Area Energy and Area Spectrum Efficiency Trade-off in 5G Heterogeneous Networks

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***Abstract*—A multi-tier architecture consisting of a macrocell overlaid with small cells, e.g., pico base station (BS), with provision of relays and device-to-device (D2D) communication is needed to satisfy the quality-of-service (QoS) requirements in a joint spectrum and energy efficient manner for the future Fifth generation (5G) networks. D2D communication enables the users located in close proximity to each other to communicate directly without going through the macro-cell, and hence, can be utilised to offload the traffic from the cellular infrastructure. This paper investigates the trade-off between Area Energy Efficiency (AEE) and Area Spectral Efficiency (ASE) in D2D-enabled uplink heterogeneous networks. The tradeoff is modelled as an optimization problem, in which each user wants to maximize its own ASE subject to its required AEE levels. Taking into consideration of the AEE requirement and maximum transmission power constraint, a distributed resource allocation approach is proposed to jointly optimize the mode selection, subcarrier and optimal power allocation by exploiting the properties of fractional programming. The relationship between the achievable AEE and ASE trade-off is investigated with different network parameters.**

***Index Terms*—Green Communications, Area Energy and Area Spectral Efficiency, Resource Allocation, Device-to-Device communication.**

I. Introduction

ONE of the fundamental system design requirements for next generation networks, such as Fifth generation (5G) networks is to jointly optimise the contradictory multi-objectives, e.g., to provide reliable coverage with higher spectral efficiency and lower energy consumption and cost per information transfer requirements [1]. Device-to-Device (D2D) communication is a promising technique which can be integrated by cellular network providers to fulfil the spectral and energy efficiency requirements for the future 5G wireless networks [2]. D2D communication can significantly improve the resource utilisation due to the hop gain, the proximity gain and the reuse gain. A D2D pair consists of a D2D transmitter and a D2D receiver lying in close proximity of each other. The concept of D2D communications in cellular networks is to allow the D2D pair in close proximity of each other to directly communicate instead of using a cellular infrastructure. On the other hand, one of the solutions to jointly improve the system throughput and to reduce the energy consumption is using heterogeneous networks (HetNets) consisting of low-power small cells (e.g., microcells, picocells, and femtocells) overlaid within the macrocell geographical area, deployed by network operator who share the same spectrum with the macrocells [3]. Each promising solution alone is unlikely to meet the QoS and throughput requirements for 5G [4]. One of the promising solution is a three-tier hierarchical HetNets in which the two above mentioned technologies can coexist in parallel to improve the network performance. In tier 1, the macrocell is used to ensure outdoor coverage whereas in tier 2, small cells are used to serve the users with low mobility in indoor and outdoor coverage. In tier 3, the users in both macrocell and small cell coverage areas can engage to communicate directly using D2D communication.

The radio resource management (RRM) mechanism in D2D communication consist of mode selection, resource allocation and power control [5]. The spectrum sharing among D2D and cellular users can be classified as either overlay or underlay. In overlay spectrum sharing scheme, the orthogonal resources are dedicated to both cellular and D2D users in order to avoid mutual interference, whereas the D2D users are allowed to reuse the resources occupied by the cellular users to improve the spectral efficiency in underlay spectrum sharing scheme [5]. One of the important RRM decisions in the D2D communication is mode selection mechanism in order to determine one of the possible three communication modes namely as cellular, dedicated (or orthogonal resource sharing) or reuse (or non-orthogonal resource sharing) mode.

EE is, in fact, one of the key performance indicators for the next generation wireless communications systems. However, most of EE gains are achieved with sacrifices in SE. Most of the work in the literature mainly focuses on either maximizing the system throughput (e.g., [5] [6]) or EE (e.g., [7] [8]) for two-tier cellular networks (i.e., macrocell overlaid with D2D communication). In this direction, a pricing scheme for two-tier 5G networks using game theory and auction theory as mentioned is proposed in [9] which also outlines the significant gains achieved by both operators and users in two-tier cellular networks as compared to the macrocell only system. A joint mode selection, channel assignment and power control to maximise the system throughput for two-tier cellular networks is proposed in [10]. The problem is decomposed into two subproblems where the power control subproblem is solved by using standard optimization method, and the mode selection and subchannel assignment subproblem is solved using branch-and-bound (BB) method. A low complexity distributed resource allocation mechanism based on auction theory in multi-tier heterogeneous networks is proposed in [11] . The objective of the considered resource allocation scenario is to maximise the achievable throughput of the small cell and D2D users as long as the interference caused to the macrocell users are within a predefined threshold.
To the best of our knowledge, there is no work in the literature

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to jointly optimize the ASE-AEE tradeoff radio resource allocation in multi-tier HetNets overlaid with D2D communication (or Hierarchical HetNets) considering multi-user multi-carrier systems in distributed manner. In this work, we address the ASE-AEE tradeoff resource allocation technique in an uplink of hierarchical HetNets. By exploiting the fractional programming concept, the optimization problem can be transformed into its equivalent subtractive form which is tractable. Numerical results demonstrate the impact of the required AEE level and the transmit power constraints on the ASE-AEE tradeoff. It is worth to mention that the scope of this paper is not to investigate the benefits of D2D communication itself, but rather its opportunistic integration with HetNets to satisfy the requirements for 5G networks to achieve higher data rates with lower energy consumption.

II. System Model

We consider an uplink scenario of three-tier hierarchical HetNets consisting of a macrocell and N pico BS's with the total number of users U and K non-overlapping subcarriers. Let $a_{u,j} \in \{0,1\}$ be a binary variable used to indicate the association of user u with the network j. The value of $a_{u,j}$ is 1 if the user u is associated to network j and 0 otherwise. We assume that the users are associated to their nearest BSs [3] [12] in order to ensure the reliable uplink association and avoid the ping pong effects due to handovers. It should be noted that the user association is completed prior to the resource allocation. Let $\mathcal{U}_{\mathrm{C}} = \{1, 2, \cdots, C\}$ denote the set of cellular users associated with either macrocell or N pico BS and $\mathcal{U}_{\mathrm{D}} = \{C+1, C+2, \cdots, D\}$ denote the set of potential D2D users. In this work, all the potential D2D users have the opportunity to select their operation mode (i.e., cellular mode or dedicated mode) as they are covered by either the macrocell or N pico BS. The set of active users in the network could be expressed as $\mathcal{U} = \mathcal{U}_{\mathrm{C}} \cup \mathcal{U}_{\mathrm{D}}$. We denote the index set of all subcarriers as $k = \{1, \cdots, K\}$. The system bandwidth B is divided equally within K subcarriers, i.e., $B_k = \frac{B}{K}$.

Each D2D pair $u \in \mathcal{U}_{\mathrm{D}}$ consists of a D2D transmitter and a D2D receiver. It is assumed that the neighbour discovery algorithms (e.g., [13] [14]) already exists to establish the D2D communication and the D2D proximity $r_{\max}$ is the maximum distance between the D2D pair due to the maximum transmit power $P_u^{\max}$ of a user and the receiver sensitivity [15]. It should be noted that the potential D2D user does not necessarily select the dedicated mode. The mode is selected based on a mode selection scheme presented later in the paper. It is also worthwhile to mention that due to the practicality reasons, it is assumed that $C > D$. Each D2D pair can communicate in two modes, i.e., cellular or dedicated. In cellular mode, the D2D transmitter communicate with a D2D receiver with the help of the macrocell or pico BS, whereas in dedicated mode, the D2D transmitter directly communicates with a D2D receiver.

In this paper, we propose three-tier Hierarchical HetNets (as shown in Fig.2) where the cellular users are given priority in order to guarantee its QoS requirements by mitigating the interference caused by D2D pairs. Depending on this assumption, each D2D pair and cellular users will be allocated dedicated subcarriers for the case of $K > C + D$. In the case of $C < K < C{+}D$, some D2D pairs will use dedicated subcarriers whereas others will reuse the subcarriers allocated to the cellular users resulting in mutual interference. Similarly, in the case of $K \leq C$, all the D2D pairs need to reuse the subcarriers allocated to the cellular users.

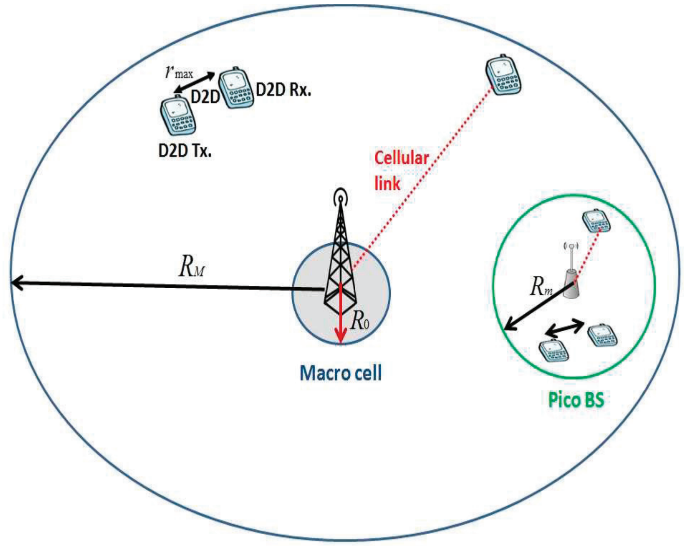

Fig. 1: Hierarchical HetNets as an evolution technology for 5G networks

In order to avoid mutual interference, we considered an orthogonal resource sharing scheme in which each subcarrier is exclusively assigned to either D2D or cellular user at any time such that $K_{\mathrm{C}} \bigcap K_{\mathrm{D}} = \emptyset$ where K_{C} and K_{D} indicate the set of subcarriers assigned to the $\mathcal{U}_{\mathrm{C}}$ and $\mathcal{U}_{\mathrm{D}}$, respectively. The instantaneous rate achieved by user u on subcarrier k choosing either dedicated mode 'd' or cellular mode 'c' are given respectively by

$$\mathrm{r}_{k,u}^{(d)} = B_k \log_2 \left(1 + \gamma_{k,u}^{(d)} \times p_{k,u}^{(d)}\right), \forall k \in K_{\mathrm{d}}, \forall u \in \mathcal{U}_{\mathrm{D}} \quad (1a)$$

$$\mathrm{r}_{k,u}^{(c)} = B_k \log_2 \left(1 + \gamma_{k,u}^{(c)} \times p_{k,u}^{(c)}\right), \forall k \in K_{\mathrm{c}}, \forall u \in \mathcal{U}_{\mathrm{C}} \quad (1b)$$

Here, $p_{k,u}^{(d)}$ and $p_{k,u}^{(c)}$ indicate the power allocated to the user u on subcarrier k for D2D and cellular modes, respectively. $\gamma_{k,u}^{(d)}$ and $\gamma_{k,u}^{(c)}$ represent the channel-to-noise-ratio (CNR) of the u-th user in D2D or cellular modes on subcarrier k, respectively, and are given as follow

$$\gamma_{k,u}^{(d)} = \frac{|h_{k,u}^{(d)}|^2}{\rho_{\mathrm{u},d}^2 \mathrm{PL}_u^{(\mathrm{d})}} \quad (2a)$$

$$\gamma_{k,u}^{(c)} = \frac{|h_{k,u}^{(c)}|^2}{\rho_{\mathrm{u},c}^2 \mathrm{PL}_u^{(\mathrm{c})}} \quad (2b)$$

$h_{k,u}^{(d)}$ represent the channel amplitude gain on subcarrier k from the u-th D2D pair to its receiver whereas $h_{k,u}^{(c)}$ represent the channel amplitude gain on subcarrier k between the u-th cellular user and the macrocell. The distance-based path loss for u-th user in D2D or cellular mode are denoted by $\mathrm{PL}_u^{(\mathrm{d})}$ and $\mathrm{PL}_u^{(\mathrm{c})}$, respectively. The noise power at the macrocell and the D2D receiver are respectively given by $\rho_{\mathrm{u},d}^2 = \rho_{\mathrm{u},c}^2 = B_k N_0$, where N_0 is the noise spectral density.

In simple terms, the potential D2D transmitter chooses a dedicated mode if $\tau_d r_{k,u}^{(d)} \geq r_{k,u}^{(c)}$, where $r_{k,u}^{(d)}$ is the achievable rate in dedicated mode, $r_{k,u}^{(c)}$ is the achievable rate in the cellular mode and τ_d is a biasing factor. In cellular mode, the D2D pair will need two subcarriers (one in uplink and one in downlink) and due to this reason $\tau_d = 2$ for the dedicated mode. To guarantee the QoS of D2D pair, both uplink and downlink CNRs should be larger than a given threshold γ_{min}. We assume that the macrocell or pico BS can tune its transmission power to ensure that $\gamma_{k,u}^{(c,\text{down})}$ is no less than $\gamma_{k,u}^{(c)}$ [8]. In order to simplify the optimisation problem, it is assumed that the subcarrier used by one D2D pair cannot be reused by any other D2D pair. Then, the achievable rate of user u on subcarrier k is

$$r_{k,u} = m_u.r_{k,u}^{(d)} + (1 - m_u).r_{k,u}^{(c)}, \tag{3}$$

where $m_u \in \{0,1\}$ is a binary variable used to distinguish between the different modes where the cellular mode is represented by $m_u = 0$ whereas the dedicated mode is represented by $m_u = 1$. The transmit power of user u on subcarrier k is given by

$$p_{k,u} = m_u.p_{k,u}^{(d)} + (1 - m_u).p_{k,u}^{(c)} \tag{4}$$

In practice, the transmission power available at u-th user, P_u, is limited to a maximum threshold, i.e., P_u^{max} which can be formulated as:

$$P_u = \sum_{k=1}^{K} p_{k,u} \leq P_u^{\text{max}}, \forall u \tag{5}$$

Hence, the overall power consumption and the transmission power in an uplink of D2D enabled communication can be modelled as:

$$P = \epsilon_0 P_{\text{T}} + (1 + m_u)\, P_{\text{C}}, \tag{6a}$$

$$P_T = \sum_{k=1}^{K}\sum_{u=1}^{U} p_{k,u} \tag{6b}$$

where ϵ_0 is an inverse of power amplifier efficiency.

Furthermore, AEE (η_{AEE}) of the Hierarchical HetNet is defined as the sum of the amount of data transferred per unit energy consumed by the macrocell, the small-cell and D2D communication per unit bandwidth per unit coverage area (b/J/Hz/km^2) and can be expressed as

$$\eta_{\text{AEE}} = \frac{\sum_{k=1}^{K}\sum_{u=1}^{U} r_{k,u}}{\theta P} = \frac{\sum_{k=1}^{K}\sum_{u=1}^{U} r_{k,u}}{A \times B\Big(\epsilon_0 P_T + (1 + m_u)P_{\text{C}}\Big)}, \tag{7}$$

where A represents the total coverage area and B is the total occupied bandwidth. The ASE of the Hierarchical HetNet is defined as the sum of the achievable rates of the macrocell, the small-cell and D2D communication per unit bandwidth per unit coverage area (b/s/Hz/km^2) and can be formulated as

$$\eta_{\text{ASE}} = \frac{\sum_{k=1}^{K}\sum_{u=1}^{U} r_{k,u}}{\theta}. \tag{8}$$

III. Problem Formulation of ASE-AEE Tradeoff

In order to analyse the ASE-AEE tradeoff, we formulate the optimisation problem to maximise ASE subject to a required AEE level and maximum transmission power constraints. The maximisation problem can be mathematically expressed as

$$\eta_{\{\text{ASE,AEE}\}} = \max_{\sigma_{k,u}^{(m_u)}, p_{k,u}^{(m_u)}} \left(\frac{\sum_{m_u=0}^{1}\sum_{k=1}^{K}\sum_{u=1}^{U} \sigma_{k,u}^{(m_u)} r_{k,u}^{(m_u)}}{\theta} \right) \tag{9a}$$

s.t.

$$\frac{\sum_{m_u=0}^{1}\sum_{k=1}^{K} \sigma_{k,u}^{(m_u)} r_{k,u}^{(m_u)}}{\theta\left(\epsilon_0 \sum_{m=1}^{M}\sum_{k=1}^{K} p_{k,u}^{(m_u)} + P_{\text{C}}\right)} \geq \eta_u^{\text{req}}, \forall u. \tag{9b}$$

$$\sum_{m_u=0}^{1}\sum_{k=1}^{K} \sigma_{k,u}^{(m_u)} p_{k,u}^{(m_u)} \leq P_u^{\text{max}}, \forall u. \tag{9c}$$

$$\sum_{m_u=0}^{1}\sum_{u=1}^{U} \sigma_{k,u}^{(m_u)} \leq 1, \forall k. \tag{9d}$$

$$p_{k,u}^{(m_u)} \geq 0, \sigma_{k,u}^{(m_u)} \in \{0,1\}\,,\ \forall u, \forall k, \forall m. \tag{9e}$$

In (9a), $\eta_{\{\text{ASE,AEE}\}}$ represents the ASE-AEE tradeoff objective function and $\sigma_{k,u}^{(m_u)}$ is a binary variable to indicate whether the subcarrier k is assigned to the user u with mode m_u or not, where $m_u \in \{0,1\}$. For the user $u \in \mathcal{U}_{\text{C}}$, which is a cellular user with only the cellular mode of transmission, and hence $\sigma_{k,u}^{(1)} = 0$. Further, η_u^{req} denotes the required AEE level. Specifically, the ratio of the total required achievable AEE over the total maximum achievable AEE is referred to as the AEE-loss-rate and can be expressed as follow:

$$\alpha_{\text{AEE}} = \frac{\eta^{\text{req}}}{\eta^{\text{max}}} = \frac{\sum_{u=1}^{U} \eta_u^{\text{req}}}{\sum_{u=1}^{U} \eta_u^{\text{max}}}, \tag{10}$$

where $0 \leq \alpha_{\text{AEE}} \leq 1$. Similarly, we define the ASE that can be achieved corresponding to η^{max} by $\text{ASE}_{\eta^{\text{max}}}$. The ASE-gain-rate is the ratio of $\text{ASE}_{\eta^{\text{req}}}$ over $\text{ASE}_{\eta^{\text{max}}}$ and can be formulated as follow:

$$\alpha_{\text{ASE}} = \frac{\text{ASE}_{\eta^{\text{req}}}}{\text{ASE}_{\eta^{\text{max}}}}. \tag{11}$$

It is worth to mention that for any required η_u^{req} level, there exists two optimal points for η_{ASE} for the case of $P_u^{\text{max}} \geq P_{\eta^{\text{max}}}$. As our optimization problem is to maximize the η_{ASE}, we will always choose the achievable $\text{ASE}_{\eta^{\text{req}}}$ which lies on the right side of the achievable η_u^{max}.

A. Optimal Power Allocation

First, the $\eta_{\{\text{ASE,AEE}\}}$-maximization problem without considering the maximum transmission power constraint is considered, serving as a milestone towards finding an $\eta_{\{\text{ASE,AEE}\}}$-optimal power allocation subject to the joint AEE and transmit power constraints. The maximisation problem $(9a)$ is an integer combinatorial fractional programming problem and is generally NP-hard. For better tractability, we first relax the integer variables, $\sigma_{k,u}^{(m_u)} \in \{0,1\}$ into continuous variables, $\tilde{\sigma}_{k,u}^{(m_u)} \in [0,1]$. The $\eta_{\{\text{ASE,AEE}\}}$-maximisation problem, hence, can be expressed as

$$\eta_{\{\text{ASE,AEE}\}} = \max_{\tilde{\sigma}_{k,u}^{(m_u)}, p_{k,u}^{(m_u)}} \frac{\sum_{m_u=0}^{1}\sum_{k=1}^{K}\sum_{u=1}^{U} \tilde{\sigma}_{k,u}^{(m_u)} r_{k,u}^{(m_u)}}{\theta} \tag{12a}$$

s.t.

$$\text{(9b)},\ \text{(9d)} \tag{12b}$$

$$\sum_{m_u=0}^{1}\sum_{u=1}^{U} \tilde{\sigma}_{k,u}^{(m_u)} \leq 1, \forall k. \tag{12c}$$

$$p_{k,u}^{(m_u)} \geq 0, \tilde{\sigma}_{k,u}^{(m_u)} \in [0,1]\,,\ \forall u, \forall k, \forall m. \tag{12d}$$

The constraint (9b) in fractional form can be transformed into its equivalent subtractive form and can be rewritten as

$$\sum_{m_u=0}^{1}\sum_{k=1}^{K}\tilde{\sigma}_{k,u}^{(m_u)}r_{k,u}^{(m_u)}-\eta_u^{\text{req}}\theta\left(\epsilon_0\sum_{m_u=0}^{1}\sum_{k=1}^{K}p_{k,u}^{(m_u)}+P_{\text{C}}\right)\geq 0 \tag{13}$$

We utilise the dual decomposition approach to solve the optimisation problem (12a). It is shown that the dual-composition approach has lower computational complexity and the duality gap for non-convex optimisation approaches to zero for sufficiently large number of subcarriers [16]. In order to apply dual decomposition method, we first need to find the Lagrangian function of (12a). Using standard optimisation methods proposed in [16], the Lagrangian function of (12a) can be written as:

$$\begin{aligned}L\left(p_{k,u}^{(m_u)},\lambda_u\right)&=\frac{1}{\theta}\sum_{m_u=0}^{1}\sum_{k=1}^{K}\sum_{u=1}^{U}\tilde{\sigma}_{k,u}^{(m_u)}r_{k,u}^{(m_u)}\\&+\sum_{u=1}^{U}\lambda_u\left(\sum_{m_u=0}^{1}\sum_{k=1}^{K}\tilde{\sigma}_{k,u}^{(m_u)}r_{k,u}^{(m_u)}\right.\\&\left.-\eta_u^{\text{req}}\theta\left(\epsilon_0\sum_{m_u=0}^{1}\sum_{k=1}^{K}p_{k,u}^{(m_u)}+P_{\text{C}}\right)\right)\end{aligned} \tag{14}$$

The equivalent dual problem can be decomposed into two subproblems, which is given by

$$\min_{\lambda_u\geq 0}\max_{p_{k,u}^{(m_u)}\geq 0}L\left(p_{k,u}^{(m_u)},\lambda_u\right) \tag{15}$$

The dual problem can be decomposed into two layers, namely, lower layer and master layer. In the lower layer, K subproblems are solved in parallel to compute the power and subcarrier allocation on each subcarrier $k\in K$ for the given values of λ_u. In the master layer, the Lagrangian multipliers are updated using subgradient method. At the optimal power allocation ${p_{k,u}^{(m_u)}}^*$, we have

$$\left.\frac{\partial L\left(p_{k,u}^{(m_u)},\lambda_u\right)}{\partial p_{k,u}^{(m_u)}}\right|_{p_{k,u}^{(m_u)}={p_{k,u}^{(m_u)}}^*}=0,\Rightarrow \tag{16a}$$

$$\left(1+\gamma_{k,u}^{(m_u)}{p_{k,u}^{(m_u)}}^*\right)=\frac{B_k\gamma_{k,u}^{(m_u)}\left(1+\frac{1}{\theta\lambda_u}\right)}{\eta_u^{\text{req}}\epsilon_0\theta\ln(2)}, \tag{16b}$$

From (16b), the optimal power distribution scheme can be found as

$${p_{k,u}^{(m_u)}}^*=\begin{cases}\left[\frac{B_k\left(1+\frac{1}{\theta\lambda_u}\right)}{\eta_u^{\text{req}}\epsilon_0\theta\ln(2)}-\frac{1}{\gamma_{k,u}^{(m_u)}}\right]^+, & \text{if } \tilde{\sigma}_{k,u}^{(m_u)}=1.\\ 0, & \text{otherwise.}\end{cases} \tag{17}$$

where $[x]^+=\max[0,x]$. Therefore, a feasible subcarrier assignment matrix for subcarrier $k\in K$ is given as:

$$\tilde{\sigma}_{k,u}^{(m_u)}=\begin{cases}1, & \text{if } (m_u^*,u^*)=\arg\max_{m_u,u}r_{k,u}^{(m_u)},\forall k\in K\\ 0, & \text{otherwise.}\end{cases} \tag{18}$$

where $\tilde{\sigma}_{k,u}^{(m_u)}=1$ indicates that the subcarrier k is assigned to user u with the mode m_u. When using the optimal power from (17), the achieved rate of each user u on subcarrier k working in the mode m_u is computed as $r_{k,u}^{(m_u)}=B_k\log_2\left(1+\gamma_{k,u}^{(m_u)}p_{k,u}^{(m_u)}\right)$. In general, the user u on subcarrier k will choose the dedicated mode $m_u=1$ if and only if the $2.r_{k,u}^{(m_u=1)}\geq r_{k,u}^{(m_u=0)}$ and otherwise it will choose cellular mode.

For solving the minimisation problem, the Lagrangian multiplier can be updated by using the subgradient method [16]. The subgradient of λ_u are given by taking the derivative of $L\left(p_{k,u}^{(m_u)},\lambda_u\right)$ with respect to λ_u, yielding

$$\begin{aligned}\frac{\partial L\left(p_{k,u}^{(m_u)},\lambda_u\right)}{\partial\lambda_u}=\sum_{m_u=0}^{1}\sum_{k=1}^{K}\tilde{\sigma}_{k,u}^{(m_u)}r_{k,u}^{(m_u)}-\eta_u^{\text{req}}\theta\\ \left(\epsilon_0\sum_{m_u=0}^{1}\sum_{k=1}^{K}p_{k,u}^{(m_u)}+P_{\text{C}}\right)\end{aligned}$$

Then, λ_u are updated by using the subgradient method as

$$\lambda_u(i+1)=\left(\lambda_u(i)-\frac{s^i}{\sqrt{i}}\beta_u\right), \tag{19}$$

where $i\geq 0$ is the iteration index, s^i is the positive step size which is taken in the direction of the negative gradient for the dual variable at iteration i and β_u is given as follow:

$$\beta_u=\sum_{m_u=0}^{1}\sum_{k=1}^{K}\tilde{\sigma}_{k,u}^{(m_u)}r_{k,u}^{(m_u)}-\eta_u^{\text{req}}\theta\left(\epsilon_0\sum_{m_u=0}^{1}\sum_{k=1}^{K}p_{k,u}^{(m_u)}+P_{\text{C}}\right) \tag{20}$$

Based on ${p_{k,u}^{(m_u)}}^*$(obtained from (17)) and $P_u^{\max}$, the solution for the maximization problem can be divided into two regions. When ${p_{k,u}^{(m_u)}}^*\geq P_u^{\max}$, the obtained solution violates the constraint on the maximum transmit power and hence, the optimal solution of (9a) can then be expressed as ${p_{k,u}^{(m_u)}}^*=\min\left({p_{k,u}^{(m_u)}}^*,P_u^{\max}\right)$. However, when ${p_{k,u}^{(m_u)}}^*\leq P_u^{\max}$, the optimal solution obtained for (9a) is similar to the power-unconstrained problem as mentioned in (12a).

Algorithm-I: Joint Mode selection, Subcarrier and Power Allocation

Input: $[\eta_u^{\textbf{req}},\epsilon_0,\gamma_{k,u}^{(m)}]$
Step 1: Initialize
$i=0$, $p_{k,u}^{(m_u)}=0,\lambda_u^{(i)}=0.01,$ **for** $u=1,\cdots,U,$
$k=1,\cdots,K,m=1,\cdots,M.$
Step 2:
For $k=1:K$
Calculate $p_{k,u}^{(m_u)}$ according to (17).
Obtain the mode selection and the sub-carrier assignment according to (18).
end **For**
Step 3:
$i=i+1$
Update $\lambda_u^{(i+1)}$ according to (19).
Step 4:
Repeat steps (2)-(3) until $\lambda_u^{(i+1)}$ are converged.
Output: $\left[p_{k,u}^{(m_u)},\tilde{\sigma}_{k,u}^{(m_u)},m_u\right]$

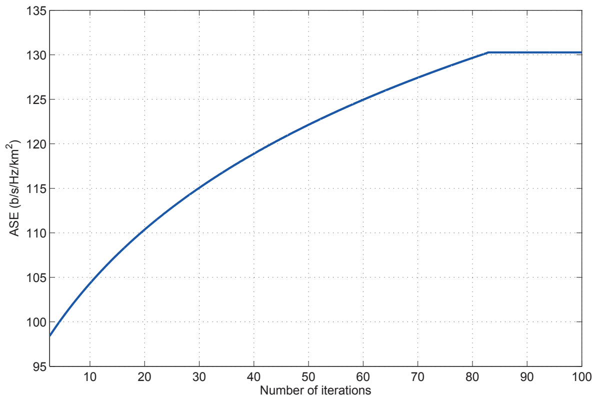

Fig. 2: The convergence of the proposed algorithm with step size $s^i = 0.01$ for $U = 100$ and $K = 100$.

IV. Simulation Results

We consider a three-tier Hierarchical HetNet environment with a single macrocell with R_{M}=500m, as otherwise stated overlaid with uniformly distributed $N = 40$ pico BSs (where N is calculated as mentioned in [17]) of R_{m}=50m. The pico BS's are deployed at the edge of a macrocell. The bandwidth of each subcarrier is 31.25 kHz. The maximum transmission power of users considered in the simulation is 200mW and the value of circuit power of users is set fixed to $P_{\text{C}} = 50\text{mW}$. We assume that the users are uniformly distributed within the simulated scenario. The noise spectral density is assumed to be $N_0 = -174\text{dBm/Hz}$. In this work, the power amplifier efficiency is assumed as 38% i.e. $\epsilon_0 = \frac{1}{0.38}$. The maximum transmission power for all users are same, hence, $P_u^{\max}$ will be referred to as $P^{\max}$. $P_{\eta^{\max}}$ and $P_{\eta^{\text{req}}}$ correspond to the transmit power required to achieve the maximum AEE and the required AEE level, respectively. All the simulation results presented are averaged over 10,000 channel realizations.

The convergence behavior of the proposed algorithm for $U = 100$ and $K = 100$ is shown in Fig. 2. The proposed algorithm converges to an optimal value with step size $s^i = 0.01$ in around 90 iterations. The total complexity of our proposed approach is approximately $O\left(KU\log_2(\frac{1}{\delta})\right)$ for δ optimality. The proposed approach has polynomial complexity regarding the problem scale K and U, which is attractive in the practical implementation.

Fig. 3 demonstrates the achievable AEE versus the macrocell radius R_{M} for various values of α_{AEE}. Due to the weaker CNR for the mobile user in the macrocell, the degradation of AEE is obvious due to the fact that more users transmit with their maximum transmission power with an increase in R_{M}. The hierarchical HetNet outperforms in terms of AEE as compared to the traditional HetNets and macrocell only system by 6.55% and 496% respectively, at $R_{\text{M}} = 300\text{m}$. This is due to the fact that the dedicated mode in hierarchical HetNet allows the cell edge users to communicate directly which enhances the overall system AEE as compared to the traditional HetNets.

Similalrly, the plot of achievable ASE versus the macrocell radius R_{M} for various values of α_{AEE} is shown in Fig. 4. Generally, as the AEE requirement level is reduced from $\eta_u^{\max}$ to $0.985\eta_u^{\max}$, each user will transmit with more power resulting in a higher achieved ASE and a lower achieved AEE. For example, in hierarchical HetNets by reducing the α_{AEE} from 100% to

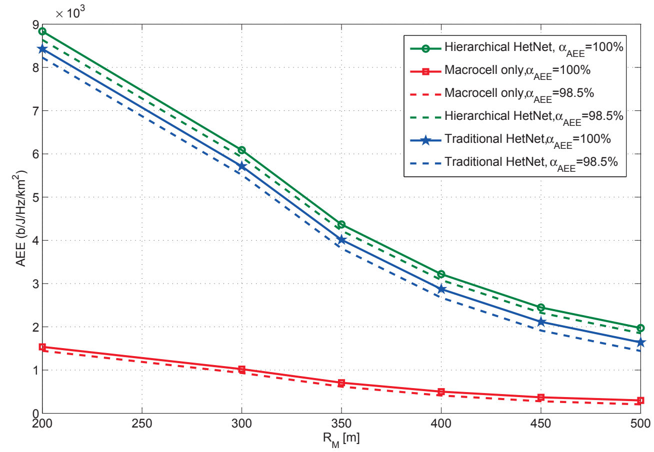

Fig. 3: Comparison of AEE versus R_{M} with $U = 100$ and $K = 100$ for various α_{AEE} in three different configurations: (i) Macrocell only network, (ii) Traditional HetNet and (iii) Hierarchical HetNet with $U_d = 20$.

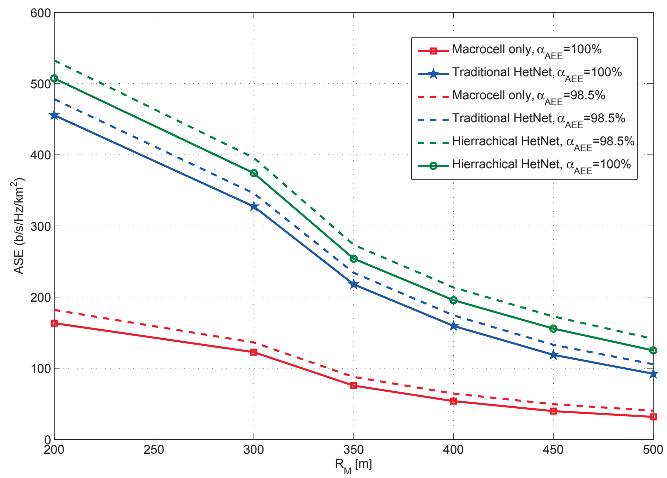

Fig. 4: Comparison of ASE versus R_{M} with $U = 100$ and $K = 100$ for various α_{AEE} in three different configurations: (i) Macrocell only network, (ii) Traditional HetNet and (iii) Hierarchical HetNet with $U_d = 20$.

98.5% (with only 1.5% loss in AEE) achieve an ASE gain for any value of R_{M}. Specifically, with $R_{\text{M}} = 300m$, the ASE is improved from 374.3 b/s/Hz/km^2 to 395.8 b/s/Hz/km^2. It is also worthwhile to mention that ASE is non-decreasing with the respect of α_{AEE} whereas AEE is non-increasing with the respect of α_{AEE}. When $\alpha_{\text{AEE}} = 100\%$ the tradeoff solution maximize the AEE whereas at the smaller values of $\alpha_{\text{AEE}} \approx 0\%$ the tradeoff solution maximize the ASE.

Fig. 5 demonstrates the total transmit power consumption of the macrocell only, traditional HetNets and Hierarchical Hetnets against the ratio of loss in AEE to the maximum achievable AEE; that is $1 - \alpha_{\text{AEE}}$. With an increase in the value of $(1 - \alpha_{\text{AEE}})$, the ASE gain increases, hence require the users to transmit with more power as long as $P^{\max} \geq P_{\eta^{\text{req}}}$. It is quite obvious that the Hierarchical HetNet users transmit with lower power due to close proximity between the D2D transmitter and receiver as compared to the pico BS and macrocell users. The Hierarchical HetNet users can reduce their transmit power with $R_{\text{M}} = 500m$ and $(1 - \alpha_{\text{AEE}}) = 7\%$ upto 48.51% and 1404% as compared to the traditional HetNet and macrocell, respectively. Fig. 5 also depicts that the total transmit power is equal to the

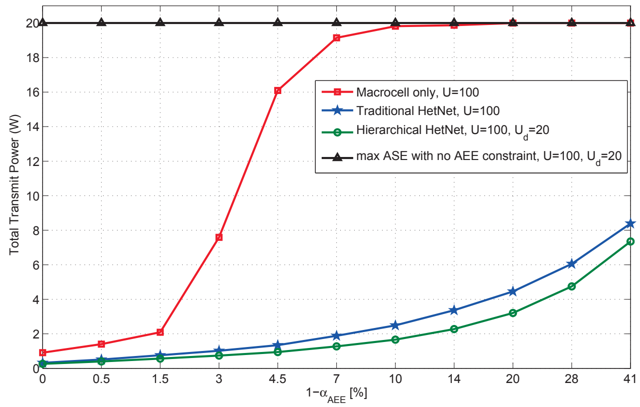

Fig. 5: Total transmit power versus $(1-\alpha_{\text{AEE}})$ with $P^{\max}=0.2$ W, $P_C=0.05$ W, and $B_k^{(m)}=31.25$ kHz.

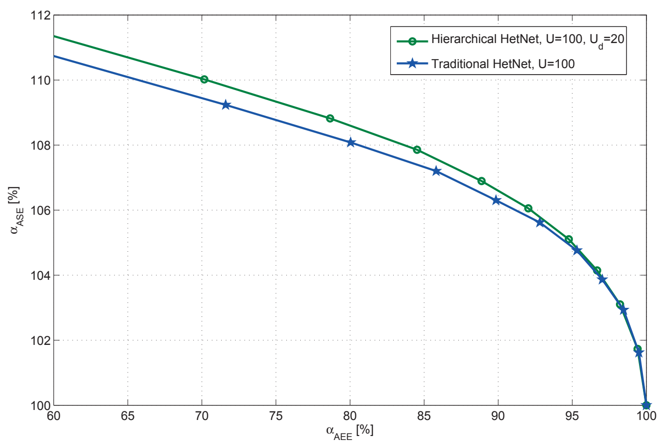

Fig. 6: α_{AEE} in percentage versus α_{ASE} in percentage for Hierarchical and Traditional HetNets with $U_d=20$.

total available transmit power of 20 W irrespective of the value of $(1-\alpha_{\text{AEE}})$ in maximization ASE with no requirement AEE level as compared to the maximization ASE with the required AEE level where the total transmit power is dependent on the value of $(1-\alpha_{\text{AEE}})$. At the value of $(1-\alpha_{\text{AEE}})=10\%$, the total transmit power in the macrocell only system converges to the total available transmit power of 20 W.

Fig.6 shows the plots for α_{AEE} in percentage versus the α_{ASE} in percentage for the traditional and Hierarchical HetNets. It also demonstrates that α_{ASE} monotonically increases with the decrease of α_{AEE}. Fig. 6 shows that a minor loss in AEE around its maximum (when α_{AEE} is close to 100%) results in a significant gain in ASE (i.e., rapid increase in α_{ASE}). When α_{AEE} is reduced beyond 95% , the gain in α_{ASE} versus reduction of α_{AEE} becomes slower. For example, at $\alpha_{\text{AEE}} = 80\%$, significant ASE gains of 108.1% and 108.7% are achieved in the traditional and hierarchical HetNets. Furthermore, higher ASE gain is observed in the hierarchical HetNet as compared to the traditional HetNet.

V. Conclusions

In this paper, we have formulated a joint optimization problem for mode selection, subcarrier assignment and power allocation in a three-tier hierarchical HetNet consisting of an underlaid D2D communication in coverage of both macrocell and pico BS's. The optimization problem is such that each user tries to maximize its own ASE subject to a required AEE level and a maximum transmit power constraint. The proposed objective function takes into account the tradeoff between ASE and AEE, and an iterative algorithm is proposed to solve the problem. The simulation results show that when the required AEE level is set to 93% of $\eta^{\max}$, the proposed scheme can reduce the tradeoff optimal transmit power upto 48.51% and 1404%, in comparison to the macrocell only and traditional HetNets, respectively.

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