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Dual Antenna Selection in Self-Backhauling Multiple Small Cell Networks

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Abstract—This paper investigates self-backhauling with dual antenna selection at multiple small cell base stations. Both half and full duplex transmissions at the small cell base station are considered. Depending on instantaneous channel conditions, the full duplex transmission can have higher throughput than the half duplex transmission, but it is not always the case. Closed-form expressions of the average throughput are obtained, and validated by simulation results. In all cases, the dual receive and transmit antenna selection significantly improves backhaul and data transmission, making it an attractive solution in practical systems.

Index Terms—Small cell networks, full duplex, self-backhauling, antenna selection, inter-cell interference.

I. INTRODUCTION

Massive deployment of small cell networks provides a viable solution for future gigabit-level data communications [1]. When small cells are densely deployed in cellular networks, it is crucial to efficiently deliver backhaul data. Both wired and wireless links may be used for backhaul data transmissions. If data and backhaul share the radio spectrum, the overall system efficiency can be significantly improved [2], [3].

Recent studies show that the using of full duplex (FD) technique can not only to improve physical layer secrecy [4], but also to improve the backhaul and data transmission efficiency in small cell networks [5]. The FD transmission has attracted much attention as a viable approach in 5G networks to avoid the spectral efficiency loss with traditional half duplex (HD) transmission. While FD communications usually suffer from self-interference, i.e. the interference from its own transmission [6], recently developed antenna, RF and digital baseband technologies reduce the self-interference (SI) to noise level [6], [7]. In [8], the capacity performance of the FD self-backhauling in a single small cell was analyzed. While the results in [8] demonstrate great potential in applying FD at small cell base stations, the system therein only considered one small cell and the analysis was based on the assumption that all interfering channels were approximated by their statistical averages. In practice, there are usually multiple small cells and interfering channels are time-varying. This motivates us to investigate the self-backhauling in small cell networks under more practical scenarios.

In this paper, we consider a multiple small cell network where both small cell base stations and mobile users are subject to interferences from neighboring small cell base stations. Further considering that small cell base stations are usually equipped with multiple antennas, we propose a novel dual antenna selection scheme at the small cell base stations. Antenna selection provides an efficient way to harvest the diversity gain by selecting a single antenna among a group of antennas. It also reduces the transceiver complexity since only one RF chain is required at the transmitter and the receiver [9]. In the proposed scheme, the small cell base station is equipped with two groups of antennas, for receive and transmit antenna selection respectively. With dual antenna selection at the small cell base station, the performance of both backhauling and data transmission can be significantly improved. The main contributions of this paper are summarized as follows:

- **Proposing a novel dual antenna selection scheme for the self-backhauling in multiple small cell networks.** Both the HD and FD at the small cell base stations are considered. To the best of authors’ knowledge, this is the first time that the dual antenna selection approach is applied to multiple small cell networks. The proposed dual antenna selection provides an efficient way to transmit backhaul and data in small cell networks.

- **Deriving closed-form expressions for the outage probabilities of the self-backhauling for both downlink and uplink in multi-small cell networks.** Unlike the analysis in [8] where interfering channels are approximated by their statistical averages, the outage analysis in this paper is based on more realistic assumptions that both the backhaul interference and residual self-interference (RSI) are modeled as Rayleigh fading. Furthermore interferences from neighboring base stations are also considered. Thus the analysis in this paper better reflects the practical scenario and shows deeper insights into the self-backhauling system in small cell networks.

II. DUAL ANTIENNA SELECTION AT TSBS

A macro/small cell network with centralized backhaul approach [2] is shown in Fig. 1, where there are one macrocell base station (MBS), one target small cell (TSC) and N neighboring small cells (NSBS) with neighboring small base station (NSBS). The base station in TSC is the target-SBS (TSBS), and we assume there is one operating mobile user (U) in TSC1. TSBS is connected to MBS through a wireless backhaul link. The data received at the TSBS and U are interfered by inter-cell interference (ICI) from neighboring NSBSj (j = 1, ⋯, N).

In this paper, we propose to apply dual antenna selection at the TSBS. To be specific, we assume TSBS is equipped with two groups of antennas, consisting of K and M antennas for receive and transmit antenna selection respectively. All other nodes are equipped with a single antenna2. For later use, the k-th receiving and i-th transmission antenna at TSBS are denoted as $TSBS_k$ (k = 1, ⋯, K) and $TSBS_i$ (i = 1, ⋯, M) respectively. The channel coefficients for $MBS \rightarrow TSBS_k$, $MBS \rightarrow TU$, $NSBS_j \rightarrow TSBS_k$, $NSBS_j \rightarrow TU$ and $TSBS_i \rightarrow TU$ are denoted as $h_{MBS_k}$, $h_{MBS_{TU}}$, $h_{NSBS_j_k}$, $h_{NSBS_j_{TU}}$ and $h_{TSBS_i_{TU}}$ respectively. We assume all channels are independent Rayleigh flat fading, and keep unchanged within one packet but vary from one packet

1 If there are several users in the target cell, only one user is operated through user scheduling [10] (e.g., random user selection).
2 Although these nodes may also have multiple antennas, this will not affect the antenna selection schemes at TSBS.
to another. The corresponding channel gains $\gamma_{ij} = |h_{ij}|^2$ are independently exponentially distributed with mean of $\lambda_j$ ($j \in \{MS_k, MU, B_j, S_k, B_j U, S_i U\}$) respectively.

The distributions for the access and backhaul SIR are obtained as (15) and (16) respectively, and substituting them into (7) immediately gives the corresponding throughputs.

The sub-optimum selection scheme has very close performance to the optimum scheme. This follows from the fact that, as is shown in (8), the transmission antenna affects the receive antenna selection through the residual self-interference term $\gamma_{S_i S_k}$. If self-interference is significantly suppressed, $\gamma_{S_i S_k}$ will have little effect on receive antenna selection. If TSBS operates in the HD mode where it receives and transmits data at different time slots, the received signals at the TSBS and TU are free from the self-interference and interference from MBS respectively. The transmit and receive antenna selection can be similarly obtained, and the ‘sub-optimum’ scheme described above becomes optimum (because no self-interference is involved).

III. AVERAGE THROUGHPUT

First, we consider the FD TSBS antenna selection. For delay-limited transmission, the average throughput is obtained as

$$T^{FD} = R(1 - P_{out}^{FD}(\gamma_{th})),$$

where $R$ (bps/Hz) is the transmission rate, $P_{out}^{FD}(\gamma_{th}) = P(\gamma_H < \gamma_{th})$ is the outage probability with $\gamma_{th} = 2^R - 1$, and $P(\cdot)$ denotes the probability of the enclosed. We have the following proposition.

Proposition 1: If the TSBS operates in the FD mode, the proposed antenna selection in downlink transmission has the outage probability as (8) at the top of next page, where $F_{2,1}(a, b, c, z)$ is the first hypergeometric function, and $C_{M-1}^M = M! - 1/[(M - 1)!]$ which is the binomial coefficient, $\alpha = \lambda_{S_i S_k} - \lambda_{B_j S_k}, \lambda_{B_j S_k} - \lambda_{B_j U}$, $\lambda_{B_j U} - \lambda_{B_j S_k}$, $\lambda_{MU} - \lambda_{B_j U}$, and $\beta = \lambda_{S_i S_k} / \lambda_{B_j U}$. If $P_{out}^{FD}(\gamma_{th}) = 1 - \sum_{l=0}^{M} C_{M-1}^M \beta^l$. If $P_{out}^{FD}(\gamma_{th}) = 1 - \sum_{l=0}^{M} C_{M-1}^M \beta^l$.

Proof: See Appendix 1.

It is interesting to note that when the ICI from NSBS-s is ignored (e.g. [2]), (8) can be simplified as

$$P_{out}^{FD}(\gamma_{th}) = 1 - \frac{\gamma_{th} \Lambda_{S_i S_k}}{\Lambda_{B_j S_k} + \Lambda_{B_j U}}$$

and

$$P_{out}^{FD}(\gamma_{th}) = 1 - \frac{\gamma_{th} \Lambda_{S_i U}}{\Lambda_{B_j U} + \Lambda_{S_i U}}.$$
On the other hand, in the HD mode, because the TSBS does
not receive and transmit simultaneously, the average throughput is
obtained as
\[
T_{HD}^{out} = \frac{1}{2} R (1 - P_{out}^{HD} (\gamma_{th})).
\]  
Following the similar procedures to those for the FD mode, the
outage probability for the HD mode can be obtained as
\[
P_{out}^{HD} (\gamma_{th}) = 1 - \left[ 1 - \left( \frac{\lambda_{MS}}{\lambda_{MS} + \lambda_{BSk}} \right) \right]^K \left( 1 - \sum_{i=1}^{M} C_i^K \right) \left( 1 - \frac{\lambda_{BSk}}{\lambda_{MS} + \lambda_{BSk}} \right)^N.
\]  
Particularly, if the ICI from NSBS-s is ignored, (11) becomes
\[
P_{out}^{HD} (\gamma_{th}) = 1 - \left[ 1 - \left( \frac{\lambda_{MS}}{\lambda_{MS}} \right) \right]^K \left( 1 - \frac{\lambda_{BSk}}{\lambda_{MS}} \right)^N.
\]  
IV. NUMERICAL SIMULATIONS
In the simulations, all noise variance and transmission powers are
normalized to unity. For comparison, the results for the traditional
scheme that no antenna selection is applied at the target small base
station are also shown. Both theoretical and simulation results are
shown, where simulation results are obtained by averaging 10⁶
independent Monte Carlo runs. In all cases, the simulation results
well match the analysis, which well verifies the closed-form outage
probabilities derived in this paper.

Fig. 2. The outage probabilities vs target rate in the FD modes.

Fig. 3. The average throughput vs channel SNR in the HD mode.

Fig. 4. Average throughput vs different $\lambda_{MU}$ in FD and HD modes.

Fig. 4 compares the average throughput between the HD and FD
modes with respective to different $\lambda_{MU}$, where $\lambda_{MS} = \lambda_{SU} = 30$
dB, $\lambda_{BSk} = \lambda_{BU} = 15$ dB, $\lambda_{SI} = 5$ dB and $\lambda_{MU} = 10$ dB. It is clearly shown that the
proposed scheme has significant better outage performance than the
traditional scheme (without antenna selection). Particularly in the
proposed scheme, the outage probability decreases consistently with
more antennas. It is also evident that, with more inter-cell interfer-
ce (i.e. larger $N$), the outage probability increases significantly. Fig. 3
compares the average throughputs in the HD mode with respective
to the channel SNR, where the average channel gains are set as $\lambda_{BSk} = 10$ dB, $\lambda_{SI} = 5$ dB, $\lambda_{MU} = 10$
dB and $R_T = 2$ b/s/Hz. It is clearly shown that, for different $\lambda_{MU}$, the throughput in the
FD mode can be either higher or lower than that in the HD mode. For example, for the cases of $K = M = 3$ and $K = M = 1$,
when $N = 3$ (i.e. the presence of intercell interference), the
average throughput for FD is higher than that for HD when $\lambda_{MU}$
is approximately smaller than 28.5 dB, and otherwise the HD
mode has higher throughput. Fig. 5 compares average throughputs
between the HD and FD modes with respect to different $\lambda_{SI}$,where $\lambda_{MS} = \lambda_{SU} = 30$ dB, $\lambda_{BSk} = \lambda_{BU} = 15$ dB, $\lambda_{SI} = 5$ dB and $R_T = 2$ b/s/Hz.
Similar to the results shown in Fig. 4, for different $\lambda_{SI}$, the FD may or may not have higher average throughputs than the HD mode. Fig. 4 and 5 imply that, according
to different channel conditions, we can switch between HD and FD

$$
\begin{align*}
F_{out}^{HD} (\gamma_{th}) &= 1 - \left[ 1 - \left( \frac{\lambda_{MS}}{\lambda_{MS} + \lambda_{BSk}} \right) \right]^K \left( 1 - \sum_{i=1}^{M} C_i^K \right) \left( 1 - \frac{\lambda_{BSk}}{\lambda_{MS} + \lambda_{BSk}} \right)^N, \\
F_{out}^{FD} (\gamma_{th}) &= 1 - \left( \frac{\lambda_{MS}}{\lambda_{MS} + \lambda_{BSk}} \right)^K. 
\end{align*}
$$
mode for higher throughput.

V. CONCLUSIONS

This paper proposed a dual antenna selection strategy in multiple small cell networks, where both FD and HD modes at TSBS were considered. Analysis showed that the FD mode at TSBS may or may not lead to higher average throughput than the HD mode. Switching between half and duplex transmission at TSBS may thus be necessary, which will be left as a future topic of research. In all cases, the dual antenna selection at TSBS mitigates the ICI from neighboring SBSs, and significantly improves the backhaul and data transmission, making it an attractive solution to realize efficient backhaul transmission in multiple small cell networks.

APPENDIX I - PROOF OF (8)

We define $x = \gamma_{M} S_{Bk}$, $y = \sum_{j=1}^{N} \gamma_{S_{Bk}}$, $x_1 = \max_{i \in \{1,...,M\}} \{\gamma_{S_{i}}\}$, $y_1 = \sum_{j=1}^{N} \gamma_{S_{ji}}$, $y_2 = \sum_{j=1}^{N} \gamma_{S_{Bk}} + \gamma_{S_{S}}$ and $y_3 = \sum_{j=1}^{N} B_{jU} + \gamma_{M} U$. The CDF of $x$ and $x_1$ can be obtained as

$$F_X(x) = 1 - e^{-\frac{x}{\gamma_{M} S_{Bk}}} \text{ and } F_{X_1}(x_1) = \left(1 - e^{-\frac{1}{x_1}}\right)^M,$$

respectively. The PDF of $y$ and $y_1$ are given by

$$f_Y(y) = \frac{y^{N-1} - \gamma_{S_{Bk}}}{\lambda_{S_{Bk}} \Gamma(N)} \text{ and } f_{Y_1}(y_1) = \frac{y_1^{N-1} - \gamma_{S_{Bk}}}{\lambda_{S_{Bk}} \Gamma(N)}$$

respectively, where $\Gamma(.)$ denotes the gamma function. And the CDF of $y_2$ and $y_3$ can be obtained as

$$F_{Y_2}(y_2) = \left[1 - \left(1 - \frac{\gamma_{BjU}}{\lambda_{S_{Bk}}}\right)^N\right] \text{ and } F_{Y_3}(y_3) = \left[1 - \left(1 - \frac{\gamma_{BjU}}{\lambda_{S_{Bk}}}\right)^N\right] \text{ and } F_{Y_3}(y_3) = \left[1 - \left(1 - \frac{\gamma_{BjU}}{\lambda_{S_{Bk}}}\right)^N\right].$$

where $\gamma(a, b)$ denotes the lower incomplete gamma function. Next, let $w_2 = \max_{k \in \{1,...,K\}} (x/y_2)$, the CDF of $w_2$ can be obtained as

$$F_W(w_2) = \int_{0}^{w_2} f_{X_1}(x) f_{Y_1}(y_1) dx, \quad \gamma(a,b) = \frac{1}{\Gamma(a)} \int_{0}^{b} x^{a-1} e^{-x} dx.$$

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