Adaptive Resource Allocation for Uplink Carrier Aggregation Scheme in LTE-A-Type Networks

Yonghoon Choi, Yonggyu Lee, and Kapseok Chang

Carrier aggregation is an essential feature in the Long Term Evolution-Advanced (LTE-A) system, which allows the scalable expansion of the effective bandwidth to be delivered to user equipment (UE) through the concurrent use of radio resources across multiple component carriers (CCs). This system's optimal radio-resource use has received much attention under simultaneous access (SA) scenarios for multiple CCs (m-CCs). This letter establishes how many CCs a UE should simultaneously connect to maintain maximum uplink capacity. Under the m-CC LTE-A system, the spectral efficiency of the m-CC SA scheme (m≥2) is compared with that of CC selection (CCS). Numerical results reveal that the 2-CC SA scheme outperforms CCS and performs almost equally to the m-CC SA scheme (m≥3).

Keywords: Carrier aggregation, LTE-Advanced, optimization, resource allocation, simultaneous access.

I. Introduction

International Mobile Telecommunications-Advanced (IMT-ADV) supports variable bandwidths up to 100 MHz to increase the highest wireless data rates [1]. The IMT-ADV technologies such as the Third Generation Partnership Project (3GPP) Long Term Evolution-Advanced (LTE-A) [2] and IEEE 802.16m [3] enable carrier aggregation (CA), where multiple carriers in the same or different frequency bands can be aggregated by user equipment (UE). The LTE-A uses orthogonal frequency division multiple access (OFDMA) in the downlink (DL) and single-carrier frequency division multiple access (SC-FDMA) in the uplink (UL) to provide higher spectral efficiency [4]. In addition, some related studies [5], [6] introduced integrated system architectures and necessary functions for higher system capacity, in which UEs use simultaneous access (SA).

When LTE-A operates in CA mode, two or more component carriers (CCs) of the same or different bandwidths are aggregated to support wider transmission (Tx) bandwidths between the evolved NodeB (eNB) and the UE. The 3GPP LTE Release 10 [2] indicates that CA signaling should support simultaneous aggregation of up to five DL CCs and five UL CCs, irrespective of intra- or inter-band CA, subject to spectrum availability and the UE's capability. With regard to the signaling overhead, [7] shows that the increase in the control overhead is not significant, even in CA deployment scenarios. These previous works evoke the aggregation question: how many CCs should a UE simultaneously connect to achieve maximal UL system capacity?

This letter provides a multiple CC (*m*-CC) SA scheme for the LTE-A CA system. First, an optimal solution for SA is analyzed in the context of throughput maximization. Second, by applying the proposed *m*-CC SA scheme, the minimum number of CCs to which a UE should connect is explored.

II. System Model and SA Scenarios

Let us describe the LTE-A-based CA system model, as shown in Fig. 1, where *m*-CC in intra-band (that is, CCs 1 and 2, or CCs 3 and 4) or inter-band (that is, Bands 1 and 2) can be aggregated for a single UE. In this model, eNB antennas are colocated by the same operator and have the same beam directions/patterns for the CCs, providing nearly the same

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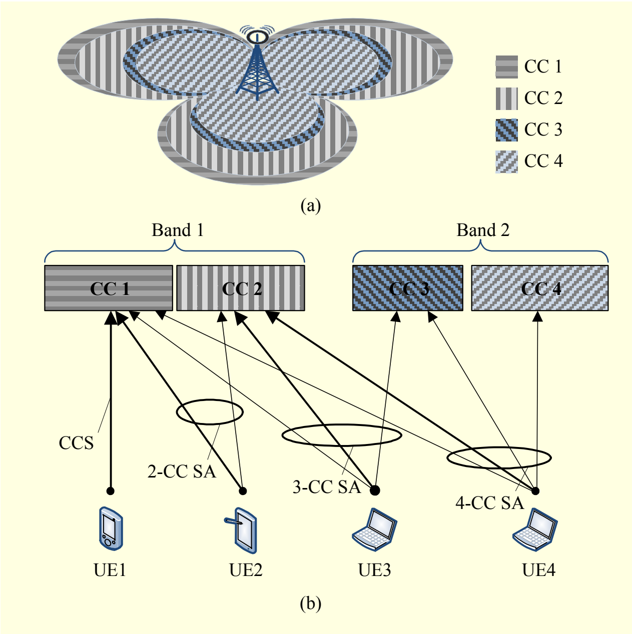

Fig. 1. CA system model: (a) CA deployment model of four CCs and (b) CA configuration for different UEs served by the same eNB.

coverage on CC 1 and CC 2 with little frequency separation and smaller coverage on CC 3 and CC 4 with large frequency separation. Even in the same band, CCs may be deployed at the eNBs with different Tx power levels to provide different coverage footprints for inter-cell interference management purposes [2]. This system model can be considered as one of the CA deployment scenarios within the same service provider [1]. Either intra- or inter-band CA allows higher user throughput at places where CC coverage overlaps. UEs are assumed to have the capability to use m-CC simultaneously and be frame-synchronized.

In CA configuration, the following access scenarios are considered for packet data transmission: i) In CC selection (CCS), UE selects only one CC (for example, CC 1, as shown in Fig. 1) based on the best link quality, and the UE fully allocates the total Tx power to CC 1; ii) In m-CC SA ($m \geq 2$), UE connects to m-CCs simultaneously (for example, CCs 1 and 2 for m=2, CCs 1 to 3 for m=3, and CCs 1 to 4 for m=4), and the UE shares its total Tx power for each access.

III. Optimal Resource Allocation for *m*-CC SA

Broadband data transmission under CA requires multi-dimensional resource allocation. Consequently, management schemes that adaptively adjust Tx power and sets of CCs are desirable. The problem formulation, which maximizes the UL system capacity while jointly adjusting the allocation of frequencies and power by taking the log function to make the computations easier, is expressed as

$$\max \sum_{u=1}^{U}\sum_{c=1}^{C}\beta_c x_{uc}\log\left(1+\frac{g_{uc}p_{uc}}{x_{uc}}\right), \tag{1}$$

$$\text{subject to } \sum_{u=1}^{U}x_{uc}\le X_c, \quad \forall c, \tag{2}$$

$$\sum_{c=1}^{C}p_{uc}\le P_u, \quad \forall u, \tag{3}$$

where U and C are the total number of UEs and CCs, respectively. The efficiency that can be guaranteed by CC c is represented by β_c ($0 \leq \beta_c \leq 1$). In (1), β_c weights each CC's efficiency to control the CC's spectral efficiency. For instance, β_c could be 0.6 for LTE (1×2) and 0.29 for IEEE 802.16m [8], which can be evaluated comparatively for different CCs although it is difficult to obtain the actual value. The allocated frequency band of CC c to UE u is represented by x_{uc} (≥ 0)[1)], the allocated Tx power of UE u to CC c is p_{uc} (≥ 0), and the channel-gain-to-noise ratio from UE u to CC c is g_{uc}. The total bandwidth of CC c is X_c, and the total Tx power that UE u can use is P_u. By using concavity of the objective function, an optimal solution can be obtained as a global maximum.

For UL resource optimality, the Lagrangian is

$$L(x_{uc},p_{uc},\lambda_c,\mu_u)=\sum_{u=1}^{U}\sum_{c=1}^{C}\beta_c x_{uc}\log\left(1+\frac{g_{uc}p_{uc}}{x_{uc}}\right) +\sum_{c=1}^{C}\lambda_c\left(X_c-\sum_{u=1}^{U}x_{uc}\right)+\sum_{u=1}^{U}\mu_u\left(P_u-\sum_{c=1}^{C}p_{uc}\right), \tag{4}$$

where λ_c and μ_u are nonnegative Lagrange multipliers. To obtain the necessary conditions for the optimal solution, differentiating $L(x_{uc}, p_{uc}, \lambda_c, \mu_u)$ with respect to x_{uc} provides the following Karush-Kuhn-Tucker (KKT) conditions:

$$\frac{\partial L}{\partial x_{uc}}=\beta_c\log\left(1+\frac{g_{uc}p_{uc}}{x_{uc}}\right)-\frac{\beta_c g_{uc}p_{uc}}{x_{uc}+g_{uc}p_{uc}}-\lambda_c\le 0, \tag{5}$$

$$x_{uc}\left(\beta_c\log\left(1+\frac{g_{uc}p_{uc}}{x_{uc}}\right)-\frac{\beta_c g_{uc}p_{uc}}{x_{uc}+g_{uc}p_{uc}}-\lambda_c\right)=0. \tag{6}$$

For the power allocation, the necessary KKT conditions with respect to p_{uc} give the relation as

$$p_{uc}=x_{uc}\left[\frac{\beta_c}{\mu_u}-\frac{1}{g_{uc}}\right]^{+}, \qquad [z]^{+}=\max\{z,0\}. \tag{7}$$

1) This decision variable would be an integer in the fixed resource allocation system, where the basic allocation unit of time/frequency is fixed, but this work relaxes the constraint as real numbers under the assumption that the allocation unit is flexible. This relaxation can be applied to the optimization problem, because the formulation changes into an NP-hard combinatorial problem if the variable is considered as integer [9].

To provide an optimal resource allocation and management scheme of CA configuration, we propose an iterative method:

Step 1. Initialize[2)] $x_{uc}^{(0)}$, $p_{uc}^{(0)}$, $\lambda_c^{(0)}$, and $\mu_u^{(0)}$.

Step 2. Decide $x_{uc}^{(k)}$ by applying $x_{uc}^{(k-1)}$, $p_{uc}^{(k-1)}$, $\lambda_c^{(k-1)}$, and g_{uc} to Newton's method as

$$x_{uc}^{(k)} = x_{uc}^{(k-1)} - \frac{f'\left(x_{uc}^{(k-1)}\right)}{f''\left(x_{uc}^{(k-1)}\right)}, \quad (8)$$

where k ($k \geq 1$) is an iteration index,

$$f'\left(x_{uc}^{(k-1)}\right) = \frac{\partial L}{\partial x_{uc}^{(k-1)}} = \beta_c \log\left(1 + \frac{g_{uc} p_{uc}^{(k-1)}}{x_{uc}^{(k-1)}}\right) - \frac{\beta_c g_{uc} p_{uc}^{(k-1)}}{x_{uc}^{(k-1)} + g_{uc} p_{uc}^{(k-1)}} - \lambda_c^{(k-1)}, \quad (9)$$

$$f''\left(x_{uc}^{(k-1)}\right) = \frac{\partial^2 L}{\left(\partial x_{uc}^{(k-1)}\right)^2} = \frac{g_{uc} p_{uc}^{(k-1)}}{x_{uc}^{(k-1)} + g_{uc} p_{uc}^{(k-1)}}\left(\frac{\beta_c}{x_{uc}^{(k-1)} + g_{uc} p_{uc}^{(k-1)}} - \frac{1}{x_{uc}^{(k-1)}}\right). \quad (10)$$

Step 3. Calculate $p_{uc}^{(k)}$ by applying $x_{uc}^{(k)}$, $\mu_u^{(k-1)}$, and g_{uc} to the joint relationship of (7).

Step 4. Update $\lambda_c^{(k)}$ and $\mu_c^{(k)}$, which are obtained by a dual function, as follows:

$$\lambda_c^{(k)} = \left[\lambda_c^{(k-1)} + \delta\left(\sum_{u=1}^{U} x_{uc}^{(k-1)} - X_c\right)\right]^+, \quad (11)$$

$$\mu_u^{(k)} = \left[\mu_u^{(k-1)} + \xi\left(\sum_{c=1}^{C} p_{uc}^{(k-1)} - P_u\right)\right]^+, \quad (12)$$

where δ and ξ (> 0) are constant update sizes that are related to the speed of convergence.

Step 5. Repeat Steps 2 through 4 with $k \leftarrow k+1$ until the optimal solution is obtained.

Following Step 5, each UE determines the number of CCs for transmission according to the following criterion: if x_{uc} of the UE has one non-zero value for CCs (for example, $x_{u1} = 100$ and $x_{u2} = \ldots = x_{uC} = 0$), one CC is selected (that is, CCS) and P_u as in (3) is allocated to the selected CC such that $p_{uc^*} = P_u$, where c^* is the selected CC index. Likewise, if m ($2 \leq m \leq C$) non-zero values of x_{uc} are obtained, the UE determines m-CC SA for the CA operation and allocates P_u to every selected CC such that $\sum p_{uc^*} = P_u$. If x_{uc} has all zeros, that is, $x_{u1} = \ldots = x_{uC} = 0$, the UE does not access any CCs, which is denoted as 0-CC access, that is, no selection (NS). In addition, for the evaluation of m-CC SA efficiency in IV, the selection rate is defined as n_s/n_t, where n_s and n_t stand for the number of selected m-CC SA/CCS/NS and the total number of access trials, respectively.

2) Corresponding initial values can be 10 KHz, 1 mW, 2.2, and 50,000, respectively. When different initial values are used to obtain the optimum, it will take longer or less time.

IV. Numerical Results

The evaluation environment considers the 4-CC CA system model[3)], as shown in Fig. 1(a), and the evaluation assumption, as shown in Table 1, as having the same efficiency (that is, β_c=1 for c=1, 2, 3, 4) for simplicity. UEs intending to transmit non-real-time traffic (for example, uploading photos) are randomly distributed at places where the coverage of CCs overlaps, because this work is interested in the SA scenarios and the m-CC SA scheme. The COST 231-Hata urban propagation model is used for the channel [10].

Figure 2 shows the spectral efficiency of the m-CC SA scheme ($2 \leq m \leq 4$) with respect to the number of UEs. The worst is the CCS scheme, which means that the m-CC SA scheme is needed regardless of an additional hardware implementation burden and signaling overhead for CA operation. Intuitively, it makes sense that one can achieve better performance by making use of CA under the condition of a UE's battery power limitation. In addition, there is no remarkable difference between the 2-CC SA scheme and the m-CC SA ($m \geq 3$) scheme. This can be explained by the selection rate of the m-CC SA method in Fig. 3, which is defined in subsection III.2. Note that the 2-CC SA shows much more incremental improvement than do the 3-CC SA and the 4-CC SA. This 2-CC SA increases spectral efficiency up to 19% in the m-CC SA scheme, although CCS has the highest selection rate. The selection rate of the m-CC SA increases and that of 0-CC access approaches zero as the number of UEs increases.

Table 1. Simulation parameters and assumption.

Parameter	Assumption
Cell radius of CCs 1, 2, 3, and 4	1, 0.9, 0.5, 0.4 km
Bandwidth of CCs 1, 2, 3, and 4	5, 10, 15, 20 MHz
Total Tx power level of UEs	20 mW
Mobility of UEs	3 km/h
Antenna type	Omni-directional
Lognormal shadowing	Gaussian distribution with 0 mean and 8 dB standard deviation
Thermal noise	–174 dBm/Hz
Frame length	10 ms
Simulation time	10,000 s

3) The co-channel interference term can be neglected when each CC is based on OFDMA in DL (or SC-FDMA in UL), so the simulation only considers SC-FDMA-based CA system.

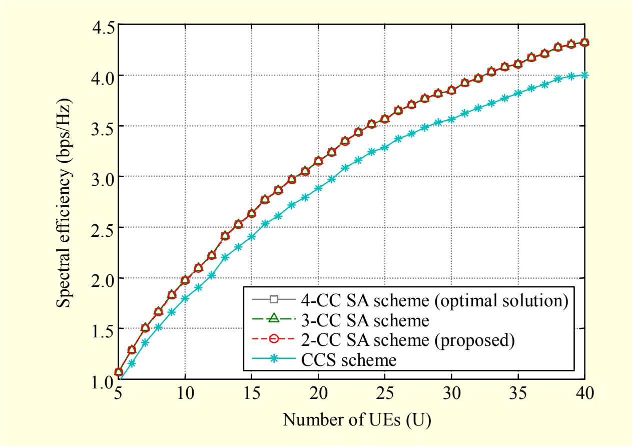

Fig. 2. Spectral efficiency vs. number of UEs (U).

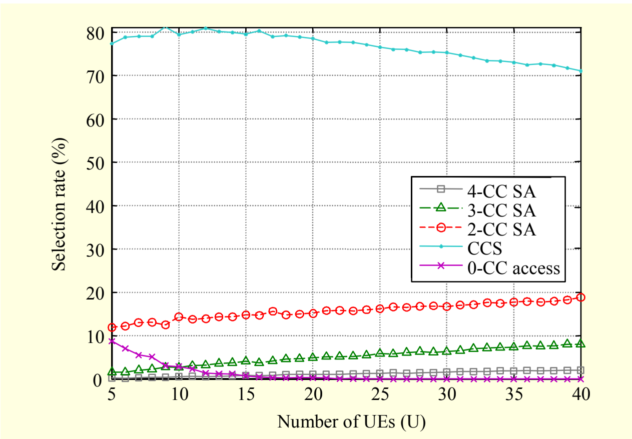

Fig. 3. Selection rate when 4-CC SA scheme is applied.

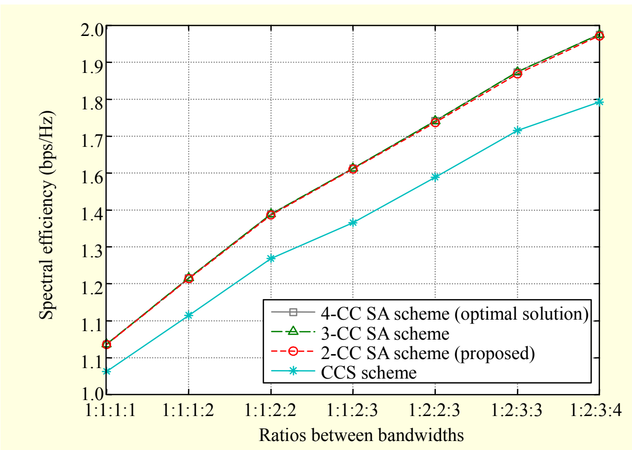

Fig. 4. Spectral efficiency vs. ratios between bandwidths, where ratio of each CC is 1:1:1:1 = bandwidth of (CC 1, CC 2, CC 3, CC 4) [MHz] = (5, 5, 5, 5); 1:1:1:2 = (5, 5, 5, 10); 1:1:2:2 = (5, 5, 10, 10); 1:1:2:3 = (5, 5, 10, 15); 1:2:2:3 = (5, 10, 10, 15); 1:2:3:3 = (5, 10, 15, 15); and 1:2:3:4 = (5, 10, 15, 20).

Therefore, when it comes to considering the *m*-CC SA scheme, the 2-CC SA scheme is sufficient to maximize UL capacity in this CA system model where eNB antennas are colocated.

Figure 4 shows how ratios between the bandwidths of the 4-CC SA system affect the spectral efficiency when there are 10 UEs. This figure indicates that the 2-CC SA scheme's spectral efficiency is very close to that of the 3- and 4-CC SA schemes, even at various ratios. Therefore, it can be reasserted that, regardless of ratios between the bandwidths, the 2-CC SA scheme has sufficient benefit in this system model from the viewpoint of spectral efficiency.

V. Conclusion

This letter analyzed a joint UL resource allocation of frequency and power for CA in an LTE-A-type system. Evaluation results showed that the proposed 2-CC SA scheme, where each UE can access up to two CCs simultaneously in the 4-CC CA deployment model, has noticeable improvement in terms of system capacity. For further work, fairness will be a good topic to study regarding additional capabilities of CA.

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