_s/N_0 = 20$ dB); (d) Extended RCI precoder and MF precoder ($N_{ul}/N_{dl} = 5/11$; E_s/N_0= 20 dB); (e) Extended RCI precoder with different number of antennas at UE ($N = 128$); (f) Extended RCI precoder with different number of antennas at UE ($N_{ul}/N_{dl} = 5/11$; E_s/N_0= 20 dB); (g) Extended RCI precoder with U2U interference ($N_{ul}/N_{dl} = 5/11$; E_s/N_0= 20 dB).

is some loss by sacrificing the degrees-of-freedom to perform self-interference suppression, the full-duplex system still has close to the twice sum-rate compared to the half-duplex system. Furthermore, both simulation results confirm that the sum-rate of the extended ZF precoder is very close to that of the extended RCI precoder. Hence, in what follows, we only consider the extended RCI precoder.

Fig. 2(c) shows the sum-rate trade-off controlled by the number of uplink and downlink antennas. As indicated by the approximation (13), the optimal ratio N_{ul}/N_{dl} that maximizes the total sum-rate is approximately $1/3$.

We next investigate the effect of the number of antennas N at the BS on the sum-rate with a fixed ratio of N_{ul}/N_{dl} . In this comparison, we include the matched filter (MF) precoding scheme, which has no self-interference cancellation property (for a finite number of antennas). The MF uses $(\mathbf{H}^d)^H$ as a precoding matrix. We assume the following parameters:

- The total number of BS antennas, N, is 16, 32, 64, 128, and 256.
- For the half-duplex system, the system configuration is $N \times 4$ in the downlink and $N \times 4$ in the uplink.
- For the full-duplex system, the system configuration is $11/16N \times 4$ in the downlink and $5/16N \times 4$ in the uplink.

Fig. 2(d) shows that extended RCI precoding achieves higher sum-rate than the MF precoder. As the number of BS antennas becomes large, the gain of full-duplex over half-duplex communication is roughly equal to $\log_2(\frac{N}{8U}\frac{E_s}{N_0})$, which can be obtained using Eqs. 11 and 12 with $E_s/N_0 = E_s^d/N_0^d = E_s^u/N_0^u$.

We additionally compare the performance of our proposed full-duplex system with a half-duplex system having 2 antennas at the UE side. Since the UEs are typically limited in size, we investigate different antenna spacings. Fig. 2(e) shows the results of the scenario with a fixed total number of BS antennas N. In the half-duplex system, the system configuration is 128×1 or 128×2 for downlink and uplink. In the full-duplex system, the system configuration is 88×1 for downlink and 40×1 for uplink. Fig. 2(f) shows the results of the scenario with fixed ratio $N_{ul}/N_{dl} = 5/11$ in full-duplex system. The number of BS antennas, N, is 16, 32, 64, 128, or 256. Our simulation results indicate that even with 2 antennas having 2λ antenna spacing at the UE side, a half-duplex system still has lower sum-rate than the full-duplex system. Moreover, 2-antenna half-duplex UEs (with 2 transmit and receive chains) require more complexity than 2-antenna full-duplex UEs (with 1 transmit and receive chains).

C. User-to-user (U2U) interference

The impact of the U2U interference on the full-duplex system is considered next. The U2U interference is treated as ZMCG noise with variance E_I. In the simulation, the U2U interference-to-noise-ratio E_I/N_0^d is 0 dB or 20 dB, while other simulation parameters are the same as the above 4 user case. Fig. 2(g) shows that the sum-rate gain of full-duplex over half-duplex increases as the number of BS antennas increases, which renders full-duplex more robust to U2U interference.

V. System Impairments

In this section, we investigate the effects of residual TX-RF impairments (measured by the EVM) at the BS transmission on the performance of the considered full-duplex system.

For large-scale MIMO, an increase in the number of BS antennas N leads to a reduction in terms of the transmit power of each BS transmitter due to the fact that we normalize the transmit power using E_s^d/N. As realized in [22], the

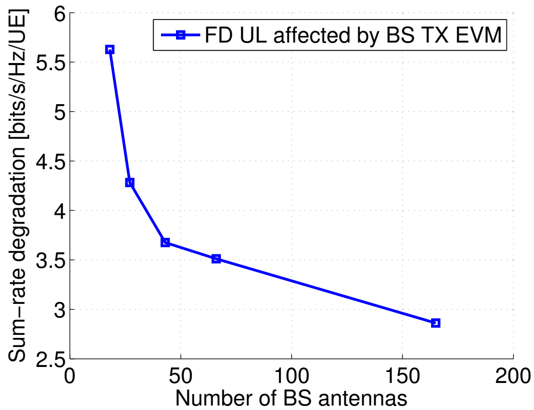

Fig. 3. FD UL sum-rate degradation by residual TX-RF impairments (EVM) at the BS. Note that increasing the number of BS antennas reduces the transmit power per RF chain and, hence, the EVM; this reduces the sum-rate loss.

EVM reduces as the transmission power decreases, which is a consequence of real-world RF chain designs [23]. With this in mind, we can simulate the impact of BS transmission EVM on the sum-rate. Because the residual self-interference due to BS TX-RF impairments remains to be strong, passive suppression methods as proposed in [20] are applied at the BS antennas by cross-polarizing the BS transmit antennas and equipping the BS receive antennas with (passive) RF absorbers between the transmit and receive antennas. This passive suppression approach can achieve up to 70 dB isolation gain [20]. The BS transmission power, E_s^d, is fixed at 20 dBm and the noise floor is assumed to be -90 dBm [9]. The number of half-duplex UEs, U, is 4. The number of BS transmitters and receivers, N, is 12, 18, 27, 43, 66, or 165.

For the full-duplex system, the system configuration is around $11/16N \times 4$ for downlink and $5/16N \times 4$ for uplink. The received uplink signal at E_s^u/N_0^u = 20 dB.

Fig. 3 shows that by increasing the number of BS antennas the transmit EVM decreases; this, in turn, reduces the sum-rate degradation caused by residual TX-RF impairments dramatically. Hence, having more transmit antennas at the BS is beneficial to reduce the residual TX-RF impairments.

VI. Conclusion

In this paper, we have investigated a combination of large-scale MIMO with full-duplex transmission. To this end, we have proposed two new self-interference suppression schemes, which leverage the excessive degrees of freedom present in large-scale MIMO systems. We have shown that the optimal (in terms of the sum-rate) transmit-to-receive antenna ratio at the base-station is approximately $1/3$ in the high-SNR regime. We have also shown that full-duplex transmission can be made more robust against inter-user (or user-to-user) interference, which inevitably occurs in multi-user (cellular) communication systems. In addition, we have demonstrated that the performance degradation caused by residual transmit-side (TX) radio-frequency (RF) impairments can be mitigated significantly, when jointly increasing the number of BS antennas and by using passive antenna isolation methods.

References

[1] T. L. Marzetta, "Noncooperative cellular wireless with unlimited numbers of base station antennas," *IEEE Trans. Wireless Commun.*, vol. 9, no. 11, pp. 3590–3600, Nov. 2010.

[2] F. Rusek, D. Persson, B. K. Lau, E. G. Larsson, T. L. Marzetta, O. Edfors, and F. Tufvesson, "Scaling up MIMO: Opportunities and challenges with very large arrays," *arXiv preprint: 1201.3210v1*, Jan. 2012.

[3] H. Huh, G. Caire, H. C. Papadopoulos, and S. A. Ramprashad, "Achieving "massive MIMO" spectral efficiency with a not-so-large number of antennas," *arXiv preprint: 1107.3862v2*, Sept. 2011.

[4] H. Q. Ngo, E. G. Larsson, and T. L. Marzetta, "Energy and spectral efficiency of very large multiuser MIMO systems," *arXiv preprint: 1112.3810v2*, May 2012.

[5] B. Yin, M. Wu, C. Studer, J. R. Cavallaro, and C. Dick, "Implementation trade-offs for linear detection in large-scale MIMO systems," in *Proc. IEEE ICASSP*, Vancouver, Canada, May 2013, pp. 2679–2683.

[6] M. Wu, B. Yin, A. Vosoughi, C. Studer, J. R. Cavallaro, and C. Dick, "Approximate matrix inversion for high-throughput data detection in the large-scale MIMO uplink," in *Proc. IEEE ISCAS*, Beijing, China, May 2013, pp. 2155–2158.

[7] B. Day, A. Margetts, D. Bliss, and P. Schniter, "Full-duplex bidirectional MIMO: Achievable rates under limited dynamic range," *IEEE Trans. Signal Process.*, vol. 60, no. 7, pp. 3702–3713, 2012.

[8] M. Jain, J. I. Choi, T. Kim, D. Bharadia, S. Seth, K. Srinivasan, P. Levis, S. Katti, and P. Sinha, "Practical, real-time, full duplex wireless," in *Proc. ACM MobiCom*, 2011, pp. 301–312.

[9] M. Duarte and A. Sabharwal, "Full-duplex wireless communications using off-the-shelf radios: Feasibility and first results," in *Proc. 44th Asilomar Conf. on Signals, Systems and Computers*, Nov. 2010, pp. 1558–1562.

[10] E. Aryafar, M. A. Khojastepour, K. Sundaresan, S. Rangarajan, and M. Chiang, "MIDU: enabling MIMO full duplex," in *Proc. ACM MobiCom*, 2012, pp. 257–268.

[11] T. Riihonen, S. Werner, and R. Wichman, "Mitigation of loopback self-interference in full-duplex MIMO relays," *IEEE Trans. Signal Process.*, vol. 59, no. 12, pp. 5983–5993, 2011.

[12] P. Lioliou, M. Viberg, M. Coldrey, and F. Athley, "Self-interference suppression in full-duplex MIMO relays," in *Proc. 44th Asilomar Conf. on Signals, Systems and Computers*, 2010, pp. 658–662.

[13] B. Chun, E.-R. Jeong, J. Joung, Y. Oh, and Y. H. Lee, "Pre-nulling for self-interference suppression in full-duplex relays," in *Proc. Asia-Pacific Signal and Information Process. Association Annual Summit and Conf.*, Sapporo, Japan, Oct. 2009.

[14] J. Bai and A. Sabharwal, "Decode-and-cancel for interference cancellation in a three-node full-duplex network," in *Proc. 46th Asilomar Conf. on Signals, Systems and Computers*, 2012, pp. 1285–1289.

[15] A. Sahai, S. Diggavi, and A. Sabharwal, "On Degrees-of-Freedom of Full-Duplex Uplink/Downlink Channel," in *Proc. ITW*, 2013.

[16] L. Hentilä, P. Kyösti, M. Käske, M. Narandzic, and M. Alatossava. (2007, December) Matlab implementation of the WINNER phase II channel model ver 1.1. [Online]. Available: https://www.ist-winner.org/phase_2_model.html

[17] C. Studer, M. Wenk, and A. Burg, "MIMO transmission with residual transmit-RF impairments," in *Proc. International ITG Workshop on Smart Antennas*, 2010, pp. 189–196.

[18] (2013, Feb.) DUPLO Deliverable D1.1. [Online]. Available: http://ec.europa.eu/information_society/apps/projects/logos/9/316369/080/deliverables/001_D11v10.pdf

[19] M. Duarte, A. Sabharwal, V. Aggarwal, R. Jana, K. K. Ramakrishnan, C. W. Rice, and N. K. Shankaranarayanan, "Design and characterization of a full-duplex multi-antenna system for wifi networks," *arXiv preprint: 1210.1639*, vol. abs/1210.1639, Oct. 2012.

[20] E. Everett, A. Sahai, and A. Sabharwal, "Passive self-interference suppression for full-duplex infrastructure nodes," *arXiv preprint: 1302.2185v1*, vol. abs/1302.2185, Feb. 2013.

[21] C. Peel, B. Hochwald, and A. Swindlehurst, "A vector-perturbation technique for near-capacity multiantenna multiuser communication-part I: channel inversion and regularization," *IEEE Trans. Commun.*, vol. 53, no. 1, pp. 195–202, 2005.

[22] C. Studer, M. Wenk, and A. Burg, "System-level implications of residual transmit-RF impairments in MIMO systems," in *Proc. 5th European Conf. on Antennas and Propagation*, 2011, pp. 2686–2689.

[23] S.-H. Baek, C. Park, and S. Hong, "A fully integrated 5-GHz CMOS power amplifier for IEEE 802.11a WLAN applications," *J. Semiconduct. Technol. Sci.*, vol. 7, no. 2, pp. 98–101, 2007.