CoMPflex: CoMP for In-Band Wireless Full Duplex

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Abstract—In this letter we consider emulation of a Full Duplex (FD) cellular base station (BS) by using two spatially separated and coordinated half duplex (HD) BSs. The proposed system is termed CoMPflex (CoMP for In-Band Wireless Full Duplex) and at a given instant it serves two HD mobile stations (MSs), one in the uplink and one in the downlink, respectively. We evaluate the performance of our scheme by using a geometric extension of the one-dimensional Wyner model, which takes into account the distances between the devices. We observe gains from using our scheme in terms of sum-rate and energy efficiency.

I. INTRODUCTION

5G wireless systems are expected to have a large number of Base Stations (BSs) per unit area. The availability of multiple proximate and interconnected BSs lays the ground to use cooperative techniques, commonly referred to as Coordinated Multi-Point (CoMP). Another important wireless trend is the use of in-band full-duplex (FD) wireless transceivers, expected to lead to a two-fold spectral efficiency gain. The key challenge in FD implementation is the high transceiver complexity that is required to cope with the strong self-interference induced by the downlink (DL) transmission path into the uplink (UL) receiving path. The high transceiver complexity will likely make the FD feasible only for the BS, while a Mobile Station (MS) will remain half-duplex (HD). In such a setting, the system can harvest the FD gain by scheduling at least two different MSs, see Fig. 1c.

Traditionally, UL and DL are treated in isolation; e.g. traditional CoMP considers unidirectional traffic patterns at a given instant, see Fig. 1a. The advent of FD has shifted the focus towards two-way optimization of wireless networks. This leads to two new transmission modes, one of which depicted on Fig. 1b while in the second mode the roles are reversed (MS1 transmits and MS2 receives). In Fig. 1b downlink and uplink are decoupled (see e.g. [6]), i.e. HD-BS1 sends the signal $x_{D1}$ in the DL to MS1, while HD-BS2 receives $x_{U2}$ in the UL from MS2. HD-BS2 receives interference from HD-BS1, while MS1 receives interference from MS2. However, HD-BS1 can use the high-bandwidth fiber connection to HD-BS2 to send the data of $x_{D1}$ to HD-BS2, such that HD-BS2 can recreate $x_{D1}$ and perfectly cancel the interference from HD-BS1. Note that $x_{U2}$ remains as interference to MS1, but it could be cancelled via e.g. scheduling. Hence, the setting on Fig. 1b operates equivalently as having a single FD-BS, see Fig. 1c. If the MSs use e.g. Time Division Duplexing (TDD), then the roles of MS1 and MS2 are reversed in the next transmission slot, thus achieving two-way service for both MSs.

The previous example constitutes the main proposal of this paper: use the CoMP infrastructure, with interconnected HD-BSs, in order to obtain a distributed FD implementation, termed CoMPflex (CoMP for in-band full duplex). Assuming a sufficient wired bandwidth between the HD-BSs, CoMPflex serves simultaneously two terminals that have opposite (UL/DL) connections. CoMPflex can be seen as a generalization of a traditional FD, which can basically be seen as a CoMPflex where the HD-BSs are at a distance zero. CoMPflex brings four advantages: (i) the antenna coupling losses between the antennas associated with each path is mitigated; (ii) the “self-interference” coming from the DL transmission is now within the same order of magnitude as the UL signal, reducing the need for a high dynamic range receiver; and (iii) the reduction of the distance between the cellular devices and HD-BS, which leads to potential energy savings both at the device and network side, and (iv) the separated transmitter and receiver of the HD-BSs can, on average, bring the infrastructure closer to the MSs, resulting in rate gains and decrease in interference.

Our analysis is based on the classical Wyner model, which is enriched to capture the geometric setting of CoMPflex and allow for studying the effect of varying the distance between the connected BSs.

II. SYSTEM MODEL

Our system model is perhaps the simplest one where the gain of CoMPflex can be demonstrated. It is based on an one-dimensional Wyner model, as shown in Fig. 2a, where the cells have radius $R$. The figure shows a 1-tier interference model, however, the model can be extended to having several

1In this letter we treat the 1-D scenario. Obviously, the analysis can be extended into a two-and three-dimensional models, but this is out of the scope for this introductory article.
interfering tiers. In the center cell, there is either one FD-BS placed at the cell center (corresponding to \( \rho = 0 \)), or two HD-BSs, one for DL placed in the left half of the cell, and one UL placed in the right half (corresponding to \( \rho > 0 \)). Both HD-BSs have the same distance \( \rho \) to the cell center. We assume a sufficient number of active users in the cell, so that one DL-MS in the left half and one UL-MS in the right half can always be scheduled. The DL-MS is placed uniformly at random at position \( v \) in the left half of the cell, and the UL-MS is placed uniformly at random at position \( u \) in the right half of the cell. The positions of the BSs and MSs in the interfering cells depend on the interference model, see Sec. II-C.

A. Signal Model

In Fig. 2, the wireless channels are indicated as arrows showing the transmission direction. They are shown as either a blue solid line for signal, or a red dashed line for interference. For clarity, only the links relevant to the center cell are shown. All channels are modeled as Rayleigh faded with unit mean power. The pathloss is modeled as \( \ell(d) = (1 + |d|)^{-\alpha} \), where \( d \) is the distance from the transmitter to the receiver and \( \alpha \) is the path loss exponent. The system bandwidth is normalized to 1 Hz and all nodes use the same frequency. We assume Additive White Gaussian Noise (AWGN), with power \( \sigma^2 \). Finally, we assume that full channel state information is available at all nodes.

The distance between BS and UL-MS is \( |u - \rho| \), and between DL-MS and BS, \( |v - \rho| \). We restrict \( \rho \) to \([0, R/2]\), since \( \rho > R/2 \) would allow the MS to be closer to an interfering BS. In the UL, the signal received at the BS, \( y_B \), is

\[
y_B = h_{MB} \ell(\rho - u)^{1/2} x_M + I_B + z_B
\]

where \( x_M \) is the symbol sent from MS and \( z_B \) is the AWGN at the BS. The term \( h_{MB} \) denotes the channel from the MS to the BS. \( I_B = I_{BB} + I_{MB} \) is the interference from BSs (\( I_{BB} \)) and MSs (\( I_{MB} \)) in the neighboring cells (see Appendix). The UL SINR is then,

\[
\gamma_U(\rho, u) = \frac{P_M(\rho)g_{MB} \ell(\rho - u)}{\sigma^2 + T_B}
\] \hspace{1cm} (1)

where \( P_M = |x_M|^2 \), \( g_{MB} = |h_{MB}|^2 \) and \( T_B = |I_B|^2 \) is the received power of the interference at the BS.

The DL-MS receives the signal \( y_M \),

\[
y_M = h_{BM} \ell(\rho - v)^{1/2} x_B + h_{MM} \ell(u + v)^{1/2} x_M + I_M + z_M
\]

where \( x_B \) is the signal sent from BS, \( h_{BM} \) and \( h_{MM} \) denote respectively the channels between BS and MS, and the intra-cell channel between the MSs. \( I_M = I_{BM} + I_{MM} \) is the interference from the BSs (\( I_{BM} \)) and the users (\( I_{MM} \)) in neighboring cells given in the Appendix, and \( z_M \) is the AWGN at the MS. The DL SINR is

\[
\gamma_D(\rho, u, v) = \frac{P_B(\rho)g_{BM} \ell(\rho - v)}{P_M(\rho)g_{MM} \ell(u + v) + T_M + \sigma^2}
\] \hspace{1cm} (2)

where \( P_B = |x_B|^2 \), \( g_{BM} = |h_{BM}|^2 \), \( g_{MM} = |h_{MM}|^2 \) and \( T_M = |I_M|^2 \) is the received interference power at the MS.

B. Power Adjustment for CoMPflex

The core of CoMPflex is in bringing the MSs and BSs closer to each other, therefore it is natural to allow them to adjust their transmission power accordingly. This transmission power is computed based on the required power received at either the BS, \( P_{req} \), and the MS, \( P_{req} \), when the MS is placed at the cell edge. The required powers are defined in Sec. [IV] We denote the adjusted power as \( P_B(\rho) \) and \( P_M(\rho) \), for the BS and MS respectively, which is computed as:

\[
P_{req} \leq P_x(\rho) \Leftrightarrow P_x(\rho) \geq P_{req} \ell(R - \rho)^{-1},
\]

given a required cell edge rate \( R_{eq} \) and a corresponding outage probability \( \epsilon \), where \( x, y \in \{B, M\} \). It can be shown that the required power received at \( y \) is \( P_{req} = -\frac{(\ell(R - \rho))^{\epsilon}}{\log(1 - \epsilon) \ell(R)} \).

Finally, in Sec. [IV] we will also evaluate the constant power case, where \( P_B = P_B(\rho = 0) \) and \( P_M = P_M(\rho = 0) \).

C. Inter-cell Interference Models

We consider two inter-cell interference models when assessing the CoMPflex performance. In the first model, nodes in the interfering cells follow the same deployment pattern as the center cell, with one FD-BS or two HD-BSs placed at distance \( \rho \) from the center of the cell. The setup is shown in Fig. 2, and the expression of the interference signals is shown in the Appendix.

The second model is the worst-case interference scenario, illustrated in Fig. 2, where the transmitting BSs and MSs are indicated by having red dashed arrows. The BSs and MSs are placed as close to the center cell as possible. The worst-case positions of the BSs and MSs depend on whether we are considering the cell to the left or right. For the cell to the left, the worst-case position of the BS is at the cell center (i.e. \( \rho = 0 \)), and the MS at the cell edge. For the cell to the right,
The derivative of the DL SINR, which is denoted \( \gamma_D(u, v, \rho) = (1 + R)^\alpha (P_M^{req} + P_B^{req}) \), with respect to \( \rho \) and the DL interference is \( I(u, v, \rho) \).

The sum-rate of CoMPflex is evaluated via the expression:

\[
\sum_{v, \rho} R_{\text{sum}}(u, v, \rho) = \sum_{v, \rho} \log_2 (1 + \gamma_D(u, v, \rho))
\]

The energy efficiency \( EE \) is defined as the amount of bits transmitted per unit of energy. It is given by

\[
EE(\rho) = \frac{R_{\text{sum}}(\rho)}{P_B(\rho) + P_M(\rho)}
\]

In the following proposition, we motivate that CoMPflex brings benefits in terms of EE, due to the dual effect of increased sum-rate and decreased transmission power with \( \rho \).

**Proposition 2.** In stationary conditions and for all \( \rho \in [0, \min\{u, v\}] \), \( EE(\rho) \leq EE(0) \).

**Proof.** From Prop. 1 we know that the numerator satisfies \( R_{\text{sum}}(\rho) \geq R_{\text{sum}}(0) \). To complete the proof we need to show that the denominator decreases with \( \rho \). This follows from

\[
P_B(0) + P_M(0) \geq P_B(\rho) + P_M(\rho) \implies (1 + R)^\alpha (P_M^{req} + P_B^{req}) \geq (1 + R - \rho)^\alpha (P_M^{req} + P_B^{req}) \implies (1 + R)^\alpha \geq (1 + R - \rho)^\alpha.
\]

**IV. PERFORMANCE RESULTS**

The sum-rate and the EE of CoMPflex are evaluated via numerical simulations in this section. The main simulation settings are listed in Tab. 1. We note that the position of the MSs is random and uniform over their half-cell, all links have fading and we include \( N \) interfering cell tiers.

**Table I: Simulation parameters.**

| Parameter | Description                        | Simulation Setting |
|-----------|-----------------------------------|--------------------|
| \( R \)   | Cell radius                        | 100 m              |
| \( \sigma^2 \) | Noise power at MS and BS        | -174 dBm           |
| \( \alpha \) | Path loss exponent            | 3.4, 5             |
| \( N \)   | Number of interfering cells       | 10                 |
| \( R_{U0} \) | Required UL rate                |
| \( R_{D0} \) | Required DL rate                |
| \( \epsilon \) | Cell edge outage probability     | 0.06 bps [10, Ch.11] |

The simulation results for the sum-rate performance are shown in Fig. 3. We observe the constant power case (blue solid curves) and the power adjustment case (red dashed curves). We have evaluated both deployments depicted in Figs. 2 and 3, the latter denoted as the worst case interference regime. We observe that the difference between the sum-rate performance of using constant power versus power adjustment is negligible, for the parameters considered. Therefore, it is worthwhile to do power adjustment, since it will lead to higher energy efficiency. Also, we see that the sum-rate increases with \( \rho \), which confirms the conclusions from Sec. III but now with more realistic conditions. Finally, although in the worst interference regime there is a significant drop in the achieved sum-rate, the shape of the sum-rate curve with \( \rho \) is the same.
To evaluate the EE gains of CoMPflex, we normalize the achieved energy efficiency at a certain $\rho$ with energy efficiency with $\rho = 0$, which corresponds to the baseline setup depicted in Fig. 1. The normalized EE, $\eta(\rho)$, is then:

$$\eta(\rho) = \frac{EE(\rho)}{EE(\rho = 0)}.$$  \hspace{1cm} (4)

We also look at the total transmission power $P_{\text{sum}}(\rho) = P_B(\rho) + P_M(\rho)$, and study how it depends on $\rho$. These curves, along with the normalized EE, are shown in Fig. 4 where we see that the total transmission power decreases as $\rho$ increases. This is to be expected since the distance between a MS and its serving BS is decreased, requiring less power is used to maintain the same performance. The combination of a lower required transmission power with a higher sum-rate results in the observed dramatic increase in EE, especially when $\rho$ tends to $R/2$. This increase is further accentuated in propagation environments with higher $\alpha$ values.

V. CONCLUSION

We have shown that the proposed CoMPflex scheme allows emulation of in-band full-duplex operation by spatially dislocating the upstream and downstream traffic into two HD-BSs. Our results show that this splitting leads to a substantial increase in sum-rate as well as an energy efficiency increase ranging from $15\times$ to $45\times$ for high BSs splitting distance and increasing path-loss exponents. This initial study uses a simple analysis that relies on more complex models, such as the ones described in the left and right interfering cells. The BS-MS, BS-BS and MS-MS distances are, respectively,

$$d^{(n)}_{M\!B,L} = 2nR - u_{n,L} + \rho,$$

$$d^{(n)}_{M\!B,R} = 2nR + u_{n,R} - \rho,$$

for the left (L) and right (R) cell respectively. $u_{n,L}$ and $u_{n,R}$ describe the same distances as $u$ and $v$ in the left and right interfering cells. The BS-MS, BS-BS and MS-MS distances are, respectively,

$$d^{(n)}_{B\!B,L} = 2nR + \rho - v,$$

$$d^{(n)}_{B\!B,R} = 2nR - \rho + v,$$

$$d^{(n)}_{M\!M,L} = 2nR - u_{n,L} - v,$$

$$d^{(n)}_{M\!M,R} = 2nR + u_{n,R} + v,$$

where the random variables $u$, $v$, $u_{n,L}$ and $u_{n,R}$ are independent. In the worst-case scenario (Fig. 2), the MS-BS, BS-MS, BS-BS and MS-MS distances are, respectively,

$$d^{(n)}_{M\!B,L} = 2nR - R + \rho,$$

$$d^{(n)}_{M\!B,R} = 2nR - R - \rho,$$

$$d^{(n)}_{M\!B,L} = 2nR - R + \rho + v,$$

$$d^{(n)}_{M\!B,R} = 2nR - R - \rho + v,$$

$$d^{(n)}_{M\!M,L} = 2nR - R - v,$$

$$d^{(n)}_{M\!M,R} = 2nR - R + v.$$

Letting $\psi \in \{MB, BM, BB, MM\}$, and $h_{\psi,\varphi}^{(n)}$, and $\varphi \in \{L, R\}$ the channel between a node in the $n$th cell and the receiver, the interference terms are then

$$I_{\psi} = \sum_{n=1}^{\infty} \left[ h^{(n)}_{\psi,L} \sqrt{\ell(d^{(n)}_{\psi,L})} x^{(n)}_L + h^{(n)}_{\psi,R} \sqrt{\ell(d^{(n)}_{\psi,R})} x^{(n)}_R \right],$$

where $x^{(n)}_L$ and $x^{(n)}_R$ are symbols sent from appropriate nodes.

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