Full Duplex Assisted Interference Suppression for Underlay Device-to-Device Communications

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***Abstract*—The paper considers underlay Device-to-Device (D2D) communications in a cellular network, where a pair of D2D users communicates subject to the interference from the base station that is transmitting to a cellular user in the downlink. To mitigate the interference while not affecting the performance of the cellular user, a full duplex (FD) assisted interference suppression mechanism is introduced and optimized. The key idea is to exploit the FD capability of the D2D transmitting user to send the desired signal and forward the received interference simultaneously to the D2D receiving user. We obtain the explicit expression of the optimal transmitted signal for the D2D link, and analyze the asymptotical performance of the proposed scheme in high signal-to-noise ratio regime. Simulations validate our analytical results and demonstrate a noticeable performance gain of the proposed FD assisted scheme over the conventional half-duplex scheme.**

***Index Terms*—Full duplex, Device-to-Device, Interference suppression.**

I. Introduction

Underlay Device-to-Device (D2D) communications in conventional cellular networks have attracted much attention recently [1]. Through the direct connection between proximal user equipments (UEs), D2D communications can potentially improve network performance with higher spectrum reuse, better coverage, and reduced traffic congestion, and can also enhance user experience with higher data rate, lower power consumption, and smaller service latency [2].

In practice, however, realizing the promised benefits of underlay D2D communications is challenging because of the new interference between the cellular and D2D links. For example, if the D2D communications utilize the cellular downlink frequency-time resources, the base station (BS) may cause severe interference to the D2D link. To solve the problem, joint power control for cellular and D2D links was studied in [3,4], the interference-avoiding multi-antenna precoding technique was proposed in [5], and resource allocation schemes for interference coordination were studied in [6]. These techniques have been shown effective for suppressing the interference from the BS to the D2D link. However, all the techniques require the coordination between cellular and D2D links, which consume some resources of the BS, e.g., transmit power or antennas, to mitigate the interference to the D2D link, leading to the performance degradation of the cellular UE.

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In this paper we strive to study the interference suppression scheme without relying on the coordination between cellular and D2D links, which will not consume the resources of the BS and therefore will not degrade the performance of the cellular UE. To this end, we consider using full duplex (FD) technique to D2D communications. Theoretically, FD communication is able to double the spectral efficiency by transmitting and receiving simultaneously over the same frequency-time resources [7]. The key challenge in implementing a FD transceiver is the self-interference caused by its own transmitter to the receiver. Therefore, various self-interference cancellation methods have been studied in the literature [8]. Recent research has approved the plausibility of FD technique for short-range point-to-point communications and demonstrated noticeable performance gain of FD over half-duplex (HD) schemes [9]. The combination of FD with D2D was first studied in [10], where the sum ergodic rate of the FD underlay D2D communications in a cellular network was analyzed. However, in [10] the interference between cellular and D2D links was not dealt with.

In this paper, we consider a pair of D2D UEs communicating subject to the interference from the BS that is transmitting to a cellular UE, where the D2D transmitting UE has the FD capability. We propose an interference suppression scheme to improve the performance of the D2D link, which is transparent to the cellular link in the sense that no changes are needed for the transmission of the cellular link. The basic idea of the proposed scheme is to let the FD D2D transmitting UE forward the received interference from the BS to the D2D receiving UE, while at the same time sending the desired signal. The optimal transmitted signal of the D2D link that maximizes the data rate is obtained, and the performance of the D2D link is analyzed asymptotically. Simulations validate our analytical results, and demonstrate a substantial performance gain of the proposed FD-assisted scheme over the conventional HD scheme.

II. System Model

Consider a D2D communication link from UE_2 to UE_3 operating in the same frequency-time resources as the cellular

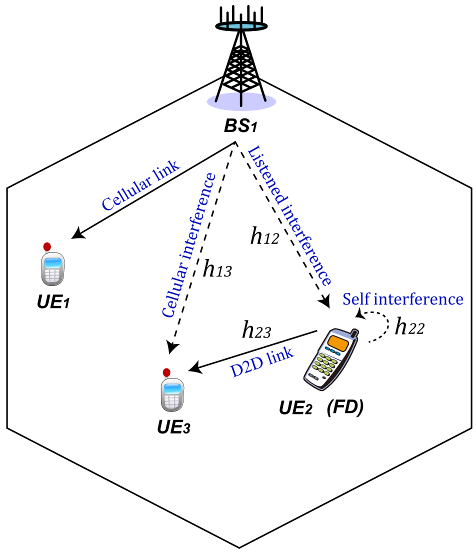

Fig. 1. System model of FD underlay D2D communications.

downlink link from BS_1 to the cellular user, UE_1,[1] as shown in Fig. 1, where all the UEs are in the coverage of BS_1. For simplicity, we refer to the interference from BS_1 to the D2D link as the *cellular interference* in the rest of the paper.

Considering the limited transmit power of UEs, we assume that UE_1 is judiciously scheduled by BS_1 and receives no interference from UE_2. Further recalling that we will not sacrifice the resources of BS_1, e.g., transmit power or antennas, to mitigate the interference to the D2D link, the performance of UE_1 will not be affected by the underlay D2D link. Therefore, in the paper we focus on the performance of UE_3.

Suppose that BS_1 has one effective transmit antenna,[2] UE_3 has one receive antenna, and UE_2 has the FD capability with one transmit and one receive antenna. We can express the received signal of UE_2 as

$$\tilde{y}_2 = \sqrt{P_1} h_{12} s_1 + h_{22} x_2 + n_2, \quad (1)$$

where P_1 is the transmit power of BS_1, h_{12} is the channel from BS_1 to UE_2, s_1 is the signal intended for UE_1 with $\mathbb{E}\{|s_1|^2\} = 1$, h_{22} is the self-interference channel between the transmit and receive antenna of UE_2, x_2 is the transmitted signal of UE_2, and n_2 is the additive white Gaussian noise (AWGN) with zero mean and variance σ_n^2.

Since the transmitted signals x_2 is known at UE_2, the self-interference can be canceled as

$$y_2 = \tilde{y}_2 - \hat{h}_{22} x_2 \triangleq \sqrt{P_1} h_{12} s_1 + e_{22} x_2 + n_2, \quad (2)$$

where $\hat{h}_{22}$ is the estimation of h_{22}, and e_{22} is the channel estimation error following complex Gaussian distribution with zero mean and variance σ_e^2.

[1] The system model can be straightforwardly extended to the case where D2D communications utilize uplink cellular resources.

[2] This model is applicable to the multi-antenna BS, where the beamforming at BS_1 to UE_1 turns the multiple antennas as one effective antenna.

The self-interference-cancelled received signal y_2 is then transmitted directly together with the desired signal of UE_3, where the decoding of y_2 is not allowed in order to produce a small processing delay. In narrow-band systems, the small delay is equivalent to a phase shift of the signal. Then the combined transmitted signal of UE_2 can be expressed as

$$x_2 = w_1 e^{j\phi} y_2 + w_2 s_2, \quad (3)$$

where w_1 and w_2 are the weights to be designed, $e^{j\phi}$ is the phase shift added to the forwarded signal caused by processing delay, and s_2 denotes the signal intended for UE_3 with $\mathbb{E}\{|s_2|^2\} = 1$.

By taking the expectations over the statistically independent channel estimation error e_{22}, noises n_2, and transmitted data s_1 and s_2, we can obtain from (2) and (3) that the transmit power of UE_2 satisfies

$$\mathbb{E}\{|x_2|^2\} = |w_1|^2 (P_1 |h_{12}|^2 + \sigma_e^2 \mathbb{E}\{|x_2|^2\} + \sigma_n^2) + |w_2|^2. \quad (4)$$

Then we can express the maximal transmit power constraint of UE_2 as

$$\mathbb{E}\{|x_2|^2\} = \frac{|w_1|^2 (P_1 |h_{12}|^2 + \sigma_n^2) + |w_2|^2}{1 - |w_1|^2 \sigma_e^2} \leq P_2, \quad (5)$$

which can be equivalently written as

$$|w_1|^2 (P_1 |h_{12}|^2 + \sigma_I^2 + \sigma_n^2) + |w_2|^2 \leq P_2, \quad (6)$$

where $\sigma_I^2 \triangleq P_2 \sigma_e^2$ denotes the average power of residual self-interference, and P_2 is the maximal transmit power of UE_2.

The received signal of UE_3 can be expressed as

$$y_3 = h_{23} x_2 + \sqrt{P_1} h_{13} s_1 + n_3, \quad (7)$$

where h_{23} and h_{13} are the channels from UE_2 and BS_1 to UE_3, respectively, and n_3 is the AWGN with zero mean and variance σ_n^2.

From (2), (3) and (7), we can obtain the signal-to-interference-plus-noise ratio (SINR) of UE_3 as

$$\mathrm{SINR}_{3,FD} = \quad (8)$$
$$\frac{|h_{23}|^2 |w_2|^2}{P_1 |h_{23} h_{12} e^{j\phi} w_1 + h_{13}|^2 + |h_{23}|^2 |w_1|^2 (\sigma_e^2 \mathbb{E}\{|x_2|^2\} + \sigma_n^2) + \sigma_n^2}.$$

When w_1 is selected as zero, the FD system reduces to a HD underlay D2D system. Considering (6), we know that in this case the SINR is maximized when $w_2 = \sqrt{P_2}$, which is

$$\mathrm{SINR}_{3,HD}^{\star} = \frac{P_2 |h_{23}|^2}{P_1 |h_{13}|^2 + \sigma_n^2}. \quad (9)$$

With FD the interference term $P_1 |h_{23} h_{12} e^{j\phi} w_1 + h_{13}|^2$ in (8) can be reduced by optimizing the weights w_1 and w_2, aimed at maximizing the SINR of UE_3. The optimization problem can be formulated as

$$\max_{w_1, w_2} \ \mathrm{SINR}_{3,FD} \quad (10a)$$
$$s.\ t.\ |w_1|^2 (P_1 |h_{12}|^2 + \sigma_I^2 + \sigma_n^2) + |w_2|^2 \leq P_2. \quad (10b)$$

III. FD Assisted Interference Suppression

A. Optimal Solution

To obtain a closed-form solution to problem (10), we first present two lemmas regarding the optimal solutions.

Lemma 1: *The globally optimal solutions to problem (10) make the constraint in (10b) hold with equality.*

Proof: By substituting the expression of $\mathbb{E}\{|x_2|^2\}$ given in (5) into (8), one can find that $\mathrm{SINR}_{3,FD}$, i.e., the objective function of problem (10) is an increasing function of $|w_2|^2$. Therefore, we can always improve the performance of UE_3 by increasing $|w_2|^2$, i.e., increasing the transmit power of the desired signal of UE_3, until UE_2 has transmitted with its maximal power. ■

With Lemma 1, we have $\mathbb{E}\{|x_2|^2\} = P_2$, and therefore the term $\sigma_e^2\mathbb{E}\{|x_2|^2\}$ in (8) can be expressed as σ_I^2.

Lemma 2: *The optimal w_1, denoted by $w_1^\star$, satisfies*

$$\frac{w_1^\star}{|w_1^\star|} = -\frac{h_{13}|h_{23}||h_{12}|e^{-j\phi}}{|h_{13}|h_{23}h_{12}}. \tag{11}$$

Proof: We can observe from (8) that the phase of w_1, i.e., $\frac{w_1}{|w_1|}$, only affects the interference term $P_1|h_{23}h_{12}e^{j\phi}w_1{+}h_{13}|^2$. Consider that $P_1|h_{23}h_{12}e^{j\phi}w_1{+}h_{13}|^2 \geq P_1(|h_{23}h_{12}w_1e^{j\phi}| - |h_{13}|)^2$, where the equality holds when $h_{23}h_{12}e^{j\phi}w_1 = -\lambda h_{13}$ with any $\lambda > 0$. Then one can easily find that the phase of the optimal $w_1^\star$ needs to satisfy (11). ■

Based on Lemma 1, we can replace w_2 with w_1. Further considering Lemma 2, we can equivalently turn problem (10) into the optimization problem with respect to $|w_1|$ as

$$\max_{|w_1|} \frac{|h_{23}|^2(P_2 - |w_1|^2(P_1|h_{12}|^2 + \sigma_I^2 + \sigma_n^2))}{P_1(|h_{23}||h_{12}||w_1|{-}|h_{13}|)^2{+}|h_{23}|^2|w_1|^2(\sigma_I^2{+}\sigma_n^2){+}\sigma_n^2} \tag{12a}$$

$$s.\ t.\ |w_1|^2(P_1|h_{12}|^2 + \sigma_I^2 + \sigma_n^2) \leq P_2 \tag{12b}$$

$$|w_1| \geq 0. \tag{12c}$$

Theorem 1: *The optimal objective value of problem (12), i.e. the maximal SINR of UE_3, can be expressed as*

$$\mathrm{SINR}_{3,FD}^\star = \frac{1}{\frac{C}{2B|w_1^\star|} - 1}, \tag{13}$$

where $|w_1^\star|$ is the magnitude of the optimal w_1 with the expression

$$|w_1^\star| = \frac{A + D - \sqrt{(A+D)^2 - \frac{AC^2}{B}}}{C}, \tag{14}$$

where $A = P_2|h_{23}|^2$, $B = P_1|h_{12}|^2|h_{23}|^2 + |h_{23}|^2(\sigma_I^2 + \sigma_n^2)$, $C = 2P_1|h_{12}||h_{13}||h_{23}|$, and $D = P_1|h_{13}|^2 + \sigma_n^2$.

Proof: See [11]. ■

The value of $|w_1^\star|$ given in (14) is real and non-negative, because the term $(A + D)^2 - AC^2/B$ is non-negative with the lower bound $(P_2|h_{23}|^2 - P_1|h_{13}|^2)^2$, which is obtained by setting $\sigma_I^2 = \sigma_n^2 = 0$ in B and D.

Based on (11) and (14), we can obtain the optimal $w_1^\star$, and then according to Lemma 1 we can obtain the optimal $w_2^\star$ as

$$w_2^\star = \sqrt{P_2 - |w_1^\star|^2(P_1|h_{12}|^2 + \sigma_I^2 + \sigma_n^2)}, \tag{15}$$

where $w_2^\star$ is selected as a real number because any phase multiplied to $w_2^\star$ will not change the optimal value of $\mathrm{SINR}_{3,FD}$.

B. Asymptotic Performance Analysis

To gain some insight on how FD assists cellular interference suppression, we next consider a cellular interference-limited scenario, where the signal-to-noise ratio (SNR) of the D2D link is high enough that σ_n^2 approaches to zero.

1) Perfect Self-interference Cancellation: Under the assumption of perfect self-interference cancellation, i.e., $\sigma_I^2 = 0$, we have $B \approx P_1|h_{12}|^2|h_{23}|^2$ and $D \approx P_1|h_{13}|^2$ in high SNR regime, where the approximations are accurate as $\sigma_n^2 \to 0$. Then based on Theorem 1, the optimal $|w_1^\star|$ can be obtained as

$$\begin{aligned}|w_1^\star| &\approx \frac{P_2|h_{23}|^2{+}P_1|h_{13}|^2 - \left|P_2|h_{23}|^2{-}P_1|h_{13}|^2\right|}{2P_1|h_{12}||h_{13}||h_{23}|} \\ &= \frac{\min(P_2|h_{23}|^2, P_1|h_{13}|^2)}{P_1|h_{12}||h_{13}||h_{23}|} \triangleq \frac{\eta}{P_1|h_{12}||h_{13}||h_{23}|}.\end{aligned} \tag{16}$$

By substituting (16) into (12a) and after some manipulations, we can obtain the maximal SINR of UE_3 as

$$\mathrm{SINR}_{3,FD}^\star \approx \frac{P_1P_2|h_{13}|^2|h_{23}|^2 - \eta^2}{(\eta{-}P_1|h_{13}|^2)^2{+}\left(\frac{\eta^2}{P_1|h_{12}|^2}{+}P_1|h_{13}|^2\right)\sigma_n^2}. \tag{17}$$

The value of η, defined in (16), depends on the relationship between $P_2|h_{23}|^2$ and $P_1|h_{13}|^2$, which are the strength of the desired signal and the cellular interference, respectively. In the following two cases are discussed.

- **Case 1:** $P_1|h_{13}|^2 < P_2|h_{23}|^2$

  In this case, the cellular interference is weaker than the desired signal. We have $\eta = P_1|h_{13}|^2$ and the maximal SINR, denoted by $\overline{\mathrm{SINR}}_{3,FD}^\star$, is

  $$\overline{\mathrm{SINR}}_{3,FD}^\star \approx \frac{P_2|h_{23}|^2 - P_1|h_{13}|^2}{\left(\frac{|h_{13}|^2}{|h_{12}|^2} + 1\right)\sigma_n^2}. \tag{18}$$

  It implies that in this case the FD UE_2 can thoroughly eliminate the interference from BS_1 by properly allocating its transmit power.

  When compared with the HD case, the performance gain of the proposed scheme can be obtained as

  $$\frac{\overline{\mathrm{SINR}}_{3,FD}^\star}{\mathrm{SINR}_{3,HD}^\star} \approx \frac{P_1\left(1 - \frac{P_1|h_{13}|^2}{P_2|h_{23}|^2}\right)}{\left(\frac{1}{|h_{12}|^2} + \frac{1}{|h_{13}|^2}\right)\sigma_n^2}. \tag{19}$$

- **Case 2:** $P_1|h_{13}|^2 \geq P_2|h_{23}|^2$

  When the cellular interference is stronger, we have $\eta = P_2|h_{23}|^2$ and the maximal SINR, denoted by $\widehat{\mathrm{SINR}}_{3,FD}^\star$, is

  $$\widehat{\mathrm{SINR}}_{3,FD}^\star \approx \frac{P_2|h_{23}|^2}{P_1|h_{13}|^2{-}P_2|h_{23}|^2{+}\frac{\frac{P_2^2|h_{23}|^4}{P_1|h_{12}|^2}+P_1|h_{13}|^2}{P_1|h_{13}|^2-P_2|h_{23}|^2}\sigma_n^2}. \tag{20}$$

For very strong interference, i.e., $P_1|h_{13}|^2 \gg P_2|h_{23}|^2$, $\widehat{\mathrm{SINR}}^{\star}_{3,FD}$ can be further approximated as

$$\widehat{\mathrm{SINR}}^{\star}_{3,FD} \approx \frac{P_2|h_{23}|^2}{P_1|h_{13}|^2 - P_2|h_{23}|^2}. \tag{21}$$

The performance gain of FD over HD in this case can be obtained as

$$\frac{\widehat{\mathrm{SINR}}^{\star}_{3,FD}}{\mathrm{SINR}^{\star}_{3,HD}} \approx \frac{1}{1 - \frac{P_2|h_{23}|^2}{P_1|h_{13}|^2}}. \tag{22}$$

From the analysis, we can obtain the following observations.

- ***Impact of*** h_{12}*:* It is shown from (18) and (20) that the performance of UE_3 increases with the growth of $|h_{12}|$. This is because given the power of UE_2 allocated for forwarding the listened cellular interference, which is $|w_1|^2(P_1|h_{12}|^2 + \sigma_n^2)$ under the assumption of perfect self-interference cancellation, a large $|h_{12}|$ will reduce the power used for forwarding the noise and thus improves the power usage efficiency. But when the system is cellular interference dominated, the impact of $|h_{12}|$ on the performance is negligible as shown by (21).
- ***Impact of*** h_{23} ***and*** h_{13}*:* It is shown by (9), (18) and (21) that increasing the strength of the desired signal $P_2|h_{23}|^2$ can improve the performance of both FD and HD. However, the performance improvement for the FD scheme is more significant because both (19) and (22) show that the performance gain of FD over HD increases with $P_2|h_{23}|^2$. It can also be seen that the performance gain of FD over HD decreases with the strength of cellular interference channel $P_1|h_{13}|^2$.
- ***Impact of FD****:* When the cellular interference is large so that UE_2 has no enough transmit power to thoroughly eliminate it by forwarding the listened interference, UE_2 needs to balance the power allocated to the desired signal and the forwarded interference. Therefore, only part of power can be used for the two purposes. However, we can observe an appealing result from (21) that the full power of UE_2 seems reusable for transmitting desired signal ($P_2|h_{23}|^2$ in the nominator) and reducing the interference ($P_2|h_{23}|^2$ in the denominator) simultaneously in the cellular interference dominated scenarios. The seemingly contradictory results can be explained as follows. With the optimal $|w_1^{\star}|$ given in (16), we can compute the strength of the desired signal and cellular interference as $\delta \cdot P_2|h_{23}|^2$ and $\delta^2 \cdot P_1|h_{13}|^2$, respectively, where $\delta = 1 - \frac{P_2|h_{23}|^2}{P_1|h_{13}|^2}$. Noting that $\delta < 1$, we can find that the proposed scheme can sacrifice the strength of the desired signal to obtain more significant reduction of cellular interference, which leads to the illusion that the power of UE_2 is reusable.

2) Large Residual Self-interference: When the self-interference cancellation for FD is imperfect and the residual self-interference, σ_I^2, is large, the parameter B is large and the term $\frac{AC^2}{B}$ is small. Then by using the first-order approximation, $\sqrt{c - z} \approx \sqrt{c} - \frac{1}{2\sqrt{c}}z$, for small z, we can approximate $|w_1^{\star}|$ given in (14) as

$$|w_1^{\star}| \approx \frac{AC}{2(A+D)B}, \tag{23}$$

where the approximation is accurate when $\frac{AC^2}{B} \to 0$.

Then the transmit power of UE_2 allocated to the forwarded cellular interference can be obtained as

$$\begin{aligned} &|w_1^{\star}|^2(P_1|h_{12}|^2 + \sigma_I^2 + \sigma_n^2) \\ &\approx \frac{P_1^2 P_2^2 |h_{12}|^2|h_{13}|^2|h_{23}|^2}{(P_1|h_{13}|^2 + P_2|h_{23}|^2 + \sigma_n^2)(P_1|h_{12}|^2 + \sigma_I^2 + \sigma_n^2)}. \end{aligned} \tag{24}$$

By substituting (23) into (13), we can obtain the maximal SINR of UE_3, denoted by $\widetilde{\mathrm{SINR}}^{\star}_{3,FD}$, as

$$\widetilde{\mathrm{SINR}}^{\star}_{3,FD} \approx \frac{P_2|h_{23}|^2}{P_1|h_{13}|^2 + \sigma_n^2} = \mathrm{SINR}^{\star}_{3,HD}. \tag{25}$$

It can be seen from (24) that the transmit power for forwarding cellular interference at UE_2 decreases with the growth of residual self-interference. When the residual self-interference is very large, all power of UE_2 is used for the transmission of desired signals, and therefore the proposed FD scheme reduces to the HD scheme, as shown by (25).

C. Remarks

Remark 1: With the proposed FD scheme, the FD user, UE_2, can adaptively switch between FD mode and HD mode by optimizing the powers allocated for transmitting desired signals and forwarding received interference. Therefore, the proposed FD scheme will always outperform the HD scheme under the condition of perfect channels.

Remark 2: To apply the proposed FD scheme, UE_2 needs to have the channels h_{12}, h_{23} and h_{13}. In time division duplex (TDD) systems, the channels h_{12} and h_{23} can be estimated at UE_2 from the received training signals sent by BS_1 and UE_3, while h_{13} can be first estimated by UE_3 and then feeded back to UE_2. We will evaluate the performance of the proposed FD scheme under imperfect channel estimation (CE) and channel feedback with limited bits in next section.

IV. Simulation Results

In this section we verify our analytical results and evaluate the performance of the proposed FD-assisted interference suppression scheme with simulations. The considered underlay D2D network is shown in Fig. 1, where BS_1 transmits with one effective antenna and the power of $P_1 = 46\ dBm$, UE_2 has one receive antenna and transmits with one antenna and the maximal power of $P_2 = 23\ dBm$, and UE_3 has one receive antenna. The cell radius r is set to $250\ m$, and the interference from neighbouring cells is modeled as AWGN. The path loss model is set as $128.1 + 37.6\log_{10} d$, where d is the distance in km [12]. Denoting the average receive SNR of users located at the cell edge as $\mathrm{SNR}_{\mathrm{edge}}$, then the noise variance σ_n^2 can be obtained as $\sigma_n^2 = P_1 - (128.1 + 37.6\log_{10} r) - \mathrm{SNR}_{\mathrm{edge}}$ in dBm. To evaluate the impact of imperfect self-interference cancellation for FD, we define the signal to self-interference ratio as $\mathrm{SIR}_{\mathrm{self}} = P_2 - \sigma_I^2$ in dB reflecting the level of

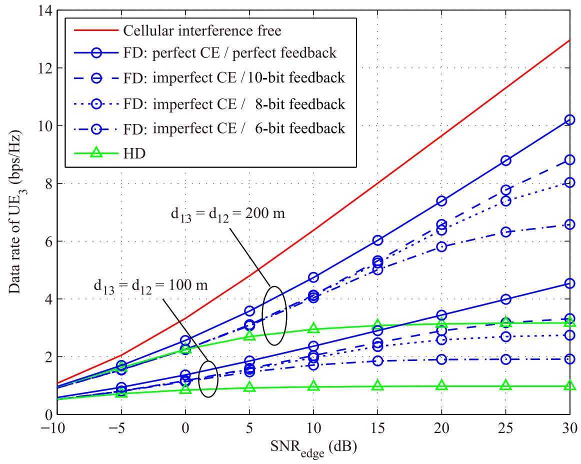

Fig. 2. Data rate of UE_3 versus SNR_{edge} for different user placements with perfect self-interference cancellation, where $d_{23} = 30\ m$.

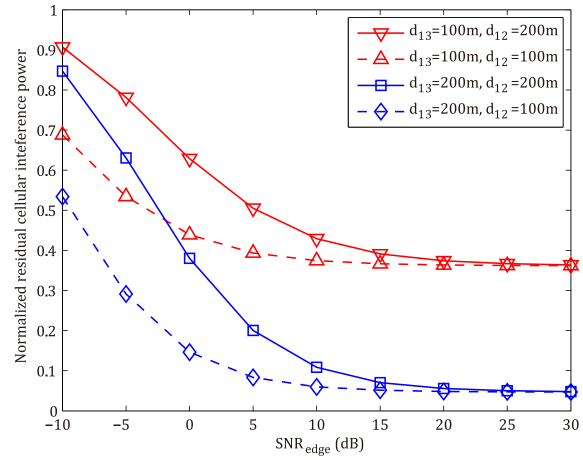

Fig. 3. Normalized residual cellular interference power with the proposed FD scheme, where perfect self-interference cancellation and perfect channel estimation as well as feedback are considered, and $d_{23} = 30\ m$.

self-interference cancellation. The independent and identically distributed (*i.i.d.*) Rayleigh flat small-scale fading channels are considered. When taking into account imperfect channel estimation and feedback, we consider that h_{12} and h_{23} can be directly estimated at UE_2 in TDD systems, which are modeled as $\hat{h}_{12} = h_{12} + e_{12}$ and $\hat{h}_{23} = h_{23} + e_{23}$, where e_{12} and e_{23} are complex Gaussian variables with zero mean and variance σ_n^2/P_1 and σ_n^2/P_2, respectively. The channel h_{13} is first estimated at UE_3 as $\hat{h}_{13} = h_{13} + e_{13}$, where e_{13} is a complex Gaussian variable with zero mean and variance σ_n^2/P_1. $\hat{h}_{13}$ is then quantized by the generalized Lloyd algorithm (specifically using the *Vector Quantizer Design Tool* of MATLAB to generate codebook to quantize the vector formed with the real and imaginary parts of $\hat{h}_{13}$) and feeded back to UE_2. Finally, the proposed FD scheme is designed at UE_2 based on $\hat{h}_{12}$, $\hat{h}_{23}$, and quantized $\hat{h}_{13}$. All the results are averaged over 1000 channel realizations.

In the analytical results, we have shown that the performance of the proposed scheme depends on the relationship between the strength of desired signal and cellular interference, i.e., $P_2|h_{23}|^2$ and $P_1|h_{13}|^2$. To verify the analysis, in the following we first consider two cases of fixed user placements to simulate weak and strong cellular interference scenarios, respectively. Specifically, we use d_{1k} to denote the distance between BS_1 and UE_k for $k = 2, 3$, and d_{23} to denote the distance between UE_2 and UE_3. In the simulations, we set $d_{23} = 30\ m$, then according to the path loss model, we find that $\mathbb{E}\{P_2|h_{23}|^2\} = \mathbb{E}\{P_1|h_{13}|^2\}$ holds when $d_{13} = 123\ m$. Therefore, we select $d_{13} = 100$ and $200\ m$ in the simulations to reflect strong and weak cellular interference, respectively. Finally, we will evaluate the performance of the proposed scheme with random user placements.

A. Perfect Self-interference Cancellation

Figure 2 shows the data rate of UE_3 achieved by the proposed FD-assisted interference suppression scheme, where both perfect and imperfect channel estimations are considered. For comparison, the performance of the HD scheme, given by $\log(1 + \mathrm{SINR}^{\star}_{3,HD})$, and the performance in cellular interference-free case, given by $\log(1 + \frac{P_2|h_{23}|^2}{\sigma^2})$, are also presented. First, we can see that all the schemes perform close in low SNR regime, where the system operates in noise-limited scenario. With the increase of SNR, a performance floor appears in HD systems, which is caused by the cellular interference from BS_1. The performance improves with the reduction of cellular interference when d_{13} increases from $100\ m$ to $200\ m$. The proposed FD scheme exhibits a noticeable performance gain over HD, which increases with the increase of d_{13}, i.e., the reduction of interference. This agrees with our previous analysis. For weak interference, e.g., $d_{13} = 200\ m$, based on our analysis, the proposed scheme can thoroughly eliminate the interference in a high probability (considering the randomness of small-scale channels). Therefore, the performance gap between the proposed scheme and the interference-free case reduces with the increase of d_{13}. The performance loss of the proposed FD scheme due to imperfect channel estimation and feedback can be observed from the figure, but the performance gain of FD over HD is still evident even when a 6-bit or 8-bit parameter quantization is employed.

Figure 3 depicts the normalized residual cellular interference power with the proposed FD scheme, given by $\frac{P_1|h_{23}h_{12}e^{j\phi}w_1 + h_{13}|^2}{P_1|h_{13}|^2}$. By comparing the cases with $d_{13} = 100$ and $200\ m$, we can find that more interference can be suppressed by the proposed scheme for smaller interference, which agrees with our previous analysis. Given d_{13}, the impact of d_{12} on the performance can be observed. It is shown that decreasing d_{12}, i.e., increasing h_{12}, can lead to more suppressed interference. This is because when UE_2 uses the same power to forward the listened interference signal, stronger h_{12} makes the forwarded signal include more useful information for interference suppression. In addition, one can find that the impact of h_{12} on interference suppression diminishes in high SNR regime, which coincides with our analytical results.

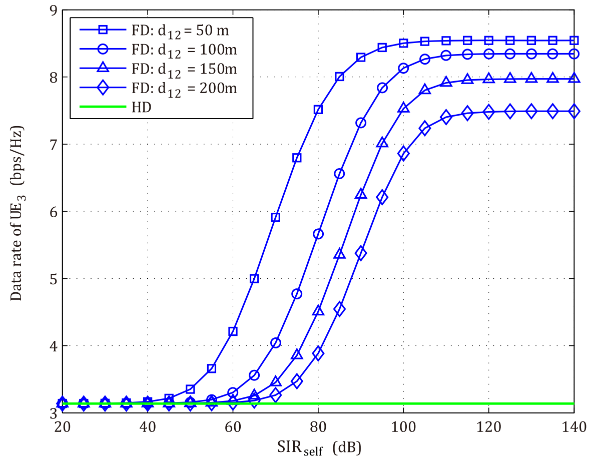

Fig. 4. Data rate of UE_3 versus SIR_{self} for different d_{12} with perfect channel estimation and feedback, where $\text{SNR}_{\text{edge}} = 20\ dB$, $d_{23} = 30\ m$, and $d_{13} = 200\ m$.

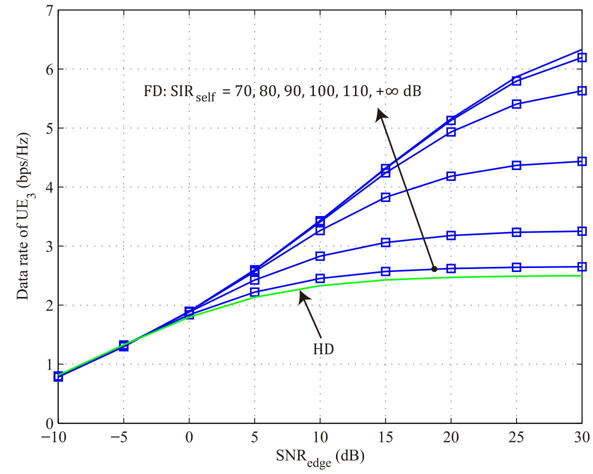

Fig. 5. Data rate of UE_3 versus SNR_{edge} with imperfect self-interference cancellation, imperfect channel estimation and 8-bit feedback, where UE_2 and UE_3 are randomly placed with $d_{23} = 30\ m$.

B. Imperfect Self-interference Cancellation

Figure 4 shows the performance of the proposed FD scheme as a function of SIR_{self}. Noting that the impact of imperfect self-interference cancellation depends on the relationship between the strength of the forwarded residual self-interference and the listened cellular interference, different d_{12} are considered in the simulations. It is shown that to achieve the same performance, the required SIR_{self} decreases with the reduction of d_{12}, meaning that high quality of the listened cellular interference can relax the requirement of self-interference cancellation for FD. In addition, we can see that the proposed FD scheme reduces to the HD scheme for small SIR_{self}, which agrees with the previous analysis.

The performance of the proposed scheme with randomly placed users is depicted in Fig. 5. We can see that the proposed scheme provides substantial performance gain over the HD scheme with the effectively cancelled self-interference, even when imperfect channel estimation and limited-bit channel feedback are taken into account.

V. Conclusions

In this paper we investigated D2D communications between a pair of users subject to the interference from the cellular network, where the D2D transmitting user has the FD capability. We proposed a FD assisted cellular interference suppression mechanism by merely designing the transmitted signals of the D2D link, therefore no changes are required for the cellular link and its performance is not affected. We found the explicit expression of the transmitted signal, and analyzed the performance of the D2D link asymptotically in high SNR regime. The results show that when the self-interference cancellation is perfect for FD, the proposed scheme can thoroughly eliminate weak cellular interference; if the cellular interference is strong, the proposed scheme can achieve an appealing effect that the power of the D2D transmitting user is reusable for sending desired signal and reducing the cellular interference simultaneously. With the increase of the residual self-interference, the proposed FD assisted scheme will reduce to the HD scheme. Simulations validate our analytical results, and demonstrate that the proposed FD assisted D2D communication system provides substantial performance gain over the HD systems even when imperfect channel estimation and feedback are taken into account.

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