Small Cell In-Band Wireless Backhaul in Massive MIMO Systems: A Cooperation of Next-Generation Techniques

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Abstract

Massive Multiple-Input Multiple-Output (MIMO) systems, dense Small-Cells (SCs), and full duplexing are three candidate techniques for next-generation communication systems. The cooperation of next-generation techniques could offer more benefits, e.g., SC in-band wireless backhaul in massive MIMO systems. In this paper, three strategies of SC in-band wireless backhaul in massive MIMO systems are introduced and compared. Simulation results demonstrate that SC in-band wireless backhaul has the potential to improve the throughput for massive MIMO systems, and applying full-duplexing techniques at SCs could provide greater gain.

Keywords

Massive MIMO, Small cells, Full duplexing, Wireless in-band backhaul

I. INTRODUCTION

In the past few decades, significant development of information and communication technologies has been realized, tremendously improving our lives. Particularly, wireless communication systems have been playing a crucial role as the demand for wireless services has been constantly increasing. Nowadays, the latest standard for the Fourth Generation (4G) of mobile telecommunication, i.e., the Third Generation Partnership Project (3GPP) Long Term Evolution Advanced (LTE-A) standard [1], has been targeting downlink and uplink data rates of 1Gbps and 500Mbps respectively [2], which is already a very challenging problem. Nonetheless, research interests has already been drawn on achieving substantially higher throughput than LTE-A, i.e., the so called Fifth Generation (5G) standard of mobile telecommunication. Obviously, the
challenge is even bigger. Despite of the difficulties, some potential candidate solutions have been considered and being under research. The three candidates that relates to this paper are briefly introduced below.

The first approach is massive Multiple-Input Multiple-Output (MIMO) systems, which were firstly proposed in [3]. A massive MIMO system considers scaling up conventional MIMO systems by possibly orders of magnitude, i.e., hundreds of antennas at a Base-Station (BS) simultaneously serve tens of User Equipments (UEs) in the same time-frequency resource. Such a system could provide tremendous advantages [3]–[6]. With the capabilities of aggressive spatial multiplexing and great array gains, a massive MIMO system could achieve capacity increase and energy efficiency improvement simultaneously. In addition, it could be build with inexpensive and low-power components. Furthermore, it also has the potential to significantly reduce the latency on the air interface, simplify the multiple-access layer, as well as increase the robustness to both unintentional artificial interference and intended jamming. In general, massive MIMO systems are considered in Time-Division Duplexing (TDD) mode, taking advantages of the channel reciprocity between the uplink and downlink.

The second approach is based on a high density deployment of Small Cells (SCs). Although SCs are currently applied mainly for traffic offloading and indoor coverage, they have the potential to offer high capacity in a cost and energy efficient way, in both indoor and outdoor environments [7], [8]. In theory, the capacity scales linearly with the cell density, hence reducing the cell size is a very effective method to improve network capacity. On the other hand, since shorter distance results in less path loss, the total network transmit power could be reduced, thus increasing the cost and energy efficiency.

Another approach is the full-duplex technique based on self-interference cancellation. Instead of transmitting and receiving signals from separate times or frequencies as the currently employed half-duplex schemes, i.e., TDD and Frequency-Division Duplexing (FDD), the full-duplex techniques have the ability to transmit and receive signals on the same frequency at the same time [9]–[13]. As a result, improved capacity could be expected, as shown in [14]. For the sake of distinction, the full-duplex scheme is called Zero-Division Duplexing (ZDD) in this paper.

Although the comparison between massive MIMO and dense SC networks has been carried out as in [15], they are not necessarily competitors. In fact, they could be allies. For example, a network model was proposed in [16], where each macro BS applies the massive MIMO technique to support highly mobile UEs, while dense SCs are employed to support lowly mobile UEs. Although it is not the only way to incorporate massive MIMO and dense SCs, it does show that the cooperation of these two approaches
Due to the potential advantages mentioned above, seeking applications with the cooperation of these three next-generation techniques is a very interesting issue. To that end, we consider a system where the massive MIMO technique is applied as in-band wireless backhaul for multiple SCs as a good application. The reasons are listed below.

1) Due to the fixed positions of SCs, the coherence time between each SC and a BS is relatively long. It is very desirable for the massive MIMO techniques, especially when employing relatively complicated processes such as Zero-forcing (ZF) [4] and Interference Rejection (IR) [17].

2) SC wireless backhaul is desirable, especially for outdoor SCs where wired backhaul is hard to be offered. SC out-band wireless backhaul is operated in a separate frequency band, but the co-channel interference between a BS and each of its associated SCs still exists. For instance, Fig. 1 is a simple example of SC out-band wireless backhaul for the downlink consisting of a BS, a SC, and two UEs, where the frequency band $F_1$ is applied for UE service while the frequency band $F_2$ is used for SC wireless backhaul. In the figure, BUE and SUE denote the UEs associated with the BS and the SC respectively. The intra-frequency interference from the SC to the BUE is shown in the figure. As a result, advanced schemes to deal with such intra-frequency interference in heterogeneous networks as

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**Fig. 1.** A simple example of out-band wireless SC backhaul for the downlink.
enhanced Inter-Cell Interference coordination (eICIC) \[18\], \[19\], included in LTE-A, are still needed. Note that eICIC is very complicated. On the other hand, with in-band SC wireless backhual, the associated SUEs could be operated in the same separate band as the SC in-band wireless backhual, e.g., Fig. 2, so that the aforementioned advanced schemes such as eICIC are not required.

3) Although ZDD could be applied to MIMO systems, it is unlikely to be employed for massive MIMO due to the extremely high complexity, at least with current technology. As a result, a SC equipped a few antennas is a good choice for the application of ZDD. With the capability of transmitting and receiving signals on the same frequency at the same time, ZDD could be applied to the SCs employed as in-band wireless backhual.

In this paper, the potential throughput improvement introduced by SC in-band wireless backhaul in massive MIMO systems was discussed. At first, the basis of massive MIMO systems is briefly reviewed in Section II. Then, three strategies are considered in Section III. The first one is Complete TDD (CTDD), which further divides the communication between the BS and SCs and the data exchanges between SCs and their associated UEs in time division. The second strategy is based on ZDD, which requires that SCs have the capability to do self-interference cancellation thus could transmit and receive signals in the same time-frequency resource. The third one is called ZDD with IR (ZDD-IR). ZDD-IR is actually an enhanced version of ZDD, which has an additional requirement that the BS can apply the IR procedure. The ergodic sum capacity values of downlink and uplink for the three strategies are derived. In Section IV, simulation
results of the three strategies are presented and compared to each other and basic massive MIMO systems. Finally, conclusions are drawn in Section V.

II. MASSIVE MIMO BASIS

Consider a TDD-based massive MIMO system in which a BS equips $N_{bs}$ antennas and supports $K \ll N_{bs}$ UEs in the same time-frequency resource. Assume that each UE has $N_{ue}$ antennas and $N_{bs} \gg KN_{ue}$. Then, the system channel is denoted by a $KN_{ue} \times N_{bs}$ matrix

$$H_{b2u} = \begin{bmatrix} \sqrt{a_{b2u,1}}H_{b2u,1}^T & \cdots & \sqrt{a_{b2u,K}}H_{b2u,K}^T \end{bmatrix}^T$$

(1)

with $k = 1, \ldots, K$, where $a_{b2u,k} < 1$ and the $N_{ue} \times N_{bs}$ matrix $H_{b2u,k}$ denote the path loss and the small-scale fading channel coefficient matrix between the BS and the $k$th UE respectively. The channel is assumed to be Rayleigh flat fading, i.e., the elements in $H_{b2u,k}$ are zero-mean unit-variance complex Gaussian variables. Let

$$A_{b2u} = \text{diag} \left[ \sqrt{a_{b2u,1}} I_{N_{ue}}, \ldots, \sqrt{a_{b2u,K}} I_{N_{ue}} \right]$$

(2)

be a $KN_{ue} \times KN_{ue}$ diagonal matrix where $I_N$ denotes the $N$-dimensional identity matrix, and let

$$H_{b2u} = \begin{bmatrix} H_{b2u,1}^T & \cdots & H_{b2u,K}^T \end{bmatrix}^T.$$  

(3)

Based on (2) and (3), the relation (1) can be rewritten as

$$H_{b2u} = A_{b2u} H_{b2u}.$$  

(4)

For the downlink, ZF beamforming is employed, and the system input-output relation is

$$y_{ue} = H_{b2u} H_{b2u}^\dagger \Phi_{dl} x_{bs} + n_{ue} = \Phi_{dl} x_{bs} + n_{ue},$$

(5)

where $(\cdot)^\dagger$ denotes the pseudo-inverse operation, the $(KN_{ue})$-dimensional vectors $y_{ue}$, $x_{bs}$, and $n_{ue}$ denote the received signals at UEs, the transmit signals at the BS with unit average power for each element, and the noise at UEs, respectively. The noise elements are assumed to be complex Additive White Gaussian Noise (AWGN) with variance $\sigma_{ue}^2$. The $KN_{ue} \times KN_{ue}$ matrix $\Phi_{dl}$ is generally a diagonal matrix to satisfy the power constraints of BS. Let $P_{bs}$ denote the total maximum power of BS, and assume that each antenna has the maximal power of $P_{bs}/N_{bs}$. Then, in the case of at least one antenna working on full power and
each UE has fair performance, $\Phi^{dl}$ reduces to a global scalar $\phi^{dl}$ as

$$
\phi^{dl} = \sqrt{\frac{P_{bs}}{N_{bs}} \left( \max \{ \| H_{b2u,i}^\dagger \| \} \right)^{N_{bs}}}^{-1},
$$

(6)

where $H_{b2u,i}^\dagger$ denotes the $i$th row of $H_{b2u}^\dagger$ [20]. As a result, with the condition (6), the post Signal-to-Noise-plus-Interference-Ratio (SINR) for each UE is

$$
\gamma^{dl} = (\phi^{dl})^2 B \sigma_{ue}^2,
$$

(7)

where $B$ denotes the system bandwidth. Therefore, the ergodic capacity for the $k$th UE without the time coefficient is

$$
c^{dl,k} = E \left\{ B N_{ue} \log_2 \left( \gamma^{dl} + 1 \right) \right\},
$$

(8)

with $k = 1, \ldots, K$. Let $T$ denote the coherence time, and define $T_{dl} \in [0, T]$ as the downlink operation time in a coherence time slot. Then, the ergodic capacity for the $k$th UE is

$$
C^{dl,k} = \left( \frac{T_{dl}}{T} \right) c^{dl,k}.
$$

(9)

According to (6)-(9), the downlink ergodic capacity is limited by the term $\left( \max \{ \| H_{b2u,i}^\dagger \| \} \right)^{N_{bs}}$. Note that $H_{b2u}^\dagger = H_{b2u}^\dagger A_{b2u}^\dagger$ and $A_{b2u}$ is a diagonal matrix. Since worse path-loss matrix $A_{b2u}$ results in better $A_{b2u}^\dagger$, the term $\left( \max \{ \| H_{b2u,i}^\dagger \| \} \right)^{N_{bs}}$ decreases. As a result, $C^{dl}$ reduces. Based on (6)-(9), the downlink ergodic sum capacity is

$$
C^{dl} = \sum_{k=1}^{K} C^{dl,k} = K C^{dl,k}.
$$

(10)

As for the uplink, ZF decoding is applied, thus the system input-output relation is

$$
y_{bs} = (H_{b2u}^\dagger)^T H_{b2u}^\dagger x_{ue} + (H_{b2u}^\dagger)^T n_{bs} = \Phi^{ul} x_{ue} + (H_{b2u}^\dagger)^T n_{bs},
$$

(11)

where the $(K N_{ue})$-dimensional vectors $y_{bs}$, $x_{ue}$, and $n_{bs}$ denote the received signals at the BS, the transmit signals at UEs with unit average power for each element, and the noise at the BS, respectively. The noise elements are assumed to be complex AWGN with variance $\sigma_{bs}^2$. The $K N_{ue} \times K N_{ue}$ matrix $\Phi^{ul}$ is generally a diagonal matrix to satisfy the power constraints of UEs. In the case of equal power allocation, $\Phi^{ul}$ reduces to a global scalar $\phi^{ul}$ as

$$
\phi^{ul} = \sqrt{\frac{P_{ue}}{N_{ue}}}.
$$

(12)
where \( P_{ue} \) denotes the maximal power of each UE. Therefore, the post SINR for the \( i \)th stream of the \( k \)th UE is
\[
\gamma_{ul}(i, k) = \frac{(\phi_{ul})^2}{B \sigma_{bs}^2 \| (H_{b2u}^\dagger)^T_j \|^2},
\]
where \((H_{b2u}^\dagger)^T_j\) denotes the \( j \)th column of \((H_{b2u}^\dagger)\), and \( j = i + (k - 1)N_{ue} \) with \( i = 1, \ldots, N_{ue} \), and \( k = 1, \ldots, K \). As a result, the ergodic capacity for the \( k \)th UE without the time coefficient is
\[
c_{ul,k} = \mathbb{E}\left\{ B \sum_{i=1}^{N_{ue}} \log_2 \left( \gamma_{ul}(i, k) + 1 \right) \right\}.
\]
Let \( T_{ul} = T - T_{dl} \) be the uplink operation time in a coherence time slot, then the ergodic capacity for the \( k \)th UE is
\[
C_{ul,k} = \left( \frac{T_{ul}}{T} \right) c_{ul,k}.
\]
Based on (12)-(15), the uplink ergodic capacity is limited by the term \( \| (H_{b2u}^\dagger)^T_j \|^2 \). Note that \((H_{b2u}^\dagger)^T = A_{b2u}^\dagger (H_{b2u}^\dagger)^T \). Because worse path-loss matrix \( A_{b2u}^\dagger \) causes better \( A_{b2u}^\dagger \), the term \( \| (H_{b2u}^\dagger)^T_j \|^2 \) reduces, which results in lower \( C_{ul}(k) \). According to (12)-(15), the uplink ergodic sum capacity is
\[
C_{ul} = \sum_{k=1}^{K} C_{ul,k}.
\]

III. STRATEGIES OF SC IN-BAND WIRELESS BACKHAUL IN MASSIVE MIMO SYSTEMS

As shown in Section II, when the path losses of UEs are severe, massive MIMO systems could not be able to provide sufficient throughput to each UE. When SCs with much smaller coverage are introduced into the system, the throughput could be significantly improved because it suffers much less path losses. In this paper, it is assumed that each SC is associated to only one UE, and SCs are carefully located so that there are no inter-SC interference. For wired backhaul and out-band wireless backhaul, the communication between the BS and SCs is separated from the data exchange between SCs and their related UEs. Then, as long as the throughput between the BS and each SC is good enough, the whole system would work. On the other hand, in the case of in-band wireless backhaul, the challenge is that the data exchange between the BS and SCs is now not independent of the communication between SCs and their associated UEs. Three strategies are discussed in this section below.
A. CTDD

Since the massive MIMO system is based on TDD, a simple way is to further separate the communication between the BS and SCs, and the data exchange between SCs and their related UEs, in time division.

For the data exchange between the BS and SCs, as each SC can be considered as a UE, the results (6)-(8) can be applied to the downlink from the BS to each SC, and the results (12)-(14) can be used for the uplink from each SC to the BS. Assume that each SC is equipped \( N_{sc} \) antennas and \( KN_{sc} \ll N_{bs} \). Similarly to Section III, define the \( KN_{sc} \times N_{bs} \) channel matrix as

\[
\mathcal{H}_{b2s} = A_{b2s} \mathbf{H}_{b2s},
\]

where

\[
A_{b2s} = \text{diag}\left[ \sqrt{a_{b2s,1}} \mathbf{I}_{N_{sc}} \cdots \sqrt{a_{b2s,K}} \mathbf{I}_{N_{sc}} \right]
\]

is a \( KN_{sc} \times KN_{sc} \) diagonal matrix whose element \( a_{b2s,k} < 1 \) denotes the path loss between the BS and the \( k \)th SC with \( k = 1, \ldots, K \), and

\[
\mathbf{H}_{b2s} = \left[ \mathbf{H}_{b2s,1}^T \cdots \mathbf{H}_{b2s,K}^T \right]^T
\]

with the \( N_{sc} \times N_{bs} \) matrix \( \mathbf{H}_{b2s,k} \) being the small-scale fading channel coefficient matrix between the BS and the \( k \)th SC in Rayleigh flat fading. Then, the downlink ergodic capacity from the BS to the \( k \)th SC without the time coefficient is

\[
c_{b2s,1}^{k} (N_{sc}) = E \left\{ BN_{sc} \log_2 \left( \frac{P_{bs}}{BN_{bs} \sigma_{sc}^2} \left( \max \{|\mathcal{H}_{b2s,i}^\dagger\|\}_{i=1}^{N_{bs}} \right)^{-2} + 1 \right) \right\},
\]

where \( \sigma_{sc}^2 \) denotes the complex AWGN noise variance for each SC. Let \( T_{b2s} \in [0, T_{dl}] \) be the transmission time from the BS to SCs, then the downlink ergodic capacity from the BS to the \( k \)th SC is

\[
C_{b2s,1}^{k} (N_{sc}) = \left( \frac{T_{b2s}}{T} \right)^{c_{b2s,1}^{k}}.
\]

On the other hand, the uplink ergodic capacity from the \( k \)th SC to the BS without the time coefficient is

\[
c_{s2b,1}^{k} (N_{sc}) = E \left\{ B \sum_{i=1}^{N_{sc}} \log_2 \left( \frac{P_{sc}}{BN_{sc} \sigma_{bs}^2} \left( \mathcal{H}_{b2s,j}^\dagger \right)^{-2} + 1 \right) \right\},
\]

where \( j = i + (k-1)N_{sc} \) with \( i = 1, \ldots, N_{sc} \), and \( P_{sc} \) is the maximal power of each SC. Define \( T_{s2b} \in [0, T_{ul}] \) as the transmission time from SCs to the BS, then the uplink ergodic capacity from the \( k \)th SC to the BS
is
\[ C_{s2b,1}^k (N_{sc}) = \left( \frac{T_{s2b}}{T} \right) c_{s2b,1}^k (N_{sc}). \] (23)

As for the communication between each SC and its associated UE, it is in fact a general point-to-point MIMO system. Let the \( N_{ue} \times N_{sc} \) matrix
\[ \mathcal{H}_{s2u,k} = a_{s2u,k} \mathcal{H}_{s2u,k} \] (24)
denotes the channel between the \( k \)th SC and its related UE, where \( a_{s2u,k} \) is the path loss, and the \( N_{ue} \times N_{sc} \) matrix \( \mathcal{H}_{s2u,k} \) is the small-scale fading channel coefficient matrix in Rayleigh flat fading. Assume that \( \mathcal{H}_{s2u,k} \) is known by both the \( k \)th SC and UE, then the optimal capacity is given in [21]. Specifically, the Singular Value Decomposition (SVD) of \( \mathcal{H}_{s2u,k} \) is
\[ \mathcal{H}_{s2u,k} = U \Lambda V^H, \] (25)
where the \( N_{ue} \times N_{ue} \) matrix \( U \) and the \( N_{sc} \times N_{sc} \) matrix \( V \) are unitary. The \( N_{ue} \times N_{sc} \) matrix \( \Lambda \) is diagonal rectangular whose \( s \)th diagonal element \( \lambda_s \in \mathbb{R}^+ \) is a singular value of \( \mathcal{H}_{s2u,k} \) in decreasing order with \( s = 1, \ldots, \min\{N_{ue}, N_{sc}\} \), where \( \mathbb{R}^+ \) denotes the set of positive real numbers. When \( S \in \{1, \ldots, \min\{N_{ue}, N_{sc}\}\} \) streams are transmitted simultaneously, the first \( S \) columns of \( U \) and \( V \), i.e., \( U_S \) and \( V_S \) are chosen as beamforming matrices at UE and SC, respectively. Then, the optimization is the water-filling power allocation as
\[ \frac{P_s}{P} = \begin{cases} 1/\gamma_0 - 1/\gamma_s, & \gamma_s \geq \gamma_0, \\ 0, & \gamma_s < \gamma_0, \end{cases} \] (26)
where \( P \in \{P_{sc}, P_{ue}\} \) and \( P_s \in \{P_{sc,s}(k), P_{ue,s}(k)\} \) denote the total transmit power and the transmit power of the \( s \)th stream for the \( k \)th SC-UE pair respectively, \( \gamma_s = P_s/(B\sigma^2) \in \{\gamma_{s2u,s}(k), \gamma_{u2s,s}(k)\} \) with \( \sigma^2 \in \{\sigma_{ue}^2, \sigma_{sc}^2\} \) being the complex AWGN noise variance, and \( \gamma_0 \in \{\gamma_{s2u,0}(k), \gamma_{u2s,0}(k)\} \) is the cutoff value. Assume that \( S \in \{S_{s2u}(k), S_{u2s}(k)\} \) is the largest number that satisfies (26). Then, the ergodic capacity from the \( k \)th SC to its associated UE under short-term power constraint without the time coefficient is
\[ c_{s2u,1}^k (N_{sc}) = E \left\{ B \sum_{s=1}^{S_{s2u}(k)} \log_2 \left( \frac{\gamma_{s2u,s}(k)}{\gamma_{s2u,0}(k)} \right) \right\}. \] (27)
Define \( T_{s2u} = T_{dl} - T_{b2s} \) as the transmission time from SCs to their related UEs, then the ergodic capacity
from the $k$th SC to its associated UE under short-term power constraint is

$$
C_{s2u,1}^k (N_{sc}) = \left( \frac{T_{s2u}}{T} \right) c_{s2u,1}^k (N_{sc}).
$$

(28)

On the other hand, the ergodic capacity from the $k$th UE to its related SC under short-term power constraint without the time coefficient is

$$
c_{u2s,1}^k (N_{sc}) = E \left\{ B \sum_{s=1}^{S_{u2s}} \log_2 \left( \frac{\gamma_{u2s,s} (k)}{\gamma_{u2s,0} (k)} \right) \right\}.
$$

(29)

Similarly, let $T_{u2s} = T_{ud} - T_{s2b}$ be the transmission time from UEs to their associated SCs, then the ergodic capacity from the $k$th UE to its related SC under short-term power constraint is

$$
C_{u2s,1}^k (N_{sc}) = \left( \frac{T_{u2s}}{T} \right) c_{u2s,1}^k (N_{sc}).
$$

(30)

Based on (20), (21), (27), and (28), the downlink ergodic sum capacity is

$$
C_{dl}^d (N_{sc}) = \sum_{k=1}^{K} \min \left\{ C_{b2s,1}^k (N_{sc}) , C_{s2u,1}^k (N_{sc}) \right\}.
$$

(31)

Similarly, according to (22), (23), (29), and (30), the uplink ergodic sum capacity is

$$
C_{ul}^u (N_{sc}) = \sum_{k=1}^{K} \min \left\{ C_{u2s,1}^k (N_{sc}) , C_{s2b,1}^k (N_{sc}) \right\}.
$$

(32)

For CTDD, the time allocation for each of the four aforementioned communication parts can be easily controlled. For a certain time duration, the best allocation strategy for a BS-UE link is that the throughput between the BS and the $k$th SC is equal to the throughput between the $k$th SC and its associated UE, i.e.,

$$
C_{b2s,1}^k (N_{sc}) = C_{s2u,1}^k (N_{sc}), \quad \text{and} \quad C_{u2s,1}^k (N_{sc}) = C_{s2b,1}^k (N_{sc}).
$$

As a result, the optimal time allocation for the $k$th UE is

$$
\text{Dowlink} : \left\{ \begin{array}{l}
T_{b2s}^k = \frac{c_{b2s,1}^k (N_{sc})}{c_{b2s,1}^k (N_{sc}) + c_{s2u,1}^k (N_{sc})} T_{dl}, \\
T_{s2u}^k = \frac{c_{s2u,1}^k (N_{sc})}{c_{b2s,1}^k (N_{sc}) + c_{s2u,1}^k (N_{sc})} T_{dl}, \\
\end{array} \right
$$

(33)

$$
\text{Uplink} : \left\{ \begin{array}{l}
T_{s2b}^k = \frac{c_{s2b,1}^k (N_{sc})}{c_{s2b,1}^k (N_{sc}) + c_{s2u,1}^k (N_{sc})} T_{ul}, \\
T_{u2s}^k = \frac{c_{s2u,1}^k (N_{sc})}{c_{s2b,1}^k (N_{sc}) + c_{s2u,1}^k (N_{sc})} T_{ul}. \\
\end{array} \right
$$

(34)

Unfortunately, (33) and (34) are generally not hold for all BS-UE links unless the relations $c_{s2u,1}^k (N_{sc}) = c_{b2s,1}^k (N_{sc})$ and $c_{u2s,1}^k (N_{sc}) = c_{s2b,1}^k (N_{sc})$ are satisfied for all $k$, which is obviously not the case in practice.
However, the local optimization results of (33) and (34) could serve as the candidates of global optimization to maximize (31) and (32) respectively by exhaustive search, denoted by CTDD-EXH. Alternatively, an suboptimal global selection, denoted by CTDD-SUB, could be

\[
T_{b2s} = \frac{\sum_{k=1}^{K} c_{b2s,1}(N_{sc})}{\sum_{k=1}^{K} c_{b2s,1}(N_{sc}) + \sum_{k=1}^{K} c_{b2u,1}(N_{sc})} T_{dl}, \\
T_{s2u} = \frac{\sum_{k=1}^{K} c_{s2u,1}(N_{sc})}{\sum_{k=1}^{K} c_{s2u,1}(N_{sc}) + \sum_{k=1}^{K} c_{s2u,1}(N_{sc})} T_{dl}, \tag{35}
\]

\[
T_{s2b} = \frac{\sum_{k=1}^{K} c_{s2b,1}(N_{sc})}{\sum_{k=1}^{K} c_{s2b,1}(N_{sc}) + \sum_{k=1}^{K} c_{s2u,1}(N_{sc})} T_{ul}, \\
T_{u2s} = \frac{\sum_{k=1}^{K} c_{u2s,1}(N_{sc})}{\sum_{k=1}^{K} c_{u2s,1}(N_{sc}) + \sum_{k=1}^{K} c_{u2s,1}(N_{sc})} T_{ul}. \tag{36}
\]

\[I_{b2u}(k) = \frac{P_{bs}B_{b2u}(k)}{N_{bs}} \left( \max \{ \| H_{b2u,i}^T \| F \}_{i=1}^{N_{bs}} \right)^{-2} \| H_{b2u,k} H_{b2u,k}^T \|_F^2. \tag{39}\]

**B. ZDD**

If SCs are capable of ZDD, SCs can transmit and receive signals in the same time-frequency resource. Under this assumption, since the communication between the BS and SCs does not need to be separated from the data exchange between SCs and their related UEs, the overall capacity could be higher than the first strategy presented in Section III-A. Assume that \( N_{sct} \leq N_{sc} \) and \( N_{scr} \leq N_{sc} \) antennas are used for transmitting and receiving in ZDD for each SC.

In the case of downlink, the communication from the BS to each SC is similar to CTDD, only with \( N_{scr} \leq N_{sc} \) receive antennas at each SC. As a result, the ergodic capacity without the time coefficient is given by (20) with \( N_{sc} = N_{scr} \), i.e.,

\[
c_{b2s,1}(N_{sc}) = c_{b2s,1}(N_{scr}). \tag{37}\]

On the other hand, however, the data transmission from each SC to its related UE is now interfered by the corresponding BS-SC link. As a result, its ergodic capacity is lower than (28) of CTDD even with \( N_{sct} = N_{sc} \). Specifically, the water-filling power allocation of (26) changes to

\[
P_{sc,s}^{'(k)}(k) = \begin{cases} 
1/\gamma_0'(k) - 1/\gamma_{s2u,s}^{'(k)}, & \gamma_{s2u,s}^{'(k)}(k) \geq \gamma_0'(k), \\
0, & \gamma_{s2u,s}^{'(k)}(k) < \gamma_0'(k), 
\end{cases} \tag{38}
\]

for the \( k \)th SC-UE link, where \( \gamma_{s2u,s}^{'(k)}(k) = P_{sc}/(B \sigma_{ue}^2 + I_{b2u}(k)) \). The interference power \( I_{b2u}(k) \) is

\[
I_{b2u}(k) = \frac{P_{bs}B_{b2u,k}}{N_{bs}} \left( \max \{ \| H_{b2u,i}^T \| F \}_{i=1}^{N_{bs}} \right)^{-2} \| H_{b2u,k} H_{b2u,k}^T \|_F^2.
\]
number that satisfies (38). Then, the ergodic capacity from the kth SC to its associated UE under short-term power constraint without the time coefficient is

$$c_{s2u,2}^k (N_{sct}) = E \left\{ B \sum_{s=1}^{S_{s2u}^k} \log_2 \left( \frac{\gamma_{s2u,s}^k (k)}{\gamma_{s2u,0}^k (k)} \right) \right\}.$$  \hspace{1cm} (40)

As for the uplink, the data transmission from UEs to their related SCs is similar to CTDD, only with $N_{scr} \leq N_{sc}$. Therefore, the ergodic capacity without the time coefficient is given by (29) with $N_{sc} = N_{scr}$ as

$$c_{u2s,2}^k (N_{scr}) = c_{u2s,1}^k (N_{scr}).$$  \hspace{1cm} (41)

On the other hand, the communication from SCs to the BS is now interfered by all UE-SC links. Therefore, its ergodic capacity without the time coefficient is lower than (22) of CTDD even with $N_{sct} = N_{sc}$. Specifically, the interference power for the i-th stream of the k-th SC $I_{u2b}(i, k)$ is

$$I_{u2b}(i, k) = P_{ue} \| (H_{b2u} H_{b2s})_j^T \|^2$$  \hspace{1cm} (42)

where $j = i + (k - 1)N_{sct}$ with $i = 1, \ldots, N_{sct}$. As a result, the ergodic capacity from the k-th SC to BS without the time coefficient is

$$c_{s2b,2}^k (N_{sct}) = E \left\{ B \sum_{i=1}^{N_{sct}} \log_2 \left( \frac{P_{sc}}{N_{sct}} \left( B \sigma_{bs}^2 \| (H_{b2s})_j^T \|^2 + I_{u2b}(i, k) \right)^{-1} + 1 \right) \right\}.$$  \hspace{1cm} (43)

For ZDD, both the downlink and uplink throughput is limited by the weaker one of their related two communication parts. Therefore, the downlink ergodic capacity of ZDD for the k-th UE is

$$C_{dl}^{zd,k} (N_{sct}, N_{scr}) = T_{dl} \min \left\{ c_{b2s,1}^k (N_{scr}) \, , \, c_{s2u,2}^k (N_{sct}) \right\}.$$  \hspace{1cm} (44)

On the other hand, the uplink ergodic capacity of ZDD for the k-th UE is

$$C_{ul}^{zd,k} (N_{sct}, N_{scr}) = T_{ul} \min \left\{ c_{u2s,1}^k (N_{scr}) \, , \, c_{s2b,2}^k (N_{sct}) \right\}.$$  \hspace{1cm} (45)

C. ZDD-IR

As shown in Section III-B, the interference in ZDD reduces $c_{s2u,1}^k (N_{sc})$ and $c_{s2b,1}^k (N_{sc})$ to $c_{s2u,2}^k (N_{sct})$ and $c_{s2b,2}^k (N_{sct})$ respectively, which would limit the overall throughput. Since $N_{bs} \gg K N_{ue}$, the interference
can be rejected at the BS by a $N_{bs} \times (N_{bs} - KN_{ue})$ matrix $R$ which satisfies

$$H_{b2u}R = 0_{KN_{ue} \times (N_{bs} - KN_{ue})},$$ (46)

where 0 denotes the all-zero matrix.

In the case of the downlink, the ZF-IR beamforming matrix is

$$G = R (H_{b2s}R)^\dagger.$$ (47)

Note that $(H_{b2s}R)^\dagger$ is a valid right inverse when $N_{bs} \geq K (N_{ue} + N_{scr})$. For the communication from the $k$th SC to its related UE, the interference power in (39) becomes

$$I'_{b2u}(k) = \frac{P_{bs} a_{b2u,k}}{N_{bs}} (\max \{ \| H_{b2s,i}^\dagger \| \}_{i=1}^{N_{bs}})^{-2} \| H_{b2u,k}G \|_F^2.$$ (48)

Note that $H_{b2u,k}G = (H_{b2u,k}R) (H_{b2s}R)^\dagger = 0_{N_{ue} \times (N_{bs} - KN_{ue})} (H_{b2s}R)^\dagger = 0_{N_{ue} \times KN_{scr}}.$ (49)

Based on (49), the interference power in (48) is then zero. As a result, the ergodic capacity from the $k$th SC to its associated UE under short-term power constraint without the time coefficient is similar to CTDD only with $N_{sc} \leq N_{sc}$, which is given by (27) with $N_{sc} = N_{set}$ as

$$c_{s2u,3}^k (N_{set}) = c_{s2u,1}^k (N_{set}).$$ (50)

On the other hand, the downlink ergodic capacity from the BS to the $k$th SC without the time coefficient becomes

$$c_{b2s,3}^k (N_{sc}) = E \left\{ BN_{sc} \log_2 \left( \frac{P_{bs}}{BN_{bs} \sigma_{sc}^2} (\max \{ \| g_i \| \}_{i=1}^{N_{bs}})^{-2} + 1 \right) \right\},$$ (51)

where $g_i$ is the $i$th row of $G$.

As for the uplink, the ZF-IR decoding matrix is $G^T$ with $N_{bs} \geq K (N_{ue} + N_{scr})$. For the data transmission from the $k$th UE to its associated SC, the ergodic capacity without the time coefficient is still the same as in ZDD, i.e.,

$$c_{u2s,3}^k (N_{scr}) = c_{u2s,2}^k (N_{scr}) = c_{u2s,1}^k (N_{scr}).$$ (52)

On the other hand, in the case of the communication from the $k$th SC to the BS, the interference power
for the $i$th stream of the $k$th SC in (42) becomes

$$I'_{u2b}(i, k) = P_{uc} \| (H_{b2u} G)_{ij} \|^2$$

(53)

where $j = i + (k - 1)N_{sct}$ with $i = 1, \ldots, N_{sct}$. Similarly to (49),

$$H_{b2u} G = A_{b2u} \left( H_{b2u} R \right) \left( H_{b2s} R \right)^{\dagger} = A_{b2u} 0_{K N_{sc} \times (N_{bs} - K N_{uc})} \left( H_{b2s} R \right)^{\dagger} = 0_{K N_{sc} \times K N_{sct}}.$$  

(54)

According to (54), the interference power in (53) is then zero. Therefore, the ergodic capacity from the $k$th SC to BS without the time coefficient becomes

$$c_{s2b,3}^k (N_{sc}) = E \left\{ B \sum_{i=1}^{N_{sc}} \log_2 \left( \frac{P_{sc}}{N_{sc}} \left[ B \sigma_{bs}^2 \| g^T_i \|_2^2 \right]^{-1} + 1 \right) \right\},$$

(55)

where $g^T_i$ is the $i$th column of $G$.

According to the discussion above, the downlink ergodic capacity of ZDD-IR for the $k$th UE is

$$C_{3,dl}^k (N_{sc}, N_{scr}) = T_{dl} \min \left\{ c_{b2s,3}^k (N_{scr}) ; c_{s2u,1}^k (N_{sct}) \right\}.$$  

(56)

On the other hand, the uplink ergodic capacity of ZDD for the $k$th UE is

$$C_{3,ul}^k (N_{sc}, N_{scr}) = T_{ul} \min \left\{ c_{u2s,1}^k (N_{scr}) ; c_{s2b,3}^k (N_{sct}) \right\}.$$  

(57)

### IV. Simulation Results

Fig. 3 presents the diagram of the considered massive MIMO system for simulations. Specifically, a BS supports $K = 8$ UEs, each of which is associated to a SC. The distances between the BS and SCs are considered to be the same. The SCs are evenly distributed, and each of them covers a disc area with the radius of 40 meters. The closed distance between a UE to its related SC is 10 meters, and it is uniformly distributed within the service area of its associated SC. In Table I, simulation parameters of the considered massive MIMO system are provided. Note that to exploit the advantages of multiple antennas, the Non-Line-Of-Sight (NLOS) models provided in [22] are considered. The downlink and uplink are separately operated in TDD mode. The percentages of operation times for the downlink and uplink are assumed to be the same, i.e., $T_{dl}/T = T_{ul}/T = 0.5$. For each scenario, SC in-band wireless backhaul systems employing CTDD-EXH, CTDD-SUB, ZDD, and ZDD-IR techniques discussed in III are considered, and their sum capacity values are calculated. In the result figures, $N_{sc} = \{N_{sc}, N_{scr}\}$ means that $N_{sc}$ and $N_{scr}$ antennas
are employed to transmit and receive signals in the same time-frequency resource for ZDD and ZDD-IR. Note that $N_{sc} \geq N_{scx} \geq N_{ue}$ and $N_{sc} \geq N_{scr} \geq N_{ue}$ are assumed.

A. Downlink

For the downlink scenario, the distance between the BS and each SC is considered to be at the range of $d_{bs} \in \{200\text{m}, \ldots, 1500\text{m}\}$. The ergodic sum capacity results of the downlink employing different
TABLE I. SIMULATION PARAMETERS

| Parameter                  | Value                                      |
|----------------------------|--------------------------------------------|
| Carrier Frequency          | $f_c = 2$GHz                               |
| System Bandwidth           | $B = 20$MHz                                |
| Number of SC               | $K = 8$                                    |
| Cell Type                  | BS: Macro; SC: Outdoor Pico               |
| Channel Model              | Large-Scale: NLOS models in [22]; Small-Scale: Rayleigh Fading |
| Maximal Power              | $P_{bs} = 35$w (46dBm); $P_{sc} = 250$mw (24dBm); $P_{ue} = 200$mw (23dBm) |
| Antenna Gain               | BS: 0dBi; SC: 5dBi; UE: 0dBi              |
| Number of Antennas         | $N_{bs} = 256$; $N_{sc} = 4$; $N_{ue} \in \{1, 2\}$ |
| Noise Power                | $N_0 = -174$dBm/Hz                        |
| Noise Figure               | BS: 5dB; SC: 13dB; UE: 9dB                |

Fig. 4. Downlink ergodic sum capacity of different techniques for $N_{sc} = 4$, $N_{ue} = 1$, with different $d_{b2s}$ values.

Techniques discussed in Section III are compared to the results of directly ZF beamforming without SCs discussed in Section II. Note that larger $d_{b2s}$ implies worse BS-SC and BS-UE links.

For $N_{ue} = 1$, Fig. 4 shows the ergodic sum capacity results of $N_{sc} = 4$. Similarly, as for $N_{ue} = 2$, the case of $N_{sc} = 4$ is presented in Fig. 5.
Compared to directly ZF beamforming without SCs, although CTDD-EXH separates the downlink into two parts with shorter time, with the help of multiple antennas at SCs and the better links of BS-SC and SC-UE, it could achieve significantly better ergodic sum capacity, when the BS-UE links are not very strong as shown in the figures. In addition, it can be expected that larger $N_{sc}$ could offer greater ergodic sum capacity. Note that both technique achieves lower ergodic sum capacity as the BS-SC links become worse, but directly ZF beamforming decays much quicker. As the result, if the BS-UE links are sufficiently strong, directly ZF beamforming could provide better ergodic sum capacity as shown in the figures. Nevertheless, by increasing $N_{sc}$, it could be expected that CTDD-EXH always has the potential to outperform directly ZF beamforming, as long as the SC-UE links are better than the BS-UE links, which is mostly the practical case. Moreover, the suboptimal CTDD-SUB could provide almost the same results as CTDD-EXH.

In the case of ZDD, as the BS-SC links become weaker, it offers better ergodic sum capacity up to a point, from where the ergodic sum capacity starts to drop. This trend can be clearly read from the figures. The reason is that the BS-SC links interfere the SC-UE links since they are operated at the same time-

**Fig. 5.** Downlink ergodic sum capacity of different techniques for $N_{sc} = 4$, $N_{ue} = 2$, with different $d_{bs}$ values.
frequency resource. When the interference is relatively strong, the SC-UE links limit the overall ergodic sum capacity. The interference decreases as the BS-SC links become weaker, then the SC-UE links become better. Therefore, the ergodic sum capacity become greater. However, when the SC-UE links are strong enough, the overall ergodic sum capacity is then limited by the BS-SC links. As a result, the overall ergodic sum capacity starts to decrease. Note that the BS-SC links are very probably better than the BS-UE links when $d_{b2s}$ is not too small, hence when the BS-SC links limit the ergodic sum capacity, it still much better than directly ZF beamforming, with the condition of $N_{scr} \geq N_{ue}$. As a result, after a certain value of $d_{b2s}$, ZDD is better than directly ZF beamforming without SCs as shown in the figures. Note that in the case of complete ZDD, which means that each SC antenna can be used for transmitting and receiving signals in the same time-frequency resource, when the BS-SC links limit the ergodic sum capacity, complete ZDD is always better than CTDD-EXH. However, in this subsection, the more conservative ZDD method in which separate transmit and receive antennas are considered. In this case, the comparison between ZDD and CTDD-EXH is more complicated. Nevertheless, the conservative ZDD still could outperform CTDD-EXH as shown in the figures.

As for ZDD-IR, as the interference of the SC-UE links from the BS-SC links is rejected, it is generally better than ZDD as shown in the figures. For the range that the ergodic sum capacity is limited by the SC-UE links, it is independent of $d_{b2s}$ as shown in Fig. 4. On the other hand, for the range that the ergodic sum capacity is limited by the BS-SC links, it decreases as $d_{b2s}$ increases, as shown in the figures. Eventually, ZDD-IR becomes similar to ZDD with slightly worse ergodic sum capacity. The reason is that the interference rejection process could result in slightly worse BS-SC links due to the power constraint for each antenna.

To sum up, if the SCs are very close to the BS, directly ZF beamforming between BS and UEs is the best choice, which means that employing SCs in this case is pointless. On the other hand, when the SCs have certain distances to the BS, all CTDD, ZDD, and ZDD-IR could outperform directly ZF beamforming without SCs. Specifically, ZDD-IR is the best choice for the middle range, while ZDD is good enough for the far range.

**B. Uplink**

Similarly, for the uplink scenario, the distance between each SC and the BS is at the range of $d_{s2b} \in \{200m, \ldots, 1500m\}$. The ergodic sum capacity results of the uplink employing different techniques dis-
Fig. 6. Uplink ergodic capacity of different techniques for $N_{sc} = 4$, $N_{ue} = 1$, with different $d_{s2b}$ values.

cussed in Section III are compared to the results of directly ZF decoding without SCs described in Section II. Note that larger $d_{s2b}$ implies worse SC-BS and UE-BS links.

For $N_{ue} = 1$, Fig. 6 presents the ergodic sum capacity results of $N_{sc} = 4$. Similarly, in the case of $N_{ue} = 2$, $N_{sc} = 4$, the results are shown in Fig. 7.

Similarly to the downlink, compared to directly ZF decoding without SCs, CTDD-EXH with each SC equipping multiple antennas and better UE-SC and SC-BS links could offer significantly better ergodic sum capacity, with the condition that the UE-BS links are not very strong, as shown in the figures. Moreover, it could be expected that larger $N_{sc}$ could provide better ergodic sum capacity. Although both technique achieves lower ergodic sum capacity as the SC-BS links become worse, directly ZF decoding decreases much fast. Hence, if the UE-BS links are sufficiently strong, directly ZF decoding could offer better ergodic sum capacity as shown in the figures. However, it could be expected that by adding $N_{sc}$, CTDD-EXH always has the potential to offer better ergodic sum capacity than directly ZF decoding, when the UE-SC links are better than the UE-BS links, which is mostly the practical assumption. Furthermore, the suboptimal
CTDD-SUB could offer almost the same results as CTDD-EXH.

As for ZDD, the uplink ergodic sum capacity increases to a point as $d_{s2b}$ becomes larger, then it becomes relatively stable for a certain range before declining, as shown in the figures. The reason is that, as $d_{s2b}$ increases, although the SC-BS links become weaker, the interference from the UE-SC links reduces as well with even a quicker rate. Therefore, the SC-BS links generally become better as $d_{s2b}$ enlarges, until the interference becomes lower than the noise power, from where the SC-BS links start to become weaker as $d_{s2b}$ increases. On the other hand, the UE-SC links are independent of $d_{s2b}$. As a result, the overall ergodic sum capacity is at first limited by the SC-BS links so that it improves as $d_{s2b}$ increases, until it becomes limited by the UE-SC links. From there, the overall ergodic sum capacity becomes independent of $d_{s2b}$ to a certain point before being limited by the SC-BS links again and starts to reduce. Due to the above properties, after a certain value of $d_{s2b}$, ZDD is better than directly ZF decoding without SCs as shown in the figures. The comparison between ZDD and CTDD-EXH is more complicated. However, even with the conservative ZDD method, ZDD could offer better ergodic capacity than CTDD, as shown in the figures.
As for ZDD-IR, as the interference of the SC-BS links from the UE-SC links is rejected, it is generally better than ZDD as shown in the figures. For the range that the ergodic sum capacity is limited by the UE-SC links, it is independent of $d_{b2s}$ and is slightly better than ZDD as shown in Fig. 6. The reason for the slightly better results is that ZDD-IR have better SC-BS links than ZDD. On the other hand, for the range that the ergodic sum capacity is limited by the SC-BS links, it is better than ZDD due to the improved SC-BS links, as shown in the figures. Moreover, in this case, ZDD-IR decreases as the SC-BS link becomes worse. Eventually, ZDD-IR becomes similar to ZDD as shown in the figures.

In summary, similarly to the downlink case, if the SCs are very near to the BS, directly ZF decoding between UEs and the BS is the best strategy, which means that applying SCs is not a efficient choice in this case. On the other hand, when the SCs have certain distances to the BS, all CTDD, ZDD, and ZDD-IR could be better than directly ZF decoding without SCs. Specifically, ZDD-IR is best strategy for the middle range, while ZDD is efficient enough for the far range. Note that for some cases, e.g., Fig. 6, ZDD could be sufficiently good for both middle and far ranges.

C. Residual Self-Interference

As shown in Section IV-A and Section IV-B, ZDD and ZDD-IR could achieve better throughput compared to CTDD and directly ZF without SCs, for both downlink and uplink. However, realistically, Residual Self-Interference (RSI) exists for ZDD and ZDD-IR. RSI results in performance degradation for the received signals. For our case, it weakens the BS-SC links for the downlink and the UE-SC links for the uplink. Based on our experiments, there is around 2dB RSI for conservative ZDD where the transmit and receive antennas are separate, while near 5dB RSI for complete ZDD where each antenna both transmits and receives signals. In this subsection, simulation results for ZDD and ZDD-IR with RSI are provided, while directly ZF without SCs and CTDD-EXH are shown as reference curves.

Figure 8 and Figure 9 show the downlink ergodic sum capacity results of different RSI cases with $N_{sc} = 4$ for $N_{ue} = 1$ and $N_{ue} = 2$ respectively. For conservative ZDD, because RSI only affects the BS-SC links, the ergodic sum capacity results for ZDD and ZDD-IR are worse than the no RSI case when the BS-SC links limit the results, as shown in the figures. Despite of the losses caused by RSI, conservative ZDD and ZDD-IR could still outperform CTDD and direct ZF without SCs. In the more complicated complete-ZDD case, it increases the number of spatial multiplexing streams for the BS-SC links and improves the array gains for the SC-UE links, compared to conservative ZDD. The increased streams of complete ZDD for the BS-SC links could provide more capacity increase than the decrease caused by higher RSI. In addition,
Fig. 8. Downlink ergodic sum capacity of different RSI cases for $N_{sc} = 4$, $N_{ue} = 1$, with different $d_{bs}$ values.

the SC-UE links of complete ZDD are better than conservative ZDD. As a result, even with 5dB RSI, complete ZDD and ZDD-IR could achieve better results than conservative ZDD and ZDD-IR respectively, as shown in the figures.

Similarly, the uplink ergodic sum capacity results of different RSI cases with $N_{sc} = 4$ for $N_{ue} = 1$ and $N_{ue} = 2$ are shown in Figure 10 and Figure 11 respectively. For the uplink, RSI only affects the UE-SC links. Therefore, compared to the no RSI case, the ergodic sum capacity results for ZDD and ZDD-IR of conservative ZDD are worse when the UE-SC links limit the results, as shown in the figures. Nevertheless, even with RSI, conservative ZDD and ZDD-IR could still outperform CTDD and direct ZF without SCs. As for the more complicated complete-ZDD case, compared to conservative ZDD, it increases the number of spatial multiplexing streams for the SC-BS links and improves the array gains for the UE-SC links. The improved array gains of the UE-SC links could offer greater capacity increase than the degradation due to worse RSI. Moreover, the increased streams ZDD could improve the SC-BS links. As a result, complete ZDD and ZDD-IR, even with 5dB RSI, could provide greater results than conservative ZDD and ZDD-IR.
Fig. 9. Downlink ergodic sum capacity of different RSI cases for $N_{sc} = 4$, $N_{ue} = 2$, with different $d_{bsu}$ values.

respectively, as shown in the figures.

V. CONCLUSIONS

In this paper, three strategies of SC in-band wireless backhaul in massive MIMO systems were provided and discussed. When the links between the BS and UEs are not very good, CTDD, ZDD, or ZDD-IR could achieve significant throughput improvement. Among the three strategies, CTDD is the simplest one and could achieve decent throughput gain. ZDD requires self-interference cancellation at SCs and could achieve better throughput than CTDD depends on the conditions, even with RSI. Other than self-interference cancellation, ZDD-IR needs the additional interference rejection process at the BS, but the increased complexity could result in generally better throughput than CTDD and ZDD. In summary, SC in-band wireless backhaul has the potential to increase the throughput for massive MIMO systems. The proper applications of SC in-band wireless backhaul in heterogeneous networks and their comparisons with other network schemes are considered as future work.
Fig. 10. Uplink ergodic capacity of different RSI cases for $N_{sc} = 4$, $N_{ue} = 1$, with different $d_{sb}$ values.

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