Full-duplex based Successive Interference Cancellation in Heterogeneous Networks

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***Abstract*—This paper studies the mitigation of cross-tier inter-cell interference (ICI) generated by a macro base station to a small-cell user equipment (SUE) in heterogeneous networks. A full-duplex based successive ICI cancellation (SIC) scheme, called *fSICIC*, is devised by applying full duplex (FD) technique at the small-cell base station (SBS). The basic idea of the fSICIC is to let the SBS send the desired signal and forward the overheard cross-tier ICI simultaneously to the SUE, where the forwarded ICI is controlled to enhance the ICI at the SUE to facilitate SIC. We first investigate the feasibility of the fSICIC, and then optimize the fSICIC to maximize the data rate of the SUE. Simulation results demonstrate the advantages of the fSICIC on mitigating cross-tier ICI, especially for strong ICI.**

I. Introduction

Cross-tier inter-cell interference (ICI) is a limiting factor of providing high throughput for heterogeneous networks (HetNets) with universal frequency reuse [1]. Various ICI coordination (ICIC) methods have been proposed in the literature. In Long-term Evolution (LTE) systems, several enhanced ICIC (eICIC) techniques were developed [2]. In the time-domain eICIC, the macro base station (MBS) remains silent in the so-called almost blank subframes, during which the user equipments in small cells (SUEs) are served without interference. In the frequency-domain eICIC, the MBS and small-cell BSs (SBSs) schedule UEs in orthogonal frequency resources in order to avoid the ICI. The eICIC methods are easy to implement, but they limit the performance of both macro UEs (MUEs) and SUEs since the UEs can be only served in partial time-frequency resources. Coordinated beamforming is another promising technique for cross-tier ICI suppression, which is actually the spatial-domain eICIC [3]. However, the performance of coordinated beamforming is limited by the number of antennas at the MBS, especially when the SBSs are densely deployed in the coverage of the MBS.

Different from eICIC techniques that control the transmission of the MBS in time, frequency, or spatial domain in order to generate an ICI-free environment for the transmission in small cells, a full-duplex (FD) based ICIC (fICIC) scheme was proposed in [4] without relying on the participation of the MBS. With the fICIC, the SBS transmits not only the desired signal of the SUE, but also sends a signal to cancel the cross-tier ICI. In order to obtain this signal, it needs to listen to the signal transmitted by the MBS at the same time as it is transmitting; this is achieved by applying FD techniques. The forwarded overheard signal is designed to weaken the ICI received by the SUE, and the weakened ICI is then treated as noise at the SUE when decoding the desired signal. The fICIC is effective for neutralizing weak-medium level of ICI but not for strong ICI due to transmit power constraint of the SBS.

Except the previously mentioned ICIC schemes, the SUE can also employ successive interference cancellation (SIC) to decode and remove the ICI signal from the received signal first and then decode the desired signal [5, 6]. However, the SIC scheme is applicable only in the scenario where the ICI signal is decodable. In this paper we generalize the concept of fICIC to widen the feasibility region of SIC. Instead of weakening the ICI as in fICIC, we now control the forwarded signal by the SBS to enhance the ICI at the SUE in order to facilitate the SIC. We call the proposed FD based SIC method *fSICIC*. We first investigate the feasibility of the fSICIC under both maximal transmit power constraint of the SBS and ICI signal decoding constraint, and then optimize the fSICIC that maximizes the data rate of the SUE. Finally, the relationship between the fSICIC and the conventional half-duplex SIC (HD-SIC) scheme is discussed. Simulation results show that the fSICIC performs much better than the HD-SIC scheme and exhibits evident performance gain over the ICI-weaken based fICIC [4] in strong ICI scenarios.

II. System Model

We consider downlink transmission of a narrowband HetNet consisting of one MBS and multiple SBSs, where the MBS serves a single MUE and each SBS serves a single SUE. The MBS has one transmit antenna, which is applicable to the multi-antenna MBS with single-stream beamforming, the FD SBS has one transmit antenna and one receive antenna, and each UE has one receive antenna. Assume that the MUE experiences negligible interference from SBSs due to the coverage range expansion of small cells, and the small cells are geographically separated so that each SUE receives much smaller interference from interfering SBSs than the interference generated by the MBS, which is treated as noise in the paper. Therefore, we focus on the suppression of the cross-tier ICI generated by the MBS to SUEs. The fSICIC scheme is implemented by every SBS without the participation of the MBS and other SBSs, which thus does not affect the performance of the MUE and other-cell SUEs. Therefore, in

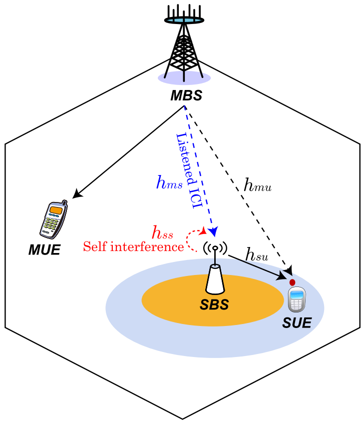

Fig. 1. HetNet layout consisting of a MBS and a reference SBS.

the sequel we only consider a reference SBS and focus on the performance of the SUE served by the reference SBS. The resulting interference environment is demonstrated in Fig. 1.

A. Signal of the SBS

By applying FD technique, the SBS can send the desired signal and forward the listened ICI simultaneously. According to the analysis in [7], the received signal of the SBS before self-interference cancellation can be expressed as

$$\widetilde{y}_s = \sqrt{P_m} h_{ms} s_m + h_{ss}(x_s + z_t) + z_r + n_s, \qquad (1)$$

where P_m is the transmit power of the MBS, h_{ms} is the channel from the MBS to the SBS, $s_m \sim \mathcal{CN}(0,1)$ is the desired signal of the MUE, h_{ss} is the self-interference channel between the transmit and receive antennas of the FD SBS, x_s is the transmitted signal of the SBS consisting of both desired signal of the SUE and forwarded ICI, $z_t \sim \mathcal{CN}(0, \mu_t \mathbb{E}\{|x_s|^2\})$ denotes the signal distortion caused by hardware impairments of the transmitter at the SBS, $\mu_t \ll 1$ is a scaling constant reflecting the combined effects of additive power-amplifier noise, non-linearities in digital-to-analog converter and power amplifier, I/Q imbalance and oscillator phase noise on the signal distortion, $\mathbb{E}\{|x_s|^2\}$ is the transmit power of the SBS, similarly $z_r \sim \mathcal{CN}(0, \mu_r \mathbb{E}\{|\widetilde{y}_s - z_r|^2\})$ denotes the signal distortion caused by hardware impairments of the receiver at the SBS, $\mathbb{E}\{|\widetilde{y}_s - z_r|^2\}$ is the power of the undistorted received signal of the SBS, $\mu_r \ll 1$ is a scaling constant, and $n_s \sim \mathcal{CN}(0, \sigma_n^2)$ is the additive white Gaussian noise (AWGN) at the SBS.

Since the SBS knows its transmitted signal x_s, the self-interference of the FD SBS can be canceled as

$$y_s = \widetilde{y}_s - \hat{h}_{ss} x_s = \sqrt{P_m} h_{ms} s_m - e_{ss} x_s + h_{ss} z_t + z_r + n_s, \qquad (2)$$

where $\hat{h}_{ss} = h_{ss} + e_{ss}$ is the estimated self-interference channel with $e_{ss} \sim \mathcal{CN}(0, \bar{\sigma}_e^2)$ denoting the channel estimation error, the variance $\bar{\sigma}_e^2$ can be obtained as $\bar{\sigma}_e^2 = |h_{ss}|^2(\mu_t + \mu_r + \mu_t\mu_r) + \frac{(1+\mu_r)\sigma_n^2}{P_{tr}}$ for least-square channel estimator [4], and herein P_{tr} denotes the transmit power of training signal of the SBS for self-interference channel estimation.

The FD SBS then transmits the desired signal of the SUE together with the self-interference cancelled received signal y_s. The combined transmitted signal of the SBS can be expressed as

$$x_s = w_I y_s e^{j\phi_1} + w_D s_s, \qquad (3)$$

where w_I and w_D are the weights of the received signal of SBS and desired signal s_s of the SUE, respectively, $\mathbb{E}\{|s_s|^2\} = 1$, and the phase shift $e^{j\phi_1}$ comes from the processing delay introduced by self-interference cancellation and the computation of w_I and w_D at the SBS in narrowband systems. It should be pointed out that in order to coherently combine the forwarded ICI and the ICI directly received at the SUE, the SBS needs to forward the received signal y_s sample-by-sample in time domain to reduce the processing delay as in (3), which is the same as fICIC [4]. In other words, the SBS cannot first decode and then forward the ICI in frequency domain because this will lead to symbol-level processing delay.

Assume that h_{ss} follows Rayleigh distribution, i.e., $h_{ss} \sim \mathcal{CN}(0, \alpha_{ss})$, where α_{ss} is the average channel gain. Then, according to (2), (3) and the result in [4], we can obtain the transmit power of the SBS as

$$P_{out} \triangleq \mathbb{E}\{|x_s|^2\} = \frac{|w_I|^2(P_m|h_{ms}|^2 + \sigma_n^2) + |w_D|^2}{1 - |w_I|^2\sigma_e^2}, \qquad (4)$$

where $\sigma_e^2 \approx \frac{\sigma_n^2}{P_{tr}} + 2\alpha_{ss}(\mu_t + \mu_r)$ reflects the residual self-interference caused by both imperfect self-interference channel estimation and hardware impairments, and the approximation comes from $\mu_t \ll 1$ and $\mu_r \ll 1$.

B. Signal of the SUE

The received signal of the SUE can be expressed as

$$y_u = h_{su} e^{j\phi_2} x_s + h_{mu}\sqrt{P_m} s_m + n_u, \qquad (5)$$

where h_{su} is the channel between the SBS and the SUE, $e^{j\phi_2}$ denotes the phase shift due to propagation delay difference experienced by the signals transmitted from the SBS and the MBS, h_{mu} is the channel between the MBS and the SUE, and $n_u \sim \mathcal{CN}(0, \sigma_n^2)$ is the AWGN.

From (2) and (3), we can rewrite (5) as

$$\begin{aligned} y_u =& h_{su} w_D e^{j\phi_2} s_s + (h_{mu} + h_{ms} h_{su} w_I e^{j\phi})\sqrt{P_m} s_m \\ &+ \underbrace{h_{su} w_I e^{j\phi}(-e_{ss} x_s + h_{ss} z_t + z_r + n_s)}_{\text{Forwarded residual self-interference and noises, } I_{self}} + n_u, \end{aligned} \qquad (6)$$

where $\phi = \phi_1 + \phi_2$ denotes the total shifted phase, and the term I_{self} follows $\mathcal{CN}\big(0, |h_{su}|^2|w_I|^2(P_{out}\sigma_e^2 + \sigma_n^2)\big)$ [4].

In order to perform SIC at the SUE, the ICI signal s_m intended for the MUE should be decoded from (6) first, which imposes the following constraint on the interference to signal plus noise ratio (ISNR)

$$\begin{aligned} \text{ISNR} =& \frac{P_m|h_{mu} + h_{ms} h_{su} w_I e^{j\phi}|^2}{|h_{su}|^2|w_I|^2(P_{out}\sigma_e^2 + \sigma_n^2) + |h_{su}|^2|w_D|^2 + \sigma_n^2} \\ \geq& 2^{R_M} - 1 \triangleq \gamma_M, \end{aligned} \qquad (7)$$

where R_M denotes the data rate of the MUE, and γ_M is the required ISNR to decode s_m.

By removing the ICI from the received signal y_u with SIC, the signal-to-interference-plus-noise (SINR) of the SUE for decoding the desired signal can be obtained as

$$\text{SINR} = \frac{|h_{su}|^2|w_D|^2}{|h_{su}|^2|w_I|^2(P_{out}\sigma_e^2+\sigma_n^2)+\sigma_n^2}. \tag{8}$$

The optimization problem aimed at maximizing the data rate of the SUE can be formulated as

$$\max_{w_I, w_D} \ \text{SINR} \tag{9a}$$

$$s.t. \ \ P_{out} = \frac{|w_I|^2(P_m|h_{ms}|^2+\sigma_n^2)+|w_D|^2}{1-|w_I|^2\sigma_e^2} \leq P_s \tag{9b}$$

$$\text{ISNR} = \frac{P_m|h_{mu}+h_{ms}h_{su}w_I e^{j\phi}|^2}{|h_{su}|^2|w_I|^2(P_{out}\sigma_e^2+\sigma_n^2)+|h_{su}|^2|w_D|^2+\sigma_n^2} \geq \gamma_M, \tag{9c}$$

where P_s is the maximal transmit power of the SBS.

III. Optimization of the fSICIC

In this section we derive the optimal fSICIC by finding the optimal weights w_I and w_D from problem (9). We begin with the optimization of the phase of w_I. We can observe from problem (9) that the phase of w_I only affects the numerator of the ISNR. Then, it is not hard to find that for any given $|w_I|$ the optimal phase of w_I can be expressed as

$$\frac{w_I}{|w_I|} = \frac{|h_{ms}||h_{su}|h_{mu}e^{-j\phi}}{|h_{mu}|h_{ms}h_{su}}. \tag{10}$$

With (10), the ISNR can be rewritten as

$$\text{ISNR} = \frac{P_m(|h_{mu}|+|h_{ms}||h_{su}||w_I|)^2}{|h_{su}|^2|w_I|^2(P_{out}\sigma_e^2+\sigma_n^2)+|h_{su}|^2|w_D|^2+\sigma_n^2}, \tag{11}$$

and now we only need to optimize $|w_I|$ and $|w_D|$ for problem (9).

Since problem (9) is not always feasible considering the ICI signal decoding constraint on ISNR in (9c), in the following we first investigate the feasibility of the fSICIC, and then optimize the fSICIC when it is feasible.

A. Feasibility of the fSICIC

In order to examine the feasibility of the fSICIC, we need to find the maximal ISNR under the transmit power constraint of the SBS. If the maximal ISNR is smaller than γ_M, then the fSICIC will be infeasible; otherwise, the fSICIC will be feasible. Considering (11), the ISNR maximization problem can be formulated as

$$\max_{|w_I|,|w_D|} \ \text{ISNR} \tag{12a}$$

$$s.t. \ P_{out} = \frac{|w_I|^2(P_m|h_{ms}|^2+\sigma_n^2)+|w_D|^2}{1-|w_I|^2\sigma_e^2} \leq P_s. \tag{12b}$$

We can find from (12) that the optimal value of $|w_D|$ should be zero. Otherwise, if the optimal value of $|w_D|$ is positive, then we can always improve the ISNR and ensure the constraints satisfied by setting $|w_D| = 0$. With this result and (11), problem (12) can be simplified as

$$\max_{|w_I|} \ \frac{P_m(|h_{mu}|+|h_{ms}||h_{su}||w_I|)^2}{|h_{su}|^2|w_I|^2(\overline{P}_{out}\sigma_e^2+\sigma_n^2)+\sigma_n^2} \tag{13a}$$

$$s.t. \ \overline{P}_{out} \triangleq \frac{|w_I|^2(P_m|h_{ms}|^2+\sigma_n^2)}{1-|w_I|^2\sigma_e^2} \tag{13b}$$

$$|w_I| \leq \sqrt{\frac{P_s}{P_m|h_{ms}|^2+P_s\sigma_e^2+\sigma_n^2}}, \tag{13c}$$

where constraint (13b) and (13c) come from (12b).

We can solve problem (13) by investigating its Karush-Kuhn-Tucker (KKT) conditions [8]. Specifically, first assume that the optimal $|w_I|$ makes constraint (13c) hold with strict inequality. Then, by substituting (13b) into (13a), we can obtain based on the first-order optimality condition that the optimal $|w_I|$ satisfies the following equation

$$2|h_{ms}||h_{su}|\sigma_n^2 - 2|h_{mu}||h_{su}|^2|w_I|(\overline{P}_{out}\sigma_e^2+\sigma_n^2) - (|h_{ms}||h_{su}||w_I|+|h_{mu}|)|h_{su}|^2|w_I|^2\sigma_e^2\frac{d\overline{P}_{out}}{d|w_I|} = 0. \tag{14}$$

It is not hard to show from (13b) that both $\overline{P}_{out}$ and $\frac{d\overline{P}_{out}}{d|w_I|}$ are monotonically increasing functions of $|w_I|$. Then it can be readily found that the left-hand side of (14) is a decreasing function of $|w_I|$. As a result, the solution to equation (14), denoted by $|w_I^\dagger|$, can be efficiently founded by e.g., a bisection method.

If $|w_I^\dagger| < \sqrt{\frac{P_s}{P_m|h_{ms}|^2+P_s\sigma_e^2+\sigma_n^2}}$ as assumed, then $|w_I^\dagger|$ is the optimal solution to problem (13); otherwise, the assumption is not valid and the optimal solution should make constraint (13c) hold with equality. In summary, the optimal solution can be expressed as

$$|w_I| = \min\left(|w_I^\dagger|, \sqrt{\frac{P_s}{P_m|h_{ms}|^2+P_s\sigma_e^2+\sigma_n^2}}\right). \tag{15}$$

B. Optimal fSICIC

We next find the optimal fSICIC when problem (9) is feasible. First, we replace all $|w_D|$ with $|w_I|$ and P_{out} based on (9b), and rewrite problem (9) as

$$\max_{|w_I|,P_{out}} \text{SINR} = \frac{P_{out}|h_{su}|^2 - P_m|h_{ms}|^2|h_{su}|^2|w_I|^2+\sigma_n^2}{|h_{su}|^2|w_I|^2(P_{out}\sigma_e^2+\sigma_n^2)+\sigma_n^2} - 1 \tag{16a}$$

$$s.t. \ P_{out} \leq P_s \tag{16b}$$

$$\text{ISNR} = \frac{P_m(|h_{mu}|+|h_{ms}||h_{su}||w_I|)^2}{|h_{su}|^2(P_{out}-P_m|h_{ms}|^2|w_I|^2)+\sigma_n^2} \geq \gamma_M. \tag{16c}$$

From (16a) we can see that for any given P_{out} the objective function is a decreasing function of $|w_I|$. Therefore, we can obtain the optimal $|w_I^*|$ with given P_{out} by finding the minimal $|w_I|$ satisfying constraint (16c). Constraint (16c) is a quadratic inequality for $|w_I|$. We show in Appendix A that the optimal $|w_I^*|$ is a piecewise function of P_{out} as follows.

- *Case 1:* If $P_{out} \in [0, \frac{1}{|h_{su}|^2}(\frac{P_m|h_{mu}|^2}{\gamma_M} - \sigma_n^2)]$, then $|w_I^*| = 0$.

- *Case 2:* If $P_{out} \in [\frac{1}{|h_{su}|^2}(\frac{P_m|h_{mu}|^2}{\gamma_M} - \sigma_n^2), P_s]$, then $|w_I^*|$ can be obtained as

$$|w_I^*| = \frac{-|h_{mu}| + \sqrt{\frac{\gamma_M((\gamma_M+1)(P_{out}|h_{su}|^2+\sigma_n^2)-P_m|h_{mu}|^2)}{P_m}}}{(\gamma_M+1)|h_{ms}||h_{su}|}. \quad (17)$$

In the following we investigate that the optimal P_{out} will fall into which of the two cases by examining the relationship between $\frac{1}{|h_{su}|^2}(\frac{P_m|h_{mu}|^2}{\gamma_M} - \sigma_n^2)$ and P_s.

1) $\frac{1}{|h_{su}|^2}(\frac{P_m|h_{mu}|^2}{\gamma_M} - \sigma_n^2) \geq P_s$*: Case 1 is valid and the optimal* $|w_I^*|$ *is zero.*

This result is obvious because now the interval for P_{out} in Case 2 is empty. This scenario is possible when, for instance, γ_M is very small or the interference channel h_{mu} is very strong so that the SUE is able to cancel the ICI by itself and forwarding ICI by the SBS is not necessary. With $|w_I^*| = 0$, the SBS is actually operating in HD mode. Now problem (16) can be reformulated as

$$\max_{P_{out}} \frac{P_{out}|h_{su}|^2}{\sigma_n^2} \quad (18a)$$

$$s.t. \;\; P_{out} \leq P_s \leq \frac{1}{|h_{su}|^2}(\frac{P_m|h_{mu}|^2}{\gamma_M} - \sigma_n^2), \quad (18b)$$

whose solution can be obtained as $P_{out}^* = P_s$.

By substituting P_{out}^* and $|w_I| = 0$ into (4), we can obtain $|w_D^*| = \sqrt{P_s}$. Since any phase multiplied to w_D will not change the SINR and ISNR, we can simply select $w_D^* = |w_D^*|$ as a real number.

This result indicates that the fSICIC reduces to the conventional HD-SIC only in the scenario where the SUE is able to perform SIC even when the SBS transmits the desired signal with its maximal power. If the SBS needs to reduce the power of desired signal to enable SIC at the SUE, then the fSICIC will operate in FD mode and outperform the HD-SIC.

2) $\frac{1}{|h_{su}|^2}(\frac{P_m|h_{mu}|^2}{\gamma_M} - \sigma_n^2) < P_s$*: Optimal* P_{out} *must fall into Case 2 as proved in Appendix B.*

In this scenario, problem (16) can be reformulated as

$$\max_{|w_I|, P_{out}} \frac{P_{out}|h_{su}|^2 - P_m|h_{ms}|^2|h_{su}|^2|w_I|^2 + \sigma_n^2}{|h_{su}|^2|w_I|^2(P_{out}\sigma_e^2 + \sigma_n^2) + \sigma_n^2} - 1 \quad (19a)$$

$$s.t. \;\; \frac{1}{|h_{su}|^2}(\frac{P_m|h_{mu}|^2}{\gamma_M} - \sigma_n^2) \leq P_{out} \leq P_s \quad (19b)$$

$$P_{out} = \frac{P_m((\gamma_M+1)|h_{ms}||h_{su}||w_I| + |h_{mu}|)^2}{(\gamma_M+1)(\gamma_M)|h_{su}|^2} + \frac{P_m|h_{mu}|^2}{(\gamma_M+1)|h_{su}|^2} - \frac{\sigma_n^2}{|h_{su}|^2}, \quad (19c)$$

where constraint (19b) is the condition of Case 2 being valid, and constraint (19c) comes from (17).

To solve problem (19), we substitute (19c) into the objective function (19a) and denote the result as $\frac{A(|w_I|)}{B(|w_I|)} - 1$, where $A(|w_I|)$ is a quadratic function of $|w_I|$ and $B(|w_I|)$ is a quartic function of $|w_I|$. Constraint (19b) can be rewritten as $c \leq |w_I| \leq d$, where the constants c and d can be obtained based on (17) and (19b). Then, we can convert problem (19) into

$$\max_{|w_I|} \frac{A(|w_I|)}{B(|w_I|)} - 1 \qquad s.t. \; c \leq |w_I| \leq d. \quad (20)$$

Problem (20) can be solved by a bisection method by defining $\lambda = \frac{A(|w_I|)}{B(|w_I|)} - 1$, which is summarized as follows.

a) Initialization by setting $\lambda_{max} = \frac{P_s|h_{su}|^2}{\sigma_n^2}$, i.e., the signal-to-noise ratio (SNR) of the SUE in ICI-free scenario, and $\lambda_{min} = \frac{A(t)}{B(t)} - 1$ for any $t \in [c, d]$.

b) Set $\lambda = \frac{\lambda_{max} + \lambda_{min}}{2}$, and solve the following problem

$$\text{Find } |w_I| \quad (21a)$$
$$s.t. \; A(|w_I|) = (1+\lambda)B(|w_I|) \quad (21b)$$
$$c \leq |w_I| \leq d. \quad (21c)$$

Problem (21) can be solved by first obtaining the solutions to the quartic equation (21b) and then examining if there is any solution satisfying (21c).

c) If problem (21) is feasible, then update $\lambda_{min} = \lambda$. Otherwise, update $\lambda_{max} = \lambda$.

d) Iterate step $b) \sim c)$ until convergence.

In summary, the optimal fSICIC can be obtained as follows.

a) *Feasibility verification:* compute $|w_I|$ with (15), and substitute it into (13a). If the value of (13a) is smaller than γ_M, then the fSICIC will be infeasible. Otherwise, the fSICIC will be feasible and continue the following steps.

b) Compare $\frac{1}{|h_{su}|^2}(\frac{P_m|h_{mu}|^2}{\gamma_M} - \sigma_n^2)$ and P_s.

c) If $\frac{1}{|h_{su}|^2}(\frac{P_m|h_{mu}|^2}{\gamma_M} - \sigma_n^2) \geq P_s$, then $w_I^* = 0$ and $w_D^* = \sqrt{P_s}$.

d) If $\frac{1}{|h_{su}|^2}(\frac{P_m|h_{mu}|^2}{\gamma_M} - \sigma_n^2) < P_s$, then the $|w_I^*|$ can be obtained by solving problem (20) with the bisection method. The phase of w_I^* is given in (10), the optimal P_{out} can be obtained from (19c), and the optimal real-valued w_D^* can be obtained from (4).

C. Discussions

1) Channel Information Requirement: To apply the fSICIC, the SBS needs to have the channels h_{ms}, h_{su}, and h_{mu}. In time division duplex systems, the channels h_{ms} and h_{su} can be estimated at the SBS from the received training signals broadcasted by the MBS and the SUE, respectively, while h_{mu} can be first estimated by the SUE and then fed back to the SBS. With imperfect channels at the SBS, the optimized weights w_I and w_D may make the decoding of ICI signal at the SUE infeasible. To solve the problem, we can add a data rate margin ϵ to R_M to design a conservative fSICIC. We will evaluate the performance of the fSICIC under imperfect channel estimation and channel feedback with limited bits in next section.

2) fSICIC v.s. HD-SIC: In HD mode we have $|w_I| = 0$. As discussed before, setting $|w_I| = 0$ is optimal only when $\frac{1}{|h_{su}|^2}(\frac{P_m|h_{mu}|^2}{\gamma_M} - \sigma_n^2) \geq P_s$ holds; otherwise, the fSICIC outperforms the HD-SIC.

By set $w_I = 0$, it is not hard to find from (9) the optimal value of w_D in HD mode as

$$w_D = \min\big(\sqrt{P_s}, \frac{1}{|h_{su}|}(\frac{P_m|h_{mu}|^2}{\gamma_M} - \sigma_n^2)^{0.5}\big). \quad (22)$$

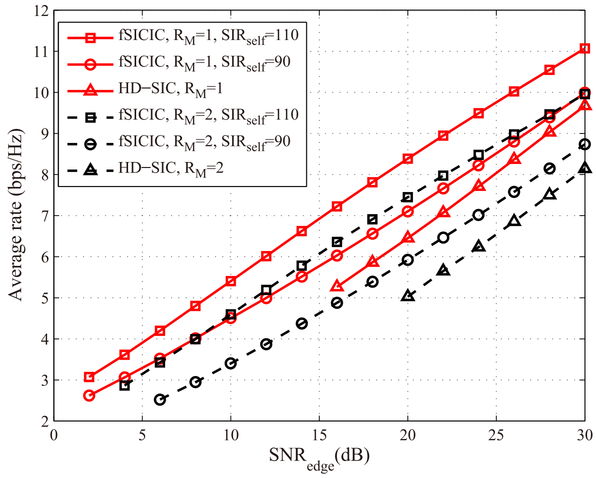

Fig. 2. Average rate of the SUE v.s. $\mathrm{SNR}_{\mathrm{edge}}$ for different R_M and $\mathrm{SIR}_{\mathrm{self}}$ with $d_s = 120\ m$.

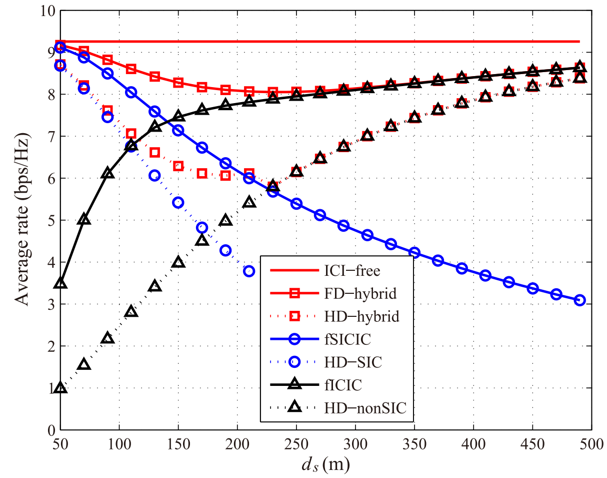

Fig. 3. Average rate of the SUE v.s. d_s with $R_M = 1$ bps/Hz, $\mathrm{SNR}_{\mathrm{edge}} = 20\ dB$ and $\mathrm{SIR}_{\mathrm{self}} = 100\ dB$.

IV. Simulation Results

In this section we evaluate the performance of the proposed fSICIC by simulations. The considered HetNet layout is shown in Fig. 1, where the MBS is located at the center of the macro cell, the SBS is located at $(d_s, 0)$, and the SUE is located at (d_s, r). We set the radius of the macro cell r_{mc} as $500\ m$, $r = 40\ m$, and different values of d_s will be simulated. The transmit power of the MBS is $P_m = 46\ dBm$ and the maximal transmit power of the SBS is $P_s = 30\ dBm$. The path loss is set as $128.1 + 37.6 \log_{10} d$ for the channels from the MBS and $141.7 + 36.7 \log_{10} d$ for the channels from the SBS, where d is the distance in km [9]. Furthermore, we consider a penetration loss of 20 dB for channels to the SUE. Define the average receive SNR of a MUE located at the edge of macro cell as $\mathrm{SNR}_{\mathrm{edge}}$, then the noise variance σ_n^2 can be obtained as $\sigma_n^2 = P_m - (128.1 + 37.6 \log_{10} r_{mc}) - \mathrm{SNR}_{\mathrm{edge}}$ in dBm. To evaluate the impact of imperfect self-interference cancellation for FD, we define the signal to self-interference ratio as $\mathrm{SIR}_{\mathrm{self}} = P_s - P_s\sigma_e^2$ in dB to reflect different levels of self-interference cancellation. Rayleigh flat fading channels are considered, and all the results are averaged over 1000 channel realizations. For a given data rate of the MUE, R_M, the feasibility of both the fSICIC and the HD-SIC depends on channel realizations. We define the fSICIC or HD-SIC being feasible for a given R_M if the success probability of decoding the ICI signal is not smaller than 95%.

Figure 2 shows the average rate of the SUE as a function of $\mathrm{SNR}_{\mathrm{edge}}$ for different data rates of ICI signals R_M and $\mathrm{SIR}_{\mathrm{self}}$. First, given the same R_M, we can see that the fSICIC is feasible in a wider SNR regime than the HD-SIC because the fSICIC can enhance the ICI to facilitate SIC. When R_M increases, we can see that the feasible SNR regime shrinks for both the fSICIC and HD-SIC as expected, and the performance degrades because of the reduction of transmit power for desired signal in order to enable the decoding of ICI signal. The performance of the fSICIC decreases with the decrease of $\mathrm{SIR}_{\mathrm{self}}$ because of the increased forwarded residual self-interference. Nevertheless, even when $\mathrm{SIR}_{\mathrm{self}} = 90\ dB$, a large performance gain of the fSICIC over the HD-SIC can be observed.

In Fig.3 we compare the performance of seven relevant ICIC schemes including two SIC-based methods (the fSICIC and HD-SIC), two methods treating ICI as noise (the fICIC with which the SBS forwards the listened signal to weaken the ICI at the SUE and the simple HD scheme that directly treats ICI as noise denoted by HD-nonSIC), an ICI-free baseline scheme, and two hybrid schemes as will be clear later. We can see that although the fICIC outperforms the HD-nonSIC and is effective when d_s is large, i.e., the ICI is not strong, it performs worse than both the fSICIC and the HD-SIC when d_s is small. This motivates us to study a hybrid fSICIC/fICIC scheme (denoted by FD-hybrid), in which the better one of the two schemes is selected for every channel realization. For comparison, the hybrid HD-SIC/HD-nonSIC scheme (denoted by HD-hybrid) is also simulated. We can see that the FD-hybrid scheme can effectively mitigate the ICI with various strengths, and exhibits an evident performance gain over the HD-hybrid scheme.

Figure 4 depicts the performance of the fSICIC with imperfect channel estimation and feedback. We consider that h_{ms} and h_{su} are directly estimated at the SBS, which are modeled as $\hat{h}_{ms} = h_{ms} + e_{ms}$ and $\hat{h}_{su} = h_{su} + e_{su}$, where e_{ms} and e_{su} are estimation errors following complex Gaussian distributions with zero mean and variance σ_n^2/P_m and σ_n^2/P_s, respectively. The channel h_{mu} is first estimated at the SUE as $\hat{h}_{mu} = h_{mu} + e_{mu}$, where e_{mu} is the estimation error following complex Gaussian distributions with zero mean and variance σ_n^2/P_m. Then, $\hat{h}_{mu}$ is 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 $\hat{h}_{mu}$) and fed back to the SBS. Finally, the fSICIC is optimized at the SBS based on $\hat{h}_{ms}$, $\hat{h}_{su}$, and quantized $\hat{h}_{mu}$.

As discussed in Section III-C1, we need to introduce a

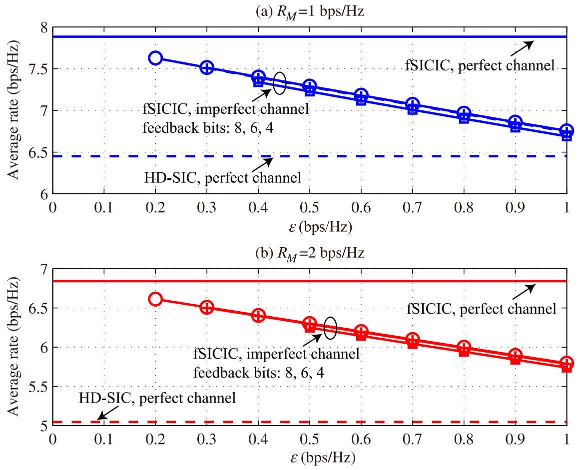

Fig. 4. Average rate of the SUE v.s. the margin ϵ for different R_M with $\text{SNR}_{\text{edge}} = 20\ dB$, $d_s = 120\ m$, and $\text{SIR}_{\text{self}} = 100\ dB$.

data rate margin ϵ to R_M for the fSICIC when imperfect channels at the SBS are considered. The impact of ϵ on the performance of the fSICIC is shown in Fig. 4. For any given R_M, say $R_M = 1$ bps/Hz, it is shown that the fSICIC will be infeasible if ϵ is selected too small, e.g., $\epsilon < 0.2, 0.3$ and 0.4 for 8, 6, and 4-bits feedback, respectively. We can see that to ensure the feasibility of the fSICIC, the required ϵ increases with the decrease of the number of feedback bits, which coincides with the intuition that a larger margin should be added when the channels are less accurate. Similar results can be observed when $R_M = 2$ bps/Hz. Yet, too large ϵ will lead to performance degradation due to the overly conservative design of the fICIC. When selecting $\epsilon = 0.2$ and considering 8-bits feedback, the fSICIC performs close to the case with perfect channels and demonstrates significant performance gain over the HD-SIC.

V. Conclusions

In this paper we devised an FD assisted successive ICI cancellation scheme (fSICIC) for HetNets, which enhances the received ICI of the SUE to enlarge the feasibility region of the SIC compared to the conventional HD-SIC scheme. We first solved the feasibility problem of the fSICIC, and then proposed a method to obtain the optimal weights of the fSICIC. Analysis results show that the fSICIC will reduce to the HD-SIC only in the scenario where the ICI is decodable when the SBS uses its maximal power to transmit desired signal, otherwise, the fSICIC always outperforms the HD-SIC. Simulations demonstrated that the fSICIC provides substantial performance gain over the HD-SIC scheme even with imperfect channel estimation and feedback, and the combination of the fSICIC and the ICI-weaken based fICIC scheme can effectively eliminate the ICI with various levels.

Appendix A
Minimal w_I with given P_{out}

Constraint (16c) can be rewritten as

$$(\gamma_M + 1)P_m|h_{ms}|^2|h_{su}|^2|w_I|^2 + 2P_m|h_{ms}||h_{mu}||h_{su}||w_I| - \gamma_M(P_{out}|h_{su}|^2 + \sigma_n^2) + P_m|h_{mu}|^2 \geq 0. \quad (23)$$

Since the coefficients of $|w_I|^2$ and $|w_I|$ are both positive, we know that if the left-hand side of (23) is non-negative at $|w_I| = 0$, then the minimum of $|w_I|$ is zero, otherwise, the minimum of $|w_I|$ makes (23) hold with equality. Therefore, the minimal $|w_I|$ is a piecewise function of P_{out}.

In first case, to let $|w_I| = 0$, we can obtain that P_{out} needs to satisfy $0 \leq P_{out} \leq \frac{1}{|h_{su}|^2}(\frac{P_m|h_{mu}|^2}{\gamma_M} - \sigma_n^2)$. In the second case, the left-hand side of (23) needs to be non-positive when $|w_I| = 0$, i.e., P_{out} should satisfy $\frac{1}{|h_{su}|^2}(\frac{P_m|h_{mu}|^2}{\gamma_M} - \sigma_n^2) \leq P_{out} \leq P_s$. Moreover, the minimum of w_I in this case can be obtained as (17).

Appendix B
The Optimality of Case 2

As we have shown, the optimal $|w_I^*|$ is a piecewise function of P_{out}. Thus, the objective function is also a piecewise function of P_{out}. In Case 1, i.e., when $0 \leq P_{out} \leq \frac{1}{|h_{su}|^2}(\frac{P_m|h_{mu}|^2}{\gamma_M} - \sigma_n^2)$, we have $|w_I^*| = 0$ and $\text{SINR} = \frac{P_{out}|h_{su}|^2}{\sigma_n^2} \triangleq \text{SINR}_1$. In Case 2, i.e., when $\frac{1}{|h_{su}|^2}(\frac{P_m|h_{mu}|^2}{\gamma_M} - \sigma_n^2) \leq P_{out} \leq P_s$, the optimal $|w_I^*|$ is given in (17) and the SINR can be obtained accordingly by substituting (17) into (16a), denoted by SINR_2.

After some regular manipulations, we can find that the SINR in the two cases is a continuous function of P_{out}. Since SINR_1 is an increasing function of P_{out}, the optimal P_{out} in Case 1 is $\frac{1}{|h_{su}|^2}(\frac{P_m|h_{mu}|^2}{\gamma_M} - \sigma_n^2)$. Yet, we can show that the first derivation of SINR_2 at the point $P_{out} = \frac{1}{|h_{su}|^2}(\frac{P_m|h_{mu}|^2}{\gamma_M} - \sigma_n^2)$ is positive. This means that we can find a P_{out} that is larger than $\frac{1}{|h_{su}|^2}(\frac{P_m|h_{mu}|^2}{\gamma_M} - \sigma_n^2)$ to make $\text{SINR}_2 > \text{SINR}_1$. Therefore, the optimal P_{out} is obtained in Case 2.

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