Joint Energy-Efficient Optimization of Downlink and Uplink with eICIC in HetNet

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Abstract. In this work, we propose to configure uplink access to the macro in almost blank subframes (ABSs) improving the its utilization. The ABSs based on Downlink and Uplink Decoupled (DUDe) are modeled as an energy-efficient optimization problem in Heterogeneous Networks (HetNets). The formulation is a mixed integer programming problem so that we provide a suboptimal algorithm. Simulation study show our proposed algorithm demonstrates better performance according to energy efficiency and capacity.

Keywords: Heterogeneous Network · Energy efficiency · Downlink/uplink decoupling (DUDe) · Joint uplink and downlink · Interference coordination

1 Introduction

The LTE-A have specified the eICIC that macrocell can keep its downlink in silence for almost blank subframe (ABS) [1]. The users accessing to small cell obtain higher data rate for ABS on account of much less interference.

Moreover, the Downlink and Uplink Decoupling (DUDe) leads to lower energy consumption of HetNets [2–4]. Joint uplink (UL) and downlink (DL) has been mainly studied in the single-tier cellular network. The radio planning is investigated to minimize power consumption of joint uplink and downlink in single-tier network [6]. The association algorithm is proposed to maximize the downlink rate and minimize the power of uplink, but they assumed that it has the same channel gain [7]. To maximize the utility of data rate of joint downlink

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and uplink, [8] designs the algorithm of joint user association and resource allocation with QoS, however, without consider the eICIC [8].

We formulate EE-eICIC [5] to the corresponding DUDe scenario. We investigate joint energy efficiency optimization of uplink and downlink for eICIC in HetNet. As a result, we use UM-ABS [9], which is to configure uplink transmission for macro in almost blank subframe (ABS) improving the utilization of ABS. And the UM-ABS with downlink and uplink Decoupled (DUDe) can be adopted into an energy efficiency optimization problem.

2 Systems Model

The TDD technology is considered in HetNet, where the subframes of uplink and downlink can be configured dynamically with eICIC. The user association is divided into two types: smallcell-accessed and macrocell-accessed, so we can obtain the SINR expression.

Table 1. The notations of variables

Variable	Definition
N_{sf}	The number of ABS frames
N_m	non-ABS for small cell
A_p	ABS for small cell
$a_u(x_{u,A})$	Time in ABS (non-ABS) used by user
$b_{u,A(nA)}$	Time in ABS (non-ABS) used by user
p_u^{BS}	The power of BS (macrocell or smallcell)
p_{ref}^{macro}	The reference signals power from macrocell over ABS subframes
$P_{Rx}(u)$	The received power in user u for downlink
$P_{Rx}(m)$	The received power in macrocell m from uplink of user u
$P_{Rx}(s)$	The received power in smallcell s from uplink of user u
$P_{small}^{Down}(u)$	The suffered interference from smallcells for downlink
$P_{u\in pico}^{Up}(u)$	The suffered interference from smallcells for uplink
$P_{macro}^{Down}(u)$	The suffered interference from macrocells for downlink
$P_{u\in macro}^{Up}(u)$	The suffered interference from macrocells for uplink
$P_{small}^{Down}(I)$	The suffered interference from smallcells for downlink
$P_{u\in pico}^{Up}(I)$	The suffered interference from smallcells for uplink
$P_{macro}^{Down}(I)$	The suffered interference from macrocells for downlink
$P_{u\in macro}^{Up}(I)$	The suffered interference from macrocells for uplink

The SINR of downlink for one user accessed to smallcell is

$$SINR_{small}^{Down}(u) = \begin{cases} \frac{P_{Rx}(u)}{P_{small}^{Down}(u)+P_{pico}^{Up}(u)+P_{macro}^{Up}(u)+N_0} & \text{ABS} \\ \frac{P_{Rx}(u)}{P_{small}^{Down}(u)+P_{macro}^{Down}(u)+P_{small}^{Up}(u)+P_{macro}^{Up}(u)+N_0} & \text{non-ABS.} \end{cases} \quad (1)$$

The SINR of uplink for one user accessed to smallcell is

$$SINR_{small}^{Up}(u) = \begin{cases} \frac{P_{Rx}(p)}{P_{small}^{Down}(I)+P_{u\in pico}^{Up}(I)+P_{u\in macro}^{Up}(I)+N_0} & \text{ABS} \\ \frac{P_{Rx}(p)}{P_{small}^{Down}(I)+P_{macro}^{Down}(I)+P_{u\in small}^{Up}(I)+P_{u\in macro}^{Up}(I)+N_0} & \text{non-ABS.} \end{cases} \tag{2}$$

The SINR of downlink for one user accessed to macrocell is

$$SINR_{macro}^{Down}(u) = \frac{P_{Rx}(u)}{P_{small}^{Down}(u) + P_{macro}^{Down}(u) + P_{small}^{Up}(u) + P_{macro}^{Up}(u) + N_0} \text{non-ABS.} \tag{3}$$

The SINR of uplink for one user accessed to macrocell is

$$SINR_{macro}^{Up}(u) = \begin{cases} \frac{P_{Rx}(m)}{P_{small}^{Down}(I)+P_{macro}^{Down}(I)+P_{u\in small}^{Up}(I)+P_{u\in macro}^{Up}(I)+N_0} & \text{ABS} \\ \frac{P_{Rx}(m)}{P_{small}^{Down}(Int)+P_{macro}^{Down}(I)+P_{u\in small}^{Up}(I)+P_{u\in macro}^{Up}(I)+N_0} & \text{non-ABS.} \end{cases} \tag{4}$$

Then, the data rate of uplink and downlink are computed by Shannon capacity.

3 Problem Formulation

The goal in our work is to maximize the energy efficiency of joint uplink and downlink. These variables $\boldsymbol{\psi} = \{R_u, P_u, a_u^{up}, a_{u,A}^{up}, a_u^{down}, b_{u,A}^{up}, b_{u,A}^{down}, b_{u,nA}^{up}, b_{u,nA}^{down}, A_p, N_m\}$ are jointly optimized to design the EE-DL-UL-eICIC algorithm by the optimization problem (P1). These variables have been shown in Table 1.

$$P1 : \max_{\boldsymbol{\psi}} \sum_u \frac{R_u}{P_u} \tag{5}$$

$$R_u = R_u^{up} + R_u^{down} \tag{6}$$

$$P_u = P_u^{up} + P_u^{down} \tag{7}$$

$$R_u^{up} \leq a_u^{up} \cdot r_{u,macro}^{up} + a_{u,A}^{up} \cdot r_{u,A,macro}^{up} + b_{u,A}^{up} \cdot r_{u,A,pico}^{up} + b_{u,nA}^{up} \cdot r_{u,nA,pico}^{up} \tag{8}$$

$$R_u^{down} \leq a_u^{down} \cdot r_{u,macro}^{down} + b_{u,A}^{down} \cdot r_{u,A,pico}^{down} + b_{u,nA}^{down} \cdot r_{u,nA,pico}^{down} \tag{9}$$

$$P_u^{down} \leq p_u^{macro} \cdot a_u^{down} + (p_u^{pico} + P_{ref}^{macro}) \cdot y_{u,A}^{down} + p_u^{pico} \cdot b_{u,nA}^{down} \tag{10}$$

$$P_u^{up} \leq p_u \cdot a_u^{up} + p_u \cdot a_{u,A}^{up} + p_u \cdot b_{u,A}^{up} + p_u \cdot b_{u,nA}^{up} \tag{11}$$

$$a_u^{up}(a_{u,A}^{up} + b_{u,nA}^{up}) = 0, \forall u \in U \tag{12}$$

$$a_u^{down}(b_{u,A}^{down} + b_{u,nA}^{down}) = 0, \forall u \in U \tag{13}$$

$$A_p + N_m \leq N_{sf}, \forall p, m \in I_p \tag{14}$$

$$\sum_{u \in U_m} (a_u^{up} + a_u^{down}) \leq N_m, m \in M \tag{15}$$

$$\sum_{u \in U_m} a_{u,A}^{up} \leq A_p, m \in M, p \in P \tag{16}$$

$$\sum_{u \in U_p} (b_{u,A}^{up} + b_{u,A}^{down}) \leq A_p, p \in P \tag{17}$$

$$\sum_{u \in U_p} (b_{u,A}^{up} + b_{u,A}^{down} + b_{u,nA}^{up} + b_{u,nA}^{down}) \leq N_{sf}, p \in P \tag{18}$$

$$a_u^{up} \geq 0, a_{u,A}^{up} \geq 0, a_u^{down} \geq 0 \tag{19}$$

$$b_{u,A}^{up} \geq 0, b_{u,A}^{down} \geq 0, b_{u,nA}^{up} \geq 0, b_{u,nA}^{down} \geq 0 \tag{20}$$

$$A_p, N_m \leq N^+, \forall p, m \in I_{BS} \tag{21}$$

here N^+ represents nonnegative integer number.

The (6) and (7) give the sum of rate and power of downlink and uplink for a user. The (8), (9) and (10), (11) give the maximum data rate and power in uplink or downlink for one user. The (12) and (13) show the uplink or downlink of a user can only associate with one BS (e.g. macrocell or smallcell). The constraint (14) gives the number of ABS subframes provided by macrocells due to the interference with smallcell. The (15), (16) and (17)ensure that the subframes allocated to the user are not larger than the available ABS. The (18) shows that the subframes allocated to user are limited by the ABS period N_{sf}.

It is obvious that P1 belongs to mixed integer programming, which is usually NP-hard [10]. However, the structure of (5) can be reformulated into fractional programming [11]. Thus, the following problem (P2) can be computed with Algorithm 1 for a given ρ (e.g., ρ_n at iteration n).

$$\begin{aligned} \max_{\psi} \; & \textstyle\sum_u (R_u^{up} - \rho_u^{up} P_u^{up}) + (R_u^{down} - \rho_u^{down} P_u^{down}) \\ \text{s.t.} \; & \quad (6)\text{–}(21) \end{aligned} \tag{22}$$

Algorithm 1. EE-DU-UL-eICIC

Choose the iteration accuracy $\varepsilon^{up} > 0, \varepsilon^{down} > 0$ and set the limit of iteration number N_{max}.
while Quit $= 0$ and $n \leq N_{max}$ **do**
  Solving the problem P2 for a certain η^n
  if $|\rho_u^{up,n}| = |(R_u^{up,n} - \rho_u^{up,n} P_u^{up,n})| < \varepsilon^{up}$ *and* $|\rho_u^{down,n}| = |(R_u^{down,n} - \rho_u^{down,n} P_u^{down,n})| < \varepsilon^{down}$ **then**
    Quit $= 1$;
    return obtain the optimum configuration of EE-DU-UL-eICIC ψ^{opt} and the result ρ_u^{opt}
  else
    compute $\rho_u = \frac{R_u}{P_u}$ and $n = n + 1$, Quit $= 0$.
  end if
end while

4 Algorithm for Nonlinear Programming

For a given $\boldsymbol{\rho}$, we relax the P2 into P3. The P3 is obtained via ignoring the (12)–(13) and making the (21) on N_m and A_p into positive real numbers. The P3 is expressed with:

$$\begin{aligned} \max_{\psi} & \sum_u (R_u^{up} - \rho_u^{up} P_u^{up}) + (R_u^{down} - \rho_u^{down} P_u^{down}) \\ \text{s.t.} & \quad (6)\text{–}(11)\ and\ (14)\text{–}(20) \\ & \quad A_p, N_m \in R^+, \forall p, m \in I_{BS}. \end{aligned} \tag{23}$$

where R^+ gives the nonnegative real number. Since the P3 is the convex programming, it is easy to solve by the CVX tools [12]. Then the result computed by CVX are rounded to obtain the feasible solution with (21).

$$Inter(x) = \begin{cases} round\,down\,(x) & x < \frac{N_{sf}}{2} \\ round\,up\,(x) & x \geq \frac{N_{sf}}{2} \end{cases} \tag{24}$$

The DL-accessed, UL-accessed and ABSs allocation schemes are displayed in Algorithm 2.

Algorithm 2. The DL/UL accessed and ABSs allocation algorithm

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1: To compute the feasible solution N_m^* and A_p^*: $N_m^* = Inter(N_m^{'})$ and $A_p^* = Inter(A_p^{'})$, where $N_m^{'}$ and $A_p^{'}$ are results from CVX tools.

2: To ensure the DL-association or UL-association for user:

$$R_{u,macro}^{up} = r_{u,A,macro}^{up} \cdot \widetilde{a}_{u,A}^{up} + r_{u,macro}^{up} \cdot \widetilde{a}_u^{up}, R_{u,small}^{up} = r_{u,A,pico}^{up} \cdot \widetilde{b}_{u,A}^{up} + r_{u,nA,small}^{up} \cdot \widetilde{b}_{u,nA}^{up} \tag{25}$$

$$R_{u,macro}^{down} = r_{u,macro}^{down} \cdot \widetilde{a}_u^{down}, R_{u,small}^{down} = r_{u,A,small}^{down} \cdot \widetilde{b}_{u,A}^{down} + r_{u,nA,small}^{down} \cdot \widetilde{b}_{u,nA}^{down} \tag{26}$$

$$P_{u,macro}^{up} = p_{u,A,macro}^{up} \cdot \widetilde{a}_{u,A}^{up} + p_{u,macro}^{up} \cdot \widetilde{a}_u^{up}, P_{u,small}^{up} = p_{u,A,small}^{up} \cdot \widetilde{b}_{u,A}^{up} + p_{u,nA,small}^{up} \cdot \widetilde{b}_{u,nA}^{up} \tag{27}$$

$$P_{u,macro}^{down} = p_{u,macro}^{down} \cdot \widetilde{a}_u^{down}, P_{u,small}^{down} = p_{u,A,small}^{down} \cdot \widetilde{b}_{u,A}^{down} + p_{u,nA,small}^{down} \cdot \widetilde{b}_{u,nA}^{down} \tag{28}$$

where $\widetilde{a}_u^{up}$, $\widetilde{a}_{u,A}^{up}$, $\widetilde{b}_{u,A}^{up}$, $\widetilde{b}_{u,nA}^{up}$, $\widetilde{a}_u^{down}$, $\widetilde{b}_{u,A}^{down}$,$\widetilde{b}_{u,nA}^{down}$ is output of CVX tools.
Computing $\rho_u^{up,small} = \frac{R_u^{up,small}}{P_u^{small}}$, $\rho_u^{up,macro} = \frac{R_u^{up,macro}}{P_u^{up,macro}}$. If $\rho_u^{up,small} > \rho_u^{up,small}$, the uplink of user can access to macro cell, or with small cell.
Computing $\rho_u^{down,small} = \frac{R_u^{down,small}}{P_u^{down,small}}$, $\rho_u^{down,macro} = \frac{R_u^{down,macro}}{P_u^{down,macro}}$. If $\rho_u^{down,macro} > \rho_u^{down,small}$, the downlink of user can access to macro cell, or with small cell.

3: Compute the time ratio of frame of every user

$$\widehat{a}_u^{down} = \frac{\widetilde{a}_u^{down} \cdot N_m^*}{A_m}, \widehat{b}_{u,A}^{down} = \frac{\widetilde{b}_{u,A}^{down} \cdot A_p^*}{B_{p,A}}, \widehat{b}_{u,nA}^{down} = \frac{\widetilde{b}_{u,nA}^{down} \cdot (N_{sf} - A_p^*)}{B_{p,nA}} \tag{29}$$

$$\widehat{a}_u^{up} = \frac{\widetilde{a}_u^{up} \cdot N_m^*}{A_m}, \widehat{a}_{u,A}^{up} = \frac{\widetilde{a}_{u,A}^{up} \cdot (N_{sf} - N_m^*)}{A_{m,A}^{up}}, \widehat{b}_{u,A}^{up} = \frac{\widetilde{y}_{u,A}^{up} \cdot A_p^*}{B_{p,A}}, \widehat{b}_{u,nA}^{up} = \frac{\widetilde{b}_{u,nA}^{up} \cdot (N_{sf} - A_p^*)}{B_{p,nA}} \tag{30}$$

Finally, the EE of joint uplink and downlink for one user are computed in macrocell or smallcell.

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5 Numerical Results

In order to verify our proposed method, we set transmission power of macrocell and small cell to 36 dBm and 30 dBm, and the reference power from macro for ABS to 23 dBm. Each result in following figure is computed by averaging 100 tries.

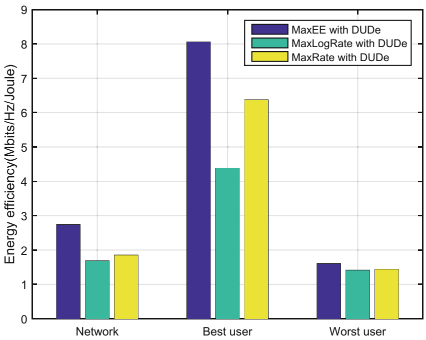

Fig. 1. EE-DU-UL-eICIC algorithm

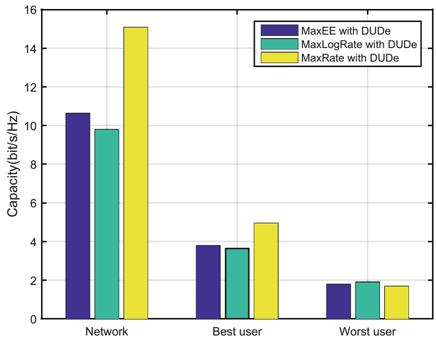

Fig. 2. Capacity vs. users

In Fig. 1, we compared the energy efficiency and capacity among these methods from three aspects: the energy efficiency for network, the best user, and the worst user corresponding to one macrocell, four smallcells, and thirty users. We observe that there is a significant gain in energy efficiency among the best user and the network achieved by MaxEE with DUDe (our proposed) compared with MaxRate with DUDe and MaxlogRate with DUDe. It is shown that the ABS configuration with DUDe need to study from energy efficiency perspective.

The Fig. 2 illustrates the capacity of MaxEE with DUDe compared with the other two algorithms following the same scenarios of Fig. 1. It can be observed that the MaxRate with DUDe achieves the largest rate of the network, the best user and the worst user, but the rates of MaxEE with DUDe is not the lowest. This is due to the fact that MaxRate with DUDe is to maximize the capacity of the network, and the MaxLogRate with DUDe is to strike a trade off between network capacity and user rate.

6 Conclusion

In the paper, we propose an energy efficiency optimization based on downlink and uplink decoupled with eICIC in HetNets. We design a joint downlink and uplink association and ABSs allocation algorithm in HetNet. Numerical results demonstrate that the proposed algorithm achieves superior energy efficiency performance of network.

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