Joint Resource Allocation for Multicasting in HetNets

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Abstract. Both heterogeneous networks (HetNets) and multicasting are key technologies for 5G wireless systems. In this paper, we investigate the joint resource allocation scheme for multicasting in HetNets. The objective is to maximize the system throughput achieved by multicast users subject to the transmit power budgets of BSs. We mathematically formulate the resource allocation scheme to an optimization problem with nonsmooth objective. We first transfer the nonsmooth objective function to an equivalent constraint, and then decompose the problem to subchannel assignment as well as power allocation subproblems to reduce the complexity. Algorithms with lower complexity are developed to find suboptimal solutions of these subproblems. Simulation results verify that our resource allocation scheme achieves higher multicast throughput than existing schemes and the iterative algorithms converge rapidly.

1. Introduction

In recent years, smart wireless terminals such as smart phones, tablets and smart TV are rapidly popularized. A huge number of Internet users transfer from wired networks to wireless networks, which is followed by explosive growth in mobile data traffic. It is expected that the network aggregate data rate will be increased by roughly 1000x from 4G to 5G [1]. However, the capacity of traditional single-tier macrocell network is approaching the theoretical limit and can no longer meet the demand. Thus, heterogeneous networks (HetNets) have been envisioned as a key network architecture for 5G wireless communication systems [2]. By adding low power nodes such as small cell base stations (BSs) or relays to conventional macrocells, the shortened signal transmission distance and the spatial spectrum reuse greatly improve the system capacity of HetNets.

On the other hand, the explosive growth of mobile data traffic is largely due to the wide application of mobile multimedia services. Many multimedia services have characteristics of high-speed and one-to-many, including multimedia entertainment services (e.g., IPTV, mobile TV, interactive games, video conferencing, etc.) and geographic information updates (e.g., traffic reports, local news, stock prices, etc.). These multimedia services account for 1/3 of mobile Internet market [4]. When multiple users in wireless network request the same content, multicasting allows them to form a group and share resources. The base station transmits the data to the group users concurrently through the natural broadcast channel of the wireless network; hence, the spectral efficiency can be greatly increased.

Therefore, HetNets and multicasting are key technologies for 5G networks. In HetNets, users of a multicast group are distributed among overlay networks and each user may have multiple networks available. Moreover, multicast services usually have a large user group and require high transmission rate. All these make the resource allocation scheme for multicasting play an important role in efficiently utilizing the resources of HetNets.

Some recent works have begun to investigate the resource allocation for multicasting in HetNets. Our previous work [5] and references [6, 7] have proposed network selection schemes for a single
multicast stream to reduce system bandwidth or energy consumption. However, these schemes do not consider the real-time scheduling of system resources and do not distinguish the difference of channel conditions between users with system resources underutilized as a result. Reference [8, 9] studied the joint resource allocation scheme to maximize the utility of multicast users in HetNets while specially for scalable video coding (SVC) streams.

In this paper, we propose a joint resource allocation scheme for the multicasting in HetNets with an objective of maximizing the overall throughput achieved by multicast users. We assume that these networks compose a single frequency network (SFN) for multicasting, where the data can be transmitted by multiple BSs simultaneously. This is based on the consideration that such SFN approach can significantly improve the received signal strength and is believed to be effective and promising for wireless multicast transmission [10]. We mathematically formulate the resource allocation scheme to an optimization problem, and then divide the problem to subchannel assignment as well as power allocation subproblems to reduce the computational complexity. Algorithms are designed to find suboptimal solutions for these subproblems.

The remainder of the paper is organized as follows. In Section 2, the model under considerations is introduced and the scheme is mathematically formulated as an optimization problem. In Section 3, the resource allocation problem is decomposed to a subchannel assignment subproblem and a power allocation subproblem, with algorithms for solving these subproblems presented. Then simulation results are illustrated in Section 4 and the paper is finally concluded in Section 5.

2. System model and Problem formulation

We consider the downlink multicast transmission in OFDMA-based HetNet, where there are $B$ small BSs covered by one macro BS as shown in Figure 1. All these BSs share $C$ subchannels and cooperatively serve $K$ users. The maximum transmit power available for multicast transmission at BS $b$ is $P_{b}^{\text{multicast}}$. Each user requests one of the $G$ multicast streams and the users requesting multicast stream $g$ are included in group $u_g$. On subchannel $c$, the power allocated by BS $b$ is denoted by $P_{b}^{c}$ and the channel gain between BS $b$ and user $k$ is denoted by $H_{b,k}^{c}$. Perfect channel state information is assumed to be known by BSs [11]. We define a channel allocation identifier $r_{g}^{c}$ and set it to be 1 when multicast group $g$ achieves subchannel $c$ (otherwise, $r_{g}^{c} = 0$).

In SFN HetNets, the data of the same multicast group can be simultaneously transmitted by multiple BSs; thus, the received signal quality can be significantly improved. We then express the signal-to-noise ratio (SNR) of the link to user $k$ on channel $c$ as

![Figure 1. Typical structure of multicast transmission in HetNets.](image)
where $N_0$ is the additive white Gaussian noise (AWGN) power. In order to assure reliable services to all subscribed users in a group, the modulation and coding scheme selected for transmitting the multicast stream needs to suit the worst channel condition of group users [3]. Therefore, the SNR of the multicast group $g$ on subchannel $c$ is given by

$$\varphi^c_g = \min_{k \in u_g} \{ SNR^c_k \}. \quad (2)$$

Then the maximum throughput obtained by multicast group $g$ is

$$\sum_{g=1}^{G} (|u_g| \sum_{c=1}^{C} \rho^c_g \Delta f \log_2 (1 + \min_{k \in u_g} \{ SNR^c_k \})),$$

where $\Delta f$ is the bandwidth of each subchannel.

In this paper, our goal is to maximize the overall multicast throughput by determining the optimal or suboptimal subchannel assignment vector $\rho = \{ \rho^c_g \forall g,c \}$ and power allocation vector $p = \{ p^c \forall b,c \}$.

We then formulate our resource allocation scheme as the following optimization problem:

$$\max_{\rho, p} \sum_{g=1}^{G} (|u_g| \sum_{c=1}^{C} \rho^c_g \Delta f \log_2 (1 + \min_{k \in u_g} \{ SNR^c_k \})) \quad (5a)$$

subject to

$$\sum_{c=1}^{C} \rho^c_g \leq p^c_{\text{multicast}}, \quad \forall b \quad (4b)$$

$$\rho^c_g \geq 0, \quad \forall b, c \quad (4c)$$

$$\sum_{g=1}^{G} \rho^c_g \leq 1, \quad \forall c \quad (4d)$$

$$\rho^c_g \in \{0,1\}, \quad \forall g, c \quad (4e)$$

The constraint (4b) ensures that the transmit power allocated by each BS cannot exceed its power budget. The constraint (4d) guarantees that each channel can be assigned to at most one group.

3. Joint Subchannel and Power Allocation

3.1. Optimization model

Problem (4) is a mixed integer nonlinear programming problem (MINLP) which is NP-hard to solve in the general case [12]. Moreover, there is an uncertain quantity $\min_{k \in u_g} \{ SNR^c_k \}$ making the objective function unsmooth and further increasing the difficulty of the problem. To find the optimal or suboptimal solution within reasonable scheduling time, the complexity of the original problem needs to be greatly reduced. Then we first transfer the uncertain quantity in the objective function to an inequality constraint and reformulate problem (4) as follows:

$$\max_{\rho, p} \sum_{g=1}^{G} (|u_g| \sum_{c=1}^{C} \rho^c_g \Delta f \log_2 (1 + \varphi^c_g)) \quad (5a)$$

subject to

$$(4b), (4c), (4d), (4e)$$
where \( k_g \) denote the user \( k \) in group \( u_g \). By adding constraint (5b), it is guaranteed that any multicast stream can be successfully demodulated and decoded by its group users; meanwhile, the transformed problem (5) has become a smooth MINLP problem.

However, as above mentioned, such MINLP problems are usually NP-hard and difficult to solve in reasonable time. An effective approach is to divide the integer and non-integer variables into subproblems to reduce complexity. Therefore, we decompose the original joint resource allocation problem (5) into a subchannel assignment subproblem and a power allocation subproblem, respectively, and then solve these two subproblems iteratively until convergence. The entire algorithm is presented in Table 1. Initially, the power of each BS is evenly distributed to all available subchannels.

Table 1. Joint subchannel and power allocation algorithm.

| Algorithm – iterative resource allocation algorithm |
|---------------------------------------------------|
| 1. Initialization:                                |
| \( i = 0 \) and \( \text{cap}(0) = 0 \).          |
| Calculate \( \Phi_b(0) = \Phi_{\text{multicast}} / C \) for all BSs. |
| 2. Iteration \( i \):                             |
| 2.1 Calculate \( \rho(i) \).                      |
| Calculate \( V_g^c = |u_g| \Delta f \log_2(1 + \phi_g^c) \) for all multicast group \( g \) and subchannel \( c \). |
| for \( c = 1 \) to \( C \)                       |
| Find its optimal user group, i.e., \( g^*(c) = \arg \max_g V_g^c \). |
| if \( g = g^*(c) \), then set \( \rho_g^c(i) = 1 \). |
| else set \( \rho_g^c(i) = 0 \). endif              |
| endfor                                           |
| Update \( \rho(i) \).                            |
| 2.2 Calculate \( p(i) \).                         |
| Set \( j = 0 \) and \( \text{powercap}(0) = 0 \).|
| Update \( H_{kb}^{cs} \) to worst channel gain of the group achieving this subchannel in step 2.1. |
| while \( \text{powercap}(j) \) does not converge or \( j < J_{\text{max}} \) |
| for \( b = 1 \) to \( B \)                       |
| Calculate \( n_b^c = (N_b + \sum p_b^c H_{kb}^{cs} / H_{kb,0}) / H_{kb,0} \) and \( m' = |u_g| \Delta f / \log(2) \) for all subchannel \( c \). |
| Calculate \( 1 / \lambda_b \).                    |
| ✷ Let \( x_i = n_b^c / m' \) and sort \( x_i \) in increasing manner. |
| ✷ Lower the water line \( L = L - 1 \) until \( \sum_{i=1}^{L} (x_i \Delta f / \log(2) - n_b^c - p_{\text{multicast}}) \leq 0 \); |
| ✷ confirm the water level \( 1 / \lambda_b = (p_{\text{multicast}} + \sum_{c=1}^{L} n_b^c \Delta f) / (L \Delta f \log(x)) \). |
| Calculate \( p_b^c(j) \) according to (17).        |
| endfor                                           |
| Update \( \text{powercap}(j) \) and increase \( j \). |
| endwhile                                         |
| Update \( p(i) \).                              |
| 3. Update total multicast throughput \( \text{cap}(i) \) based on \( \rho(i) \), \( p(i) \), and set \( i = i + 1 \). |
| Return to step 2 until \( i = 1 \) or \( \text{cap}(i) = \text{cap}(i - 1) \) |
| 4. Output \( \rho \) and \( p \).                |
At the $i^{th}$ iteration, the subchannel assignment subproblem is solved first in step 2.1 based on $p(i-1)$ obtained at last iteration. Then with the newly obtained $p(i)$, the power allocation subproblem is solved in 2.2. Finally, the sum throughput $\text{cap}(i)$ achieved by all multicast users is updated according to $p(i)$ and $\rho$.  

3.2. Subchannel allocation

At each iteration, we first solve the subchannel allocation subproblem. To further reduce the complexity of the problem, we deploy a Lagrangian approach to relax the complex constraints (4b), (4d) as well as (5b), and get

$$L = \sum_{g=1}^{G} \sum_{c=1}^{C} |u_g| |p_{g,c}^e| \Delta f \log_2 \left(1 + \phi_g^c\right) - \sum_{b=0}^{B} \lambda_b \left(\sum_{c=1}^{C} p_{b,c}^e - p_{b,\text{multicast}}^e\right) - \sum_{c=1}^{C} \beta_c \left(\sum_{g=1}^{G} p_{g,c}^e - 1\right) - \sum_{c=1}^{C} \sum_{g=1}^{G} \sum_{k=1}^{|C|} \alpha_{c,k}^g \left(\phi_g^e - \frac{\sum_{b=0}^{B} p_{b,k} c_g^{b,c} H_{k,b}^c}{N_0}\right)$$  

(6)

where $\lambda_b$, $\beta_c$ and $\alpha_{c,k}^g$ are Lagrangian multipliers. Based on the Karush-Kuhn-Tucker (KKT) conditions, it can be derived that

$$\frac{\partial L}{\partial \rho_i^e} = \begin{cases} < 0, & \rho_i^e = 0 \\ 0, & 0 < \rho_i^e < 1, \forall g, c. \\ > 0, & \rho_i^e = 1 \end{cases}$$  

(7)

Meanwhile, we have

$$\frac{\partial L}{\partial \rho_g^e} = |u_g| \Delta f \log_2 \left(1 + \phi_g^e\right) - \beta_g, \forall g, c.$$  

(8)

Taking the binary nature of $\rho_i^e$ into account, we substitute (8) into (7) and then obtain

$$\rho_i^e = \begin{cases} 1, & \beta_c < V_g^c \\ 0, & \beta_c > V_g^c \end{cases}$$  

(9)

where

$$V_g^c = |u_g| \Delta f \log_2 \left(1 + \phi_g^e\right).$$  

(10)

Since the constraint (4d) has been relaxed in (6), the solution obtained by (9) cannot guarantee each subchannel allocated to at most one group. On the other hand, because our goal is to maximize the total throughput of multicast users, each subchannel will definitely be allocated to one group indeed. Based on these considerations, we allocate each subchannel to the group with the highest $V_g^c$, that is

$$\rho_g^e = \begin{cases} 1, & g = g^* (c) \\ 0, & g \neq g^* (c) \end{cases}$$  

(11)

where $g(c) = \arg\max_g V_g^c$. Since $V_g^c$ naturally represent the multicast throughput achieved by multicast group $g$ on subchannel $c$, we can obtain a local optimal subchannel assignment solution through (11) under given power allocation solution. The subchannel assignment algorithm is summarized in step 2.1 in Table 1.

3.3. Power allocation

After subchannel allocation, a local subchannel assignment solution has been determined and then problem (5) can be simplified to a power allocation problem. However, different from the power allocation in traditional macrocells that only distributes the power of single cell to its covered users, the resource controller in HetNets needs to allocate the power of all BSs in the system jointly and
effectively to optimize the overall system performance. The SFN approach further increases the
difficulty of the problem since much more users and BSs are involved in the calculation. Thus,
traditional waterfilling algorithm usually used in macrocells cannot be deployed directly in HetNets.

Here, we first remove the subchannel assignment related variables from (6) and simplify it as:

\[ L = \sum_{g=1}^{G_c} \sum_{c=1}^{c_b} u_g \left| \Delta f \log_2 \left( 1 + \varphi_g \right) - \sum_{b=0}^{B} \lambda_b \left( \sum_{c=1}^{c_b} p_c^b - p_b^{multicast} \right) \right. \]

\[ - \sum_{c=1}^{c_b} \sum_{g} \alpha^c_{k_g,b} \left( \varphi_g - \frac{\sum_{b=0}^{B} p_b^c H_{k_g,b}^c}{N_0} \right) \]  

(12)

The KKT conditions for the optimal solution specify that

\[ \frac{\partial L}{\partial \varphi_g} = \frac{|u_g| \Delta f}{(1 + \varphi_g) \ln 2} - \alpha^c_{k_g,b} = 0, \quad \forall c, g \]  

(13a)

\[ \frac{\partial L}{\partial p_b^c} = \alpha^c_{k_g,b} \left( \frac{H_{k_g,b}^c}{N_0} \right) - \lambda_b = 0, \quad \forall c, b \]  

(13b)

\[ \lambda_b \left( \sum_{c=1}^{c_b} p_c^b - p_b^{multicast} \right) = 0, \quad \forall b \]  

(13c)

\[ \alpha^c_{k_g,b} \left( \varphi_g - \frac{\sum_{b=0}^{B} p_b^c H_{k_g,b}^c}{N_0} \right) = 0, \quad \forall c, g \]  

(13d)

\[ \varphi_g^c - \frac{\sum_{b=0}^{B} p_b^c H_{k_g,b}^c}{N_0} \leq 0, \quad \forall c, g \]  

(13e)

\[ \sum_{c=1}^{c_b} p_c^b \leq p_b^{multicast}, \quad \forall b \]  

(13f)

\[ \lambda_b \geq 0, \quad \forall b \]  

(13g)

\[ \alpha^c_{k_g,b} \geq 0, \quad \forall g, c \]  

(13h)

Here, \( k_g' \) denotes the user of group \( g \) presenting the worst channel gain. Using these conditions, we
can derive the local optimal power allocation solution, which is

\[ p_b^c = \left\{ \frac{|u_g| \Delta f}{\lambda_b \ln 2} - \frac{N_0 + \sum_{b=0}^{B} p_b^c H_{k_g,b}^c}{H_{k_g,b}^c} \right\}^* \]  

(14)

where \((\cdot)^* = \max(\cdot, 0)\). Indeed, the variable \( p_b^c \) cannot be calculated from (14) directly as the variables
of other BSs in the equation are not determined either. Therefore, we develop an iterative power
allocation algorithm to find the suboptimal solution. Major operations are illustrated in step 2.2 in
Table 1. After subchannel allocation, we first update the channel gain on each subchannel \( c \) from each
BS \( b \) to be the worst channel gain of the users in the multicast group achieving this subchannel. Then
we iteratively update the power allocation vector of each BS by fixing the vectors of other BSs until
convergence. We deploy a waterfilling like method to calculate \( \lambda_b \) of each BS \( b \) by treating it as the
water level and then calculate the power allocation solution according to (14).
4. Simulation results

Simulation results are presented in this section for evaluating the performance of our resource allocation scheme and algorithms. Various HetNet multicasting scenarios have been established based on the system level Long Term Evolution (LTE) simulator [13]. There are $C = 50$ downlink subchannels available for multicast transmission, each of which has a bandwidth of 180 kHz. We established the wireless channel as in [14]. The maximum number of iterations for power allocation algorithm and joint resource allocation algorithm are both set to be 100. The small BSs are uniformly located within the coverage of macrocell and multicast users are uniformly located within macrocell and small cells.

We first evaluate the performance of the proposed joint resource allocation scheme by comparing it with two existing schemes. The first scheme is proposed in [3]. Its objective is similar to ours but the power allocation algorithm is different. The other scheme is the traditional round-robin (RR) scheme by which both subchannels and transmit power are allocated equally.

Figure 2 compare the total throughput achieved by all the multicast users with these three schemes. Various scenarios have been built to simulate real applications through changing the numbers of multicast groups, users and small BSs, respectively. The results are averaged over 50 transmission time intervals (TTIs). We can see from these figures that our proposed resource allocation scheme can always achieve the highest overall multicast throughput. The RR scheme always sequentially and equally allocate subchannels and power of BSs to multicast groups ignoring the users’ channel conditions. As a result, the lowest multicast throughput is obtained by RR. Meanwhile, although the resource allocation scheme proposed in [3] can also allocate the subchannel and power resources with

![Figure 2](image_url)

**Figure 2.** The total multicast throughput comparison: (a) $B = 10$, $|v_k| = 10$; (b) $B = 10$, $G = 5$, and the users within small cells is 10 which are randomly distributed to the multicast groups; (c) $B = 5$, the number of users in small cells is 10 and all the users are equally distributed to the multicast groups.
the same objective to ours, its two-phase power allocation algorithm achieve less optimal solution than our algorithm as illustrated in figures.

Moreover, it can be observed from these results that our scheme work well with the increase of the number of small BSs and multicast users. This means that our scheme is especially suitable for the HetNets of high density or high traffic load, which are just the trend of 5G.

In the simulation, we also examined the performance of the iterative algorithms including the overall resource allocation algorithm and the power allocation algorithm. Based on the same key parameters, we evaluate the algorithms in three different scenarios with different BS and user positions. As shown in Figure 3, both of these two algorithms converged within several iterations.

5. Conclusion
In this paper, we propose a joint resource allocation scheme for multicasting in HetNets with an aim of maximizing the throughput achieved by multicast users. It is supposed to be the first piece of work jointly optimizing the subchannel assignment as well as power allocation problems for multicasting in HetNets. The formulated optimization problem is firstly transferred to be smooth and then decomposed into a subchannel assignment subproblem and a power allocation subproblem, respectively. Iterative algorithms are further developed to find the suboptimal solutions of the scheme. Simulation results have verified the effectiveness of our scheme and algorithms.

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