Interference coordination in full-duplex HetNet with large-scale antenna arrays

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Key words: Massive MIMO; Full-duplex; Small cell; Wireless backhaul; Distributed algorithm

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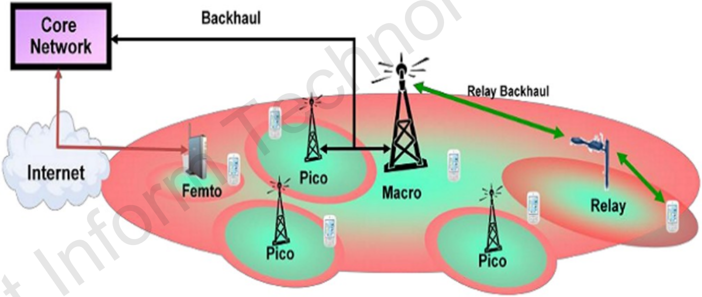
Overview

Overview

1. Motivation
2. System model
3. Problem formulation
4. Interference coordination with centralized algorithms
5. Interference coordination with distributed algorithm
6. Performance evaluation

Heterogeneous Network

Heterogeneous Network (HetNet): A network that consists of a mix of high-power macro cells and low-power nodes, e.g., Pico, Femto cells.



Heterogeneous Network

- **Benefits**:
  - Achieve higher spectrum efficiency.
  - Meet the tremendous mobile data traffic growth of 5G.
- **Challenges**:
  - Complicated cross-tier interference and co-tier interference.
  - Small cell BSs are not always in easy-to-reach locations, which makes conventional fiber backhaul in cellular network impractical.

Massive MIMO and Full-Duplex

- Massive MIMO and Full-Duplex are also very promising techniques for future 5G communication systems.
  - Massive MIMO scales up the conventional MIMO by orders of magnitude, thus providing aggressive spatial multiplexing capabilities and significant array gains.
  - Full-Duplex helps BSs efficiently reuse the radio access network spectrum by transmitting and receiving signals on the same frequency at the same time.
- Motivation: When combining massive MIMO and Full-Duplex in HetNet, how to effectively suppress the co-tier interference and cross-tier interference in such scenarios ?

Overview

System Model

- We consider the downlink of a two-tier HetNet: A MBS is equipped with N antennas and serves K MUEs, while each of the S SBS employs a single antenna to serve its associated SUE using full-duplex techniques; the MBS provides wireless backhaul connections to these SBSs.

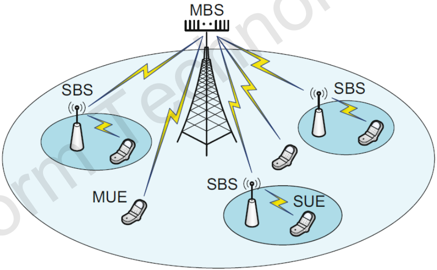


Fig. A two-tier HetNet system with one massive MIMO macro-cell base station and S full-duplex small-cell base stations

Assumption

- Massive MIMO in MBS, $N \gg K$ and $N \gg S$.
- TDD.
- Linear zero-forcing beamforming (LZFBF) precoder.
- Channel model: Path loss, Shadow fading, Rayleigh fading.

Full-Duplex Modes of SBS

- **Out-of-band Full-duplex Mode (OBFD)**: access link and backhaul link employ different frequency bands.
- **In-band Full-duplex Mode (IBFD)**: access link and backhaul link are conducted at the same frequency band.

Interference Mode

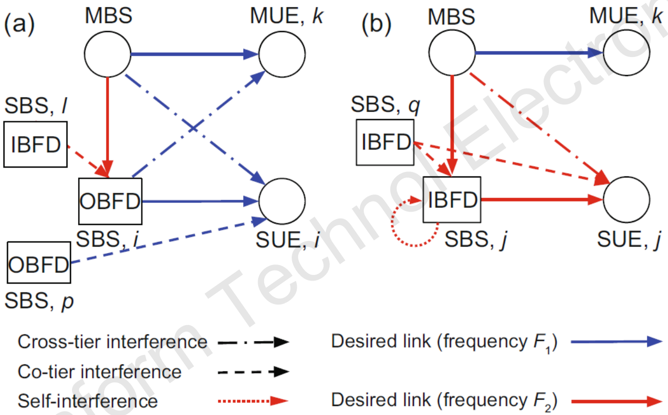


Fig. 2 Graphical illustration of the different interference in OBFD (a) and IBFD (b) modes. Downlink cross- and co-tier interferences experienced at MUE, SBS, and SUE are illustrated

Macro-cell Transmission Model

- Access link from the MBS to MUEs:

$$y_{\mathrm{MUE},k}(t)=\mathbf{h}_{\mathrm{b2mu},k}\mathbf{W}\mathbf{x}_{\mathrm{b2mu}}(t)+\sum_{i\in\mathcal{S}_{\mathrm{O}}} h_{\mathrm{s2mu},ik}x_{\mathrm{s2su},i}(t)+n(t).$$

$$\gamma_{\mathrm{MUE},k}=\frac{\frac{P_{\mathrm{M}}}{K}\|\mathbf{h}_{\mathrm{b2mu},k}\mathbf{W}\|^2}{P_{\mathrm{S}}\sum_{i\in\mathcal{S}_{\mathrm{O}}}\|h_{\mathrm{s2mu},ik}\|^2+\sigma^2}.$$

Small-cell Transmission Model

- SBS in OBFD Mode:
  - Backhaul link from the MBS to SBSs:

$$y^{\mathrm{O}}_{\mathrm{SBS},i}(t) = \mathbf{h}_{\mathrm{b2s},i}\mathbf{G}\mathbf{x}_{\mathrm{b2s}}(t) + \sum_{l\in\mathcal{S}_{\mathrm{I}}} h_{\mathrm{s2s},il}x_{\mathrm{s2su},l}(t) + n(t).$$

$$\gamma^{\mathrm{O}}_{\mathrm{SBS},i} = \frac{\frac{P_{\mathrm{M}}}{S}\left\|\mathbf{h}_{\mathrm{b2s},i}\mathbf{G}\right\|^2}{P_{\mathrm{S}}\sum_{l\in\mathcal{S}_{\mathrm{I}}}\left\|h_{\mathrm{s2s},il}\right\|^2 + \sigma^2}.$$

  - Access link from SBS to SUE:

$$\begin{aligned} y^{\mathrm{O}}_{\mathrm{SUE},i}(t) = {} & h_{\mathrm{s2su},ii}x_{\mathrm{s2su},i}(t) + \sum_{p\in\mathcal{S}_{\mathrm{O}}\backslash i} h_{\mathrm{s2su},ip}x_{\mathrm{s2su},p}(t) \\ & + \mathbf{h}_{\mathrm{b2su},i}\mathbf{W}\mathbf{x}_{\mathrm{b2mu}}(t) + n(t). \end{aligned}$$

Modified ZF Precoder

- To mitigate the cross-tier interference from the MBS, we exploit the modified zero-forcing precoder proposed in Li et al. (2015)[1]:

$$\mathbf{W} = \mathbf{R}(\mathbf{H}_{\mathrm{b2mu}}\mathbf{R})^{+}\mathbf{\Gamma}_{\mathbf{W}}^{\frac{1}{2}},$$

  where $\mathbf{R}$ is a matrix that satisfies $\mathbf{H}_{\mathrm{b2su}}\mathbf{R} = \mathbf{0}$, and $\mathbf{\Gamma}_{\mathbf{W}}^{\frac{1}{2}}$ is a diagonal matrix that normalizes $\mathbf{R}(\mathbf{H}_{\mathrm{b2mu}}\mathbf{R})^{+}$.

- The SINR of the i-th SUE:

$$\gamma_{\mathrm{SUE},i}^{\mathrm{O}} = \frac{P_{\mathrm{S}} \left\| h_{\mathrm{s2su},ii} \right\|^2}{P_{\mathrm{S}} \sum_{p \in \mathcal{S}_{\mathrm{O}} \setminus i} \left\| h_{\mathrm{s2su},ip} \right\|^2 + \sigma^2}.$$

[1] Li, B., Zhu, D., Liang, P., 2015. Small cell in-band wireless backhaul in massive MIMO systems: a cooperation of next generation techniques. IEEE Transactions on Wireless Communications, 14(12):7057–7069.

- SBS in IBFD Mode:
  - Backhaul link from the MBS to SBSs:

$$y_{\mathrm{SBS},j}^{\mathrm{I}}(t) = \mathbf{h}_{\mathrm{b2s},j}\mathbf{G}\mathbf{x}_{\mathrm{b2s}}(t) + \sum_{q\in\mathcal{S}_{\mathrm{I}}\setminus j} h_{\mathrm{s2s},jq}x_{\mathrm{s2su},q}(t) + \sqrt{I_{\mathrm{SI}}}w(t) + n(t).$$

$$\gamma_{\mathrm{SBS},j}^{\mathrm{I}} = \frac{\frac{P_{\mathrm{M}}}{S}\left\|\mathbf{h}_{\mathrm{b2s},j}\mathbf{G}\right\|^2}{P_{\mathrm{S}}\sum_{q\in\mathcal{S}_{\mathrm{I}}\setminus j}\left\|h_{\mathrm{s2s},jq}\right\|^2 + I_{\mathrm{SI}} + \sigma^2}.$$

Small-cell Transmission Model

- SBS in IBFD Mode:
  - Access link from SBS to SUE (**G** is also a modified ZF precoder):

$$y_{\mathrm{SUE},j}^{\mathrm{I}}(t) = h_{\mathrm{s2su},jj} x_{\mathrm{s2su},j}(t) + \sum_{q \in \mathcal{S}_{\mathrm{I}} \backslash j} h_{\mathrm{s2su},jq} x_{\mathrm{s2su},q}(t) + \mathbf{h}_{\mathrm{b2su},j} \mathbf{G} \mathbf{x}_{\mathrm{b2s}}(t) + n(t).$$

$$\gamma_{\mathrm{SUE},j}^{\mathrm{I}} = \frac{P_{\mathrm{S}} \left\| h_{\mathrm{s2su},jj} \right\|^2}{P_{\mathrm{S}} \sum_{q \in \mathcal{S}_{\mathrm{I}} \backslash j} \left\| h_{\mathrm{s2su},jq} \right\|^2 + \sigma^2}.$$

Overview

Total Throughput

- The total throughput of this two-tier HetNet

$$
\begin{aligned}
C &= C_{\mathrm{M}} + C_{\mathrm{S}}^{\mathrm{O}} + C_{\mathrm{S}}^{\mathrm{I}} \\
&= \sum_{k\in\mathcal{K}} \frac{1}{2}\log_2\left(1+\gamma_{\mathrm{MUE},k}\right) \\
&+ \sum_{i\in\mathcal{S}_{\mathrm{O}}} \frac{1}{2}\log_2\left(1+\min\left(\gamma_{\mathrm{SBS},i}^{\mathrm{O}},\gamma_{\mathrm{SUE},i}^{\mathrm{O}}\right)\right) \\
&+ \sum_{j\in\mathcal{S}_{\mathrm{I}}} \frac{1}{2}\log_2\left(1+\min\left(\gamma_{\mathrm{SBS},j}^{\mathrm{I}},\gamma_{\mathrm{SUE},j}^{\mathrm{I}}\right)\right).
\end{aligned}
$$

Throughput Optimization

- We note $x = [x_1, x_2, \ldots, x_S]$ is the set of all SBSs, and set as follows

$$\begin{cases} x_i = 1, & \text{if the } i\text{-th SBS is in IBFD mode} \\ x_i = 0, & \text{if the } i\text{-th SBS is in OBFD mode} \end{cases}.$$

- The throughput maximization problem

$$\begin{aligned}
\max_{\mathbf{x}} \ C = & \sum_{k\in\mathcal{K}} \log_2\left(1 + \frac{1}{\sum_{i\in\mathcal{S}}(1-x_i)\alpha_{k,i} + \beta_k}\right) \\
& + \sum_{i\in\mathcal{S}} (1-x_i)\log_2\left(1 + \min\left(\frac{1}{\sum_{j\in\mathcal{S}} x_j a_{i,j} + b_i}, \frac{1}{\sum_{j\in\mathcal{S}}(1-x_j)c_{i,j} + d_i}\right)\right) \\
& + \sum_{i\in\mathcal{S}} x_i \log_2\left(1 + \min\left(\frac{1}{\sum_{j\in\mathcal{S}} x_j e_{i,j} + f_i}, \frac{1}{\sum_{j\in\mathcal{S}} x_j g_{i,j} + h_i}\right)\right) \\
s.t. \ \ & x_i \in \{0,1\}, \quad \forall i \in \mathcal{S}.
\end{aligned}$$

- The parameters

$$\alpha_{k,i} = \frac{KP_{\mathrm{S}}\left\|h_{\mathrm{s2mu},ik}\right\|^2}{P_{\mathrm{M}}\left\|\mathbf{h}_{\mathrm{b2mu},k}\mathbf{W}\right\|^2}, \qquad \beta_k = \frac{K\sigma^2}{P_{\mathrm{M}}\left\|\mathbf{h}_{\mathrm{b2mu},k}\mathbf{W}\right\|^2},$$

$$a_{i,j} = \frac{SP_{\mathrm{S}}\left\|h_{\mathrm{s2s},ij}\right\|^2}{P_{\mathrm{M}}\left\|\mathbf{h}_{\mathrm{b2s},i}\mathbf{G}\right\|^2}, \qquad b_i = \frac{S\sigma^2}{P_{\mathrm{M}}\left\|\mathbf{h}_{\mathrm{b2s},i}\mathbf{G}\right\|^2},$$

$$c_{i,j} = \begin{cases} \frac{\left\|h_{\mathrm{s2su},ij}\right\|^2}{\left\|h_{\mathrm{s2su},ii}\right\|^2}, & j \neq i \\ 0, & j = i \end{cases}, \qquad d_i = \frac{\sigma^2}{P_{\mathrm{S}}\left\|h_{\mathrm{s2su},ii}\right\|^2},$$

$$e_{i,j} = \begin{cases} \frac{SP_{\mathrm{S}}\left\|h_{\mathrm{s2s},ij}\right\|^2}{P_{\mathrm{M}}\left\|\mathbf{h}_{\mathrm{b2s},i}\mathbf{G}\right\|^2}, & j \neq i \\ 0, & j = i \end{cases}, \qquad f_i = \frac{S(I_{\mathrm{SI}}+\sigma^2)}{P_{\mathrm{M}}\left\|\mathbf{h}_{\mathrm{b2s},i}\mathbf{G}\right\|^2},$$

$$g_{i,j} = \begin{cases} \frac{\left\|h_{\mathrm{s2su},ij}\right\|^2}{\left\|h_{\mathrm{s2su},ii}\right\|^2}, & j \neq i \\ 0, & j = i \end{cases}, \qquad h_i = \frac{\sigma^2}{P_{\mathrm{S}}\left\|h_{\mathrm{s2su},ii}\right\|^2}.$$

Problem Formulation

- A combinatorial optimization problem.
- The complexity is $\Theta(2^S)$ using brute force algorithm.
- To solve this problem more efficiently, we assume that the throughput of backhaul link is always larger than that of small-cell access link.
- The assumption is practical due to the performance gain provided by massive MIMO and advanced self-interference cancellation techniques in full-duplex systems.

Problem Formulation

- Final optimization problem

$$\max_{\mathbf{x}} \ C = \sum_{k\in\mathcal{K}} \log_2\left(1 + \frac{1}{\sum_{i\in\mathcal{S}}(1-x_i)\alpha_{k,i} + \beta_k}\right)$$
$$+ \sum_{i\in\mathcal{S}} (1-x_i)\log_2\left(1 + \frac{1}{\sum_{j\in\mathcal{S}}(1-x_j)c_{i,j} + d_i}\right)$$
$$+ \sum_{i\in\mathcal{S}} x_i \log_2\left(1 + \frac{1}{\sum_{j\in\mathcal{S}} x_j c_{i,j} + d_i}\right)$$
$$s.t. \quad x_i \in \{0,1\}, \quad \forall i \in \mathcal{S}.$$

Overview

Centralized Algorithms

- The objective function is non-convex.
- The optimal vector $\mathbf{x}$ can hardly be obtained even if we relax the constraint $x_i \in \{0, 1\}$.
- To find a near-optimal solution, we propose two centralized algorithms, i.e., a genetic algorithm and a greedy algorithm.

Genetic Algorithm

Algorithm 1 Genetic algorithm

set $IndividualLength = S$, $PopulationSize = S + 10$, $MaxIteration = 100$, $CrossoverPro = 0.6$, $MutationPro = 0.01$.
Generate initial population randomly, i.e., $x_i = randint(1)$, $\forall i \in \mathcal{S}$.
for $i = 1$ to $MaxIteration$ **do**
    Calculate the fitness of each individual, fitness is the value of the objective function.
    Roulette wheel selection.
    if $rand(1) < CrossoverPro$ **then**
        Crossover selection.
    end if
    if $rand(1) < MutationPro$ **then**
        Mutation selection.
    end if
    Generate new population.
end for

Genetic Algorithm

- An adaptive heuristic search algorithm based on the evolutionary ideas of natural selection and genetics.
- The overall complexity of the GEA is $\mathcal{O}(S^3)$.

Algorithm 2 Greedy algorithm

Generate initial solution randomly, i.e., $x_i = randint(1)$, $\forall i \in \mathcal{S}$
loop
    $Max = 0$
    for $i = 1$ to S **do**
        $\mathbf{y} = \mathbf{x}$
        $y_i = 1 - y_i$
        $Delta = C(\mathbf{y}) - C(\mathbf{x})$
        if $Delta > Max$ **then**
            $Max = Delta$
            $MaxIndex = i$
        end if
    end for
    if $Delta > 0$ **then**
        $x_i = 1 - x_i$
    else
        break
    end if

- At each iteration we switch the mode of an SBS when this switch can bring the largest throughput gain; the iteration will terminate if the largest throughput gain becomes negative.
- The complexity of one iteration is $\mathcal{O}(S^3)$, the overall complexity of GRA will be no less than $\mathcal{O}(S^3)$.

For the iterative process in the proposed GRA, we prove its convergence in the following proposition.

Proposition 1

For any initial solution, the greedy algorithm can converge.

Proof: We note the number of iterations as $t = 1, 2, \cdots$, and the iterative procedure of GRA is in fact a sequence of C_t. We always promise that the *Delta* > 0, i.e., $C_{t+1} > C_t$, thus C_t is monotonous increasing with t. Also, we can prove that the C_t has an upper bound.

Greedy Algorithm

$$
\begin{aligned}
C = & \sum_{k \in \mathcal{K}} \log_2 \left(1 + \frac{1}{\sum_{i \in \mathcal{S}} (1-x_i)\alpha_{k,i} + \beta_k}\right) \\
& + \sum_{i \in \mathcal{S}} (1-x_i) \log_2 \left(1 + \frac{1}{\sum_{j \in \mathcal{S}} (1-x_j) c_{i,j} + d_i}\right) \\
& + \sum_{i \in \mathcal{S}} x_i \log_2 \left(1 + \frac{1}{\sum_{j \in \mathcal{S}} x_j c_{i,j} + d_i}\right) \\
& < \sum_{k \in \mathcal{K}} \log_2 \left(1 + \frac{1}{\beta_k}\right) + \sum_{i \in \mathcal{S}} \log_2 \left(1 + \frac{1}{d_i}\right) = U,
\end{aligned}
$$

where U is a constant that only depends on β_k and d_i which are limited by CSI, noise variance, and transmit power.

Because C_t is monotonous increasing with t and has an upper bound U, Proposition 1 holds based on the monotone convergence theorem.

Overview

Distributed Graph Color Algorithm

- The co-tier interference is only incurred when SBSs are in the same full-duplex modes, thus we can determine that there is an intuitive relationship between our problem and the graph coloring problem if we regard these two full-duplex modes as two distinct colors.
- To find a near-optimal solution, we propose a distributed graph color algorithm (DGCA), which could sufficiently reduces the computation overhead of the MBS by having each SBS choose the full-duplex mode by itself.

Adjacent Graph

Definition 1

The i-th SBS and the j-th SBS are adjacent if and only if $\eta_{i,j} = 1$

$$\eta_{i,j} \triangleq \begin{cases} 1, \text{if } c_{i,j} > \Gamma_{\mathrm{th}} \text{ or } c_{j,i} > \Gamma_{\mathrm{th}} \\ 0, \text{otherwise} \end{cases}$$

- Applying this definition to all SBS pairs, an adjacent graph is generated.
- If we regard these two full-duplex modes as two distinct colors, we should assign adjacent SBSs with different colors as far as possible to minimize the co-tier interference.
- The incurred cross-tier interference when a SBS is colored with OBFD mode makes our contribution different from the conventional graph color algorithms.

Price

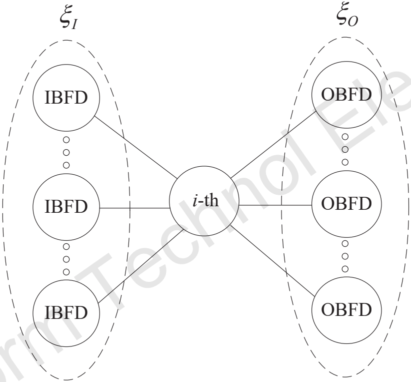
Definition 2

Let C_{I} denote the throughput when all SBSs are in IBFD mode, and let $C_{i,\mathrm{O}}$ be the throughput when only the i-th operates in OBFD mode. Then the price of the i-th SBS is defined as

$$\xi_i \triangleq C_{i,\mathrm{O}} - C_{\mathrm{I}}.$$

- It is needed to determine which type of interference is more predominate for each SBS.
- ξ_i represents the balance between co-tier interference and cross-tier interference induced by the i-th SBS.
- If ξ_i is negative and low, it means SBS i induces severe cross-tier interference and tends to choose the IBFD mode.
- If ξ_i IS positive and high, it shows that SBS i results in serious co-tier interference, and is better to operate in a different mode with its adjacent SBSs.

Combined Price for adjacent SBSs



- List all the adjacent SBSs of SBS i and divide them into two categories based on their full-duplex modes.

Combined Price for adjacent SBSs

Definition 3

For SBS i and its adjacent SBS j, their combined *price* is

$$\xi_{i,j} \triangleq \begin{cases} \xi_i + \xi_j, \text{ if } x_i = x_j = 1 \\ \omega \times 2^{-\xi_i}, \text{ if } x_i = 0,\, x_j = 1 \\ \omega \times 2^{-\xi_j}, \text{ if } x_i = 1,\, x_j = 0 \\ \xi_i + \xi_j + \omega \times 2^{-\xi_i} + \omega \times 2^{-\xi_j}, \text{ if } x_i = x_j = 0 \end{cases}$$

- If SBS i and SBS j both operate in IBFD mode, it is trivial that their combined *price* is the summation of the individual *prices*.
- If SBS i and SBS j are in different modes, co-tier interference no longer exists but one of them is bound to create cross-tier interference.
- if SBS i and SBS j both work in OBFD mode, the individual *prices* as well as the extra *price* induced by cross-tier interference need to be considered.

Sum Price of SBS

Proposition 2

The sum *price* of SBS i and all its adjacent SBSs is

$$\xi_{\mathrm{sum},i} = \begin{cases} \xi_{\mathrm{I}} + \xi_i + \sum_{l \in \mathcal{S}_{\mathrm{O},i}^{\mathrm{adj}}} \omega \times 2^{-\xi_l}, & \text{if } x_i = 1 \text{ and } \xi_{\mathrm{I}} \neq 0 \\ \sum_{l \in \mathcal{S}_{\mathrm{O},i}^{\mathrm{adj}}} \omega \times 2^{-\xi_l}, & \text{if } x_i = 1 \text{ and } \xi_{\mathrm{I}} = 0 \\ \xi_{\mathrm{O}} + \xi_i + \sum_{l \in \mathcal{S}_{\mathrm{O},i}^{\mathrm{adj}}} \omega \times 2^{-\xi_l} & \\ \qquad + \omega \times 2^{-\xi_i}, & \text{if } x_i = 0 \text{ and } \xi_{\mathrm{O}} \neq 0 \\ \sum_{l \in \mathcal{S}_{\mathrm{O},i}^{\mathrm{adj}}} \omega \times 2^{-\xi_l} + \omega \times 2^{-\xi_i}, & \text{if } x_i = 0 \text{ and } \xi_{\mathrm{O}} = 0 \end{cases}$$

Full-Duplex Selection Rule

Proposition 3

The i-th SBS should select the full-duplex mode with the following rules:
Case I: If $\xi_{\mathrm{I}} = 0$, then $x_i = 1$.
Case II: If $\xi_{\mathrm{I}} \neq 0$, $\xi_{\mathrm{O}} \neq 0$, then

$$x_i = \begin{cases} 1, & \text{if } \xi_{\mathrm{I}} < \xi_{\mathrm{O}} + \omega \times 2^{-\xi_i} \\ 0, & \text{otherwise} \end{cases}$$

Case III: If $\xi_{\mathrm{I}} \neq 0$, $\xi_{\mathrm{O}} = 0$, then

$$x_i = \begin{cases} 1, & \text{if } \xi_{\mathrm{I}} + \xi_i < \omega \times 2^{-\xi_i} \\ 0, & \text{otherwise} \end{cases}$$

Algorithm 3 Distributed graph coloring algorithm

1: Obtain adjacent graph $B = [\eta_{ij}]_{S\times S}, \forall i, j \in \mathcal{S}$.
2: Obtain the *price* of each SBS. Then sort these *prices* in ascending order, and denote the sorted sequence of SBSs as $\mathrm{SBS}_1, \mathrm{SBS}_2, \cdots, \mathrm{SBS}_S$.
3: **for** $i = 1$ to S **do**
4: SBS_i collects the full-duplex modes and *prices* informations of its adjacent nodes.
5: SBS_i colors itself using the rules in Proposition 3.
6: **end for**

Overview

Simulation Parameters

Parameter	Value
Macro-cell radius, R_{M}	1000 m
Small-cell radius, R_{S}	40 m
Carrier frequency, f_{c}	2 GHz
System bandwidth, B	20 MHz
Number of MUEs, K	20
Transmit power of MBS, P_{M}	46 dBm
Transmit power of SBS, P_{S}	24 dBm
Noise power , σ^2	-174 dBm/Hz

Simulation Results

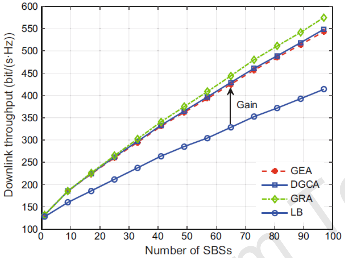


Fig. 4 Downlink capacity versus the number of SBSs when the number of transmit antennas in MBS is 200

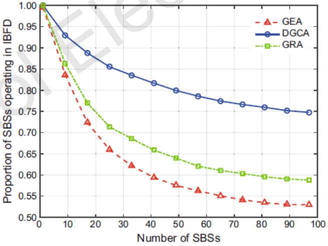


Fig. 5 Selection proportion of IBFD mode versus the number of SBSs when the number of transmit antennas in MBS is 200

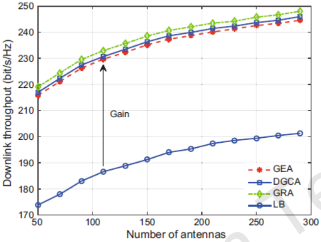


Fig. 6 Downlink capacity versus the number of antennas N when the number of single-antenna SBSs is 20

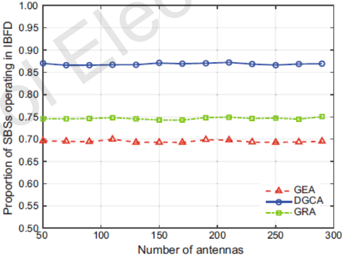


Fig. 7 Selection proportion of IBFD mode versus the number of antennas N when the number of single-antenna SBSs is 20

Simulation Results

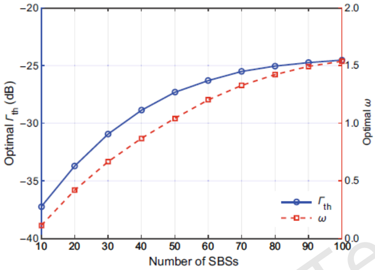


Fig. 8 The optimal Γ_{th} and ω of DGCA versus the number of SBSs when the number of transmit antennas in MBS is 200

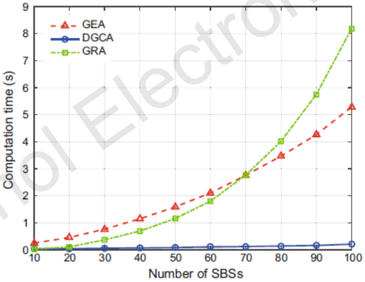


Fig. 9 CPU time of the proposed algorithms versus the number of SBSs when the number of transmit antennas in MBS is 200

Thank You !