Efficient Sub-Carrier Allocation Algorithm for OFDM based Wireless Systems

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ABSTRACT

Carrier aggregation is a key functionality for next generation wireless communication systems that enables mobile network operators to create larger "virtualâ" carrier bandwidths for data hungry applications by aggregating available component carriers. In this paper, sub-carrier allocation problem in orthogonal frequency division multiplexing based wireless systems with carrier aggregation is studied. A two-step solution including component carrier and sub-carrier allocation is proposed. Performance of the proposed solution has been evaluated using system level simulations and results show clearly that the proposed algorithm outperforms the highly complex combinatorial algorithm introduced as an optimal solution in terms of cell throughput and user throughput.

KEYWORDS

ofdm; carrier aggregation; sub-carrier allocation;

1 INTRODUCTION

According to Cisco systems as a result of the exponential growth of wireless data services and the growing number of wireless users global mobile data traffic is estimated to reach 24.3 ExaBytes (EBs) per month in 2019 - a nearly six-fold increase over 2015 [1]. Furthermore, according to the Korea Times, Next Generation Mobile Networks (NGMNs) will be defined as a network âĂIJcapable of transmitting data at up to 20 GbpsâĂİ, a speed which would enable users to download HD movies in just a few seconds [2].

Related to wireless data traffic, the key parameter to consider is wireless throughput which is defined as: Throughput (bits/s) = Bandwidth (Hz) $\times$ Spectral efficiency (bits/s/Hz). To improve the throughput, some new technologies which can increase the bandwidth or the spectral efficiency or both should be exploited. For instance in LTE-A, to support peak data rates of up to 3 Gbps, the use of high channel bandwidth is imperative. Unfortunately, worldwide Mobile Network Operators (MNOs) do not have access to a continuous segment of wide bandwidth (e.g. 100 MHz) due to the spectrum fragmentation and an inefficient command and control spectrum management approach [3].

To end this, recently Carrier Aggregation (CA) is introduced as one of the most important features to achieve high data rate transmission. CA allows efficient and flexible usage of fragmented spectrum by aggregating multiple Component Carriers (CCs) [4, 5]. In other words, CA enables MNOs to create large virtual carrier bandwidths for data hungry users by aggregating multiple CCs with different bandwidths, dispersed within intra or inter bands [6]. The aggregated CCs can be simultaneously utilized to provide higher data rates, better coverage and simplified multi-band traffic management, resulting enhanced user quality of experience.

Orthogonal Frequency Division Multiplexing (OFDM) is an excellent choice of multiplexing scheme for the NGMNs. Although it involves added complexity in terms of resource scheduling, but it provides outstanding capabilities to combat multipath fading, high spectral efficiency as well as providing frequency, time and user diversity due to its flexible and precisely per Sub-Carrier (SC) allocation capability with finer granularity [7]. OFDM has attracted lots of interest in academia and industry and has been adopted in several latest wireless standards, such as LTE, DVB-T, IEEE 802.11x, 802.16e, 802.15.3, etc.

OFDM systems has become one of the most intensively studied paradigms in wireless com-

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munications. The vast majority of previous contributions in the literature focused on solutions for cases where the users use the non-CA OFDM technologies [8],[9]. However, capacity and coverage gains can be improved dramatically if users employ CA to increase the transmission bandwidth and provide an additional frequency diversity [6]. To the best of authors' knowledge, this work is the first to investigate allocation of SCs with CA in an OFDM system with the practical constraints of users's CA capabilities. Most of the existing research either solve the allocation problem in a non-CA based OFDM system [8], [9] or solve it with CA for LTE-Advanced [10], [11]. In contrast to existing state-of-the-art solutions, this paper's major contributions can be summarised as follows:

1. SC allocation with CA functionality is formulated as an optimization problem under the practical constraints of limited number of CCs available for each user.
2. A sub-optimal low-complexity solution is proposed to solve the optimization problem.
3. Simulation based study is provided to evaluate the performance of the proposed method and compare tit with the optimum solution.

This paper is organised as follows. In Section 2, SC allocation with CA functionality is described and an optimization problem is formulated. The proposed algorithm is explained in Section 3; combinatorial algorithm is explained very briefly in Section 4. Simulation results are discussed in Section 5, followed by conclusions in Section 6.

2 SYSTEM MODEL

Consider an OFDM based wireless network with a central Access Point (AP) consisting of $\mathcal{N}$ users as $\boldsymbol{\alpha} = \{\alpha_1, \alpha_2, \cdots, \alpha_{\mathcal{N}}\}$. Each user $\alpha_n \in \boldsymbol{\alpha}$ may have different CA capability and modelled as $\boldsymbol{\mu} = \{\mu_n | \mu_n \in \mathbb{N}\}_{1\times\mathcal{N}}$, where μ_n represents the maximum number of CCs that $\alpha_n \in \boldsymbol{\alpha}$ can support (for instance, $\mu_n = 1$ for user $\alpha_n \in \boldsymbol{\alpha}$ that can not utilize more than one CC). All users in a given scheduling Time Slot (TS), compete for $\mathcal{M}$ non-overlapping orthogonal CCs as $\boldsymbol{\beta} = \{\beta_1, \beta_2, \cdots, \beta_{\mathcal{M}}\}$ where each $\beta_m \in \boldsymbol{\beta}$ has a different number of SCs (maximum $\mathcal{P}$) and can be written as $\boldsymbol{\gamma} = \{\gamma_m | \gamma_m \in \mathbb{N}\}_{1\times\mathcal{M}}$ where γ_m shows the number of SCs in a given β_m. Bandwidth of each β_m can be calculated as $\gamma_m \Delta f$ for $1 \le m \le \mathcal{M}$ and Δf denotes SC frequency spacing; for simplicity, we assume $\Delta f = 1$.

Define a *SC allocation matrix* as a binary matrix $\mathbf{A}$ as:

$$\mathbf{A} = \{a_{m,\rho,n} | a_{m,\rho,n} \in \{0, 1\}\}_{\mathcal{M}\times\mathcal{P}\times\mathcal{N}} \qquad (1)$$

representing SC allocation map where $a_{m,\rho,n} = 1$ if and only if ρ^{th} SC located in m^{th} CC is allocated to n^{th} user uniquely and $a_{m,\rho,n} = 0$ otherwise. The SC allocation matrix $\mathbf{A}$ must satisfy the interference constraint as defined in (2) i.e. two or more users cannot utilize same SC simultaneously:

$$\sum_{n=1}^{\mathcal{N}} a_{m,\rho,n} \le 1 \qquad (2)$$

Similarly, a *CC allocation matrix* can be defined as a binary $\mathcal{M} \times \mathcal{N}$ matrix as follows:

$$\mathbf{E} = \{e_{m,n} | e_{m,n} \in \{0, 1\}\}_{\mathcal{M}\times\mathcal{N}} \qquad (3)$$

where $e_{m,n}$ represents whether the β_m is assigned to α_n or not, i.e.

$$e_{m,n} = \begin{cases} 0 & \iff \sum_{\rho=1}^{\mathcal{P}} a_{m,\rho,n} = 0 \\ 1 & \iff \sum_{\rho=1}^{\mathcal{P}} a_{m,\rho,n} \ge 1 \end{cases}$$

For simplicity purposes, we assume that power is assigned equally among SCs. The allocated power to each SC is defined as follows:

$$p = \frac{P_T}{\sum_{m=1}^{\mathcal{M}} \gamma_m} \qquad (4)$$

where P_T is power budget of the AP and p is power per SC. We also define a *channel quality matrix* $\mathbf{H}$ as a $\mathcal{M} \times \mathcal{P} \times \mathcal{N}$ matrix:

$$\mathbf{H} = \{h_{m,\rho,n} | h_{m,\rho,n} \ge 0\}_{\mathcal{M}\times\mathcal{P}\times\mathcal{N}} \qquad (5)$$

where $h_{m,\rho,n}$ is channel quality of ρ^{th} SC located in β_m at the user α_n location. A *SC channel gain matrix* **G** can be defined as:

$$\mathbf{G} = \left\{ g_{m,\rho,n} | g_{m,\rho,n} = \frac{h_{m,\rho,n}}{N_0 \Delta f} \right\}_{\mathcal{M}\times\mathcal{P}\times\mathcal{N}} \quad (6)$$

where N_0 is noise spectral density and assumed to be constant for all SCs.

We assume that the fading characteristics for each SC are constant over one TS but vary from SC-to-SC. We further assume that AP has knowledge about the CA capability of all users i.e. AP knows $\boldsymbol{\mu}$.

The aggregated sum-rate of network (R) based on Shannon-Hartley theorem can be formulated as:

$$R = \sum_{n=1}^{\mathcal{N}} V_n = \sum_{n=1}^{\mathcal{N}} \sum_{m=1}^{\mathcal{M}} r_{m,n} = \sum_{n=1}^{\mathcal{N}} \sum_{\rho=1}^{\mathcal{P}} \sum_{m=1}^{\mathcal{M}} e_{m,n} a_{m,\rho,n} \log_2 (1 + p g_{m,\rho,n}) \quad (7)$$

where V_n is the aggregated rate of α_n and $r_{m,n}$ is the rate of α_n in β_m. In this paper, SC and CC allocations are formulated as a constrained optimization problem with the objective of maximizing the aggregated sum-rate R defined in (7). Hence, the optimization problem can be formulated as:

$$\max_{a,\ p} \sum_{n=1}^{\mathcal{N}} \sum_{\rho=1}^{\mathcal{P}} \sum_{m=1}^{\mathcal{M}} e_{m,n} a_{m,\rho,n} \log_2 (1 + p g_{m,\rho,n}) \quad (8)$$

subject to

$$e_{m,n} \in \{0, 1\} \quad (9)$$

$$\sum_{m=1}^{\mathcal{M}} e_{m,n} \leq \mu_n \quad (10)$$

$$a_{m,\rho,n} \in \{0, 1\} \quad (11)$$

$$\sum_{n=1}^{\mathcal{N}} a_{m,\rho,n} \leq 1 \quad (12)$$

for $1 \leq m \leq \mathcal{M}, 1 \leq \rho \leq \mathcal{P}, 1 \leq n \leq \mathcal{N}$. For the optimization problem defined in (8)-(12), constraint in (10) guarantees the CA restriction for each user in the network. Due to the presence of binary variables, the resulting problem is combinatorial in nature and hard to solve, i.e. CC and SC should be allocated jointly to solve the optimization problem; however the solution is prohibitively computationally complex [12, 13].

3 PROPOSED EFFICIENT SUB-CARRIER ALLOCATION ALGORITHM

As mentioned in Section 2, the optimization problem formulated in (8)-(12) is a complex 0-1 integer programming problem and is computationally expensive. In this paper, we propose a novel approach referred to as Efficient Sub-Carrier Allocation Algorithm (ESAA) to convert given problem into a two-step optimization problem and obtain a sub-optimal solution, i.e. first step is for the carrier selection and second step is for assigning SCs. The two-step allocation algorithm is described in the sub-sections of this section as follows:

3.1 Carrier Selection

In this step, initial assignment of CCs to each user is determined. Initially, we assume that all users can aggregate unlimited number of CCs, i.e. $e_{m,n} = 1$ for $1 \leq n \leq \mathcal{N}$ and $1 \leq m \leq \mathcal{M}$. An optimum solution for the mentioned problem based on waterfilling algorithm is by assigning each SC to the user with the best SC channel gain given by $g_{m,\rho,n}$ i.e. ρ^{th} SC in m^{th} CC is assigned to α_{n^*} if:

$$a_{m,\rho,n^*} = 1 \iff g_{m,\rho,n^*} = \max_{\forall 1 \leq n \leq \mathcal{N}} g_{m,\rho,n} \quad (13)$$

After obtaining $a_{m,\rho,n}$, we can estimate data rate for each user on different CCs and refer it as $r'_{m,n}$:

$$r'_{m,n} = \sum_{\rho=1}^{\gamma_m} a_{m,\rho,n} \log_2 (1 + p g_{m,\rho,n}) \quad (14)$$

For each user α_n, we sort $r'_{m,n}$ in descending order and select μ_n CCs with the highest $r'_{m,n}$. Based on selected CCs, we set corresponding $e_{m,n}$'s of each user to 1 and rest to zero. Once CC assignment for each user is done, the SCs are assigned within selected CCs to each user according to second step. ESAA's first step can be summarized as follows:

1: Initialize $\mathbf{A} = \mathbf{0}$ and $\mathbf{E} = \mathbf{1}$.
2: Find **A** using solution based on (13).
3: Estimate $r'_{m,n}$ for $1 \leq m \leq \mathcal{M}$ and $1 \leq n \leq \mathcal{N}$ using (14).
4: Sort $r'_{m,n}$ for each user α_n, $1 \leq n \leq \mathcal{N}$ in descending order.
5: Select μ_n CCs with highest rate, for each user α_n, $1 \leq n \leq \mathcal{N}$.
6: Set $e_{m,n}$ to 1 based on index of selected CCs of each user α_n, $1 \leq n \leq \mathcal{N}$.
7: Pass obtained **E** to second step (SC allocation).

3.2 Sub-Carrier Allocation

In this step, SCs within selected CCs are allocated optimally to each user based on obtained **E**. It is similar to the previous step, only difference is that, all CCs are not available to each user i.e. some elements of **E** are set to zero. The solution is given as follows:

$$a_{m,\rho,n^*} = 1 \iff g_{m,\rho,n^*} = \max_{\forall 1 \leq n \leq \mathcal{N}} g_{m,\rho,n} \\ and\ e_{m,\rho,n^*} = 1 \tag{15}$$

ESAA's second step can be summarized as follows:

1: Initialize $\mathbf{A} = \mathbf{0}$ and get obtained **E** from previous step.
2: Find **A** using solution based on (15).
3: Send final results **E** and **A** to users in network.

4 COMBINATORIAL ALGORITHM

As mentioned in previous sections, SC allocation with CA for OFDM systems is an NP-hard problem; and to best of authors knowledge there is not such a work in literature to solve the problem optimally. Thus, to evaluate the performance of ESAA, we compare it with a Combinatorial Algorithm (COA) introduced here. COA is built based on the fact that water-filling solution is optimum solution when optimum CC allocation is pre-known; therefore,to find best possible CC allocations, all possible CC allocations are examined in terms of the network's throughput. In the COA, CC allocation with smallest contribution of a user who aggregated over its aggregation capability is removed. This process continues until there is no more user who aggregated more than its CA capability. To make it clear COA's can be summarized as follows:

1: **repeat**
2: Initialize $\mathbf{A} = \mathbf{0}$ and $\mathbf{E} = \mathbf{1}$.
3: Estimate $r'_{m,n}$ for $1 \leq m \leq \mathcal{M}$ and $1 \leq n \leq \mathcal{N}$ using (14).
4: Find pair of α_n and β_m with lowest $r'_{m,n}$ provided that $\sum_{m=1}^{\mathcal{M}} e_{m,n} > \mu_n$ and $e_{m,n} = 1$.
5: Set $e_{m,n}$ to 0 and update **E**.
6: **until** There is no more α_n that satisfies $\sum_{m=1}^{\mathcal{M}} e_{m,n} > \mu_n$ for $1 \leq m \leq \mathcal{M}$.

5 SIMULATION RESULTS

To assess the performance of our proposed algorithm, the performance of ESAA is compared with the optimal solution of COA. The performance of the introduced algorithm is measured and compared in terms of the single-cell throughput, users' throughput and throughput (load) of each CC. The key simulation parameters are listed in Table I.

Table 1. Simulation parameters

Parameter	Value
$\mathcal{M}$	8
P_T	10mdB
$\mu_n \in$	$\{1, 2, 3, 4, 5\}$
$\gamma_m \in$	$\{2, 3, 4\}$

As the computational complexity of the COA is high, in this paper we focus on a case of $\mathcal{M} = 8$, and maximum number of four SCs. Fig. 1 shows normalized values of single-cell throughput versus number of users. As shown in Fig. 1, throughput increases by increasing the number of users from 10 to 20 in both algorithms. However, compared to ESAA, optimal solution, COA utilizes all available SCs quicker than ESAA; the performance gap between the ESAA and COA is small; performance gap becomes even smaller as $\mathcal{N}$ increases; which is a case for realistic settings.

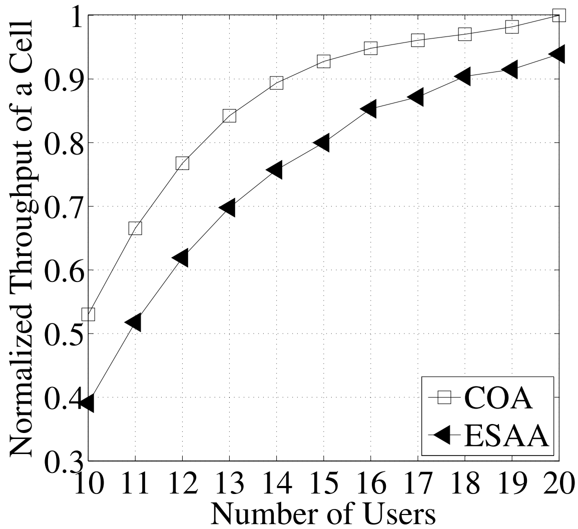

Figure 1. Normalized value of single cell throughput versus number of users

We further analyse throughput of different users when there are only 10 users and 8 CCs in network. As shown in Fig. 2, user indexes are ordered based on their CA capability i.e. user index 1 does not have CA capability, but user index 8, 9, and 10 can aggregate 5 different CCs. In this case, both algorithms similarly offer users with the higher CA capability and better SC channel quality, better throughput than other users in network.

In Fig. 3, CCs' load is presented with different CC numbers. The high level of load indicates that the CC is one of main contributors to deliver data in the cell; which itself is dependent on number of its SCs and experienced channel quality of overall CC for different users. For instance, CC index 8's load is higher than other CCs in network. implying better channel quality and higher number of SCs. As COA shows optimum results regarding load-balancing, it can be used as reference to be compared. It can be found that the

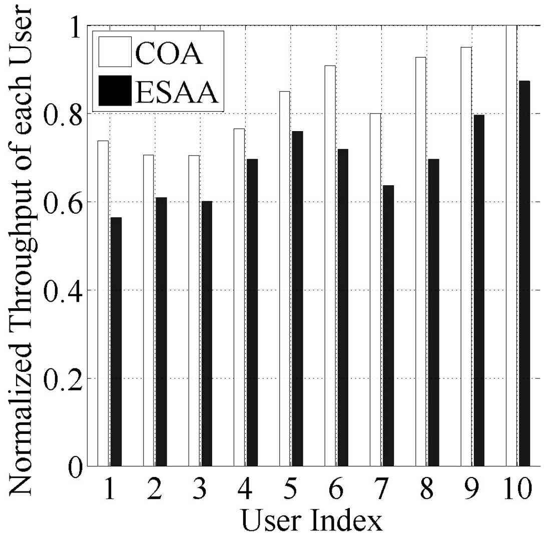

Figure 2. Per user normalized throughput versus user index which is ordered based on users' CA capability [1 2 3 3 3 4 4 5 5 5]

COA and ESAA implement almost the same performance in aspect of load distribution and the former is slightly higher than the latter one in most time, but ESAA is inferior to COA in a small extent.

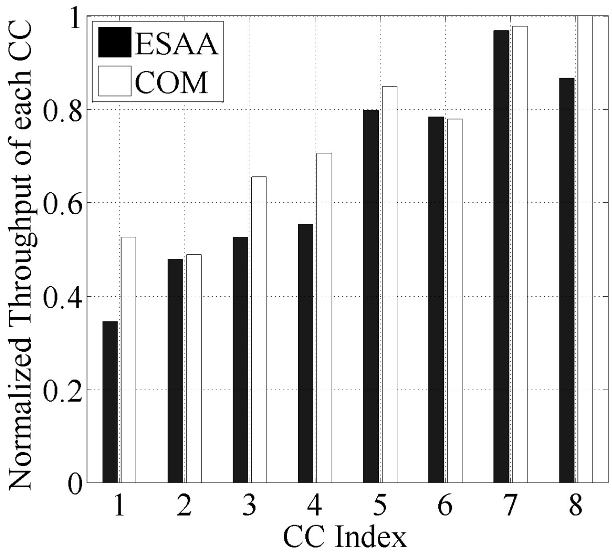

Figure 3. Per CC normalized throughput (load) versus CC index which is ordered based on CCs' number of SCs [2 2 3 3 4 4 4 4]

6 CONCLUSIONS

In this paper, SC allocation problem for OFDM based system with CA is formulated as an optimization problem. With practical constraints of finite number of CCs available for each user, optimization problem becomes a binary integer programming problem with mathematically intractable solution. We propose a novel SC allocation algorithm to solve optimization problem sub-optimally. The proposed algorithm is based on two-step approach, carrier-selection and SC allocation. Using simulations, the performance of the proposed algorithm is evaluated in terms of single cell throughput, per user throughput and per CC load. As the simulation results illustrate, ESAA not only makes good balance of CC load, but also achieves near to optimum throughput with low complexity.

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