

Uplink spectrum resource allocation in heterogeneous networks (small cell/macrocell)

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Abstract Small cells are expected to increase network capacity, extend the macrocell coverage and to add edge-based intelligence. These advantages are achieved by overlaying macrocell networks with the small cells, resulting in a two-tier network. However, the average capacity of the network is reduced due to interference generated by the two-tier configuration. Conventional small cells are configured to have either an open or closed access scheme. Small cells with a hybrid access scheme or partially open access scheme are known for their flexibility and improved performance achieved through their interference-mitigating ability and adaptive resource allocation capabilities. In a hybrid access scheme, resource allocation is a vital issue in the design of small cells networks. In this paper, we propose an uplink resource allocation technique to enhance

hybrid small cell capacity in orthogonal frequency division multiple access (OFDMA) two-tier cellular networks. In particular, we investigate a new possibility available for developing an optimal scheme for OFDMA hybrid access small cells. We formalize the problem as an optimization problem for an uplink resource allocation that partitions the bandwidth for both subscribed or unsubscribed users. Moreover, we propose a convex optimization model for the gradient of the capacity difference between closed access and hybrid access capacity. We present two schemes, firstly an optimal scheme and secondly a scheme that is the simple version of the optimal scheme. Numerical results show the effectiveness of the proposed bandwidth resource allocation, where the simple solution shows inferior performance than the optimal solution with a small margin while the optimal solution has a more mathematical complexity disadvantage due to the mathematical functions it employs. Numerical results also show the convergence and effectiveness of the proposed uplink bandwidth resource allocation scheme.

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1 Introduction

The deployment of small cells overlaying a macrocell provides an innovative alternative for operators. This is due to their associated advantages, including cellular coverage improvement, offloading, and the capability to provide services to user equipment (UE) [1]. Orthogonal frequency division multiple access (OFDMA) femtocells are one of the classifications of small cells for which there is a growing demand due to their improved small office or home office (SOHO) coverage [2]. It has been predicted statistically that about 90 % of the data services and 60 % of voice

service will originate from this SOHO environment. The indoor location of a femtocell base station (FBS) ensures a significant improvement in the signal-to-interference-noise ratio (SINR) and quality of service due to the short transmitter-receiver distance. This enables the FBS to lower transmitter power, which further enhances the battery life time of the UE [3].

The FBS can be equipped with any of the following three types of access schemes, which are responsible for how UE can be granted permission to access a specific FBS. The first scheme is known as an open subscriber group (OSG) access method and has the advantage of reducing cross-tier interference [4]. The OSG is an operator preference because it grants unconditional permission to all UE to connect and access the FBS, to the extent that the offloading rates from the macrocell are increased. However, the OSG FBS has an adoption challenge in the home environment because the owner is expected to purchase an FBS, and to pay for electricity and back-haul. The second option is for the FBS to adopt a close subscriber group-closed (CSG-closed) scheme which is preferred by the owner due to its privacy advantage [5]. The owner of the FBS has the right to define the list of UE that may be granted permission to access the FBS. These are known as member femtocell UE or subscribed femtocell UE (*sFUE*). However, a CSG-closed FBS experiences an uplink interference from the UE located in close proximity with no access permission known as non-member femtocell UE or unsubscribed femtocell UE (*uFUE*), while the same *uFUE* experiences a downlink interference from the FBS. The third type of access scheme is known as a hybrid access or closed access group-open (CSG-open), and it has the ability to grant access permission to both *uFUE* and *sFUE* with preferential service to *sFUE*. Furthermore, the hybrid FBS provides a tradeoff between open and closed access schemes [6].

In particular, a hybrid access OFDMA femtocell base station (FBS) has been proposed to support adaptive resource allocation with advanced interference mitigation advantages. It is vital to investigate resource allocation for network performance improvement [7]. The hybrid or CSG-Open FBS is required to temporarily adaptively adjust its bandwidth and power resource allocation (RA) if the latter strongly interfere with a *uFUE*, such that the *uFUE* can handover to the CSG-Open. This approach addresses the coverage hole experienced when adopting the CSG-closed access scheme, and thus enhances the throughput of the system [8].

In this paper, we focus on the development of an optimal uplink resource allocation (RA) technique for hybrid femtocells based on the capacity of the CSG-closed scheme. This ensures that the capacity of the hybrid access scheme performs better than the CSG-closed. The derived RA scheme achieves optimal efficiency through its ability to

appropriately partition the bandwidth resource. An optimal RA can be beneficial for indoor as well as outdoor UE that falls under the coverage of a hybrid FBS and macrocell. However, several problems must be addressed with a view to the efficient exploitation of a hybrid FBS. Firstly, if there is no *uFUE* within the coverage of the FBS, bandwidth resource should be allocated optimally. However, if there is a *uFUE*, the FBS should have the ability to allocate the resource efficiently so that both *uFUE* and *sFUE* can establish a connection with an acceptable quality of service (QoS).

The contribution of this paper is as follows: Firstly, we propose a new optimal RA scheme for an OFDMA hybrid FBS and a macrocell base station (MBS) to enhance the small cell uplink system capacity. The RA scheme is derived by a concave optimization procedure (a global optimization solution). Subsequently, evaluation of the optimal RA performance in forth-generation OFDMA networks with femtocells is evaluated to illustrate its efficiency. A simple mathematical model that estimates the optimal function is derived and a simple RA scheme is obtained by substituting the logarithmic function of the optimal function with its series representation. The performance of the simple RA is compared to that of the optimal RA and the other promising RA scheme. The proposed schemes determine the RA ratio by minimizing the gradient function of the average capacity. It is expected that through the proposed schemes, will enable the FBS to determine how much bandwidth resource is allocated for the member femtocell user equipment (*sFUE*) as compared to *uFUE*.

The remainder of the paper is organized as follows: Section 2 gives a summary of related work. Section 3 introduces the two uplink settings. Section 4 presents the hybrid-based RA schemes (simple and optimal). Numerical results and analyses are provided in Section 5 followed by concluding remarks in Section 6.

2 Related work

The approach adopted in this article is derived from an FBS access type change (FBS-ATC) method suggested in [8, 9]. In [8], the author presents a hybrid access control method known as CSG-open or semi CSG-Closed. This semi CSG-Closed reference is mentioned because the FBS operates as a CSG-closed access FBS until the macrocell base station (MBS) offloads some of its macrocell user equipment (MUEs). The status of the MUE offloaded to the hybrid access changes to *uFUE*. However, the author does not propose a RA scheme, except for suggesting its operational framework.

A study of the code division multiple access (CDMA)-based network shows poor performance in average capacity

where adaptive bandwidth resource allocation is not feasible [10]. In a wideband CDMA (WCDMA) study [11], different RA factors are adopted. The allocation is as follows: 30 % of the bandwidth resource is reserved for μ FUE, while 70 % of the FBS bandwidth is reserved for s FUE. This proposed scheme is fixed and it lacks a description of its derivation procedure or formulation. However, contrary to RA based on CDMA, the WCDMA-based hybrid access enhances the system capacity. In [12], the author presents an adaptive RA for hybrid access FBS; this study adopts an orthogonal frequency division multiple access (OFDMA) system. However, it focuses on enhancing downlink system capacity by proposing a cell selection scheme of non-member femtocell user equipment (μ FUE).

The authors of [13] propose an uplink interference suppression scheme in two-tier femtocell networks by means of power control. The scheme takes into consideration the quality of service (QoS) of the MUE and FUE with respect to their signal-to-interference-noise ratio (SINR). This includes the transmit power efficiency of both the MBS and FBS which is achieved by designing a multi-objective function. The function is a weighted sum of transmission power and squared SINR difference between femtocell user's maximum SINR and actual SINR. It suggests an optimal power resource allocation and is supported by results. In [14], Elias et al. propose a distributed collaborative uplink scheduling scheme in OFDMA systems for a multicell scenario with and without base station. This scheme uses power control interference avoidance by using interference information or adopting a probabilistic approach.

Whereas Yanzan et al. presents uplink interference mitigation in an OFDMA two-tier (macrocell and femtocell) network, the current article adopts a partial cochannel deployment strategy. Firstly, an inter-tier interference mitigation scheme is presented that considers the location of the MUE and the FBS. This scheme groups the UE into either femtocell-interfering UE or regular UE. All the femtocell-interfering UE are allocated to the dedicated subcarriers and the regular UE are allocated to the shared subcarrier. Secondly, an intra-tier mitigation solution is proposed which employs an auction algorithm to optimize the subcarrier assignment for both the MBS and FBS. This results in interference mitigation between FUE and MUE and causes the enhancement of the system throughput [15].

When compared to the listed related work on resource allocation, it becomes evident that our proposal is unique in several aspects. First, we consider the capacity of the CSG-Closed, which ensures that our approach is always superior to that of the CSG-Closed yet it is open to μ FUE. This approach ensures no bandwidth resource is wasted. Secondly, most approaches adopt power control, while our article addresses the issue of bandwidth allocation.

3 System description and model

We consider an uplink OFDMA system for the two-tier heterogeneous cellular network configuration. The setup consists of one macrocell and N number of FBS. Interference from the MUE to the FBS is the major interference observed in a non-dense uplink configuration of the FBS and MUE. This network configuration is based on a partial co-channel spectrum allocation, where part of the spectrum is shared between femtocell and macrocell, and the other remaining spectrum is dedicated to MUE associated with the macrocell base station (MBS). Furthermore, the MUE that severely interferes with the FBS is offloaded and converted to a μ FUE. In this paper, two system models are considered (i.e., the two-user and multi-user models). The two-user model comprises two users distributed in the coverage area as show in Fig. 1. It also considers two cases: case 1 adopts the CSG-closed while case 2 adopts the hybrid access mode (shown in Fig. 1). In case 2, both users are associated with the FBS. The second model (multi-user model) shown in Fig. 1 (see case 3) consists of one MBS and N number of FBSs with multiple MUEs and multiple FUEs. The uplink capacity of the FBS is varied due to the propagation loss, signal-to-noise ration (SNR), and bandwidth allocation per user. Note that Table 1 shows the major modeling symbols used in this article.

4 Resource allocation scheme

This section presents a mathematical analysis of the RA ratio for a hybrid-access FBS. Firstly, we provide a mathematical motivation for the problem. Secondly, we present a derivation of a hybrid access-based RA scheme (both optimal and simple). A hybrid-access FBS equipped with these schemes allocates resource to both μ FUE and s FUE, while it gives preference to s FUE by reserving a minimum bandwidth resource. The RA ratio for μ FUE is specifically limited, while the RA ratio for s FUE can be equal to 1, which means that the s FUE can be allocated with the whole shared bandwidth as described later in this article.

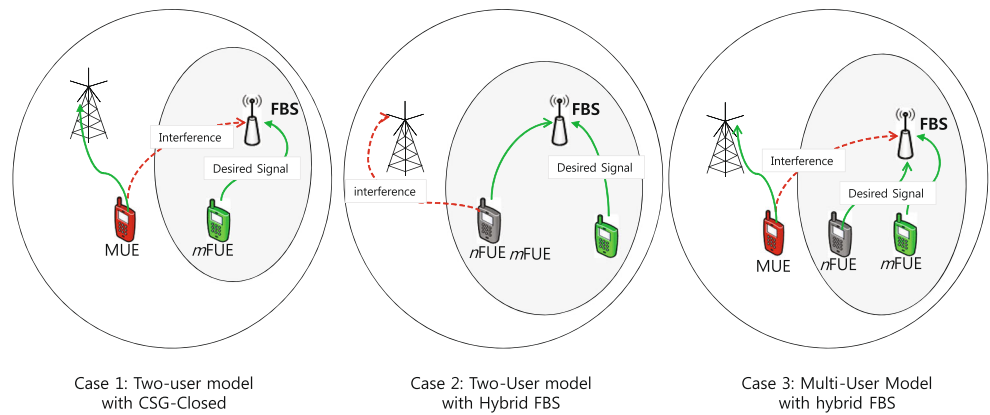
4.1 Two-user-based scheme

In respect of case 1 and case 2 in Fig. 1, only two users are considered in the system. Assuming a CSG-closed access, the uplink capacity of the FBS is modeled as

$$C_c^f = \frac{B}{N_s} \log_2 \left(1 + \frac{P^{ff} |H^{ff}|^2}{I^{mf} + (BN_0/N_s)} \right), \quad (1)$$

where B is the bandwidth of the femtocell and N_s is the number of s FUE. P^{ff} is the power transmitted by the FUE to the FBS and the channel response between the FUE and

Fig. 1 Different models of consideration for CSG-closed and CSG-open (hybrid) access schemes



FBS is represented by $|H^{ff}|^2$. $I^{mf} = P^{mf}|H^{mf}|^2$ is the interference from the MUE to the FBS: P^{mf} is the power transmitted from the MUE to the FBS and $|H^{mf}|^2$ is the channel response between the MUE and FBS. It should be noted that the transmit power of both the FUE and MUE are equal ($P^{ff} = P^{mf}$) for analyses purposes, during simulation power control is considered. Also, N_0 is the noise power density.

On a different note, the uplink capacity for the hybrid access FBS is defined as

$$C_o^f = \frac{(1-\mu)B}{N_s} \log_2 \left(1 + \frac{P^{ff}|H^{ff}|^2}{\frac{BN_0}{(1-\mu)}} \right) + \frac{\mu B}{N_u} \log_2 \left(1 + \frac{P^{mf}|H^{mf}|^2}{\frac{BN_0}{\mu}} \right), \tag{2}$$

where N_u denotes the number of u FUE and the number of UE is assumed to be $N_u = N_s = 1$. Furthermore, (2) is

simplified by substituting the variables representing the number of UE with assumptions; this is modeled by

$$C_o^f = (1 - \mu)B \log_2 \left(1 + \frac{P^{ff}|H^{ff}|^2}{\frac{BN_0}{(1-\mu)}} \right) + \mu B \log_2 \left(1 + \frac{P^{mf}|H^{mf}|^2}{\frac{BN_0}{\mu}} \right), \tag{3}$$

where the RA ratio μ can be expressed by $\mu = B_0/B$. B_0 is the bandwidth allocation variable for all u FUE on the FBS. It should be noted that the derivation resulting in Eq. 3 considers a two-user scenario as shown in Fig. 1 case 2, but is applicable to the multi-user scenario due to its linear relationship.

The RA ratio for u FUE is limited proportionally to the current linked s FUE with respect to the number of subscribed s FUE. On the other hand, the s FUE can be allocated the whole bandwidth, which is represented by

$$0 < \mu_{min} \leq \mu \leq \mu_{max} < 1. \tag{4}$$

In Eq. 4, μ_{max} and μ_{min} represent the maximum and minimum RA that can be observed in the schemes presented. The constraints in μ represents the assumption that the minimum number of s FUE and u FUE is greater or equal to one ($N_{smin} \geq 1$ and $N_{umin} \geq 1$). Especially, we assume that there is a maximum number of subscribed s FUE in the FBS given by N_{smax} . Therefore, the maximum RA ratio is expressed by $\mu_{max} = 1 - \frac{N_s}{N_{smax}}$ given that $1 \leq N_s \leq N_{smax}$ [12]. In order to simplify the expression given in Eqs. 1 and 3, we define M and N as follows:

$$M = \frac{P^{ff}|H^{ff}|^2}{BN_0}, \quad N = \frac{P^{mf}|H^{mf}|^2}{BN_0}. \tag{5}$$

Then, substituting (5) into (1) and (3) results in the following equations

$$C_c^f = B \log_2 \left(1 + \frac{M}{N+1} \right), \tag{6}$$

$$C_o^f = B \log_2 \left(1 + \frac{M}{1-\mu} \right)^{1-\mu} + B \log_2 \left(1 + \frac{N}{\mu} \right)^\mu. \tag{7}$$

Table 1 Notation of parameters used for description of the proposed scheme

Symbol	Definition
C_c^f	Uplink capacity of the CSG-Closed FBS
I^{mf}	Interference from the MUE to the FBS
P^{ff}	Transmit power from the FUE to the FBS
H^{ff}	Channel response between FUE and FBS
N_s	The number of s FUE
B	Bandwidth of the FBS
N_u	The number of u FUE
P^{mf}	Transmit power from MUE to FBS
H^{mf}	Channel response between MUE and FBS
N_0	Noise power density
μ	Resource allocation ratio given by B_0/B
DS	Degree series
C_o^f	Uplink capacity of the hybrid FBS
μ_{opt}	optimal resource allocation

The two functions presented above are the basic terms for our optimization function. The objective function is derived by subtracting the CSG-closed capacity function in Eq. 6 from the hybrid capacity function in Eq. 7. The result of this subtraction should be greater than 0 ($C(M, N, \mu) = C_o^f - C_c^f > 0$), and satisfying this condition ensures the enhancement of the capacity. The detailed objective function is described as follows:

$$C(M, N, \mu) = C_o^f - C_c^f = B \log_2 \left(W \left(1 + \frac{N}{\mu} \right)^\mu \left(1 + \frac{M}{1-\mu} \right)^{1-\mu} \right), \tag{8}$$

where

$$W = \left(1 + \frac{M}{N+1} \right)^{-1}. \tag{9}$$

It is shown in Eq. 8 that for all instances of $0 < \mu_{min} \leq \mu \leq \mu_{max} < 1$, $C_o^f - C_c^f$ is positive. This indicates that there is a value of μ that maximizes $C(M, N, \mu)$. In the next sections, we present the derivation of the RA scheme which gives the optimal value of μ , while it maximizes the capacity for the two-user scenario and the multi-user scenarios, respectively.

In order to investigate the concavity of the function $C(M, N, \mu)$, the function C should satisfy the following conditions. A function $C : R^n \rightarrow R$ is concave if **dom** C is concave set and if for all $\mu_1, \mu_2 \in \mu \in \mathbf{dom}C$ and that $0 \leq \theta \leq 1$, where

$$C(\theta\mu_1 + (1-\theta)\mu_2) \geq \theta C(\mu_1) + (1-\theta)C(\mu_2). \tag{10}$$

The proof for concavity of $C(M, N, \mu)$: based on Eq. 8, lets define the function of K to check the concavity of C . In Eq. 10, by setting $\mu_1 = 1$ and $\mu_2 = 0$ followed by substituting this μ value into (8), we get the following:

$$K = C(\theta) - \theta C(1) - (1-\theta)C(0) \tag{11}$$

$$= B \log_2 \left(\frac{1-\theta+M}{1-\theta+(1-\theta)M} \right)^{1-\theta} + B \log_2 \left(\frac{\theta+N}{\theta+\theta N} \right)^\theta.$$

$$\mu_{opt} = \operatorname{argmin}_{\mu_{min} \leq \mu \leq \mu_{max}} \left| B \log_2 \left(\frac{1 + \frac{N}{\mu}}{1 + \frac{M}{1-\mu}} \right) - \frac{N}{c(\mu + N)} - \frac{M}{c(1-\mu + M)} \right| \tag{18}$$

$$C(M, N, \mu) = \sum_{i=1}^{N_s} \frac{(1-\mu)B}{N_s} \log_2 \left(1 + \frac{(p^{ff}|H^{ff}|^2)_i}{\frac{BN_0}{N_s}} \right) + \sum_{j=1}^{N_u} \frac{\mu B}{N_u} \log_2 \left(1 + \frac{(p^{mf}|H^{mf}|^2)_j}{\frac{\mu BN_0}{N_u}} \right) \tag{19}$$

$$\mu_{opt} = \operatorname{argmin}_{0 \leq \mu \leq \mu_{max}} \left| -\frac{1}{N_s} \sum_{i=1}^{N_s} \left(B \log_2 \left(1 + \frac{M_i}{1-\mu} \right) + \frac{M_i}{\ln(2)(1-\mu + M_i)} \right) + \frac{1}{N_u} \sum_{j=1}^{N_u} \left(B \log_2 \left(1 + \frac{N_j}{\mu} \right) - \frac{N_j}{\ln(2)(\mu + N_j)} \right) \right| \tag{20}$$

It is observed in both two terms of Eq. 11 that the denominators are either equal or smaller than the numerator when considering that $0 \leq \theta \leq 1$. This implies that the quotient is always greater than one and the exponent is never negative. It can therefore be concluded that the function is greater than or equal to 0, which satisfies the concavity conditions. Due to the concavity of the function, we can simply maximize the objective function $C(M, N, \mu)$. This can be achieved by minimizing its gradient functions' absolute with respect to μ . This will result in the optimal ratio μ_{opt} , where the minimum absolute value of the gradient function is described as follows:

$$\mu_{opt} = \operatorname{argmin}_{0 \leq \mu \leq \mu_{max}} \left| \frac{\partial C(M, N, \mu)}{\partial \mu} \right|. \tag{12}$$

In order to simplify the objective function $C(M, N, \mu)$, we divide it into two terms as presented below

$$C_1 = (1-\mu)B \log_2 \left(1 + \frac{M}{(1-\mu)} \right), \tag{13}$$

$$C_2 = \mu B \log_2 \left(1 + \frac{N}{\mu} \right). \tag{14}$$

Therefore, the inside of the minimization operator in Eq. 12 is given by

$$\frac{\partial C(M, N, \mu)}{\partial \mu} = \frac{\partial C_1}{\partial \mu} + \frac{\partial C_2}{\partial \mu}. \tag{15}$$

The first term in Eq. 15 is as follows:

$$\frac{\partial C_1}{\partial \mu} = -B \log_2 \left(1 + \frac{M}{(1-\mu)} \right) - \frac{M}{\ln(2)(1-\mu + M)}, \tag{16}$$

and the second term in Eq. 15 is also given by the following expression,

$$\frac{\partial C_2}{\partial \mu} = B \log_2 \left(1 + \frac{N}{\mu} \right) - \frac{N}{\ln(2)(\mu + N)}. \tag{17}$$

The solution for this section is the optimal RA scheme based on a two-user model, which is clearly described in Eq. 18. This solution was attained by adding the two terms in Eqs. 16 and 17.

4.2 Multi-user-based scheme

The multi-user scheme follows the same concept as suggested in the first two-user model. It differs in that the equation has a multiple terms which are proportional to the number of UE associated with the FBS as shown in Eq. 19. The function is further divided into two terms; the first term is the average uplink capacity from all the *s*FUE as shown below

$$C_a = \sum_{i=1}^{N_s} \frac{(1 - \mu)B}{N_s} \log_2 \left(1 + \frac{(P^{ff} |H^{ff}|^2)_i}{(1 - \mu)BN_0/N_s} \right). \quad (21)$$

The second term is the average uplink capacity from *u*FUE and is given by

$$C_b = \sum_{j=1}^{N_u} \frac{\mu B}{N_u} \log_2 \left(1 + \frac{(P^{mf} |H^{mf}|^2)_j}{\mu BN_0/N_u} \right), \quad (22)$$

where N_s and N_u are the number of *s*FUE and *u*FUE, respectively. The optimization function is given by the linear summation of the two terms of the hybrid FBS capacity equation subtracted by the capacity of the CSG-Closed as shown below

$$C(M, N, \mu) = C_a + C_b - C_c^f. \quad (23)$$

The solution of the objective function depends on the function $C(M, N, \mu)$, and it is expressed as follows:

$$\begin{aligned} \mu_{opt} &= \operatorname{argmin}_{0 \leq \mu \leq \mu_{max}} \left\{ \frac{\partial(C(M, N, \mu))}{\partial \mu} \right\}, \\ &= \operatorname{argmin}_{0 \leq \mu \leq \mu_{max}} \left\{ \frac{\partial(C_a + C_b - C_c^f)}{\partial \mu} \right\}, \end{aligned} \quad (24)$$

where variables used in this multi-user section are the same as the variable in a two-user section, hence their explanation is ignored. The two terms shown in Eqs. 21 and 22 of the hybrid-access FBS’s capacity are a log function, implying that we can optimize the capacity function through its gradient function. Since the equation is linear, we can solve the differentiation terms separately as shown below

$$\frac{\partial C_a}{\partial \mu} = -\frac{1}{N_s} \sum_{i=1}^{N_s} \left(B \log_2 \left(1 + \frac{M_i}{1 - \mu} \right) + \frac{M_i}{c(1 - \mu + M_i)} \right), \quad (25)$$

$$\mu_{opt} = \operatorname{argmin}_{0 \leq \mu \leq \mu_{max}} \left| -\frac{1}{N_s} \sum_{i=1}^{N_s} \left(2B \frac{M_i \log_2 e}{2 - 2\mu + M_i} + \frac{M_i}{\ln(2)(1 - \mu + M_i)} \right) + \frac{1}{N_u} \sum_{j=1}^{N_u} \left(2B \frac{N_j \log_2 e}{2\mu + N_j} - \frac{N_j}{\ln(2)(\mu + N_j)} \right) \right| \quad (30)$$

This is achieved by quantizing the values of μ into a discrete set that is proportional to the number of available subcarriers. The discrete set of μ values (μ_{dis}) is given by $\mu_{dis} = \{ \frac{1}{N_{sc}}, \frac{2}{N_{sc}}, \frac{3}{N_{sc}}, \dots, \mu_{max} \}$, where N_{sc} is the number of subcarriers in the FBS.

where c denotes a constant value $\ln 2$ and the term of the gradient function is expressed as follows:

$$\frac{\partial C_b}{\partial \mu} = \frac{1}{N_u} \sum_{j=1}^{N_u} \left(B \log_2 \left(1 + \frac{N_j}{\mu} \right) - \frac{N_j}{\ln(2)(\mu + N_j)} \right). \quad (26)$$

Where the following variables are simplifiers of the derivation equation, they are given by

$$M_i = \frac{P_i^{ff} |H_i^{ff}|^2}{\frac{BN_0}{N_s}}, \quad N_i = \frac{P_j^{mf} |H_j^{mf}|^2}{\frac{BN_0}{N_u}}. \quad (27)$$

The sum of the two terms (25) and (26) results in the equation outlined in Eq. 20.

4.3 Simple RA scheme

In previous sections, we presented an optimal solution of the objective function. In this section, we simplify μ_{opt} of the functions shown in Eqs. 18 and 20. In both the two-user and multi-user cases, it is noted that the first terms of both the solutions shown in Eqs. 18 and 20 are logarithmic. Hence, we substitute the logarithmic function with their “synonym” function or series representation [16]. The synonym or series representation is given by

$$\ln(x) = 2 \sum_{k=1}^{DS} \frac{1}{2k - 1} \left(\frac{x - 1}{x + 1} \right)^{2k-1}, \quad DS = \infty, \quad (28)$$

where DS denotes the degree series, given that $DS = 1$ then the equation in Eq. 28 is reduced to

$$\log_2(x) = \ln(x) / \ln(2) = 2(x - 1) / ((x + 1) * \ln(2)). \quad (29)$$

Substituting Eq. (29) by Eq. 20 results in the simplified version which constitutes the final results for this work and is presented in Eq. 30. This expression presented in Eq. 30 is also applicable to the two-user model scenario where we simplify the continuous μ function.

5 Numerical results

In this section, we evaluate the performance of our two proposed schemes by conducting a system level simulation

Table 2 Simulation parameters

Parameter	Description/assumption
Carrier frequency	2000 MHz
FBS bandwidth	10 MHz
FBS coverage radius	10 m
Total transmit power of μ FUE and s FUE	10 dBm
FBS Ant. Gain	0dB
FBS Ant. pattern	Omni-directional
Log-normal shadowing standard deviation	4 dB
Max. # of member UE (s FUE) N_{smax}	4
Resource allocation (RA)	$\mu_{min} \leq \mu \leq \mu_{max}$
maximum RA μ_{max}	$1 - N_s/N_{max}$
Current active number of s FUE (L)	1 or 2(depend on simulation)
House size	10 m x 10 m
Number of share subcarriers (N_{sc})	1024 (50 % of 2048)
WGN power density (N_0)	-174 dBm/Hz

using the MATLAB environment. All evaluations are based on Monte-Carlo methods, where each point of the plots has an average value of 1000 multiple independent snapshots as recommended in [17]. Firstly, the results are used to compare the performances of the multiuser and two-user models with respect to the proposed two schemes. Secondly, the results are used to compare the performance of the simple RA scheme with that of the optimal RA scheme. Thirdly, the results are used to evaluate the performances of the different degree series in the simple RA scheme.

5.1 Simulation environment

We consider an MBS/FBS two-tiered cellular network, where one MBS is located at the center of the cell, and

the number of FBS, μ FUE (N_u), and s FUE (N_s) are varied independently as per specific simulation test. The minimum distance is limited as follows: the distance between the FBS and the MBS is 35 m, between the FBS and FUE is 20 cm, and between macrocell base station (MBS) and UE is 35 m [17]. The bandwidth is distributed equally amongst μ FUE and amongst s FUE separately. Each device (FBS or UE) is equipped with one omnidirectional antenna. The pathloss models adopted in this work are suggested in [17]. Other basic simulations parameters are listed in Table 2.

5.2 Simulation results

Figure 2 illustrates the achievable cumulative distribution function (CDF) of the FBS capacity according to the different models (two-user and multi-user). This evaluation is further based on four type of schemes: an equal RA for the CSG-closed, simple RA, optimal RA, and 30 % Fixed RA. The 30 % fixed RA is shown in [5], and is a conventional fixed resource reservation of 30 % on a hybrid FBS for μ FUE. Also, the equal RA is the conventional RA for CSG-closed, where all UEs associated with the FBS share the bandwidth resource equally. In the multi-user model, 100 FBSs are distributed randomly in the cell, 2 s FUEs are located indoor, and 200 μ FUEs are randomly distributed in the cell. The MUE associates itself with the FBS that has the strongest signal-to-noise ratio. The simple RA scheme adopts a degree series of one. It is observed that the two-user model performs superior to the multi-user, which implies that the RA schemes does not significantly affect the performance when comparing the two models. It is also found that optimal RAs achievable capacity is slightly higher than simple RA and simple is higher than both 30 % fixed RA and the equal RA.

In Fig. 3, we compare the proportionality of the uplink FBS capacity with the CDF of the capacity according to the

Fig. 2 The comparison of the schemes capacity performances under two-user and multi-user scenarios case

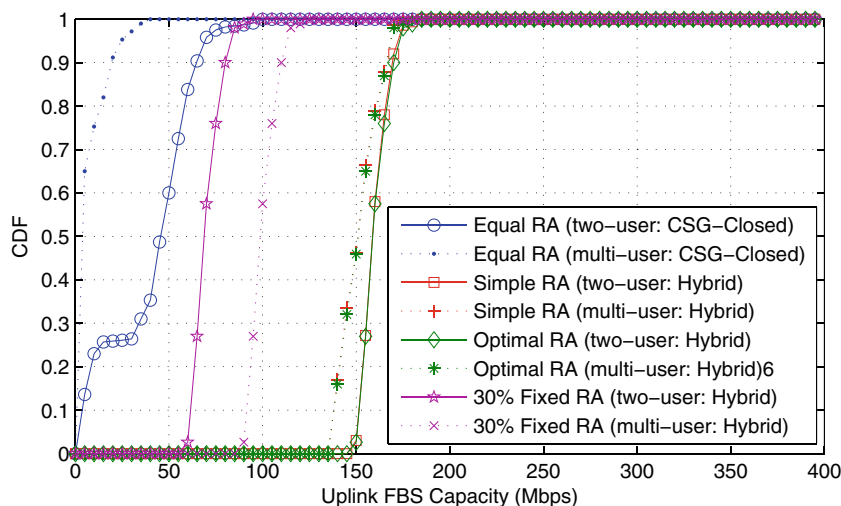
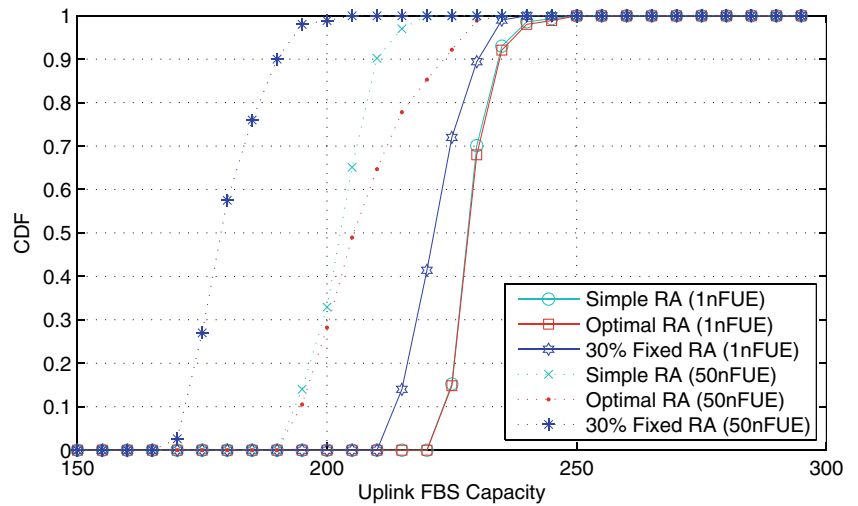


Fig. 3 The performance of the simple RA vs Optimal RA scheme

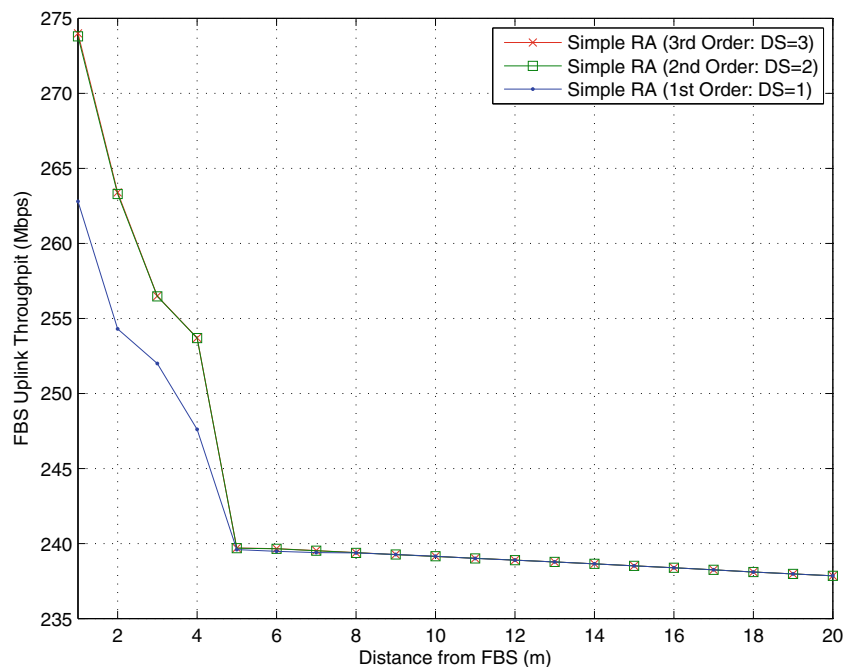


different number of u FUE ($N_u = [1, 50]$) per FBS. These u FUE are uniformly distributed in the coverage area of the FBS as shown in Fig. 1. Two s FUE are uniformly distributed indoors where the FBS is located. Also, 100 FBS are uniformly distributed within the coverage area of the macrocell. It is observed that the optimal RA scheme allocates the bandwidth resource effectively, and that the capacity performance under this scheme is always superior. On the other hand, all the RA schemes performances decrease with the increase in number of u FUE. This is due to the average wall penetration loss and increased pathloss experienced by u FUE. Contrary to the previous evaluation, it is clearly shown that the performance of the optimal RA scheme is superior than that of simple RA scheme. The 30 % fixed RA

performs worst when compared to the simple and optimal due to its lack of dynamic response.

Figure 4 shows the uplink average capacity according to the degree series ($DS = [1, 3, 5]$) of the simple RA scheme. We then compare the capacity to the distance between one u FUE and the FBS, while two s FUE are randomly distributed indoors. From the graph, it can be observed that the increase in the degree series results in an increase in the simple RAs performance. However, the degree series of 1 is less mathematically complex or have a low computational cost yet its performance is not significantly small. It is also found that the capacity decreases as the u FUE moves away from the FBS; this test shows little impact by the scheme.

Fig. 4 The order of complexity of the simple RA scheme



6 Conclusion

In this paper, we have proposed two bandwidth RA strategies for hybrid FBS. The proposed solutions are divided into two parts, namely the optimal RA scheme that has a superior performance and a high computational cost and the simple RA scheme that is less complex yet still offers high sub-optimal capacity performance. We also showed that the capacity performance of the simple scheme improves proportionally to an increase in the degree series level adopted. The implementation of the solution developed in this study shows that a hybrid FBS can ensure greater uplink average capacity than the CSG-closed and the 30 % fixed RA.

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