SCIENCE CHINA
Information Sciences

• RESEARCH PAPER •
Special Focus on 5G Wireless Communication Networks

February 2016, Vol. 59 022306:1–022306:15
doi: 10.1007/s11432-015-5507-3

Concurrent transmission for energy efficiency of user equipment in 5G wireless communication networks

Xiao MA[1], Min SHENG[2*], Jiandong LI[2] & Qiuju YANG[1]

[1]*School of Physics and Information Technology, Shaanxi Normal University, Xi'an* 710119*, China;*
[2]*State Key Laboratory of Integrated Service Networks, Xidian University, Xi'an* 710072*, China*

Received July 24, 2015; accepted November 24, 2015; published online January 4, 2016

Abstract In this paper, we investigate concurrent transmission among multiple radio access technologies (RATs) for energy efficiency (EE) of multi-mode user equipment (MUE) in 5G wireless communication networks. Considering both the static circuit power consumption of the MUE and channel state information of different RATs, we propose an EE maximization concurrent transmission (EXACT) strategy by fully utilizing the multi-RAT combining gain of concurrent transmission. In particular, we formulate such EE maximization concurrent transmission problem as a mixed binary integer programming (MIP), and under some given static circuit power conditions, the optimal RATs selection and transmission rates for establishing concurrent transmission among multiple RATs are derived. Furthermore, in order to deal with the challenging MIP, an approximate expression is derived to simplify the integer constraints, thus the original MIP is transformed into a nonlinear continuous optimization problem. Consequently, a low complexity heuristic algorithm for general static circuit power conditions, which can achieve the near-optimal solution, is presented. Simulation results confirm the effectiveness of the EXACT strategy and show that the EE performance of the MUE can be significantly improved by reasonable and effective utilization of multiple RATs to execute concurrent transmission.

Keywords energy efficiency, green communication, concurrent transmission, 5G wireless communication networks, data splitting

Citation Ma X, Sheng M, Li J D, et al. Concurrent transmission for energy efficiency of user equipment in 5G wireless communication networks. Sci China Inf Sci, 2016, 59(2): 022306, doi: 10.1007/s11432-015-5507-3

1 Introduction

With the increasing awareness of environmental protection and price of energy, the main metric for designing wireless networks shifts from the previous spectral efficiency to energy efficiency (EE) [1]. Most of the researches focus on the energy saving of radio access technologies (RAT)[1)] and relatively little attention has been paid to that of user equipment (UE). However, EE is crucial to the usability of UE [2], due to that the whole energy consumption of UE relies on the limited battery energy which determines its operational period per battery charging. More importantly, data-hungry applications, which is regarded as a popular application of 5G networks, request extremely high energy consumption to satisfy the quality-of-service (QoS) with limited network resources [3]. More than 60% users complain that the

* Corresponding author (email: msheng@mail.xidian.edu.cn)
1) In this paper we use network and RAT interchangeably.

limited battery capacity is the most important factor impeding their use of data-hungry applications[2]. Therefore, how to reduce the energy consumption of UE is becoming increasingly important, especially for running data-hungry applications.

On the other hand, in the 5G wireless networks, different types of networks (such as GPRS, UMTS, LTE and WiFi, etc.) will be widely deployed in the same area to provide seamless and ubiquitous connectivity [4,5]. There is no interference between these wireless networks since different spectrums are assigned to different networks according to the static spectrum assignment policy [6]. Therefore, in the overlapped area, the multi-mode UE (MUE) equipped with multiple transceivers can establish the connections with all the available networks simultaneously. Then, the whole traffic flow of MUE will be split into some subflows which will be transmitted via these networks concurrently. This transmission approach is referred as concurrent transmission [7–9]. It is widely recognized that concurrent transmission can be used to improve the total throughput of MUE [9]. However, it is still unknown whether concurrent transmission can be used to save the MUE's energy, and how much energy-efficient gain can we obtain by effectively utilizing these resources of different networks simultaneously.

To address this challenge, we formulate the EE oriented concurrent transmission problem[3] as a mixed binary integer programming (MIP) problem. Generally speaking, the globally optimal solution for such optimization problem with integer variables can only be found by the exhaustive search method which has a relatively high computational complexity. To solve this issue, we first explore the capability of concurrent transmission to improve EE performance. Meanwhile, a phenomenon that utilizing as many RATs as possible may not mean the maximum EE is found. This phenomenon seems inconsistent with the intuition, i.e., the more resources we use the better EE performance we can obtain [10]. More specially, we demonstrate that the EE maximization can be achieved by optimal resource usage combination among all the available RATs, and propose the EE maximization concurrent transmission (EXACT) strategy to obtain the maximum EE of MUE. To the best of our knowledge, this is the first paper that studies the concurrent transmission via multiple RATs for EE from the perspective of UEs.

The main contributions of this paper are as follows:

(1) We exploit the multi-RAT combining gain by establishing concurrent transmission in several RATs to improve the MUE's EE.

(2) We give the RATs selection theorem to determine the optimal sort-law of RATs, and derive how many resources should be used among the available RATs under some special conditions of the static circuit power.

(3) We calculate the optimal transmission rate for each selected RAT to obtain the maximum EE. Furthermore, under these special static circuit power conditions, we propose a low computational complexity strategy for maximum MUE's EE.

(4) We simplify the MIP problem to a continuous optimization problem, and design a novel heuristic algorithm which can obtain the near-optimal solution of the MIP problem for general conditions.

The remainder of this paper is organized as follows. In Section 2, we summarize the existing work. Section 3 describes the system model. In Section 4, we formulate the EE maximization problem and derive some critical conclusions. Two low computational complexity algorithms are proposed to achieve the maximum MUE's EE in Section 5. In Section 6, the improvement of EE performance is presented through simulations. Finally, conclusions are presented in Section 7.

2 Related work

In green communication field, four fundamental tradeoffs of green wireless networks are proposed in [10]: deployment efficiency, spectrum efficiency, bandwidth-EE, and delay-EE. This implies that we cannot improve the system EE without sacrificing any other performance. In Heterogeneous Networks (HetNets), based on these tradeoffs, extensive researches have been conducted to improve the EE from both network side and user side.

2) zdc.zol.com.cn/201/2019387.html.

3) Referred to as the EE maximization problem in the rest of this paper.

For EE communication from network side, a principal approach is the sleep mechanism, which is based on the deployment efficiency tradeoff and can save the energy of networks by turning on and off RATs adaptively. In [11], authors propose two different kinds of sleep mechanisms to minimize energy consumption by shutting down some resources of the system. In [12], an optimal resource on-off switching framework has been described to maximize the energy saving. The basic principle of sleep mechanism is to obtain EE benefit from switching off some resources. Therefore, very limited improvement can be obtained by sleep mechanism in heavy load scenario.

Some reserches, based on the tradeoffs of spectrum efficiency and bandwidth-EE, focus on improving system EE instead of capacity by power and resource allocation. In [13], a power allocation scheme has been proposed to maximize EE by link adaptive transmission according to the channel states and circuit power consumption. Ref. [14] presents an optimal power allocation algorithm which obtained the maximum EE subject to the total transmit power and interference constraints. By formulating the resource allocation problem as a Stackelberg game, an EE oriented resource allocation algorithm in heterogeneous cognitive radio networks with femtocells has been proposed in [15]. The delay-EE tradeoff shows that the slower transmission rate implied smaller power consumption. Based on this principle, Ref. [3] proposes an EE packet scheduling policy which can minimize the average transmission energy expenditure under the QoS constraint. However, these kinds of strategies cannot be directly used to improve the EE of UE.

Compared with the achievements of EE from the network's perspective, relatively fewer researches focus on the EE from the user side although most users complained about the limited battery capacity. In [16], a bandwidth allocation scheme, based on bandwidth-EE tradeoff, has been proposed to optimize the EE of total users in an uplink OFDMA system. Authors of [17] considered both resource and power allocation in the same scenario. An accurate closed-form approximation of spectrum efficiency tradeoff for uplink of coordinated multi-point system has been derived in [1], where the fact that coordinated multi-point was more energy efficient than non-cooperative system was shown.

All of above mentioned approaches of EE for users dedicate to maximize the sum EE of all users in the network by exploiting the multi-user diversity gain. The defect of these approaches is that they cannot be used to improve the EE of one certain UE, which is more important than that of the sum of all users, especially for the UE which runs data-hungry applications.

By now, the existing researches just focus on improving the EE of network or the EE of users through just one RAT. To the best of our knowledge, they pay no attention to the gain of current transmission via multiple RATs. How to utilize multiple RATs to achieve the EE is a more interesting topic. In our previous work [18], we first explored that concurrent transmission via multiple RATs can be used to improve the EE of networks, where we only focus on the network side, and ignore the influence of static circuit power. In this paper, we are mainly interested in whether concurrent transmission is helpful to improve the EE of an MUE with data-hungry applications rather than maximum EE of all users in the system, and how the static circuit power influences the EE performance.

3 Network model

We consider the HetNets consisting of K ($K \geqslant 2$) different wireless networks. In this paper, we mainly focus on the uplink scenario due to the uplink transmission dominates the UE's transmission power. As shown in Figure 1, in the area overlapped by the K different RATs, there are two kinds of UE belonging to the K different wireless networks, the single-mode UE and MUE. The single-mode UE is the traditional UE equipped with single transceiver and can access to only one RAT. In contrast, the MUE can establish the connection with all available RATs simultaneously. Therefore, the concurrent transmission can be executed and the whole traffic of the MUE will be split into subflows and allocated to the connected RATs. For example, for the uplink transmission, the whole traffic of MUE_j is split into 3 subflow units (see Figure 1 for example) and will be transmitted via 3 independent RATs simultaneously. Note that the constitution of a subflow unit depends on the splitting granularity (e.g., one packet as the smallest granularity).

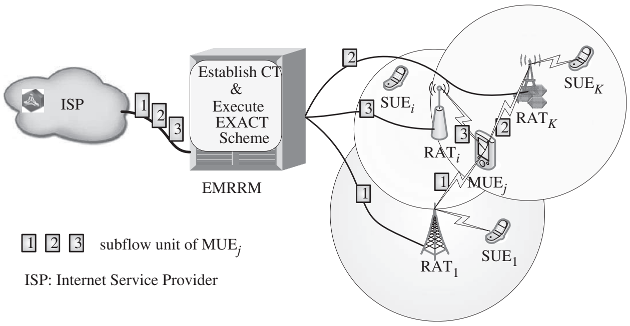

Figure 1 Heterogeneous wireless networks model.

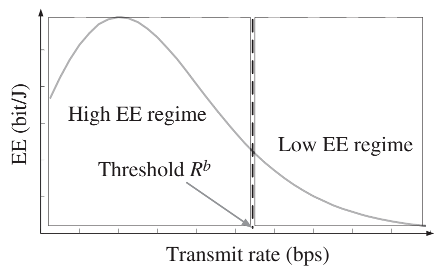

Figure 2 Relationship between EE and data rate.

A new function entity called multi-radio resource management is adopted in such HetNets scenario to manage multiple RATs [7]. The similar entity in 3GPP Release 7 [19] is referred to as generic access network controller. In order to execute EXACT, we enhance the function of multi-radio resource management and rename it as enhanced multi-radio resource management (EMRRM). The EMRRM will decide not only which RATs should be selected to participate in concurrent transmission, but also how to split the whole traffic of an MUE into these different selected RATs to obtain the maximum EE.

Consider a point-to-point transmission, the power consumed by UE, denoted as P, can be found by the well-known Shannon formula as

$$P = P^{\rm tr}(R) + P^{\rm cst} \geqslant (2^{\frac{R}{B}} - 1)(N_0 B/g) + P^{\rm cst}, \tag{1}$$

where $N_0/2$, B, g, R and $P^{\rm tr}(R)$ are the noise power spectral density, the system bandwidth, the channel power gain from the transmitter to receiver, the transmit rate and transmit power, respectively. $P^{\rm cst}$ denotes the fixed static circuit power[4)] consumed by transceiver of the corresponding RAT except transmission power for data transmission [11]. Because $P^{\rm cst}$ is only determined by the hardware parameters, it can be considered as a constant value and will not change with the varying data rate.

The channel power gain is expressed as $g = \|h_{\rm tr}\|^2$, where $h_{\rm tr}$ denotes the channel gain from the transmitter to the receiver. The expected value of received SNR is $\gamma = Pg/N_0B$. When P/N_0B is fixed, the distribution of g determines the distribution of γ and vice versa.

EE can be defined as the number of bits that the transmitter can deliver per joule of energy [20], and which is given by

$$\eta_{\rm EE} = \frac{R}{P} = \frac{R}{(2^{\frac{R}{B}} - 1)(N_0 B/g) + P^{\rm cst}} \text{ (bit/Joule)}. \tag{2}$$

4 EE concurrent transmission problem description and analysis

4.1 Basic idea

Figure 2 shows the relationship between EE and the transmission rate according to (2) for any case of $P^{\rm cst} \neq 0$. We find that, when the transmission rate is high, the EE decreases rapidly with the increasing of transmission rate. According to the changing rate of EE, we divide the curve into two regimes: high EE regime and low EE regime. The high EE regime denotes the region in which MUE has a relatively high EE, and it is unnecessary to improve EE by executing concurrent transmission among multiple RATs. However, the data-hungry applications always imply the high transmission rate. Therefore, it is easy to enter the low EE regime for running data-hungry applications. In this regime, EE deteriorates dramatically so that concurrent transmission should be adopted to improve the EE of MUE.

Inspired by this phenomenon, if the MUE can establish multiple connections with all available RATs, and offload the traffic from the RATs working in high EE regime to that in low EE regime, the EE of

4) Note that the $P^{\rm cst}$ in this paper only denotes the circuit power of transceivers and dose not contain the power of other hardware such as processer, user interface, memory, etc.

MUE can be improved. In particular, we sort all of the K available RATs according to a certain sort-law, and then select the first RAT to transmit the whole traffic. If the RAT enter the low EE regime, we add the second RAT into the concurrent transmission to offload part of the traffic, i.e., the two RATs transmit the traffic concurrently. Furthermore, if the second RAT enter the low EE regime, we add the third RAT into the concurrent transmission to enhance the EE, and so on. Therefore, the maximum EE can be obtained when we select the optimal RATs combination and derive the optimal transmission rate of each RAT.

To achieve this objective, there exist three key problems. First, a sort-law of all the available RATs should be investigated to make sure that the better RATs will be selected preferentially. Second, the optimal transmission rate of each selected RAT should be derived. Third, the critical value R^b (threshold) for each RAT, namely, the boundary between high EE regime and low EE regime, should be found out to determine when the next RAT should participate into the concurrent transmission.

Note that, the value of R^b implies whether or not the concurrent transmission should be used to improve EE. If $R^b = +\infty$, the concurrent transmission is unnecessary, and transmitting via single RAT is enough to obtain the maximum EE. On the other hand, $R^b = 0$ means the concurrent transmission should be always executed. In the following part, we will show that R^b is decided by the channel parameters of the available RATs, and $0 < R^b < +\infty$. Therefore, which and how many RATs will be selected to execute concurrent transmission are jointly decided by the data rate of requested traffic and channel parameters of the available RATs.

4.2 Problem formulation

Consider the HetNets described in Section 3. There is an MUE in the overlapped area of K RATs (see Figure 1 for example). The maximum EE of the MUE can be calculated as follows

$$\mathbf{P1}: \max\ \eta_{\mathrm{EE}}^{\mathrm{MUE}}(\boldsymbol{R}) = \max\ \frac{\sum_{i=1}^{K}\alpha_i R_i}{\sum_{i=1}^{K}\alpha_i P_i(R_i)} = \max\ \frac{R_{\mathrm{req}}}{\sum_{i=1}^{K}\left(\frac{N_0 B_i}{g_i}(2^{\frac{R_i}{B_i}}-1)+\alpha_i P_i^{\mathrm{cst}}\right)} \tag{3}$$

$$\text{s.t. } R_{\mathrm{req}} = \sum_{i=1}^{K}\alpha_i R_i, \tag{4}$$

$$0 \leqslant R_i \leqslant R_{\mathrm{iMAX}}, \tag{5}$$

$$\alpha_i = \{0,1\}, \tag{6}$$

where $\boldsymbol{R} = \{R_1, R_2, \ldots, R_K\}$ denotes the vector of transmission rate of subflows transmitted by the corresponding RATs. $P_i(R_i)$ represents the transmission power consumed by the MUE via RAT_i. B_i and g_i denote the available bandwidth of RAT_i utilized by MUE and the corresponding channel power gain respectively. $\boldsymbol{P}^{\mathrm{cst}} = \{P_1^{\mathrm{cst}}, P_2^{\mathrm{cst}}, \ldots, P_K^{\mathrm{cst}}\}$ denotes the vector of static circuit power consumed by the transceiver of corresponding RATs. R_{req} is the data rate of traffic required by this MUE. α_i is a binary variable. If RAT_i will be used, $\alpha_i = 1$, and $\alpha_i = 0$ otherwise.

Note that, with the help of admission control schemes, the maximum rates of RATs can satisfy the user's requirement, or the traffic will be blocked. Therefore, the constraint (5) can be simplified. Furthermore, R_{req} is decided by the type of applications, and remains unchanged with different transmission strategies. Thus, **P1** can be simplified as follows

$$\mathbf{P2}: \min\ P(\boldsymbol{R}) = \sum_{i=1}^{K}\left(\frac{N_0 B_i}{g_i}\left(2^{\frac{R_i}{B_i}}-1\right)+\alpha_i P_i^{\mathrm{cst}}\right), \tag{7}$$

$$\text{s.t. } R_{\mathrm{req}} = \sum_{i=1}^{K}\alpha_i R_i, \tag{8}$$

$$R_i \geqslant 0, \tag{9}$$

$$\alpha_i = \{0, 1\}. \tag{10}$$

The optimization problem **P2**, which not only involves continuous variable R_i but also has a binary variable α_i, is known as the MIP. Because each RAT has two possibilities (selected or unselected), there are a total of 2^K possible combinations of these binary variables (i.e., the complexity of the exhaustive search method is $\mathrm{O}(2^K)$). Consequently, it is hard to find out the closed-form solution directly for such problem within polynomial time.

It is worth noting that, from the perspective of mathematics, the binary variables and continuous variables, in such problem, are independent of each other. For example, although the $\alpha_i = 0$ and $R_i > 0$ is not the optimal solution of **P2**, it is still a feasible solution. Therefore, we can divide this MIP problem into two subproblems: (a) which RATs should be selected for concurrent transmission; (b) what is the optimal transmission rate for each selected RAT and how to split the whole traffic to each selected RAT.

In the following, we firstly derive the optimal transmission rates assuming the optimal RATs selection is known. Then, we obtain some critical characteristics for maximum EE of concurrent transmission with $\boldsymbol{P}^{\mathrm{cst}} = \mathbf{0}$. More importantly, we illustrate that these characteristics can be applied to determine the optimal RATs sort-law and selection with $\boldsymbol{P}^{\mathrm{cst}} \neq \mathbf{0}$. Finally, two algorithms are proposed to obtain the optimal solutions and near-optimal solutions under different $\boldsymbol{P}^{\mathrm{cst}}$ conditions, respectively.

4.3 Optimal transmission rate of selected RATs

Let $\boldsymbol{R}^* = \{R_1^*, R_2^*, \ldots, R_K^*\}$ denote the optimal solution for problem **P2**. Note that the traffic should be transmitted at least via one RAT. Hence, $R_1^*, R_2^*, \ldots, R_K^*$ are not all zero. Thus, for any $R_i^* > 0$, if we shift an arbitrarily small amount of flow $\delta > 0$ from RAT_i to any other RAT_j, the total power consumption of the MUE must not reduce. Otherwise, the optimality of $\boldsymbol{R}^*$ would be violated. Let $\partial P(\boldsymbol{R})/\partial R_i = (N_0/g_i)2^{\frac{R_i}{B_i}} \ln 2$ denote the partial derivative of power consumption of MUE with respect to variable R_i. The change in power from this shift is $\Delta P = \delta\frac{\partial P(\boldsymbol{R}^*)}{\partial R_j} - \delta\frac{\partial P(\boldsymbol{R}^*)}{\partial R_i} \geqslant 0$. Furthermore, we get (11) for any $R_i^* > 0$.

$$\frac{\partial P(\boldsymbol{R}^*)}{\partial R_j} \geqslant \frac{\partial P(\boldsymbol{R}^*)}{\partial R_i}. \tag{11}$$

Without loss of generality, assume that there are N of K RATs being utilized for concurrent transmission, i.e., $R_1^*, R_2^*, \ldots, R_N^* > 0$ and $R_{N+1}^* = R_{N+2}^* = R_K^* = 0$. According to (11), for any $R_i^*, R_j^* > 0$, we learn $\partial P(\boldsymbol{R})/\partial R_i^* \geqslant \partial P(\boldsymbol{R})/\partial R_j^*$ and $\partial P(\boldsymbol{R})/\partial R_j^* \geqslant \partial P(\boldsymbol{R})/\partial R_i^*$, which means $\partial P(\boldsymbol{R})/\partial R_i^* = \partial P(\boldsymbol{R})/\partial R_j^*$. Therefore, the optimal transmission rate $\boldsymbol{R}^*$ can be easily derived by solving (12).

$$\begin{cases} \begin{pmatrix} 1 & -1 & 0 & \cdots & 0 & 0 \\ 0 & 1 & -1 & \cdots & 0 & 0 \\ 0 & 0 & 1 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 1 & -1 \end{pmatrix} \begin{pmatrix} \frac{\partial P(\boldsymbol{R})}{\partial R_1}\Big|_{R_1=R_1^*} \\ \frac{\partial P(\boldsymbol{R})}{\partial R_2}\Big|_{R_2=R_2^*} \\ \vdots \\ \frac{\partial P(\boldsymbol{R})}{\partial R_N}\Big|_{R_N=R_N^*} \end{pmatrix} = (0), \\ R_{\mathrm{req}} = \sum_{i=1}^N R_i. \end{cases} \tag{12}$$

4.4 Optimal order of selected RATs

From the above analysis, we find that it is important to determine which RATs should be selected and in what order to select these RATs for achieving the maximum EE of MUE. In this subsection, we illustrate that the optimal order for RATs selection problem can be obtained when $\boldsymbol{P}^{\mathrm{cst}}$ satisfies some special conditions.

Lemma 1. If the channel power gain of RAT_i is larger than that of RAT_j, namely $g_i > g_j$, RAT_i should be selected precedence over RAT_j when $\boldsymbol{P}^{\mathrm{cst}} = \mathbf{0}$.

Proof. The function $P(\boldsymbol{R})$ is differentiable at $\boldsymbol{R} = 0$ when $\boldsymbol{P}^{\mathrm{cst}} = \mathbf{0}$, and $\partial P(0)/\partial R_i = (N_0/g_i)\ln 2$. According to (11), for any $R_i^* > 0, R_j^* = 0$, we learn $\partial P(\boldsymbol{R})/\partial R_i^* \leqslant \partial P(\boldsymbol{R})/\partial R_j^*$. Therefore, for the optimal transmission rate $\boldsymbol{R}^*$, we find the fact that the partial derivatives of $P(\boldsymbol{R})$ respect to the nonzero value variables are equal, and smaller than that respect to the zero value variables. For example, given $R_1^*, R_2^*, \ldots, R_N^* > 0$ and $R_{N+1}^* = R_{N+2}^* = R_K^* = 0$, we get (13).

$$\left.\frac{\partial P(\boldsymbol{R})}{\partial R_1}\right|_{R_1=R_1^*} = \cdots = \left.\frac{\partial P(\boldsymbol{R})}{\partial R_N}\right|_{R_N=R_N^*} \leqslant \left.\frac{\partial P(\boldsymbol{R})}{\partial R_i}\right|_{R_i=R_i^*}, \ \forall i = N+1, \ldots, K. \tag{13}$$

Furthermore, $\partial P(\boldsymbol{R})/\partial R_j$ is a monotonically increasing function of R_j $(j = 1, 2, \ldots, K)$. That means RAT_j will be used only when $\partial P(\boldsymbol{R})/\partial R_j|_{R_j=0} = (N_0/g_j)\ln 2$ is smaller than the partial derivatives of $P(\boldsymbol{R})$ respect to the already used RAT. And $\partial P(\boldsymbol{R})/\partial R_j|_{R_j=0}$ is determined by g_j. Therefore, RAT_i should be selected precedence over RAT_j when $g_i > g_j$.

This lemma implies that the lower the partial derivatives of power consumption are, the slower power consumption increases. In order to obtain the maximum EE, the partial derivative should be kept as low as possible. In other words, the RATs with lower partial derivatives should be utilized preferentially. More importantly, we can draw the conclusion that the available RATs will be selected according to the descending order of channel power gain.

Note that this lemma is derived under $\boldsymbol{P}^{\mathrm{cst}} = \boldsymbol{0}$. However, the transceivers of MUE may be independent of each other. The MUE can switch off the transceivers of the unused RATs. Thus, the $\boldsymbol{P}^{\mathrm{cst}}$ may not be zero. In the following, we extend this conclusion for some $\boldsymbol{P}^{\mathrm{cst}} \neq \boldsymbol{0}$ conditions.

First, we will give some useful definitions. It is easy to know, for any two RATs RAT_i and RAT_j with $g_i > g_j$ and $B_i < B_j$, there exist two intersection points $R_{ij}(P_i^{\mathrm{cst}}, P_j^{\mathrm{cst}})$ and $R_{iC}(P_j^{\mathrm{cst}})$ which definite as follows.

Definition 1. Let $R_{ij}(P_i^{\mathrm{cst}}, P_j^{\mathrm{cst}})$, short for R_{ij}, be the data rate corresponding to the intersection point (see Figures 3 and 4 for example) for power consumption curves of single RAT_i and RAT_j transmission.

Definition 2. Let $R_{iC}(P_j^{\mathrm{cst}})$, short for R_{iC}, be the data rate corresponding to the intersection point (see Figures 3 and 4 for example) for power consumption curves of single RAT_i transmission and concurrent transmission via both RAT_i and RAT_j with the optimal rates R_i^* and R_j^*.

Definition 3. We say RAT_i has precedence over RAT_j iff the transmission power consumption of only using RAT_j is larger than that of only using RAT_i or using both RAT_i and RAT_j.

RAT_i has precedence over RAT_j means that RAT_i will participate into concurrent transmission earlier than RAT_j with increase of the R_{req}. In other words, only using RAT_j without RAT_i can not obtain the maximum EE all the time.

Theorem 1. If the channel power gain of RAT_i is larger than that of RAT_j (i.e., $g_i > g_j$), RAT_i should be selected precedence over RAT_j when the $\boldsymbol{P}^{\mathrm{cst}}$ of MUE satisfies one of the two following conditions:

(i) $P_i^{\mathrm{cst}} \leqslant P_j^{\mathrm{cst}}$ when $B_i \geqslant B_j$; or

(ii) $R_{iC} \leqslant R_{ij}$ when $B_i < B_j$.

Proof. For all RAT_i and RAT_j $(i, j = 1, 2, \ldots, K)$ satisfying $g_i \geqslant g_j$, there are two cases left: $B_i \geqslant B_j$ and $B_i < B_j$.

Case 1: $B_i \geqslant B_j$. We can get $\partial P(\boldsymbol{R})/\partial R_i \leqslant \partial P(\boldsymbol{R})/\partial R_j$ for any data rate. The transmission power of RAT_i is no more than that of RAT_j at the same transmission rate when $P_i^{\mathrm{cst}} \leqslant P_j^{\mathrm{cst}}$. This means that RAT_i is used precedence over RAT_j.

Case 2: $B_i < B_j$. This case is much more complex. Due to $g_i \geqslant g_j$, there exist R_{ij} and R_{iC} which can be calculated by (14) and (15), respectively.

$$\frac{N_0 B_i}{g_i}(2^{\frac{R_{ij}}{B_i}} - 1) + P_i^{\mathrm{cst}} = \frac{N_0 B_{i+1}}{g_{i+1}}(2^{\frac{R_{ij}}{B_j}} - 1) + P_j^{\mathrm{cst}}, \tag{14}$$

$$\begin{cases} \frac{N_0 B_i}{g_i}\left(2^{\frac{R_{iC}}{B_i}} - 2^{\frac{R_i^{*iC}}{B_i}}\right) = \frac{N_0 B_j}{g_j}\left(2^{\frac{R_j^{*iC}}{B_j}} - 1\right) + P_j^{\mathrm{cst}}, \\ R_i^{*iC} = \frac{B_i R_{iC} - B_i B_j \log_2 \frac{g_j}{g_i}}{B_i + B_j}, \\ R_j^{*iC} = \frac{B_j R_{iC} + B_i B_j \log_2 \frac{g_j}{g_i}}{B_i + B_j}, \end{cases} \tag{15}$$

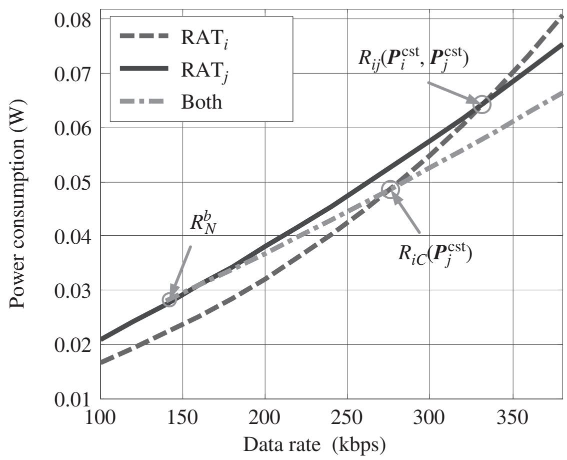

Figure 3 The low $\boldsymbol{P}^{\rm cst}$ conditions.

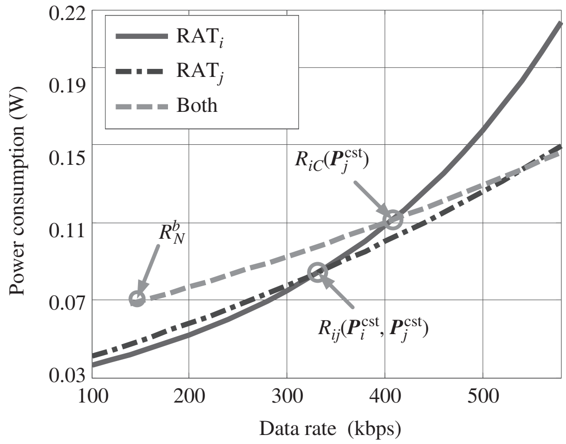

Figure 4 The high $\boldsymbol{P}^{\rm cst}$ conditions.

where R_i^{*iC} and R_j^{*iC} denote the optimal transmission rate of RAT_i and RAT_j, and are derived by (12), respectively. As shown in Figure 3, for the low $\boldsymbol{P}^{\rm cst}$ conditions, i.e., the transmission power rather than static circuit power can dominate the whole power consumption, R_{iC} is smaller than R_{ij} (i.e., $R_{iC} < R_{ij}$). It is clear that, singly using RAT_j never achieves the smallest power consumption. Thus, from the Definition 3, under such conditions, RAT_i will be utilized priority over RAT_j.

However, for the high $\boldsymbol{P}^{\rm cst}$ conditions (see Figure 4 for example), R_{iC} is larger than R_{ij} (i.e., $R_{iC} > R_{ij}$). Contrary to the low $\boldsymbol{P}^{\rm cst}$ conditions, there exists a data rate region in which the power consumption of single RAT_j is smaller than that of single RAT_i or both of the two RATs. In other words, within this region, the RATs will not be utilized according to the descending order of channel power gain.

This theorem shows that the priority of available RATs is irrelevant to bandwidth, and only depends on the channel power gains of RATs. More importantly, to obtain the maximum EE, all the K available RATs should be sorted in descending order according to channel power gain when all of them satisfy the conditions provided in Theorem 1. Without confusion, we denote the set of sorted available RATs as $\text{RAT} = \{\text{RAT}_1, \text{RAT}_2, \ldots, \text{RAT}_K\}$, and the corresponding data rate as $\boldsymbol{R} = \{R_1, R_2, \ldots, R_K\}$.

4.5 The critical transmission rate

From the analysis in Subsection 4.1, we notice that RAT_{N+1} will be used only when the transmission process of RAT_N enters the stage low EE regime, i.e., $R_N^* > R_N^b$ (where R_N^b denotes the threshold of RAT_N). In other words, when $R_N^* = R_N^b$, the $R_{N+1}^* = 0$. According to the inequality (13), given $\boldsymbol{P}^{\rm cst} = \boldsymbol{0}$, when RAT_N works in the threshold, we derive the below equation:

$$\frac{\partial P(R_N^b)}{\partial R_N} = \frac{\partial P(0)}{\partial R_{N+1}} \Rightarrow \left(\frac{N_0}{g_N}\right) 2^{\frac{R_N^b}{B_N}} \ln 2 = \left(\frac{N_0}{g_{N+1}}\right) \ln 2. \tag{16}$$

Let $\boldsymbol{R}^b = \{R_1^b, R_2^b, \ldots, R_K^b\}$ denote the set of threshold of all available RATs when $\boldsymbol{P}^{\rm cst} = \boldsymbol{0}$. R_N^b can be expressed as follows:

$$\begin{cases} R_N^b = B_N \log_2(\frac{g_N}{g_{N+1}}), & \text{when } N < K, \\ R_N^b = +\infty, & \text{when } N = K. \end{cases} \tag{17}$$

Obviously, $R_N^b > 0$ when $g_N > g_{N+1}$. According to the above analysis, RAT_{N+1} should not be used when $R_{\rm req}$ is small. In the following, we will derive the traffic rate at which the RAT_{N+1} should be used. Let $R_N^{{\rm req}b}$ denote the particular value of $R_{\rm req}$ at which the data rate of RAT_N just reaches the threshold, i.e., $R_N^* = R_N^b$. When $R_{\rm req} > R_N^{{\rm req}b}$, the RAT_{N+1} should be used. From (16) and (17) we get (18) and $R_N^{{\rm req}b}$ can be calculated for any $N < K$ (especially $R_K^{{\rm req}b} = R_K^b = +\infty$ for obviously reasion). And so on, $\boldsymbol{R}^{{\rm req}b} = \{R_1^{{\rm req}b}, R_2^{{\rm req}b}, \ldots, R_K^{{\rm req}b}\}$, which denotes the set of particular value of $R_{\rm req}$ for all available RATs, can be derived easily.

$$\begin{cases} \frac{\partial P(R_1^*)}{\partial R_1} = \frac{\partial P(R_2^*)}{\partial R_2} = \cdots = \frac{\partial P(R_N^*)}{\partial R_N} = \frac{\partial P(0)}{\partial R_{N+1}}, \\ R_N^{\mathrm{req}b} = \sum_{i=1}^{N} R_i^*. \end{cases} \tag{18}$$

However, because of the influence of $\boldsymbol{P}^{\mathrm{cst}}$, the threshold of each RAT will be different with the value $\boldsymbol{R}^b$ calculated by (17). Let $\boldsymbol{R}^{b'} = \{R_1^{b'}, R_2^{b'}, \ldots, R_K^{b'}\}$ denote the set of threshold when $\boldsymbol{P}^{\mathrm{cst}} \neq \mathbf{0}$. $R_N^{b'}$ $(N < K)$ can be calculated by (19)–(21) and $R_N^{b'} = +\infty$ $(N = K)$. Similarly, the $\boldsymbol{R}^{\mathrm{req}b}$ should be modified when $\boldsymbol{P}^{\mathrm{cst}} \neq \mathbf{0}$. Let $\boldsymbol{R}^{\mathrm{req}b'} = \{R_1^{\mathrm{req}b'}, R_2^{\mathrm{req}b'}, \ldots, R_K^{\mathrm{req}b'}\}$ be the modified set of $\boldsymbol{R}^{\mathrm{req}b}$ for $\boldsymbol{P}^{\mathrm{cst}} \neq \mathbf{0}$.

$$\left(2^{\frac{R_N^{b'}}{B_N}} - 1\right)\left(\frac{N_0 B_N}{g_N}\right) = \left(2^{\frac{R_N^*}{B_N}} - 1\right)\left(\frac{N_0 B_N}{g_N}\right) + \left(2^{\frac{R_{N+1}^*}{B_{N+1}}} - 1\right)\left(\frac{N_0 B_{N+1}}{g_{N+1}}\right) + P_{N+1}^{\mathrm{cst}}, \tag{19}$$

$$R_N^{b'} = R_N^* + R_{N+1}^*, \tag{20}$$

$$B_N R_{N+1}^* - B_{N+1} R_N^* = B_N B_{N+1} \log_2\left(g_{N+1}/g_N\right). \tag{21}$$

R_N^* and R_{N+1}^* represent the optimal data rate of RAT_N and RAT_{N+1}, respectively. Eq. (19) indicates that, at the critical point, the power consumed by RAT_N at data rate $R_N^{b'}$ should be equal to the static power of RAT_{N+1} (i.e., P_{N+1}^{cst}) plus the sum of power consumed by both RAT_N and RAT_{N+1} at the optimal rate with previous threshold R_N^b (i.e., $P_N(R_N^{b'}) = P_N(R_N^*) + P_{N+1}(R_{N+1}^*) + P_{N+1}^{\mathrm{cst}}$). Eq. (20) shows that modifying the threshold should not change the total data rate. Eq. (21) represents that the first derivative of power should be equal at the optimal data rate.

Notably, $R_i^{b'}$ will be larger than R_i^b when $P_{i+1}^{\mathrm{cst}} > 0$ for any $i < K$. That means there will be at most $N+1$ RATs chosen to participate the concurrent transmission when $R_N^{\mathrm{req}b} \leqslant R_{\mathrm{req}} < R_{N+1}^{\mathrm{req}b}$.

By now, we solve all the three main problems for maximum EE of MUE which satisfy the conditions provided in Theorem 1: (a) the RATs should be sorted according to their channel power gain; (b) the sets of thresholds for each RAT $\boldsymbol{R}^{b'}$ and the corresponding traffic rate $\boldsymbol{R}^{\mathrm{req}b'}$ is found; and (c) optimal data rate carried by each selected RAT is derived.

5 EE maximization concurrent transmission strategy

In this section, we will propose the core algorithms of EXACT strategy based on the characteristics described above. Firstly, an algorithm is presented to obtain the optimal solution of the EE maximization problem under the conditions provided in Theorem 1. And then, for general conditions, we give a more generic algorithm which can be used for all conditions and obtain the near-optimal solution.

5.1 The low static circuit power conditions

In most cases, the static circuit power consumed by different components for corresponding transceiver of one MUE is roughly the same, and much lower than the power consumed by wireless data transmission [2]. This means that most real situations can satisfy the conditions provided in Theorem 1.

Here, we consider the low static circuit power conditions under which Theorem 1 holds. The algorithm is described in Algorithm 1. According to the analysis above, this algorithm achieves the optimal solution with the complexity no larger than $\mathrm{O}(K)$. Compared with the exhaustive search method, Algorithm 1 has a much smaller complexity.

5.2 The high static circuit power conditions

If one or more transceivers have high static circuit power, Theorem 1 is no longer hold. And Algorithm 1 cannot find the optimal solution of the problem **P1**. Thus, a more general heuristic algorithm is given to achieve the near-optimal solutions for improving the EE of MUE.

Algorithm 1 EE maximization concurrent transmission strategy for MUE under low static circuit power conditions

1: **Initialize** $N=0$, $\boldsymbol{R}^*=\{0\}$, $R^{b'}=0$, $M=1$.
2: **Sort** available RATs in descending order according to the channel power gain: $\{\mathrm{RAT}_1,\ldots,\mathrm{RAT}_i,\ldots,\mathrm{RAT}_K|g_1\geqslant\cdots\geqslant g_i\geqslant\cdots\geqslant g_K\}$.
3: **Calculating** the $\boldsymbol{R}^{\mathrm{req}b'}$.
4: **while** (1) **do**
5:   **if** $R_M^{\mathrm{req}b'}\leqslant R_{\mathrm{req}}<R_{M+1}^{\mathrm{req}b'}$ **then**
6:     **Set** $N=M+1$.
7:     **break**.
8:   **else**
9:     **Set** $M=M+1$.
10:   **end if**
11: **end while**
12: **Calculating** the optimal data rate of N used RATs $\{R_1^*,\ldots,R_N^*\}$ by (12) and set $\boldsymbol{R}^*=\{R_1^*,\ldots,R_N^*,0,\ldots,0\}$.
13: **if** $N=1$ **then**
14:   **Set** $\boldsymbol{R}^*=\{R_1^*,0,\ldots,0\}$ and **stop**.
15: **end if**
16: **if** $N<K$ **then**
17:   **Calculate** the $R_N^{b'}$ by (19)–(21).
18: **else**
19:   **Set** $R_N^{b'}=+\infty$.
20: **end if**
21: **Set** $R^b=R_N^{b'}$.
22: **if** $R_N^*<R^b$ **then**
23:   **Set** $N=N-1$, **Goto 12**.
24: **else**
25:   **Set** $\boldsymbol{R}^*=\{R_1^*,\ldots,R_N^*,0,\ldots,0\}$ and **stop**.
26: **end if**

Recall the optimization problem **P1**, it is difficult to solve mainly because of the influence of the binary variables α. Let $I(R)$ denote an indicator function, i.e., $I(R)=1$ when $R>0$, and $I(R)=0$ otherwise. Replace α_i with $I(R_i)$, only continuous variable R_i is left, and the problem is simplified as

$$\min P(\boldsymbol{R})=\min\sum_{i=1}^{K}\left(\frac{N_0B_i}{g_i}(2^{\frac{R_i}{B_i}}-1)+I(R_i)P_i^{\mathrm{cst}}\right) \tag{22}$$

$$\text{s.t.}\quad R_{\mathrm{req}}=\sum_{i=1}^{K}I(R_i)R_i, \tag{23}$$

$$R_i\geqslant 0, \tag{24}$$

$$I(R_i)=\begin{cases}0, & R_i=0,\\ 1, & R_i>0.\end{cases} \tag{25}$$

However, the objective function and constraint conditions for the new optimization problem are still non-continuous and cannot be solved directly.

We find a deformation of Euler's Formula $\varphi(x)$ as given in (26), which is the smooth approximation of indicator function $I(R)$. Especially, when μ tends to ∞, $\varphi(x)$ is equivalent to $I(x)$, namely $\lim\limits_{\mu\to\infty}\varphi(x,\mu)\Leftrightarrow I(x)$.

$$\varphi(x)=\left(\frac{\mathrm{e}^{\mu x}-1}{\mathrm{e}^{\mu x}+1}\right). \tag{26}$$

Therefore, indicator function $I(R)$ can be replaced by $\varphi(x)$. The modified optimization problem is stated as follows.

$$\min P(\boldsymbol{R})=\min\sum_{i=1}^{K}\left(\frac{N_0B_i}{g_i}\left(2^{\frac{R_i}{B_i}}-1\right)+\varphi(R_i)P_i^{\mathrm{cst}}\right), \tag{27}$$

$$\text{s.t.}\quad R_{\mathrm{req}}=\sum_{i=1}^{K}\varphi(R_i)R_i, \tag{28}$$

$$R_i \geqslant 0. \tag{29}$$

It is easy to know that the new optimization problem is easily solved by the interior point method introduced in [21]. Let $\boldsymbol{R}^{*\prime}$ denote the solution found by interior point method. Unfortunately, due to the continuity of $\varphi(x)$, $\boldsymbol{R}^{*\prime}$ is the sub-optimal rather than the optimal solution for our original problem **P1**. Thus, $\boldsymbol{R}^{*\prime}$ should be modified to approach the optimal value $\boldsymbol{R}^{*}$ of the original problem. In other words, some RATs with low data rate values should not be selected when taking into consider the influence of the integer constraints.

For example, we sort the RATs in descending order according to $\boldsymbol{R}^{*\prime}$ as $\mathrm{RAT} = \{\mathrm{RAT}_1, \mathrm{RAT}_2, \ldots, \mathrm{RAT}_K\}$. Let RAT_N denote the last nonzero RATs, namely $R_1^{*\prime} \geqslant \cdots \geqslant R_i^{*\prime} \geqslant \cdots \geqslant R_N^{*\prime} > 0$ and $R_j^{*\prime} = 0, j = N+1, \ldots, K$. It is clear that, the RAT_N should not be selected if the MUE's EE increasing when we shift the data rate $R_N^{*\prime}$ from RAT_N to another RAT (e.g., RAT_{N-1}), namely the inequality (30) is hold.

$$\left(2^{\frac{R_{N-1}^{*\prime}+R_N^{*\prime}}{B_{N-1}}} - 2^{\frac{R_{N-1}^{*\prime}}{B_{N-1}}}\right)\frac{N_0 B_{N-1}}{g_{N-1}} \leqslant \left(2^{\frac{R_N^{*\prime}}{B}} - 1\right)\frac{N_0 B_N}{g_N} + P_N^{\mathrm{cst}}. \tag{30}$$

Furthermore, the value of $\boldsymbol{R}^{*\prime}$ is decided by resources states (bandwidth and the corresponding channel power gain) and $\boldsymbol{P}^{\mathrm{cst}}$ of the available RATs. The RAT_i with high $R_i^{*\prime}$ should be used preferentially. Therefore, based on this conclusion, a novel heuristic algorithm, presented as Algorithm 2, is derived to achieve the near-optimal solution of problem **P1**.

Algorithm 2 EE Maximization Concurrent Transmission strategy for MUE under general conditions

1: **Initialize** $\boldsymbol{R}^{*\prime} = \{\boldsymbol{0}\}$, $R^{b'} = 0$, the set of available RATs $\mathrm{RAT} = \{\mathrm{RAT}_1, \mathrm{RAT}_2, \ldots, \mathrm{RAT}_K\}$, $\boldsymbol{R}^{*} = \{\boldsymbol{0}\}$.
2: **Calculate** $\boldsymbol{R}^{*\prime}$ by the interior point method.
3: **Sort** the RATs in descending order according to $R_i^{*\prime}$ and remove the unused RATs from the available set, i.e., set $\mathrm{RAT} = \{\mathrm{RAT}_1, \ldots, \mathrm{RAT}_i, \ldots, \mathrm{RAT}_n | R_1^{*\prime} \geqslant \cdots \geqslant R_i^{*\prime} \geqslant \cdots \geqslant R_n^{*\prime} > 0\}$ for $R_j = 0, j = n+1, \ldots, K$.
4: **Set** $N = n$. (n is the number of RAT which is the last RAT with non-zero data rate)
5: **if** $N = 1$ **then**
6:     **Set** $\boldsymbol{R}^{*} = \boldsymbol{R}^{*\prime}$ and **stop**.
7: **else**
8:     **Judge** whether $R_N^{*\prime}$ is the near-optimal solution for original problem by (30).
9:     **if** (30) hold **then**
10:         **Set** $R_{N-1}^{*\prime} = R_{N-1}^{*\prime} + R_N^{*\prime}$ and $R_N^{*\prime} = 0$.
11:         **Remove** the RAT_N from the available set, i.e., set $\mathrm{RAT} = \{\mathrm{RAT}_1, \mathrm{RAT}_2, \ldots, \mathrm{RAT}_{N-1}\}$.
12:         **Calculate** $\boldsymbol{R}^{*\prime}$ for RAT by interior point method.
13:         **Sort** the RATs in descending order according to $R_i^{*\prime}$.
14:         **Set** $N = N - 1$ and **Goto 5**.
15:     **else**
16:         **Set** $\boldsymbol{R}^{*} = \boldsymbol{R}^{*\prime}$ and **stop**.
17:     **end if**
18: **end if**

The proposed heuristic algorithm consists of two loops. The inner loop solves the optimization problem by the interior point method. The outer loop checks the optimality of solution found by the interior point method, and finds the near-optimal solution. The complexity of outer loop is no larger than $\mathrm{O}(K)$. Therefore, Algorithm 2 has a polynomial time complexity, and can be implemented for real-time.

6 Performance evaluation

In this section, we present the performance evaluation of the EXACT. First, we compare the optimality of Algorithm 1 and Algorithm 2 with that of exhaustive search method in 4 RATs scenario. And then, we discuss the simulation setup for 5G networks. Finally, we present the EE performance of MUE.

6.1 Optimality verification

We first verify the optimality of the algorithms proposed above. HetNets with 4 RATs is considered here. We use exhaustive search method and the interior point method to find the optimal network selection

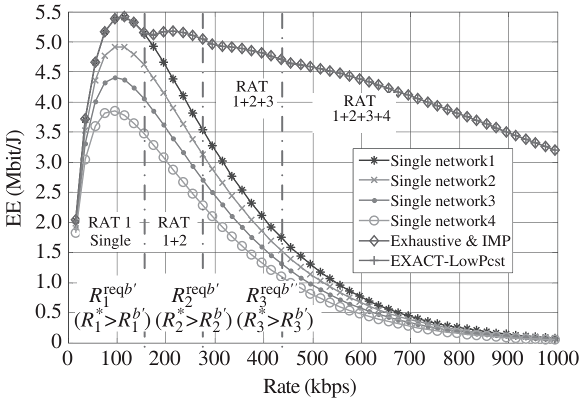

Figure 5 The performance of the EXACT in low $\boldsymbol{P}^{\rm cst}$.

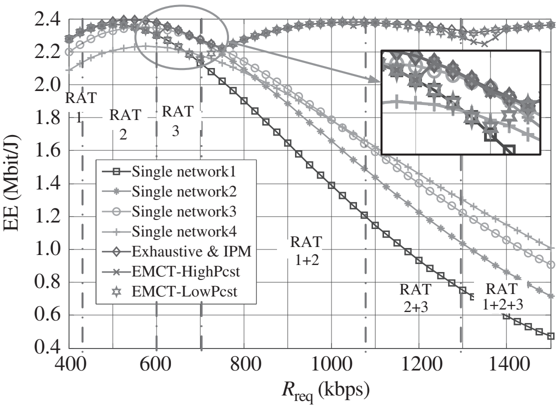

Figure 6 The performance of EXACT in High $\boldsymbol{P}^{\rm cst}$.

and optimal data rate splitting respectively. The exhaustive search considers all the $2^4 - 1$ possibilities[5)] of RATs selection. For each possibility, the EE maximization problem will become a convex problem. The optimal transmission rate can be easily found by the interior point method. Thus, this method can definitely find the optimal solution of the primal problem **P1**.

We set bandwidth of all available RATs as 100 kHz. Assume $N_0 = 10^{-9}$ W/Hz. The corresponding channel power gains are 0.008, 0.007, 0.006 and 0.005, respectively. To verify the performance of Algorithm 1, we set the static circuit power of each RAT to 6 mW. As shown in Figure 5, the Algorithm 1 has the same performance of the Exhaustive and the interior point method (i.e., the exhaustive & IPM curve in the figure). This means that Algorithm 1 obtains the optimal value of this problem with low $\boldsymbol{P}^{\rm cst}$. It is worth noting that the available RATs participate into concurrent transmission one by one according to their channel power gains which is consistent with the previous analysis. Single RAT_1 is used when $R_{\rm req} \leqslant R_1^{{\rm req}b'}$, i.e., $R_1^* \leqslant R_1^{b'}$. Then, RAT_2 is selected and participates into the concurrent transmission when the $R_{\rm req}$ increase larger than $R_1^{{\rm req}b'}$. With the further increase of $R_{\rm req}$, RAT_3 participates into the concurrent transmission when $R_{\rm req} > R_2^{{\rm req}b'}$, i.e., $R_2^* > R_2^{b'}$. Then RAT_4 and so on. Note that, all of the 4 RATs are used to execute concurrent transmission only when the $R_{\rm req} > R_3^{{\rm req}b'}$.

In the following example, we change the static circuit power of each RAT to 100 mW. In this scenario, Algorithm 2 is adopted due to the relatively high $\boldsymbol{P}^{\rm cst}$. As shown in Figure 6, most of the near-optimal values derived by Algorithm 2 approximate the optimal value. Note that, consistent with our analysis, high $\boldsymbol{P}^{\rm cst}$ will change the using order of available RATs. For example, when 1.1 Mbps $< R_{\rm req} <$ 1.3 Mbps, to obtain the maximum EE, RAT_2 and RAT_3 will execute the concurrent transmission, and RAT_1 will not be utilized even though RAT_1 has the largest channel power gain. This means that, RATs will not participate into the concurrent transmission according to the descending order of channel power gain. In other words, the optimal value cannot be obtained by Algorithm 1 due to its choice of the inappropriate RATs, e.g. when 600 kbps $< R_{\rm req} <$ 700 kbps, Algorithm 1 uses RAT_1 which has a worse performance than RAT_3. Therefore, for high $\boldsymbol{P}^{\rm cst}$ condition, Algorithm 2 should be implemented.

6.2 Simulation setup

Then, we consider a 5G networks scenario. It is still unsettled what will 5G be. However, unlike the previous four generations, the ultra-densification HetNets and multiple access are regarded as the foundational characteristics of 5G, namely, 5G will be highly integrative: tying any promising air interface and spectrum together with the current wireless technology, such as LTE, high-speed packet access (HSPA), GPRS and WiFi to provide universal high-rate coverage and a seamless user experience [5]. Therefore, to fully verify the performance of the proposed strategy, two networks (i.e., LTE and GPRS cellular networks) with great difference have been selected to consisting of the simulation scenario. Furthermore, China Mobile operates TD-LTE and GPRS simultaneously, which make it easier to evolve to 5G.

5) At least one RAT is used, thus the case without any RAT should be removed.

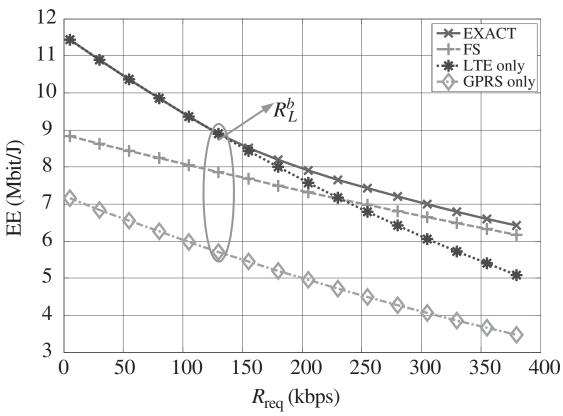

Figure 7 EE of RATs with different traffic rate.

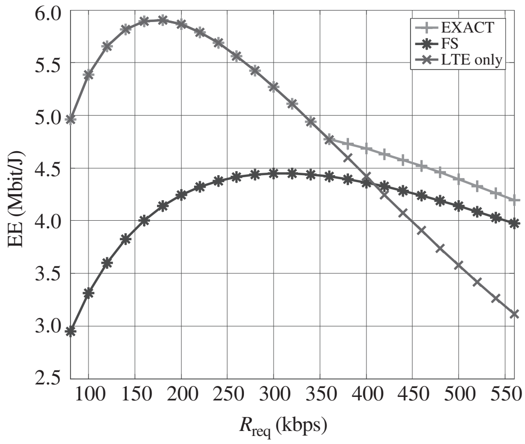

Figure 8 EE performance of MUE.

In the area covered by both LTE eNodeB and GPRS BS (including high power node, low power node, femtocell, etc.), the MUE can use both physical resource block (PRB) [22] of LTE and sub-channel of GPRS. If necessary, the MUE can establish the connection with two cellular networks simultaneously and the concurrent transmission can be executed to transmit the traffic. The bandwidth of PRB and sub-channel for LTE and GPRS are 180 kHz and 200 kHz respectively. The different channel power gains are used to investigate the influence of different transmission distance of the available RATs, which imply the variation of deployment density.

We mainly compare the EXACT with single RAT transmission and another well-known concurrent transmission strategy so-called fixed splitting (FS) [9,23] strategy designed to achieve the maximum throughput by splitting the traffic with fixed probabilities corresponding to the throughput of each available RAT. The single RAT transmission means that the whole traffic will be transmitted via only one RAT which can be referred to as SM strategy [11,12].

6.3 Performance of zero static circuit power

We now show the EE performance when $\boldsymbol{P}^{\rm cst} = \mathbf{0}$. In this simulation, one PRB of LTE network and one subchannel of GPRS are allocated to the MUE. The equivalent channel power gain for these resources are 0.008 and 0.005 respectively. Figure 7 shows the EE of RATs with different $R_{\rm req}$. The horizontal and vertical axes represent $R_{\rm req}$ and EE performance respectively. It can be seen that the EXACT strategy achieves maximum EE among all strategies. Especially for the high $R_{\rm req}$, the EXACT has a much better EE performance than the Single RAT transmission (SM strategy [11]).

6.4 Performance of nonzero static circuit power

Finally, we discuss the influence of $\boldsymbol{P}^{\rm cst}$. The static power for both LTE transceiver and GPRS transceiver of MUE are 10 mW. For the convenience of description, we vary channel power gain of GPRS channel to 0.006 in this simulation. As shown in Figure 8, the EE curve of the MUE becomes non-convex and non-concave due to the influence of the static power. However, the EXACT still dominates other strategies.

Assume there is a 3.7 V 1000 mAh (3.7 Wh) battery equipped in the MUE. Generally speaking, about 50% power will be used to data transmission (the processing unit, memory unit, LCD, etc. will respond to the other 50%). Figure 9 shows the operational period per charging of the MUE when different applications have been run. It can be seen that the EXACT can extend operational period of the MUE significantly especially for the data-hungry applications.

In wireless communication system, the time-varying characteristics of radio propagation channel and mobility of user will cause the channel fading which will influence the performance of transmission. Figure 10 shows the EE performance with different channel power gain. We keep $R_{\rm req}$ at 300 kbps, and change the channel power gain of GPRS channel from 0.004 to 0.007 gradually. It can be seen that the

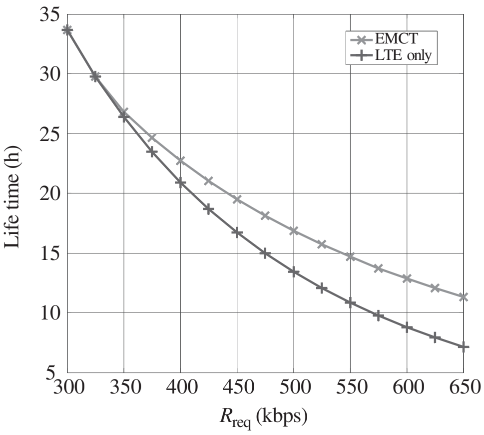

Figure 9 Life time of MUE.

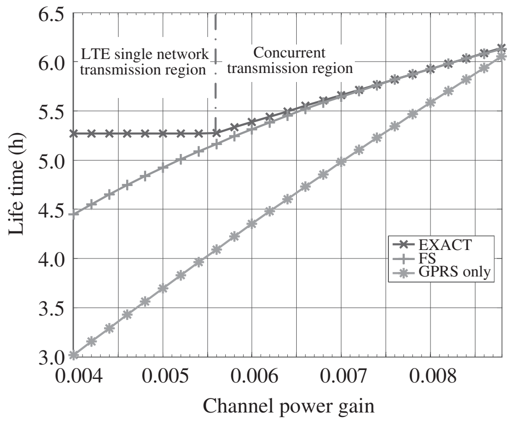

Figure 10 Influence of channel power gain.

variety of channel power gain not only influences the EE performance of the MUE, but also affects the threshold $R_L^{b'}$. GPRS network will not be utilized when the channel power gain of GPRS channel is low. With the increase of channel power gain, $R_L^{b'}$ becomes small. GPRS network will participate into the concurrent transmission to improve the EE of the MUE until $R_L^{b'} < R_{\text{req}}$.

Therefore, in summary, the ultra-densification deployment and multiple access characteristics of 5G can be used to obtain the multiple RATs diversity gain which will improve the EE performance of MUE. In addition, the greater number of available RATs we have, the better EE performance we can get. However, the RATs will be selected in descending order of their conditions, the rate of EE performance gain will diminish with the increasing number of available RATs. Furthermore, the simulation result shows that the proposed EXACT strategy can achieve the optimal EE performance effectively.

7 Conclusion

The concurrent transmission via multiple RATs can greatly enhance the EE performance of the MUE. An EE maximization concurrent transmission strategy is proposed, which splits the whole traffic into different subflows and allocates these subflows to different RATs for energy conservation. The optimal concurrent transmission problem is formulated as an MIP. Two algorithms are proposed to achieve the optimal and near-optimal solution under different static circuit power conditions, respectively. Moreover, the implementation scheme for the EXACT showed how the proposed strategy works well in 5G networks. Finally, Simulation results have shown encouraging results from the perspective of EE.

Acknowledgements
This work was supported by National Natural Science Foundation of China (Grant Nos. 61501285, 41504122), Natural Science Basic Research Plan in Shaanxi Province of China (Program No. 2014JQ2-6032), Fundamental Research Funds for the Central Universities (Program No. GK201503018), National High-tech R&D Program of China (863 Program) (Grant No. 2014AA01A701), 111 Project (Grant No. B08038).

Conflict of interest The authors declare that they have no conflict of interest.

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