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Energy Efficient Carrier Aggregation for LTE-Advanced

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Abstract— **Traditional wireless and mobile network focuses on higher throughout, coverage and larger capacity. In future, energy efficiency is of vital importance for wireless networks due to a large number of connected and battery constrained mobile devices. In Long Term Evolution Advanced (LTE-Advanced), Carrier Aggregation (CA) is proposed to increase the transmission bandwidth and hence data rate. This paper studies the effect of CA on the total power transmitted by the LTE-Advanced eNodeB based on the Orthogonal Frequency Division Multiple Access (OFDMA) downlink while taking the users Quality of Service (QoS) constraints into consideration. The numerical analysis and results show that by using CA a reduction in total power consumption can be achieved.**

Keywords— Energy-efficient mobile network; LTE-A; OFDMA downlink; CA ; QoS.

I. Introduction

Today there are approximately five billion mobile phone users and it is estimated that the number will increase to seven billion wireless devices in the next three years [1]. This huge growth in the number of wireless users is causing higher power consumption in the base stations (BS) or eNodeB. It is projected that communication industry's contribution to the ecological carbon footprint would be more than double in the next ten years [2]. Currently there are more than four million BS worldwide; each BS on average consumes 25MWh per year [3]. This enormous number of BS causes more than 55% of the whole power consumption in the network [2]. Reducing the power consumption in the base station is critical for the network operator because of its economic and environmental effects.

After the successful deployment of LTE, communication industry is now focusing on the LTE-Advanced (or beyond 4G) technology. LTE-Advanced introduces additional functionalities that may influence overall power consumption of the network such as carrier aggregation, extended MIMO, heterogeneous networks etc. Carrier aggregation allows eNodeB to transmit multiple LTE carriers each with a bandwidth up to 20MHz that increases transmission bandwidth resulting higher bit rates.

Energy efficiency in LTE-Advanced is getting the centre of attention for wireless communication researchers in the last couple of years. Several techniques have been proposed to reduce the power consumption, such as cell zooming, sleep mode, cognitive radio etc. According to [4] changing the cell size (i.e. cell zooming) to adapt to the user's traffic condition can solve the traffic imbalance problem and reduce the energy consumption. Additionally, the following four techniques were suggested to implement the cell zooming in the mobile networks: Physical adjustment of BS, BS cooperation, Relaying and BS Sleep mode. Cognitive radio was proposed to reduce the energy consumption and it was demonstrated in [5] that changing the transmission parameters according to the channel conditions result energy conservation in the network. In [6], the authors developed a power scaling law for optimal range adaptation. Similarly, several research studies evaluate the performance of CA in terms of achievable data rate [7]. To date, the majority of the studies either focuses on the bit rate performance of CA or energy efficiency in mobile network without considering CA.

In this paper, we investigate the effect of CA on the total power transmitted by eNodeB in single and multi-cell scenarios. We consider LTE-Advanced network having OFDMA downlink air-interface with users in each cell having strict QoS requirements. We derive a general expression that describes the relationship between the total power transmitted by the eNodeB and the users assigned bandwidth. The users' distribution in each cell is considered as a Homogeneous Poisson Point Process (HPPP) distribution.

The paper is organised as follows: system model is presented in section II and derives the eNodeB transmit power for the system. We defined two different scenarios for the performance evaluation and are presented in section III. The numerical results of the study and related discussion are provided in section IV. Finally, section V concludes this paper.

II. System Model

A. System Overview

We consider a downlink OFDMA based LTE-Advanced network with ζ mobile users uniformly distributed in the cell with a density of ρ. For the sake of simplicity, we assumed that all users are active and have same QoS requirements, so the LTE channel bandwidth (as per standard), ω, can be equally divided among users. We assumed channel noise as Additive White Gaussian Noise (AWGN) for all sub-carriers with N_0 as noise power spectral density. According to 3GPP release 10 and onwards, it is possible for the eNodeB to aggregate more than one carrier to achieve high data rates. In our system, both contiguous and non-contiguous CA is supported. In this section, we derived a general expression for the total power transmitted by the eNodeB in a single cell scenario.

B. eNodeB Total Transmit Power (eNTP)

The $eNTP$ is derived to examine the effect of CA on the total transmit power according to the cell radius and given QoS constraints. The user QoS is defined in terms of the capacity C_i per user is defined as follows:

$$C_i = BW \;\; log_2\left(1 + \frac{P_{Ri}}{\partial \; BW \; N_0}\right) \tag{1}$$

where BW is the user assigned bandwidth, P_{Ri} is the user received power from the eNodeB and the coding and modulation coefficient is referred here as ∂.

The total bandwidth is assumed to be equally divided; therefore the user assigned bandwidth is equal to $BW = \frac{\omega}{\zeta}$; from the assumption and (1), the capacity for a single user is

$$C_i = \frac{\omega}{\zeta} \; log_2\left(1 + \frac{P_{Ri}}{\partial \; \frac{\omega}{\zeta} \; N_0}\right) \tag{2}$$

The general form for the received power can be expressed as

$$P_{Ri} = P_T \; k \; \left(\frac{d_i}{d_0}\right)^{-\alpha} \tag{3}$$

where P_T is the transmitted power from the base station to a user and k is the path loss at the reference point. The path loss at the reference point (near filed) can be obtained by Friis free space equation. The distance between the user and the eNodeB is d_i, d_0 is the distance of the eNodeB to the reference point and α is the path loss exponent.

To derive a general expression for $eNTP$ to fulfil the QoS constraints for all users, the outage probability of transmitting a data rate less than the QoS threshold data rate (capacity) $\bar{C}$ is considered [6]. For simplicity the outage probability P_{out} is assumed to be equal for all users.

$$P_{out} = \; Prob\left\{\sum_{i=1}^{L} C_i < (L \times \bar{C})\right\} \tag{4}$$

where L is the number of sub-carriers assigned to the i^{th} user. From the assumption that the channel bandwidth is equally divided among users, L equal to the total number of resource blocks, as defined in the LTE-A standard, is divided by the number of users using the channel.

As the QoS relates to the total data rate received by the user, the outage probability can be expressed as the intersection of the sub-carriers outage probabilities, that all the subcarriers assigned to a user achieve the QoS threshold limit. Hence the outage probability can be expressed as,

$$P_{out} = \prod_{i=1}^{L} Prob\{ \; C_i < \; \bar{C} \; \} \tag{5}$$

By assuming that the outage probability is equal for all the subcarriers, it can be expressed as

$$P_{out} = [Prob(\; C_i < \; \bar{C} \;)]^L \tag{6}$$

By substituting equation (2) in (6)

$$P_{out} = \left[Prob\left(\frac{\omega}{\zeta} \; log_2\left(1 + \frac{P_{Ri}}{\partial \; \frac{\omega}{\zeta} \; N_0}\right) < \; \bar{C}\right)\right]^L \tag{7}$$

or,

$$P_{out} = \left[Prob\left(P_{Ri} < \left(\partial \; \frac{\omega}{\zeta} \; N_0\right)\left(2^{\frac{\bar{C} \times \zeta}{\omega}} - 1\right)\right)\right]^L \tag{8}$$

The outage probability can be expressed as Cumulative Distribution Function (CDF), to get the summation of all probabilities less than the threshold limit. Knowing that P_{Ri} is an exponential function with a mean of $\overline{P_{Ri}}$, the outage probability can be expressed as [6]

$$P_{out} = 1 - \left[e^{-\left(\partial \frac{\omega}{\zeta} N_0\right)\left(2^{\frac{\bar{C} x \zeta}{\omega}} - 1\right)\left(\overline{P_{Ri}}\right)^{-1}}\right]^L \tag{9}$$

$$\overline{P_{Ri}} = \frac{\left(\partial \; \frac{\omega}{\zeta} \; N_0\right)\left(2^{\frac{\bar{C} \, x \, \zeta}{\omega}} - 1\right)}{-Ln[1 - P_{out}]^{\frac{1}{L}}} \tag{10}$$

To get the power transmitted by the base station to a user, we substitute (3) in (10)

$$\overline{P_T} = \frac{\left(\partial \; \frac{\omega \; N_o}{\zeta \; k}\right)}{-Ln[1 - P_{out}]^{\frac{1}{L}}}\left(2^{\frac{\bar{C} \times \zeta}{\omega}} - 1\right)\left(\frac{d_i}{d_o}\right)^{\alpha} \tag{11}$$

$$\overline{P_T} = \; \gamma \; {d_i}^{\alpha} \tag{12}$$

where $\gamma = \frac{\left(\partial \frac{\omega \; N_o}{\zeta \; k}\right)}{-Ln[1 - P_{out}]^{\frac{1}{L}}}\left(2^{\frac{\bar{C} \times \zeta}{\omega}} - 1\right)\frac{1}{{d_o}^{\alpha}}$.

The total power transmitted $eNTP$ from the eNodeB for a ζ number of users according to the Poisson distribution, to fulfil the QoS have a random value, so expectation of $\overline{P_T}$ can be used. In this case, the expectation of $\overline{P_T}$ over random users' locations given $\zeta = \eta$ is defined by law of iterated expectation, then $eNTP$can be expressed as

$$eNTP = E\left[E\left\{\overline{P_{T|_{\zeta = \eta}}}\right\}\right] \tag{13}$$

$$eNTP = E\left[\sum_{i=1}^{\eta} \overline{P_T} \; (r_i, \eta))\right] \tag{14}$$

where $E[.]$ denote the expectation operator.

From the HPPP distribution properties the inner expectation in (14) can be expressed as

$$eNTP = \eta \; E[\overline{P_T} \; (r_i, \eta)] \tag{15}$$

For the sake of simplicity, assume circular shape of the cell with radius R, so the users distribution inside the cell have a probability density function of $2d_i/R^2$. Then the expectation of $\overline{P_T}$ (the inner expectation) assuming both r_i and η are known can be obtained by

$$E[\overline{P_T}\,(r_i,\eta)] = \int_0^R \overline{P_T}\,\frac{2d_i}{R^2}\,dr_i \qquad (16)$$

To calculate the expectation of $\overline{P_T}$ knowing both r_i and η we used the value in (12), then the expectation can be expressed as

$$E[\overline{P_T}\,(r_i,\eta)] = \frac{2\gamma}{R^2}\int_0^R {d_i}^{\alpha+1}\ dr_i \qquad (17)$$

Then the total power transmitted, $eNTP$, can be expressed as

$$eNTP = \eta\,\frac{2\gamma}{\alpha+2}R^{\alpha} \qquad (18)$$

Finally by substituting the value of γ in (18), the general expression of $eNTP$ can be written as

$$eNTP = \frac{2R^{\alpha}\left(2^{\frac{\overline{C}\times\zeta}{\omega}}-1\right)(\partial\omega N_o)}{(\alpha+2)\,kd_o^{\alpha}\left(-Ln[1-P_{out}]^{\frac{1}{L}}\right)} \qquad (19)$$

From (19) it is obvious that the channel bandwidth ω has a significant effect on the total power transmitted by the eNodeB under given QoS constraints. Moreover, the cell radius R also has impact on the $eNTP$ as evident from (19). The number of users is proportional to the cell area under the assumption that the users are uniformly distributed throughout the cell.

III. System Testing Scenarios

The performance of the overall system in terms of the effect of CA on the total power transmitted by the eNodeB is tested under two scenarios: single-cell and multi-cell scenario.

A. Single Cell Scenario

The first scenario is an extreme case of a single cell network. The users are uniformly distributed in the cell and the cell QoS requirements are assumed to be equal for all the users. The users are also assumed to be active and receiving data from the eNodeB at all time. The power transmitted by the eNodeB varies with respect to the cell radius. For this scenario, we study the effect of aggregating two component carriers on the power transmitted by the eNodeB.

B. Multi-cell Scenario

In the second scenario we assumed a multi-cell network and cells covers a pre-defined area. It is assumed in this scenario that all cells are identical i.e. each cell has the same properties (e.g. users distribution, noise power etc.) as with the cell in the single cell scenario. The total power transmitted by all the cells that covers the area is calculated by the summation of the power transmitted by each cell. The total power transmitted by all eNodeB is studied according to the cells radius with all the sub-carrier combinations of aggregating two subcarriers.

Fig. 1 shows the relation between the number of cell to cover an area and the cell radius. It's obvious from Fig. 1 that the number of cells increases when the cell radius is smaller. In multi-cell scenario the number of cells is related to the area that they cover as shown in Fig. 1. To efficiently cover the pre-defined area with a circular shape cells, 80 cells of 200m radius are needed, on the other hand, nine cells of 600m radius can efficiently cover it or four cells of 1000m radius.

IV. Numerical Results and Discussion

In this section, the overall performance is obtained numerically using the following parameters. We assumed channel path loss exponent as $\alpha = 3$ and the minimum data rate per user (i.e. QoS) is $\overline{C}$ = 150 Kbit/sec. The total number of active users, ζ, are determined by the area covered and the users' density. It was also assumed that the primary sub-carrier bandwidth is 5MHz, and all the sub-carriers that had been defined by 3GPP for LTE-A is tested to be secondary sub-carrier. Without loss of generality, coding and modulation coefficient ∂ is assumed to be 1.

The noise power is a function of the channel bandwidth ω and the noise temperature, T, where N_o is equal to KT with K as Boltzmann constant (K= 1.38 × 10^{-23} m^2 kg s^{-2} K^{-1}). The path loss at the reference point k is equal to -55dB, the distance between the reference point and the eNodeB d_0 is equal to 100m. The total area that the cells cover in the second scenario is equal to 10000 km^2. The outage probability is assumed to be 10^{-3} and the numbers of resource block assigned to each user are assumed to be the division of the total number of resource blocks by the number of users.

The CA combination that has been used in this paper is two sub-carriers aggregation (due to the physical device limitations). The primary component carrier is the 5 MHz and the secondary sub-carrier is one of the carriers that had been defined in the LTE-A standard. The primary and secondary sub-carriers combinations shown in Table 1 were used in both scenarios.

Table 1 LTE-ADVANCED CARRIERS COMBINATION

5 MHz	Secondary Sub-carries (MHz)					
	1.4	3	5	10	15	20
CA combination (MHz)	6.4	8	10	15	20	25

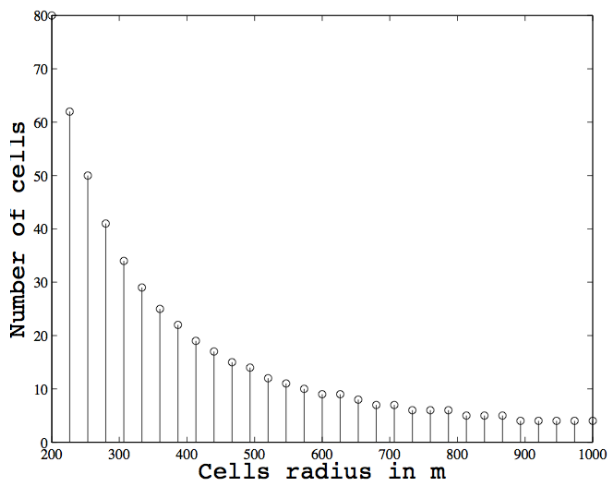

Fig. 1. Relation between number of cells and cell radius.

Fig. 2 shows the total power transmitted by the eNodeB to fulfil the QoS constrains for different cell radiuses in single cell scenario. It is noticeable from Fig. 2 and the numerical analysis of eNTP, the effect of CA on the power transmission.

According to Fig. 2 the channel bandwidth is inversely proportional to the total transmit power under given user's QoS constraints. The maximum bandwidth that can be assigned to a user according to the 3GPP LTE-Advanced standard with the 5MHz primary carrier is the 25MHz combination. For instance, the power transmitted to fulfil the QoS constrains without CA by using a 5MHz sub-carrier is equal to 77.74 dBW at cell radius of 600m. On the country the power transmitted by using aggregating two carriers to achieve a 25MHz per user is equal to 28.27 dBW to fulfil the same QoS constrains and also on the same cell radius.

In the single cell scenario aggregating two carriers, reduced the power transmitted by the eNodeB to fulfil the QoS requirements at a cell radius of 600m by 49.47dBW. By aggregating the 5 MHz and the 20 MHz carriers, the power needed to meet the QoS requirements is equal to approximately 36% of the power needed by using a 5MHz single carrier.

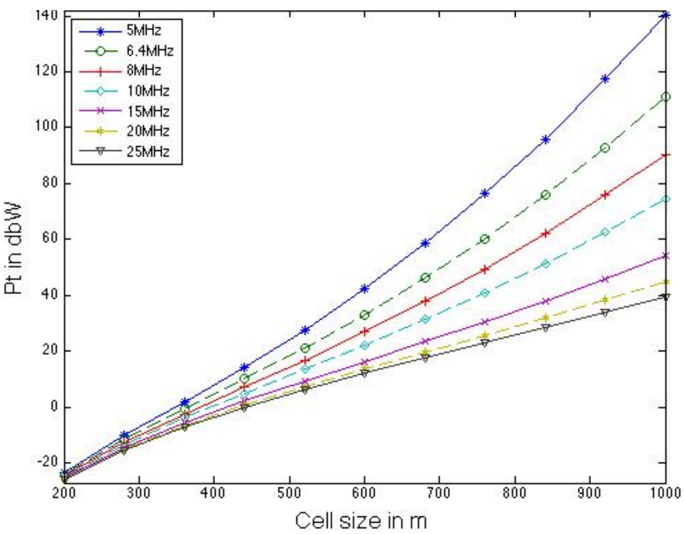

Fig. 2. Total power transmitted by the eNodeB in a singel cell network

Aggregating two carriers in the multi-cell scenario also reduced the power needed to meet the QoS requirements as shown in Fig.3, for instance the total power transmitted by the eNodeB to fulfil the QoS in the multi-cell scenario by using a 5 MHz carrier in a nine 600m cell radius is approximately equal to 344 dBW. On the country, by aggregating the 5MHz and the 20 MHz the power needed to fulfil the same QoS requirements is equal 125 dBW. In the multi cell scenario the power needed to meet the QoS requirements is reduced by 65% by aggregating two carriers.

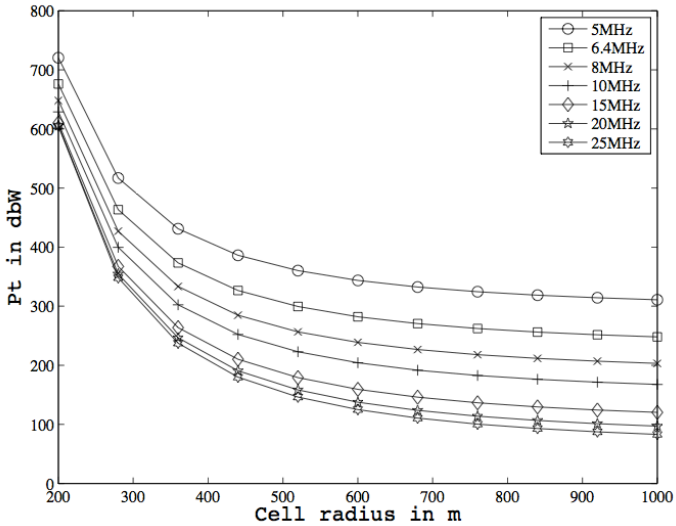

Fig. 3. Total power transmitted by the eNodeB in a multi-cell network

V. CONCLUSION

In this paper, we investigated the effect of CA on an OFDMA downlink of LTE-Advanced. A general expression for the total power transmitted by the eNodeB with strict QoS constraints was derived. Afterwards, two different scenarios were studied and in each scenario two component carriers were aggregated and compared with the single sub-carrier power transmission. The general expression showed the effect of the cell radius and the carrier bandwidth on the energy efficiency of the overall system. Numerical results show that the CA can reduce the transmission power to fulfil the QoS constraints in both scenarios by approximately 65% and hence improving the overall energy efficiency of the system.

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