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A delay-constrained energy-efficient component carrier adjusting scheme for LTE-Advanced systems①

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Abstract

The energy efficiency and packet delay tradeoffs in long term evolution-advanced (LTE-A) systems are investigated. Analytical expressions are derived to explain the relation of energy efficiency to mean packet delay, arrival rate and component carrier (CC) configurations, from the theoretical respective which reveals that the energy efficiency of multiple CC systems is closely related to the frequency of CCs and the number of active CCs. Based on the theoretical analysis, a CC adjusting scheme for LTE-A systems is proposed to maximize energy efficiency subject to delay constraint by dynamically altering the on/off state of CCs according to traffic variations. Numerical and simulation results show that for CCs in different frequency bands with equal transmit power, the proposed scheme could significantly improve the energy efficiency of users in all aggregation levels within the constraint of mean packet delay.

Key words: energy efficiency, carrier aggregation (CA), delay constraint, component carrier (CC) scheduling, long term evolution-advanced systems

0 Introduction

The tremendous developments in information and communication technologies (ICT) have changed people's lives by providing various services with high data rate. However, the counter effects brought along by the large scale deployment of ICT infrastructures are the huge amount of energy consumption and greenhouse gas emissions. According to the report from the International Telecommunications Union (ITU), the ICT industry is accountable for 8% of total electrical energy consumption, among which a large proportion is consumed by cellular networks[1]. As mobile user traffics are expected to grow four times per year[2,3], it is urgent to study energy consumption reduction schemes as the continuous expansion of cellular networks. Concerning the time dependent traffic load variations each day, eNode B (eNB) scheduling schemes have been investigated to put underutilized network components into sleep mode during low traffics to achieve overall energy efficiency[4-7]. In LTE-A systems, intra/inter frequency carrier aggregation (CA) is proposed as a key enhancement feature which allows the aggregation of several component carriers (CCs) to provide higher peak data rates and improved system capacity[8]. With the feature, multiple CCs will be required in each cell and the per cell energy consumption will rise as the increase of radio frequency (RF) chains and signal processing units[9]. Therefore it is more imperative to design energy-efficient transmission schemes for multiple CC systems.

Currently, researches on the multiple CC systems are mainly focused on resource scheduling schemes to attain improved fairness, throughput or reduced packet delay, whereas energy saving aspects have not been well investigated. Ref. [10] proposes a quantized water-filling packet scheduling algorithm to reduce mean packet delay. Ref. [11] proposes a proportional fair scheduling algorithm based on user grouping to achieve allocation fairness when the aggregated carriers have different coverage areas, while Ref. [12] further considers the real time and non-real time traffics in the de-

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signing of proportional fair scheduling algorithm. Ref. [13] focuses on cross-CC packet scheduling algorithm to improve the coverage performance and the resource allocation fairness among users. Assuming that each user equipment (UE) is connected to only one CC during packet transmission, a dynamic power and CC adjustment algorism is proposed in Ref. [14] to minimize the transmit power of eNB while fulfilling the user data rate requirements.

In this paper, to further explore the characteristics of CA and bursty traffics, we consider data transmissions of LTE-A users on multiple CCs. Unlike the above mentioned works, we mainly focus on the energy efficiency aspects of such systems.

Analytical expressions are firstly obtained to investigate the relation among energy efficient packet delay, arrival rate and CC configurations, based on which an energy-efficient CC adjusting scheme is then proposed to dynamically modify the CC configurations so that the maximum energy efficiency is achieved subject to the delay constraint.

The remainder of this paper is organized as follows. In Section 1, the system model for multiple CC cellular communication systems is established. Then in Section 2, the theoretical expressions are derived and analyzed, based on which the detailed procedures of the proposed scheme are introduced. Following that, the performance evaluation results on energy efficiency and delay tradeoffs are presented in Section 3, and finally we conclude this work in Section 4.

1 System model

A single cell scenario in the macro urban environment with multiple CCs is proposed. As shown in Fig. 1, K users are uniformly distributed and are able to perform inter band CA. Since our main concern is to improve energy efficiency on the eNB side, the focus is on downlink transmission. Assuming that N CCs with equal transmit power are employed in the cell, numbered from 1 to N according to the ascending order of their frequency bands, i. e., $f_1 \leqslant f_2 \leqslant \cdots \leqslant f_N$. Note that f_n here represents the central frequency of the frequency band which CC n belongs to. Let P_t be the transmission power on CC 1 to N which is attenuated by path loss and shadow fading, the received power on CC n is denoted by

$$P_{r,n} = P_t K_n r^{-\alpha} \exp(\beta X_s) \tag{1}$$

where K_n is the constant of path loss for transmission on CC n. r is the distance between the UE and eNB and α is the path loss exponent which is assumed to be equal for all CCs. β is a constant which equals to $\frac{\ln(10)}{10}$. X_s is the random variable modeling the shadow fading which can be assumed to follow a Gaussian distribution with zero mean and variance σ. In consequence, the received signal $P_{r,n}$ in log domain is approximated to follow a log-nomal distribution conditioned on the location of each user with the probability density function (PDF)[15]

$$f_{P_{r,n}}(z \mid r,\theta) = \frac{1}{2\sigma_s \sqrt{2\pi}} \exp\left[\frac{-(\ln z - \mu_n)}{2\sigma_s^2}\right] \tag{2}$$

where z represents the received signal power on CC n. r and θ indicate the location of the users in polar coordinates. $\mu_n = \ln(P_t K_n) - \alpha \ln r$ and $\sigma_s = \beta\sigma$.

Based on the user grouping method described in Refs[10,11], users are separated into N groups according to their path loss on each CC. The coverage area of CC n can be obtained through

$$R_n = \left(\frac{K_n}{K_1}\right)^{1/\alpha} R_1 \tag{3}$$

Obviously we have $R_1 \geqslant R_2 \geqslant \cdots \geqslant R_N$. Denote user k in group n as $k \in G_n$, and Ω_n as the set containing CC 1 to n which are used by group n users. For users in group n, the path loss values on CCs in Ω_n are all lower than the predefined threshold, indicating that UEs in this group could transmit data on n aggregated CCs simultaneously.

A finite buffer model with fixed packet size of S bits is considered as the user traffic model, where the arrival rate of packets follows the standard homogenous Poisson process. For user k, the packet arrival rate is denoted as λ_k. Owing to the additivity of Poisson process, the overall packet arrival rate in the system is also a poisson process with arrival rate $\lambda = \sum_{k=1}^{K} \lambda_k$.

As mentioned above, many resource scheduling models and schemes have been studied to improve total

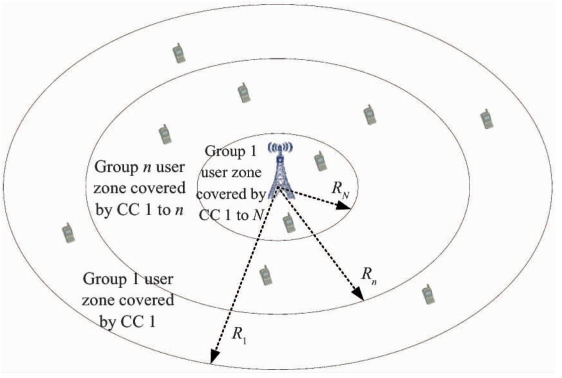

Fig. 1 System model for single cell with multiple CCs

throughput and fairness of multiple CC systems. In Ref. [10], it is assumed that the arrived packets will first be buffered respectively into their group queues before being scheduled for transmission following the first come first serve (FCFS) discipline. In addition, when a packet is under transmission, all the packets in queue behind it are not allowed to be transmitted, irrespective of how many CCs are in idle state during the current transmission. In this paper, this packet scheduling model and the service discipline are adopted to evade from the disparities caused by various packet scheduling schemes and better focus on the energy efficiency improvement aspect. To further simplify the resource scheduling process, it is assumed that every user in G_n is capable of utilizing the spectrum resources of CC 1 to n. Hence, based on the Shannon formula, for user k ($k \in G_n$), the maximum data rate that can be obtained through CA is given as

$$\eta_{k,G_n,\Omega_n} = \sum_{i \in \Omega_n} W_i \log_2\left(1 + \frac{P_{r,i}}{N_0 W_i}\right) \tag{4}$$

where W_i is the bandwidth of CC i in CC set Ω_n, $P_{r,i}$ is the received signal power on CC i, N_0 represents the white noise per Hz. The aggregated data rate indicates that each packet for user k ($k \in G_n$) is transmitted simultaneously on n CCs.

2 Theoretical analysis and the proposed scheme

In this section, analytical expressions are obtained to explore the relation among energy efficiency, packet delay, arrival rate and CC configuration. In the first part, the expression of mean packet delay is obtained, which is a function of packet arrival rate and CC configuration parameters. In the second part, the relation between energy efficiency and CC configuration is analytically established. Based on the theoretical analysis, the proposed energy efficient CC adjusting scheme is described in the third part.

2.1 Derivation of mean packet delay

Following the packet scheduling model and the service discipline described in the system model, each burst packet is separated into n subpackets with different lengths, which are transmitted simultaneously on n CCs in Ω_n. In case that the length of each packet S is not an integral multiple of n, there will be bits left, requiring additional transmission time. Therefore, the minimum serve time per packet for user k($k \in G_n$) transmitting on aggregated CCs in Ω_n can be obtained as[10]

$$\begin{cases} X_{k,G_n,\Omega_n} = S/\eta_{k,G_n}, & n = 1 \\ X_{k,G_n,\Omega_n} \leqslant S/\eta_{k,G_n} + 1/\min\limits_{i \in \Omega_n} \eta^i_{k,G_n}, & n \geqslant 2 \end{cases} \tag{5}$$

where η_{k,G_n} is obtained in Eq. (4) and η^i_{k,G_n} is the achievable transmission data rate to user k supported by CC i. Since we consider packet size in Kbits, the third term in Eq. (5) when n is larger than or equal to 2 will be neglected in the following description.

Judging from the Poisson arrival process and the classified serve rates, the considered queueing system can be treated as a multi-class M/G/1 system. Owing to the additivity of poisson process, the arrival rate for group n user can be written as

$$\lambda_{G_n} = \sum_{k \in G_n} \lambda_k \tag{6}$$

The mean serve time for packets belonging to each group is derived as

$$\overline{X_{G_n,\Omega_n}} = \sum_{k \in G_n} X_{k,G_n,\Omega_n} / K_{G_n} \tag{7}$$

where K_{G_n} is the number of users in group n. For the entire system with N active CCs, the mean serve time for each packet can be expressed as

$$\overline{X_N} = \sum_{n=1}^{N} \sum_{k \in G_n} X_{k,G_n,\Omega_n} / K \tag{8}$$

where K is the total number of users in the cell. For conventional M/G/1 queueing system with arrival rate λ and mean serve time $\bar{X}$, the mean wait time can be obtained directly through the Pollaczek-Khinchin (P-K) formula as

$$W = \frac{\lambda \bar{X}^2}{2(1 - \lambda \bar{X})} \tag{9}$$

where $\bar{X}^2$ is the second moment of the serve time per packet. However, for the multi-class M/G/1 system, since the mean serve time per packet for users in different groups is not identically distributed, the averaged delay is derived by aggregating serve time and wait time of users in different groups separately, which is expressed as[10]

$$W_{\Omega_n} = \frac{\sum_{n=1}^{N} \lambda_{G_n} \overline{X^2_{G_n,\Omega_n}}}{2\left(1 - \sum_{n=1}^{N} \overline{X_{G_n,\Omega_n}} \lambda_{G_n}\right)} \tag{10}$$

where $\overline{X^2_{G_n,\Omega_n}}$ is the second moment of the serve time per packet for users in group n. And the mean packet delay for group n users is obtained as the summation of mean wait time and mean serve time[16], which is written as

$$T_{G_n}(\lambda) = \overline{X_{G_n,\Omega_n}} + W_{\Omega_n} \tag{11}$$

2.2 The relation between energy efficiency and CC configuration

In this subsection, we analyze the energy efficiency of eNB during transmission under different CC configurations to uncover the discipline between them. The energy efficiency with N available CCs is defined as data rate per unit energy consumption, which is denoted as

$$\xi_{EE,N} = \frac{S}{\sum_{n=1}^{N} \overline{X_{G_n,\Omega_n}} P_N(G_n) \Pr(G_n)} \tag{12}$$

where S is the size of each packet. $\overline{X_{G_n,\Omega_n}}$ is the mean serve time per packet for group n users when transmitting on CCs in Ω_n. $P_N(G_n)$ represents the power consumption when transmitting to group n users with N CCs available. $\Pr(G_n)$ is the probability for a user to be sorted into group n. Similarly, the energy efficiency of group N users is derived as

$$\xi_{EE,G_N} = \frac{S}{\overline{X_{G_N,\Omega_N}} P_N(G_N)} \tag{13}$$

Based on the service discipline described in Section 2, $P_N(G_n)$ is written as

$$P_N(G_n) = nP_{\text{active}} + (N-n)P_{\text{idle}} \tag{14}$$

where P_{active} and P_{idle} are the power consumption of each active CC and each idle CC. Referring to the power consumption model derived in Ref. [17], they can be written as

$$P_{\text{active}} = \delta P_T^{\max} + \omega \tag{15}$$

$$P_{\text{idle}} = \delta\gamma P_T^{\max} + \omega \tag{16}$$

where $P_T^{\max}$ is the maximum transmit power on each CC when working in active state. δ and ω are constants featuring load-dependent and load-independent power consumption. γ is the percentage capturing the remained power consumption of each CC in idle state. To figure out the relation between energy efficiency and active CC number, comparison should be made between energy efficiency under different CC configurations.

The comparison of energy efficiency for transmission on $N-1$ active CCs in Ω_{N-1} and N active CCs in Ω_N is shown by the ratio

$$\Gamma_{EE} = \xi_{EE,N-1}/\xi_{EE,N} \tag{17}$$

where Γ_{EE} represents the gain of energy efficiency for $N-1$ active CCs over that for N active CCs. It can be observed from Eqs(12) and (14)-(16) that the divergence between $\xi_{EE,N}$ and $\xi_{EE,N-1}$ is closely related to the difference between f_N and f_{N-1}. For simplicity, we assume that $f_n = f_{n-1}$ for $n = 1,2,\cdots,N-1$ and the bandwidths of all CCs are the same. This can also be extended to the situation when $f_n > f_{n-1}$. Hence the coverage ranges of CC 1 to $N-1$ are the same, we have $\Pr(G_n) = 1-\Pr(G_N)$, $n = 1,\cdots,N-1$. Eq. (17) is rewritten as

$$\Gamma_{EE} = \frac{A+B}{C+D} \tag{18}$$

where

$$A = \overline{X_{G_N,\Omega_N}} NP_{\text{active}} \Pr(G_N) \tag{19}$$

$$B = \overline{X_{G_{N-1},\Omega_{N-1}}}[(N-1)P_{\text{active}} + P_{\text{idle}}]\Pr(G_{N-1}) \tag{20}$$

$$C = \overline{X_{G_N,\Omega_{N-1}}}(N-1)P_{\text{active}} \Pr(G_N) \tag{21}$$

$$D = \overline{X_{G_{N-1},\Omega_{N-1}}}(N-1)P_{\text{active}} \Pr(G_{N-1}) \tag{22}$$

In the follows, we will prove that for $f_n \geqslant f_{n-1}$, Γ_{EE} is larger than or equal to 1.

Proof: Obviously, B is larger than D. Thus if it is proved that A is larger than C, than we have $\Gamma_{EE} \geqslant 1$. The proof could be separated into two parts according to the assumption that $f_N \geqslant f_{N-1}$. First, if $f_N = f_{N-1}$, the analytical forms of $\overline{X_{G_N,\Omega_{N-1}}}$ and $\overline{X_{G_N,\Omega_N}}$ are given as

$$\overline{X_{G_N,\Omega_{N-1}}} = \frac{S}{\pi R_N^2 (N-1) W} I \tag{23}$$

$$\overline{X_{G_N,\Omega_N}} = \frac{S}{\pi R_N^2 N W} I \tag{24}$$

where

$$I = \int_{P_{\min}}^{P_t} \int_0^{2\pi} \int_0^{R_N} \frac{f_{P_r}(z \mid r,\theta)}{\log_2\left(1 + \frac{z}{N_0 W}\right)} \mathrm{d}r\mathrm{d}\theta\mathrm{d}z \tag{25}$$

and z represents the received signal power P_r. $P_{\min}$ is the predefined minimum received power.

Thus $\Gamma_{EE} = 1$ when $f_N = f_{N-1}$. Second, if $f_N > f_{N-1}$, The analytical form of $\overline{X_{G_N,\Omega_{N-1}}}$ and $\overline{X_{G_N,\Omega_N}}$ are given as

$$\overline{X_{G_N,\Omega_{N-1}}} = \int_{P_{\min}}^{P_t} \int_0^{2\pi} \int_0^{R_N} \frac{S}{E} f_{P_r}(z_{N-1} \mid r,\theta)\,\mathrm{d}r\mathrm{d}\theta\mathrm{d}z_{N-1} \tag{26}$$

$$\overline{X_{G_N,\Omega_N}} = \int_{P_{\min}}^{P_t} \int_{P_{\min}}^{P_t} \int_0^{2\pi} \int_0^{R_N} \frac{S \cdot f_{P_r}(z_{N-1} \mid r,\theta)}{E+F} \cdot f_{P_r}(z_N \mid r,\theta)\,\mathrm{d}r\mathrm{d}\theta\mathrm{d}z_{N-1}\mathrm{d}z_N \tag{27}$$

where

$$E = \pi R_N^2 (N-1) W \log_2\left(1 + \frac{z_{N-1}}{N_0 W}\right) \tag{28}$$

$$F = \pi R_N^2 W \log_2\left(1 + \frac{z_N}{N_0 W}\right) \tag{29}$$

and z_{N-1} represents the received signal power of CC 1 to CC $N-1$ and z_N is the received signal power of CC N. $f_{P_r}(z_{N-1} \mid r,\theta)$ is the PDF distribution of the received signal power on CC 1 to $N-1$ conditioned on the location r and θ in polar coordinates. From Eqs (1) and (2), we can obtain that $z_{N-1} > z_N$ and $\mu_{N-1} > \mu_n$, while the variances are the same. Thus we have

$$\overline{X_{G_N,\Omega_N}} > \int_{P_{\min}}^{P_t} \int_0^{2\pi} \int_0^{R_N} \frac{S f_{P_r}(z_{N-1} \mid r,\theta)}{E + E/(N-1)} \mathrm{d}r\mathrm{d}\theta\mathrm{d}z_{N-1} \tag{30}$$

Through Eqs(18) to (22) and Eqs(26) - (30), it is proved that

$$\Gamma_{EE} > \frac{A}{C} = \frac{\overline{X_{G_N,\Omega_N}}N}{\overline{X_{G_N,\Omega_{n-1}}}(N-1)} > 1 \quad (31)$$

Judging from the analysis above, Γ_{EE} is mainly affected by two factors. One is the frequency ratio, denoted by

$$\Gamma_f = \frac{f_N}{f_{N-1}} \quad (32)$$

when Γ_f increases, the received power on CC N deteriorates, making the disparity between $\sum_{k\in G_N} X_{k,G_N,\Omega_{N-1}}$ and $\sum_{k\in G_N} X_{k,G_N,\Omega_N}$ shrink due to the decreased achievable data rate on CC N. The other factor is the total number of CCs, denoted by N. It is obvious that with the increase of N, $\frac{N-1}{N}$ will increase monotonously, whereas the changes in Γ_{EE} is quite ambiguous. To better observe the variation of Γ_{EE} with the increase of Γ_f, the respective mean serve time per packet of users using different serve CC sets should be computed. From Eqs(26) and (29), it is perceived that the exact analytical value of X_{G_N,Ω_N} requires a numerical $(N+2)$ - fold integration, which is computationally burdensome and may subject to stability problems. Therefore, we choose to estimate the change of energy efficiency gain Γ_{EE} with the increased Γ_f using Monte Carlo simulation. The results are shown and analyzed in Section 4.

2.3 Description of the proposed scheme

Discussions in the previous subsection have shown that for multiple CC systems with equal transmit power on CCs in different frequency bands, switching off CCs in higher frequency bands could increase the overall energy efficiency. Therefore we propose a CC adjusting scheme which enables eNB to automatically adjust the number of active CCs based on channel conditions and packet arrival rates of UEs, so that maximized energy efficiency can be achieved subject to the mean packet delay constraint.

The optimization problem could be described as

$$\max_{n\in\psi} \xi_{EE}(n) \quad (33)$$

subject to $\tau(n) < \tau_{th}$ (34)

where $\psi = \{1,2,\cdots,N\}$ is the CC number set. $\xi_{EE}(n)$ is the energy efficiency. $\tau(n)$ is the packet delay when n CCs are active. τ_{th} is the delay constraint. Based on the theoretical analysis, assuming that all of the N CCs are active initially and the mean delay for group N users is set to be the QoS metric, the proposed CC adjusting scheme containing six steps is shown in Fig. 2.

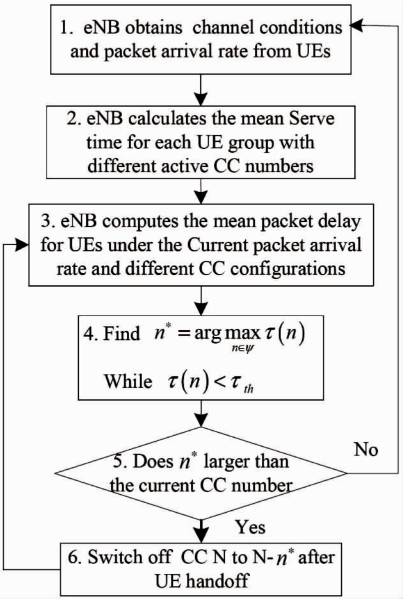

Fig. 2 Flow diagram of the coordinated scheduling mechanism

Note that in step 3 and 4, the determination of active CC number is based on the predefined delay threshold. To make the decision process more straightforward, the arrival rate can be chosen as a metric for threshold setting. Defining the probability for each user to be allocated to group n as $\Pr(G_n)$, the total arrival rate for group n is $\lambda_{G_n} = \Pr(G_n)\lambda$. Therefore based on Eq. (10), the arrival rate threshold is derived by

$$\lambda_{th,\Omega_{N-1}} = \frac{2W_{th}}{2W_{th}\sum_{n=1}^{N}\Pr(G_n)\rho + \sum_{n=1}^{N}\Pr(G_n)\upsilon} \quad (35)$$

where ρ represents $\overline{X_{G_n,\Omega_{N-1}}}$ and υ represents $\overline{X^2_{G_n,\Omega_{N-1}}}$. When the packet arrival rate exceeds $\lambda_{th,\Omega_{N-1}}$, CC N should be switched on to fulfill the delay constraint.

Referring to Eq. (3), $\Pr(G_n)$ can be obtained as

$$\Pr(G_n) = \begin{cases} \left(\frac{K_{n+1}}{K_1}\right)^{2/\alpha} - \left(\frac{K_n}{K_1}\right)^{2/\alpha}, & n = 1,\cdots,N-1 \\ \left(\frac{K_N}{K_1}\right)^{2/\alpha}, & n = N \end{cases} \quad (36)$$

The analytical and simulation results of the arrival rate thresholds for active CC adjustments are compared in Section 4.

3 Performance evaluation and discussions

In this section, we evaluate the performance of the proposed delay-constrained energy-efficient CC adjusting scheme for LTE-A system through numerical results and extensive simulations. First, the relation between energy efficiency and CC configuration analyzed in Section 3 is verified through simulations. Following that, variations of the mean packet delay under different CC configurations are compared when the packet arrival rate changes. Finally, simulation and numerical results for the energy efficiency and mean wait time of the proposed scheme are presented.

3.1 Simulation scenario

As described in the system model, a single macro cell configured with multiple CCs is considered where 500 users are uniformly distributed. We adopt the standard path loss model $PL_n(r) = 58.83 + 37.6 \log_{10}(r) + 21 \log_{10}(f_n)$. The detailed parameters for the simulation settings are shown in Table 1. In Eq. (4), Shannon formula is used for data rate estimation. To better approximate practical modulation coding scheme, the minimum and maximum bound for signal noise ratio (SNR) are set to be −6.5dB and 17dB, with maximum throughput 4.8 bit/s/Hz, and the data rate obtained in Eq. (4) is scaled by an attenuation factor 0.75 to get estimated realistic data rate[18]. The parameters for energy model in Eqs (5) and (6) are also shown in Table 1.

Table 1 Simulation settings

Parameter	setting
Cell radius	1(km)
Total number of CCs	4
Bandwidth of each CC	5(MHz)
Transmit power on each CC	43(dBm)
Shadow fading	6(dB)
UE noise figure	9(dB)
Noise per Hz	−174(dB)
Maximum mean wait time	0.06(s)
Packet size	800(kbits)
δ	8.5
ω	56.1
γ	40%

In the first part, the relation between energy efficiency and CC configuration analyzed in Section 3 is verified through simulation and numerical results. To evaluate the impact of Γ_f, we assume that CC 1 to CC $N-1$ are from the same frequency band $f_n = 900$MHz, $n = 1, \cdots, N-1$. Let the central frequency of CC N change from 900 MHz to 3600 MHz to observe the variation of the corresponding energy efficiency gain Γ_{EE}. For the number of CCs, the variations of Γ_{EE} with the increase of Γ_f are evaluated under three values $N = 3$, 4, 5 respectively. Note that in the evaluation, the serve time per packet for each user is obtained through simulation, while other computations are based on the equations derived in Section 3.

In the second part, the performance of the proposed scheme is evaluated and is compared with a baseline scheme which keeps all the configured CCs active without traffic-aware CC adjustment. We assume that four CCs can be utilized in the cell. From CC 1 to CC 4, the frequency bands are $f_1 = 900$MHz, $f_2 = 1500$MHz, $f_3 = 2100$MHz, $f_4 = 2700$MHz. The arrival of packets follows the Poisson process. The arrival rates for all users are assumed to be equal and the total packet arrival rate ranges from 25 to 35 packets/s. To approximate a stable queueing system, the observation time is set to be 30000s and we simulate 2000 times to get average results. Note that in both the simulation and numerical computation, the serve time of each user is obtained through simulation, while the mean wait time is obtained respectively through simulating a multi-class queueing system and through numerical computation based on the equations derived in Section 3. In addition, $\lambda_{th,\Omega_{N-1}}$ for CC adjustment obtained in Eq. (35) is validated through simulation and numerical results.

3.2 Numerical and simulation results

The relation between averaged energy efficiency and CC configuration can be observed in Fig. 3, where the definition of Γ_{EE} and Γ_f are denoted in Eqs (17) and (32). For $\Gamma_f = 1$, the energy efficiency gain Γ_{EE} is also 1, complying with the result derived in Section 3. With the increased Γ_f, Γ_{EE} also increases due to the deteriorated received power on CC N and the reduced size of user group N in accordance with the previous

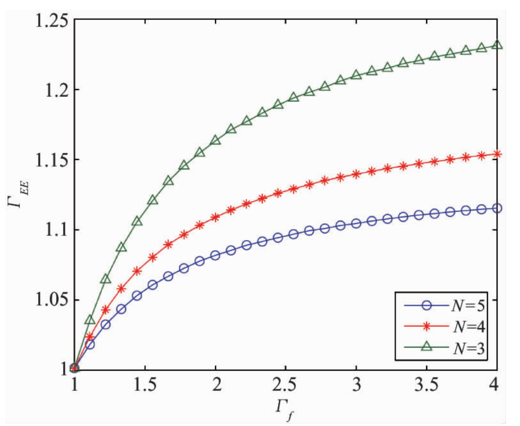

Fig. 3 Averaged energy efficiency gain ξ_{EE,G_N} under different values of (Γ_{EE} and Γ_f are defined in Eqs(17) and (32))

analysis. Comparing the energy efficiency gain Γ_{EE} under different values of N, the energy efficiency gain for lower value of N is higher for the same frequency proportion Γ_f. This effect indicates that for systems configured with less number of CCs, the energy efficiency gain attained by switching off a CC in high frequency band is larger.

Note that the reduction of active CC numbers will lead to prolonged packet serve time and increased wait time. Therefore, the adjusting of CC numbers should also take into account the delay constraints. In Eq. (11), the mean delay is obtained by adding the mean serve time with the wait time. For different user groups, the mean serve time are various, but the wait time is the same. Hence in the simulation, we choose wait time as the QoS constraint for users.

For three kinds of CC configurations, the mean wait time of user packets under different arrival rates are shown in Fig. 4. It is observed that the divergences among the three curves are smaller for low arrival rates but increase sharply when arrival rates are higher; indicating that for lower arrival rates, the tradeoff in mean wait time is smaller when adopting the proposed energy-efficient scheme. According to the curves shown in Fig. 4, when the arrival rates are below 26 packets/s, the differences between wait time are fairly small. Thus when the arrival rate fluctuates within the system capacity range, the proposed scheme is effective for a wide range of traffic loads.

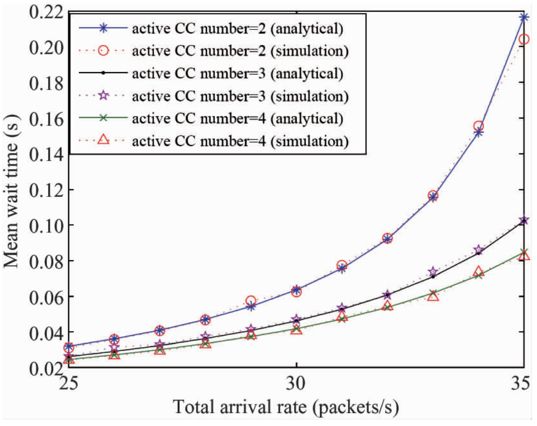

Fig. 4 Variations of mean wait time under different total arrival rates

In the performance evaluation, the required maximum wait time is set to be 0.06s. For the system configured with two active CCs, the wait time is within the constraint for the arrival rates lower than 29.6 packets/s. For higher arrival rates, more active CCs are required. The exact value of arrival rate threshold can be derived in Eq. (35) through theoretical analysis. For N equals 4, 3 and 2, the respective value of $\lambda_{th,\Omega_{N-1}}$ is computed and demonstrated in Table 2, which shows excellent consistency with the simulation results in Fig. 4. The averaged energy efficiency is also listed in Table 2.

Table 2 Mean serve time, energy efficiencies and arrival rate thresholds under different CC configuration

Number of active CCs	Mean serve time X_N /(s)	ξ_{EE} /(kbits/J)	$\lambda\ th,\Omega_{N-1}$ (packets/s)
4	0.0223	45.015	32.8043
3	0.0232	50.774	31.9170
2	0.0254	53.560	29.6460

For the proposed delay-constrained energy-efficient CC adjusting scheme, the performance of the mean wait time and the energy efficiency is compare with the baseline scheme as depicted in Fig. 5, where in the baseline scheme, all CCs are assumed to be active without traffic aware CC adjustment. Referring to the thresholds listed in Table 2, when the arrival rates are below 29.64 packets/s, the activation of 2 CCs is enough to fulfill the delay constraint. While for arrival rates between 29.64 and 31.92 packets/s, three active CCs are needed. For higher traffics, all of the four CCs should remain active. Fig. 6 compares the energy efficiency of group N users between the proposed and baseline scheme under different CC configurations, where the proposed scheme utilizes $N-1$ CCs. The energy efficiency of group N users of the proposed scheme is shown to be higher than the baseline scheme, and the advantage increased as the number of CC decreases. Since it is assumed that $f_n = f_{n-1}$ for $n = 1, 2, \cdots, N-1$ and the bandwidths of all CCs are the same, based on Eqs (13) and (14), the energy efficiency of group N users of the proposed scheme coincides when

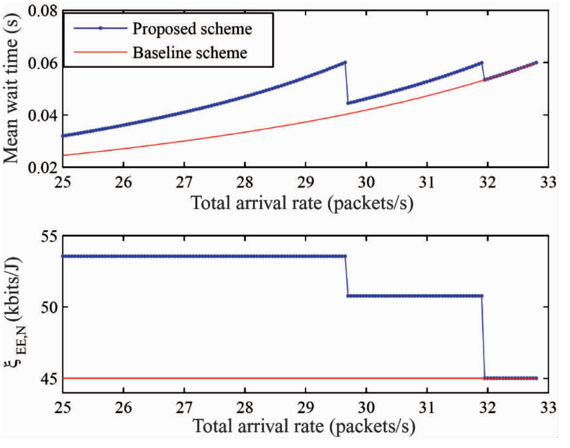

Fig. 5 Mean wait time and energy efficiency performance of different schemes

the number of CCs varies. Overall, the advantage of the proposed scheme can be observed clearly that by dynamically adjusting the number of active CCs, energy efficiency is maximized subject to delay constraint.

4 Conclusions

In this paper, the relation of energy efficiency to mean packet delay, arrival rate and CC configurations are theoretically analyzed. Especially for multiple CC LTE-A systems, a practical traffic-aware CC adjusting scheme is designed based on the theoretical analysis to increase the energy efficiency of LTE-A systems. The proposed delay-constrained energy efficient CC adjusting scheme adaptively alters the number of active CCs according to the current traffic load. Numerical and simulation results show that the proposed scheme could achieve higher energy efficiency while maintaining the user requirement for packet delay constraints under a wide range of data traffics.

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