Computer Networks 110 (2016) 192–205

Contents lists available at ScienceDirect

Computer Networks

journal homepage: www.elsevier.com/locate/comnet

Joint and selective periodic component carrier assignment for LTE-A

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ARTICLE INFO

Article history:
Received 10 February 2016
Revised 21 September 2016
Accepted 27 September 2016
Available online 3 October 2016

Keywords:
LTE-A
Component carrier assignment
Resource allocation
Queuing analysis

ABSTRACT

The bandwidth demand for mobile Internet access is significantly increased with the number of mobile users. Carrier aggregation has been proposed to answer this demand in mobile networks. In carrier aggregation, the best available one or more component carriers of each band are assigned to each user to provide efficient services. Several works have been reported in the literature on mandatory and periodic component carrier assignment methods. Although the former works, especially periodic component carrier assignment methods, have significantly improved the performance of LTE-A systems, many limitations still exist. One limitation of previous works is that data transfer is interrupted during periodic component carrier assignment operations thus, decrease the performance of the system. Therefore, in this paper, selective periodic component carrier assignment technique, which allows continuous data transfer during periodic carrier assignment operations, is proposed and followed by integration of selective technique into four component carrier assignment methods: Least Load, Least Load Rate, Random, and Channel Quality to observe the performance improvements. Results indicate that the proposed selective technique increases the throughput ratio up to 18% and decreases average delay up to 50%. Our analysis and proposed technique will assist service providers to build efficient periodic component carrier assignment methods to improve the performance of the system by reducing delay and increasing throughput ratio.

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1. Introduction

Mobile devices (such as tablet, smartphones, etc.) are being an essential part of human life [1–3]. This necessity results in an enormous growth in the number of mobile devices. According to Gsma Intelligence report [4], the number of active mobile devices passed human population in the world. Currently, there are 7.6 billion mobile devices with 3.7 billion unique mobile subscribers [4]. In 2013, the number of purchased smartphones passed one billion and in 2017, two billion smartphones are expected to be sold [5]. The most notable reason for the increase in the number of such devices is that the users can reach a wide range of applications under different platforms (e.g., GooglePlay, AppStore) by cutting cross time and place restrictions [6–8]. For example, more than 100 billion applications downloaded in 2013 and more than 250 billion applications are expected to be downloaded in 2017 [5]. Therefore, the demand for bandwidth in mobile Internet is increasing with the number of mobile users [9]. To answer the user demands, Carrier Aggregation (CA) has been developed. In CA, multiple bands are used, and the bands can have different communication coverages. With carrier aggregation and MIMO technologies, LTE-A system can provide 1.5 Gbps for uplink and 3 Gbps for downlink peak data rates to mobile users [10].

Fig. 1 demonstrates a multi-band architecture scenario in mobile networks [10]. In the architecture, each band has several Component Carriers (CCs), and bandwidth of CCs can be 1.5 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz, and 20 MHz. User Equipment (UE) can simultaneously connect one or multiple carriers from different bands. Therefore, there are three types of CA, *Intra-band contiguous, Intra-band non-contiguous and Inter-band non-contiguous* [10]. Base stations (EnodeB) arrange the number of simultaneous connections of UEs from each band. However, if Component Carrier Assignment (CCA) is not carefully designed, one band can be overloaded while the other bands can be idle. Thus, carrier assignment methods significantly affect system performances [11,12]. To manage high performance in CA, mandatory [13,14] and periodic [15] carrier assignment methods have been developed. Mandatory Component Carrier Assignment (mCCA) methods which only update carriers based on necessary changes (include path loss, CQI changes, etc.). However, In the

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http://dx.doi.org/10.1016/j.comnet.2016.09.024
1389-1286/Published by Elsevier B.V.

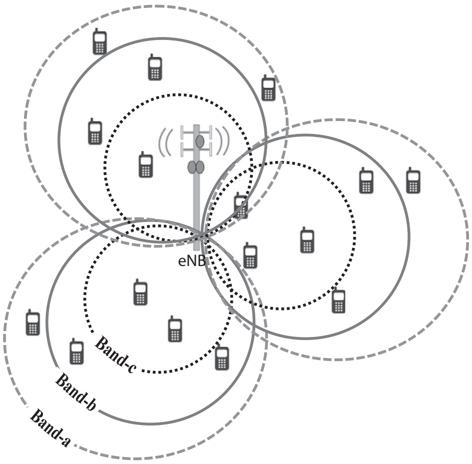

Fig. 1. eNodeB (eNB) with multi bands and several users.

periodic carrier assignment, CCs of all users are updated periodically in addition to mandatory carrier assignment. As presented in [15], periodic carrier assignment improves the performance of LTE-A systems further. Nevertheless, one known limitation of such system is interruption of data transfer during the periodic carrier assignment process. This interruption is due to reassignment all carriers of users at the same time in periodic carrier assignment [15]. Such technique can be called as Joint Periodic Component Carrier Assignment Technique (j-pCCA). The performance of periodic carrier assignment can be increased more because joint technique causes frequent packet transfer interruptions and results in delay and packet drops during periodic carrier assignment operations. Therefore, the *aim* of this paper to overcome packet interruptions of joint technique.

1.1. Objective and contributions

The *objective* of this paper is to consider packet drops and delay which are experienced by users during the periodic carrier assignment process and propose selective periodic carrier assignment technique (s-pCCA) to increase the performance of periodic carrier assignment methods in LTE and LTE-A systems. The main idea behind selective technique is to periodically and selectively update carriers for all users instead of update all carriers at the same time.[1] The key *contributions* of this work are as follows: (i) Selective periodic carrier assignment technique is proposed. (ii) The system models for joint and selective techniques are explained by using Disjoint Queue Scheduler [16]. (iii) The performance metrics for joint and selective techniques are analytically derived by using M/M/m/N for Disjoint Queue Scheduler during carrier assignment operations and verified by an extensive finite buffer simulation. (vi) Joint and selective techniques are compared by using four carrier assignment methods, Least Load (LL), Least Load Rate (LR), Random (R), and Channel quality (CQ) (The detail information about methods is given in Section 3.3) within an extensive simulation. *Results* indicate that the proposed technique increases throughput ratio up to 18% and decreases average delay up to 50% comparing to joint technique. Our proposed technique and related analysis will help service providers build efficient periodic component carrier assignment methods to increase throughput and decrease average delay time.

1.2. Organization of the paper

The rest of the paper is organized as follows: Section 2 summarizes the previous works. In Section 3, the system model of carrier assignment procedure for joint and selective techniques are explained and followed by queuing analysis of both techniques in Section 4. Simulation environments with parameters are described in Section 5. In Section 6, simulation results are presented and examined. Lastly, Section 7 has the concluding remarks.

2. Related works

Several carrier assignment methods have been proposed and analyzed [12,17,18–28] in the literature. In [12,17], Round Robin and Mobile Hashing methods have been investigated. Both of the methods are based on load balancing strategy. In [18], firstly, Channel Quality Indicator (CQI) rates from all users for each component carrier are obtained, and then according to the highest rate, the carriers are assigned to users. In [21], a service-based method is proposed by giving priority for some traffic types while assigning carriers to users. In [19], Absolute and Relative carrier assignment methods are proposed according to a predetermined CQI threshold and PCC CQI, respectively. In [20], G-factor is proposed by considering load balancing for non-edge users to have better coverage for edge users. Edge users are the users who are located away from eNB. In [22], firstly, bands of pico and macro cells [29,30] are decided according to interference, then beamforming is used to provide service to each user. In [23], a self-organized method, which presumes the availability of CQI for each resource block to avoid interference, is proposed. A resource block is the smallest unit of resources that can be allocated to a user. In [24], the least loaded carriers with highest CQI are considered to assign carriers to users. In [25], the mobility of users is estimated in real time while assigning carriers to users to decrease carrier reselection and handover. In [26–28], uplink carrier assignment methods have been proposed by considering a ratio function, traffic type and CQI to increase throughput while sending data from users to eNB. While the objective of the uplink carrier assignment is to optimize bandwidth and power limitation, downlink carrier assignment aims to optimize only bandwidth.

In addition to the above methods, approaches to measure CQI have been proposed as well as packet scheduling algorithms in [31–36]. In [31–34], methods are proposed to measure CQI. In [35,36], full or partial feedbacks related to CQI are used to determine the best available resource blocks in carriers for each user. In [37], service-based methods are proposed by giving priority to some services while assigning resource blocks to users. In [38,39], multiple resource blocks are allocated to users in such a way that delay is decreased. In [40,41], uplink resource scheduling has been proposed by considering a ratio function, traffic type and CQI to increase throughput while sending data from users to eNB.

All of the above works can be grouped under mCCA methods, and the further information on current mCCA methods can be found in [13,14]. In [15], a Periodic Component Carrier Assignment (pCCA) method is proposed, and carriers are periodically assigned to each user in the specified time interval. Algorithms such as Min-delay, higher CQI can be used in periodic carrier assignment methods to optimize delay or throughput of systems. For example, the periodic carrier assignment method in [15] is a form of min-delay-based method, which attempts to minimize delay which is experienced by users.

To overcome the packet interruptions, we have developed selective technique [42]. In [42], selective technique is compared to the two methods which are based on random and load balancing strategies by using Joint Queue Scheduler [16]. In this paper, selec-

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[1] The detail information for selective technique is explained in Section 3.2.

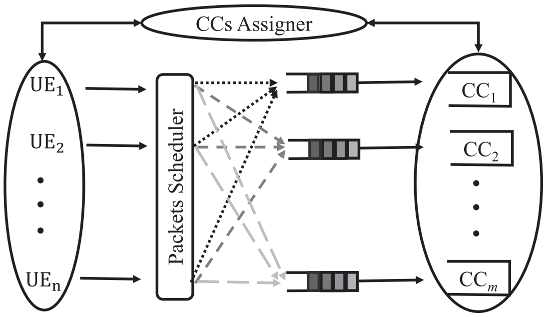

Fig. 2. General system model with n users and m available CCs.

tive technique is integrated into Disjoint Queue Scheduler [16], the performances of selective and joint techniques are analyzed by using queuing theory during carrier assignment operations according to Disjoint Queue Scheduler, the overall performance of joint and selective will be presented by an extensive simulation, and the analytic results are affirmed by an extensive finite buffer simulation

3. System model with joint and selective techniques

Fig. 2 demonstrates a simple example of carrier assignment methods and packet schedulers. There are n number of users, and each user can only connect m number of CCs. Today, LTE-A system can only support up to five simultaneous CCs connection for each user providing IMT-A level service [43]. One of the CCs is Primary Component Carrier (PCC) for uplink and downlink, and can only be updated during handover or cell reselection [43], and the rest of the carriers are Secondary Component Carriers (SCCs) which are updated for each user based on CQI of channels, path loss, and so on. However, as stated in [15], periodic carrier assignment is a new method which tries to reassign all CCs periodically in addition to mandatory carrier assignments. Thus, both PCC and SCCs are updated during periodic carrier assignment operations for all users [15]. At the final stage of the carrier assignment process, Packed Scheduler transfers packets over selected carriers in time and frequency domains. Currently, Proportional Fairness and max-min are common packet schedulers in LTE systems [12,15].

3.1. Joint periodic component carrier assignment (j-pCCA)

Mandatory carrier assignment methods allocate users to carriers based on mobility of users (including path loss, connection problems, low CQI and so on) because uplink and downlink carriers must be updated to maintain the connection. On the other hand, periodic carrier assignment methods allocate users to carriers based on time and periodically updates carriers in the specified time interval [15] regardless of necessary changes. During joint periodic carrier assignment process, all carriers are simultaneously updated for all users; packet transfer of users is thus interrupted. After joint periodic carrier assignment process is completed, packet transfer is restarted.

3.2. Proposed selective periodic component carrier assignment (s-pCCA)

As explained in Section 3.1, the disadvantage of joint technique is the simultaneous reassignment of all carriers to users resulting in interruption of packet transfer. To provide better service, we have proposed a novel method, selective periodic carrier assignment, to overcome the disadvantage of joint technique. In selective technique, only selected carriers of users are periodically updated. Nevertheless, it may update all carriers during the selective periodic carrier assignment process according to the selection algorithm.

Our proposed Selective technique takes into account the time and CQI during the periodic carrier assignment process in addition to strategies of carrier assignment methods. For example, LL method with selective technique is given in Algorithm 1 and processed as follows for each periodic time:

- The threshold of CQI is predetermined for selection Algorithm (The highest possible CQI is selected as the predetermined threshold for s-pCCA). Here, the threshold can be dynamically set by using user profile information for each user as done in our past work [44].
- Partially or entirely CQI feedback is obtained to measure the carrier qualities for each user.
- Carriers are ascendingly sorted according to the number of served users because of Least Load method (line 3 in Algorithm 1).
- The carriers, which have a higher CQI than the predetermined threshold, are reassigned to each user. This is because of selective technique (from line 9 to line 19 in Algorithm 1).
- Select new carriers after finding out that the user needs new carriers (from line 20 to line 33 in Algorithm 1).
- Until now, the newly assigned carriers have the least number of active users, and their CQIs are equal or higher than the threshold. However, it is possible not to have enough available carriers with desired quality. Therefore, it is critical to test it (line 34 in Algorithm 1).
- Now assign more carriers to the user if the number of newly assigned carriers is not equal to the previous number of carriers for the user (from line 34 to line 37 in Algorithm 1). For example; assume that UE_i receives data by using C_1, C_2, and C_3 component carriers; and CQI of C_1 and C_2 are lower than the threshold. Therefore, selective technique chooses C_1 and C_2 to update. However, selective technique only finds CQI of C_4 is equal or higher than the threshold from all available CCs for UE_i. Therefore, LL method with selective technique assigns C_4 and the CC, which has the least number of active users to UE_i.
- To increase the efficiency and QoS, the packet transferring priority is given to the CC, which belongs to $Band-c$, then $Band-b$, and then $Band-a$.

Similar to the carrier assignment of LL method with selective technique (which is explained above), LR, R and CQ methods with selective technique are processed as above except that the strategies of the carrier assignment methods. The method details are explained in Section 3.3.

3.3. Methods

To examine the impacts of joint and selective techniques on carrier assignment, four different carrier assignment methods are used. The methods are Random (R), Least Load (LL), Least Load Rate (LR) and Channel Quality (CQ). The methods are chosen because of their common usage in the literature, and the methods use different properties while assigning carriers to users.

3.3.1. Random (R)

R method is one of the well-known methods in the literature [12]. R randomly selects carriers for users. Hence, it only well balances user loads across carriers in long term. However, R method disregards Quality of Service (QoS) requirements of each user and CQI of channels.

3.3.2. Least Load (LL)

LL method is also one of the well-known methods in the literature [12]. LL assigns users to least loaded carriers. Thus, it well bal-

Algorithm 1 Selective technique with Least Load carrier assignment method.

```
procedure Least Load Selective(userList, carrierList, cqiThreshold)[1]
    CarrierPairWithUserLoad ← GetCarriersWithNumberOfUsersOnCarriers(carrierList)
    Sort(CarrierPairWithUserLoad)
    while user in $userList$ do
        userType ← GetUserType(user)
        numCC ← GetMaxNumberCC(userType)
        carriers ← GetUserCarrierList(user)
        $k, i \leftarrow 0$
        while $k \le numCC$ and $i \le$ lenght(CarrierPairWithUserLoad) do
            if carriers.Contain(CarrierPairWithUserLoad[i]) then
                if isAssignable(CarrierPairWithUserLoad[i], user) then
                    if carrierList[CarrierPairWithUserLoad[i].carrier].cqi $\ge$ cqiThreshold then
                        toReturn[user][k] = CarrierPairWithUserLoad[i].carrier;
                        $k \leftarrow k++$
                    end if
                end if
            end if
            $i \leftarrow i++$
        end while
        if $k < numCC$ then
            $i \leftarrow 0$
            while $k \le numCC$ and $i \le$ lenght(CarrierPairWithUserLoad) do
                if carriers.NotContain(CarrierPairWithUserLoad[i]) then
                    if isAssignable(CarrierPairWithUserLoad[i]) then
                        if carrierList[CarrierPairWithUserLoad[i].carrier].cqi $\ge$ cqiThreshold then
                            toReturn[user][k] = CarrierPairWithUserLoad[i].carrier;
                            $k \leftarrow k++$
                        end if
                    end if
                end if
                $i \leftarrow i++$
            end while
        end if
        if $k < numCC$ then
            $i \leftarrow 0$
            while $k \le numCC$ and $i \le$ lenght(CarrierPairWithUserLoad) do
                if carriers.NotContain(CarrierPairWithUserLoad[i]) then
                    if isAssignable(CarrierPairWithUserLoad[i]) then
                        if carrierList[CarrierPairWithUserLoad[i].carrier].cqi $<$ cqiThreshold then
                            toReturn[user][k] = CarrierPairWithUserLoad[i].carrier;
                            $k \leftarrow k++$
                        end if
                    end if
                end if
                $i \leftarrow i++$
            end while
        end if
    end while
    return toReturn
end procedure
```

ances user loads across carriers in short and long terms [12]. However, LL method also disregards QoS requirements of each user and CQI of channels. It is important to note that ignoring CQI does not mean the performance of LL method is lower than other methods.

3.3.3. Channel Quality (CQ)

There are several versions of CQ similar to the approach presented in [19]. Here, CQ method assigns carriers to users by selecting the carriers which have the highest CQI [35], and it is similar to Relative method in [19]. Therefore, user loads and QoS requirements of users are ignored. It is important to note that CQI can be varied according to positions of UEs because of obstacles and distance.

3.3.4. Least Load Rate (LR)

LR method assigns carriers to users by selecting the highest rate which is measured by using total capacity in terms of bandwidth, the number of users and CQI for each carrier. The rate is measured as follows as similar to [18] but instead of considering only CQI rate (queue length is considered in the packet scheduling rather than carrier assignment for all methods), we have used the number of users.

$$\text{Rate} = \frac{\text{CQI of carrier} \times \text{Bandwidth of carrier}}{\text{The number of users on carrier}} \tag{1}$$

4. Analysis

In this section, analytic expressions of performance metrics will be derived for joint and selective techniques during periodic carrier assignment operations by using queuing theory according to Disjoint Queue Scheduler.

4.1. Notations

The notations used for the analysis in the rest of the paper are listed in Table 1.

4.2. Queuing models of j-pCCA and s-pCCA for downlink

Fig. 3 illustrates the downlink process for n users with one CC. The queuing model scheduler is Disjoint Queue Scheduler [16]. We have used Disjoint Queue Scheduler because Disjoint Queue Scheduler is more realistic than Joint Queue Scheduler [13]. While Joint Queue Scheduler allows each user to have a single buffer for all CCs [16], Disjoint Queue Scheduler allows all CCs to have disjoint buffers for each user as shown in Fig. 3.

Downlink packet arrival rate for UE$_i$ is λ_i, each CC represented by a server and service rates of CCs are μ_j where $j \in \{1, 2, \ldots, m\}$ and each buffer, Q_j, can hold at most N packets. Packet schedulers

Table 1
Notations.

i	$\in \{1, 2, \ldots, n\}$
j	$\in \{1, 2, \ldots, m\}$
$Q_{CC_{ij}}$	Queue of UE_i for CC_j
N	Size of Queues
μ_j	Service rate of CC_j
λ_j	Packet arrival rate to jth queue
λ_i	Packet arrival rate of UE_i
λ_{ij}	Packet arrival rate of UE_i to jth queue
δ	Average delay during carrier reassignment
n	Average queue length during carrier reassignment
D	Drop probability during carrier reassignment

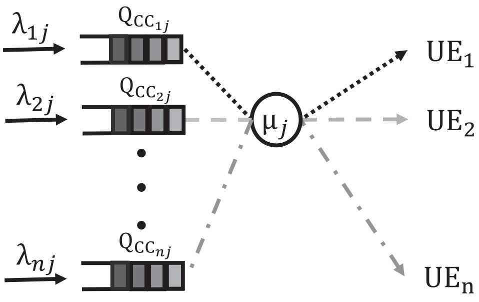

Fig. 3. Downlink Disjoint Queue Model with *n* users and *one* available CC.

enqueue an arrived packet which is requested by a user to one of the assigned CCs. During joint periodic carrier assignment operation, packet transfer of UE_i is terminated all the time. However, packet transfer of UE_i is terminated if all carriers need to be updated, or if PCC needs to be updated during selective periodic carrier assignment operations (If PCC is updated then all carriers may be required to be updated). Therefore, there are three cases in the system for joint and selective techniques:

- **Case 1:** PCC is required to be updated. Therefore, SCCs may need to be updated.
- **Case 2:** All carriers are required to be updated.
- **Case 3:** SCCs need to be updated, but PCC is not required to be updated.

It is worth to note that if it were possible to convert one of SCCs as PCC when PCC is required to be updated in LTE-A, there would be four cases. Simply, Case 1 would be divided into two cases: Case 1-a: There is one SCC, which is not required to be updated, can be altered as PCC. Case 1-b: There is no such SCC. Therefore, all carriers are required to be updated. It is important to note that while PCC is updated, SCCs may not require being updated because the RRCConnectionReconfiguration IE may contain a list of new SCCs which are same or different sets of carriers.

The performance metrics of joint and selective techniques are same for Case 1 and Case 2. Hence, only Case 3 is explained to distinguish differences between joint and selective techniques. During periodic assignment operation (Case 3) in joint technique for UE_i, the packet transfer operation is as follows: (i) Packet transfer is interrupted for the user; (ii) All CCs of the user are updated; (iii) Packet transfer is restarted for the user over new carriers. On the other hand, during periodic carrier assignment operations (Case 3) in selective technique, the process is as follows: (i) For all users, some carriers (CCs) are selected to be updated according to the selective algorithm (here, it is based on channel quality indicator); (ii) Packet transfer is only interrupted on carriers which are needed to be updated for each user; (iii) New carriers are assigned to users; (iv) Packet transfer is started on new carriers for the users.

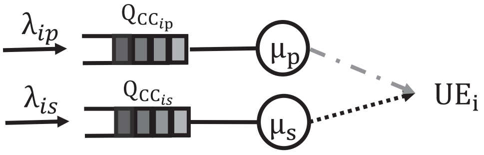

Fig. 4. Downlink system model with one user with primary and secondary carrier queues.

4.3. Assumptions

To make the model analytically tractable, it is assumed that there is only one UE in the system as demonstrated in Fig. 4. All carriers are capable of transferring all types of packets, the queuing system is under heavy traffic flows, packet arrivals follow Poisson distribution, and service times for packets are exponentially distributed. Type of queue discipline used in the analysis is FIFO. Bandwidth and CQI of carriers can be different. Thus, service rate of all servers can also be different. The assumption of one user in the system makes the derivation of analytical expressions of performance metrics simpler.

The model can be more realistic by considering priority-based packet arrivals. In such system, packets are classified according to their priorities; then the priority queue system will be used to derive of analytical expressions of performance metrics. In [45], we consider priority-based packet arrivals while deriving the analytical expressions. Therefore, it is assumed that the system has one user without packet classification in this model. Moreover, assuming existence of more than one user in the system will not affect realism of the system model while deriving of analytical approximations because the arrival rate (λ) can be considered to represent arrival rates of multiple users rather than one user, and there would be more than one service rate of primary and secondary component carriers.

4.4. Performance metrics

In this subsection, we approximately derive drop rate, average queue length, and average delay for joint and selective technique for Case 3 because the performance metrics of joint and selective techniques are same for Case 1 and Case 2. In both joint and selective techniques, min-delay scheduler is used, and the system is under heavy traffic flows. Consequently, the total service rate ($\mu_p + \mu_s$) and overall arrival rate (λ_i) can be used instead of a separate analysis for both queues.

In joint periodic carrier assignments, all carriers are updated for UE_i. Therefore, the service rate is zero, and the system is not in steady state. Hence, we only mention the possibilities for the performance of joint technique. On the other hand, we approximately derive performance metrics of selective technique.

The drop probability of packets in the system for UE_i can be approximated using standard M/M/1/N formula as follows [46]:

$$D_i(t) = \begin{cases} \frac{\rho_i(t)^N(1-\rho_i(t))}{1-\rho_i(t)^{N+1}}, & \rho_i(t) \neq 1 \\ \frac{1}{N+1}, & \rho_i(t) = 1 \end{cases} \tag{2}$$

where

$$\rho_i(t) = \frac{\lambda_i(t)}{\mu_p(t) + \mu_s(t)}. \tag{3}$$

The average queue length for UE_i in selective technique can also be approximated by using standard M/M/1/N formula as follows [46]:

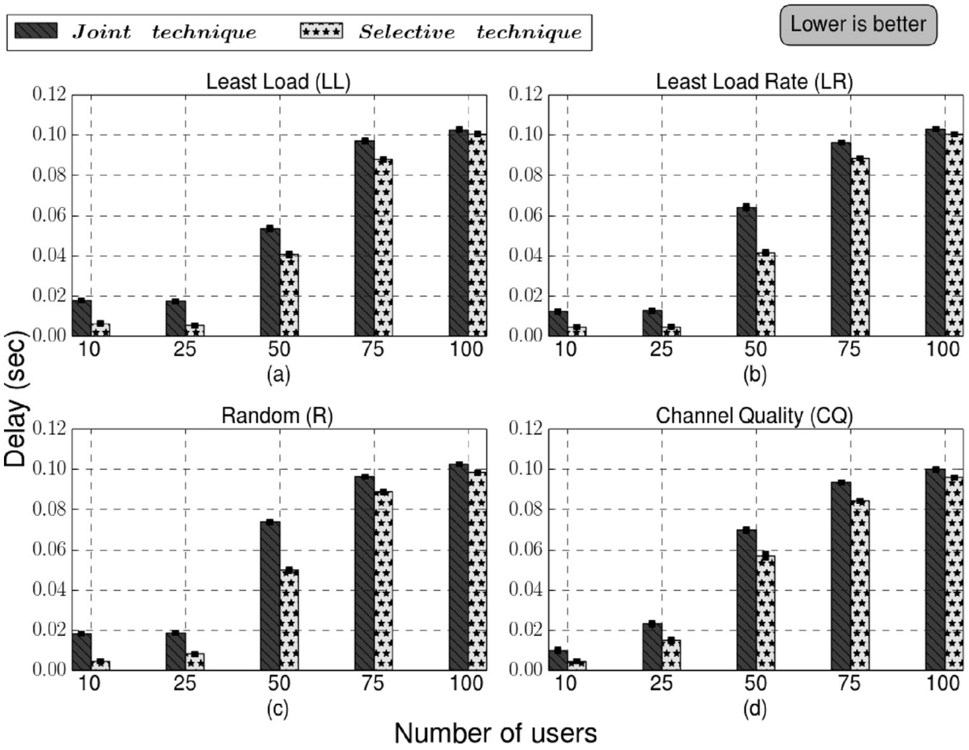

Fig. 5. Delay during periodic carrier assignment operations for joint and selective techniques.

$$n_i(t) = \begin{cases} \frac{\rho_i(t) - (N+1)\rho_i(t)^{N+1} + N\rho_i(t)^{(N+2)}}{(1-\rho_i(t))(1-\rho_i(t)^{N+1})}, & \rho_i(t) \neq 1 \\ \frac{N}{2}, & \rho_i(t) = 1 \end{cases} \tag{4}$$

By Little's Law [47], and using Eqs. (2) and (4); average delay ($\delta_i(t)$) for UE$_i$ can be written as:

$$\delta_i(t) = \frac{n_i(t)}{\lambda_i(1 - D_i(t))}. \tag{5}$$

Similarly, drop probability ($D_i(t)$) and average queue length ($n_i(t)$) of selective technique can be represented by using same Eqs. (2), (4), and (5) during the periodic carrier assignment process. However, $\rho_i(t)$ needs to be updated as:

$$\rho_i(t) = \begin{cases} \frac{\lambda_i(t)}{\mu_p(t) + \mu_s(t)}, & \mu_s(t) \neq 0 \\ \frac{\lambda_i(t)}{\mu_p(t)}, & \mu_s(t) = 0 \end{cases} \tag{6}$$

Since selective technique may or may not interrupt packet transfers for UE$_i$, service time will be at most $1/\mu_p(t)$ and at least $1/(\mu_p(t) + \mu_s(t))$. In other words, if there are m CCs of which v are not updated (assuming $v \leq m$ and CC$_1$, CC$_2$, ... , CC$_v$ are not updated during the periodic carrier assignment process, and CC$_1$ is PCC), then;

$$\rho_i(t) = \frac{\lambda_i(t)}{\sum_{k=1}^{v} \mu_k(t)}. \tag{7}$$

On the other hand, for joint technique, average queue length (n) will be $n \approx N$. Therefore, average delay (δ) will be $\delta \approx \infty$. However, because periodic carrier assignment time duration is limited to a number (assume τ), then $\delta = \tau$

In Section 4.4, we approximately derive analytic performance metrics for selective technique and possible performance values of joint technique for Case 3. The obtained queue-based delay performance for joint and selective periodic carrier assignment shows that selective technique has improved the performance of the system during periodic carrier assignment operations (the simulation result of delay during the periodic carrier assignment process in Figs. 5 and 6 also verifies the correctness of the improvements.). However, overall system performance metrics can be different because service rates of carriers for each user are time and position dependent. Therefore, we have implemented simulation to observe the overall system performances of joint and selective techniques.

5. Simulation of the system

Discrete event simulation has been implemented in Java by considering carrier assignment methods which are mentioned in Sections 3 and 3.3 in addition to eNB specifications, modulations, device-type-based carrier aggregation, signaling ranges, CQI feedback and reporting, and resource block assignment for each user. Simulation setups and the parameters are explained in following subsections.

5.1. *Assumptions for eNBs*

It is assumed that there is only one eNB which has three bands to provide service to users. The parameters of eNB are given in Table 2.

In the simulation, Scenario *b* is used to represent the general macro model. Only one eNB is considered not to deal with the handover process in case users change base stations. However, assuming one eNB does not affect the obtained results in terms of performance comparison between methods. The eNB provides service to users by using three bands similar to real case scenarios. Each band can have four CCs with 10 MHz bandwidth. The number of CCs in each band is selected as four because LTE-A type equipment can connect at most four CCs to download data. Therefore, even a LTE-A type user in the coverage of only *Band – a* can connect four CCs to get services similar to real case scenario. Aggregated carriers can be from same or different bands. Therefore, Carrier aggregation type can be any of *Intra-band contiguous, Intra-band non-contiguous and Inter-band non-contiguous*. Although each CA type has some advantages over others, we assume the system behaves as Inter-band non-contiguous CA in the simulation. To

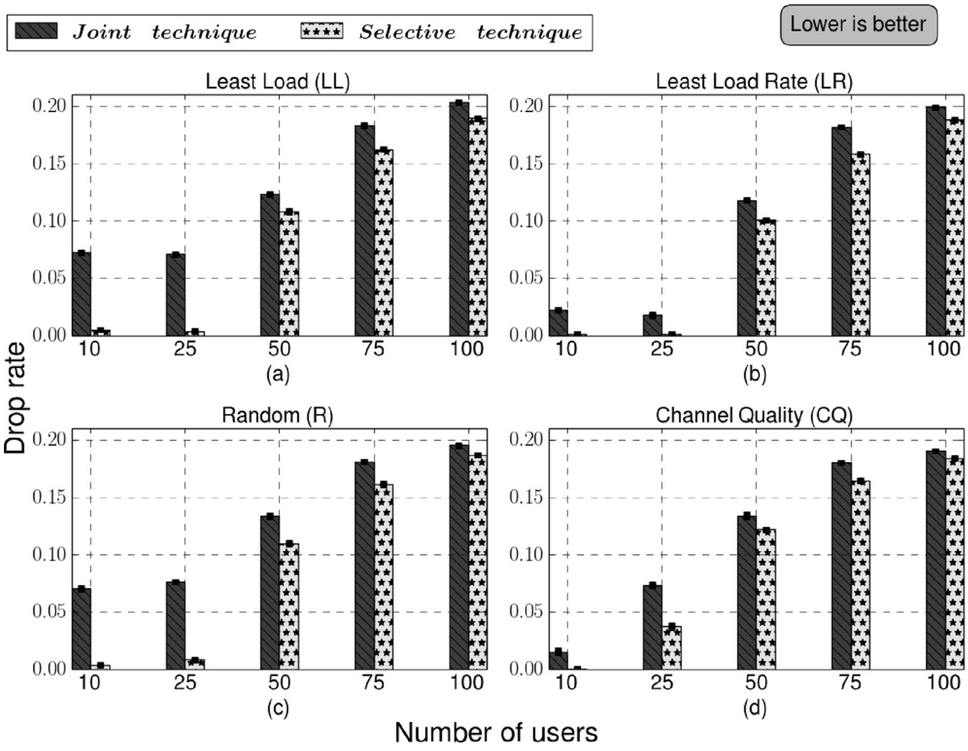

Fig. 6. Packet Drop Rate during periodic carrier assignment operations for joint and selective techniques.

Table 2
*e*NB parameters.

Scenario [48]	b
Number of eNB	1
Used bands	800 MHz, 1.8 GHz, 2.6 GHz
Number of CCs in each band	4
Total number of CCs	12
Queue length of each queue	50 packets
Bandwidth of CCs	10 MHz
Modulations	BPSK, QPSK, 16QAM, and 64QAM
CQI	3, 5, 7, and 11
Transmission time interval	10 ms (10 ms is average, it can be more or less)
Time for CCA	20 ms (at most 20 ms)
CQI threshold	The highest possible
Simulation model	Finite buffer [49]

simulate saturation of the system, a higher number of CCs are not selected. 10 MHz and 20 MHz bandwidths are used in LTE-A to provide IMT-A level speed [48]. Therefore, 10 MHz bandwidth is used in the simulation. BPSK, QPSK, 16QAM and 64QAM are the modulation techniques to transfer bits according to CQI in LTE systems. Therefore, to simulate those modulations, four CQI levels are used, and each CQI level is the modulation changing point. The average Transmission Time Interval (TTI) is 10 ms for a packet (TTI can be less or more according to different packet sizes) to simulate the low and high latency requirements because the accepted TTI in LTE is 1ms to meet the low latency requirements [48]. To show the lowest improvements of selective technique comparing to joint technique, time for CCA is kept as 20 ms and lower because the carrier assignment operations can consume a considerable amount of time according to carrier assignment methods. In the simulation, finite buffer model is used because finite buffer model well presents the reality comparing to full buffer model [49].

5.2. Assumptions for UEs

There are two types of equipment, LTE and LTE-A types, in the system. Half number of equipment is LTE type and can only use one carrier and the other half are LTE-A type and can use multiple carriers (up to five). In the simulation, four CCs can be simultaneously used by LTE-A type equipment because maximum five CCs can be used by LTE-A type equipment, and one of them must be used for upload primary component carriers (see Section 3). Users are initially non-uniformly distributed in the simulated area which means that most users are located nearby to eNB. 50% of users can move around of the eNB in the specified time interval according to random waypoint model [50].

Each user can only download one type of traffic. Packet arrivals follow Pareto Distribution with shape parameter 2.5 and different packet arrival rates. Pareto Distribution is selected for simulation because Pareto-based traffic models well simulate the high-speed networks with unexpected demand on packet transfers by considering the long-term correlation in packet arrival times [51]. If there is one user in the system, the total packet arrival rate is 250 per second. If there are two users in the system, the total packet arrival rate is 500 per second. Different users can have distinct or same packet arrival rates. During the simulation, at most each user can generate 10,000 packets, and the packet service times are between one and ten ms. The arrival rate and packet sampling is simulated in such a way as be more realistic and suitable to finite buffer simulation [49]. Therefore, total arrival rates of traffic are enlarged when the number of users increases.

It is important to note that we also tested our system with Poisson Distribution. Although there are some similarities and differences between the result which are obtained by using Poisson and Pareto distributions, selective technique is better than joint technique in both distributions. Therefore, we only give the results based on Pareto Distribution. Moreover, we also tested joint and selective techniques by using different predetermined thresholds than the highest possible threshold to see the effects of threshold on selective technique. Although the performance of selective techniques decreases for the lowest possible threshold, again selective techniques are better than joint technique.

5.3. Packet scheduling

In the simulation, we have used a min-delay packet scheduling method to compare joint and selective techniques. Proportional Fairness is not preferred because Proportional Fairness packet scheduling can block packet transfers [12]. Therefore, the performance of carrier assignment methods could not be observed correctly.

Packet arrival traffic is kept same for all test cases. Because of UEs and eNB positions, CQI Index for all carriers can be one of four options which are given in Table 2. Each packet is transferred by using one of the assigned carriers. To increase the efficiency and QoS, the packet transferring priority is given to the CC, which is the closest to the eNB and minimizes packet delay if multiple carriers are available. If there are no available assigned carriers to serve arrived packets, packets are enqueued to corresponding user queues. The queue for each user in each carrier can hold 50 packets. Buffer sizes are kept small [52], similar to real routers to reduce packet delay. If there are not any empty spaces in queues, arrived packets are dropped.

5.4. Observation methodology

The results in Section 6 are averages of 200 realizations for different size of users. The impacts of light and heavy user loads on joint and selective techniques are investigated by using four different methods which are explained in Section 3.3. The methods are selected for test cases because of common usage in the literature and simplicity. In each figure, the method name is given on the title and labels are used to distinguish joint and selective techniques.

We present the performance of joint and selective techniques by comparing CC utilization, throughput ratio, and delay. Confidential intervals because of realization results from different simulation runs are also presented according to %95 level. However, the confidential intervals are insignificant because of three reasons. First, the packet arrivals follow Pareto Distribution; thus, the differences between the obtained results from the different realizations are insignificant. Second, the number of samples is high regarding realizations and sampled packets though random waypoint model. Third, the confidential intervals for true mean values are obtained by using z-score.

CC utilization shows how efficiently CCs are used. It is measured by dividing the busy time of CCs to simulation time. Throughput ratio indicates how much data are successfully transferred out of generated packets and is measured by dividing transferred packets to all processed packets. Therefore, while the number of users is increased, throughput ratio decreases because of carriers capacities. Block rate is not given because it is just the inverse of throughput ratio.

Average delay per packet shows how much time a packet waits to transfer. Here, waiting time of dropped packets is ignored, and only delay of transferred packets is considered. It is determined based on waiting time in queues with service time. Additionally, delay and drop rate which are experienced by packets during the periodic carrier assignment process are shown to verify the analytic approaches in Section 4. To measure the delay during carrier assignment operations, we consider the time of packet arrival, the beginning time of carrier assignment process and the finishing time of carrier assignment process for each packet. After summing delays by experience by all packets during carrier assignment operations, the sum is divided by the number of processed packets (transferred and dropped packets). Drop rate during the carrier assignment operations is measured by dividing the total number of dropped packets during the carrier assignment operations to the number of processed packets. Some packets may or may not experience delay because of carrier assignment process, but the overall delay is affected by any delay. Furthermore, the performances of joint and selective techniques are evaluated in terms of equipment types (LTE and LTE-A type equipment) by using the explained performance metrics.

As a result of delay, throughput ratio and CC utilization comparison between joint and selective techniques, trade-off between resource usage and managed QoS are compared.

6. Results

In this section, delay experienced by users during carrier assignment operations, overall system performance and equipment type based performance are presented for joint and selective techniques.

6.1. Delay during carrier assignment operations

In this section, delay, which is the sum of the partial delays, due to carrier assignment operations is presented to show how different methods are affected by joint and selective techniques in terms of delay. Fig. 5 demonstrates delay due to carrier assignment operations for joint and selective techniques. When the number of users is 10 and 25, delay is lower than 0.03 s for all methods and delay is significantly lower in selective technique. When the number of users is 50 and more, delay also gradually increases for all cases, but delay of joint is again higher than delay of selective for the methods due to less number of packet interruption in selective technique. However, delay gap between joint and selective technique is decreasing while the number of users is raising. Fig. 5 shows that selective technique significantly reduces delay experienced by packets during carrier assignment operations.

6.2. Packet drop rate during carrier assignment operations

In this section, packet drop rate, which is the rate of dropped packets during the carrier assignment operations to the all served and dropped packets, is presented to show how different methods are affected by joint and selective techniques in terms of packet drops. Fig. 6 shows packet drop rate due to carrier assignment operations for joint and selective techniques. When the number of users is 10 and 25, packet drop rates in selective technique are significantly lower than the ones in joint technique because selective technique does not block the service during the carrier assignment operations. However, when the number of users is 50 and more, the gain is decreasing because the number of users in the system is high; therefore, the number of the arrived packets to the system during carrier assignment operations are high. Fig. 6 shows that selective technique reduces the packet drop rate, especially when the system has a low number of users.

6.3. Overall performance of the system

In this subsection, overall system performance of the methods with joint and selective techniques is presented by using utilization, average delay and throughput ratio.

6.3.1. Utilization

Fig. 7 shows carrier utilization for the methods with joint and selective techniques. Due to heavy data traffic loads, utilization is similar and almost equal to 1.0 for LL, LR and R methods with both techniques when the number of users is 50 and more. However, CQ has slightly lower utilization than other methods. When the number of users is 25 and less, R and CQ have lower utilization than LL and LR for joint and selective technique. CQ has the lowest utilization for both techniques because load balancing affects system more when the system is under heavy data traffic flows.

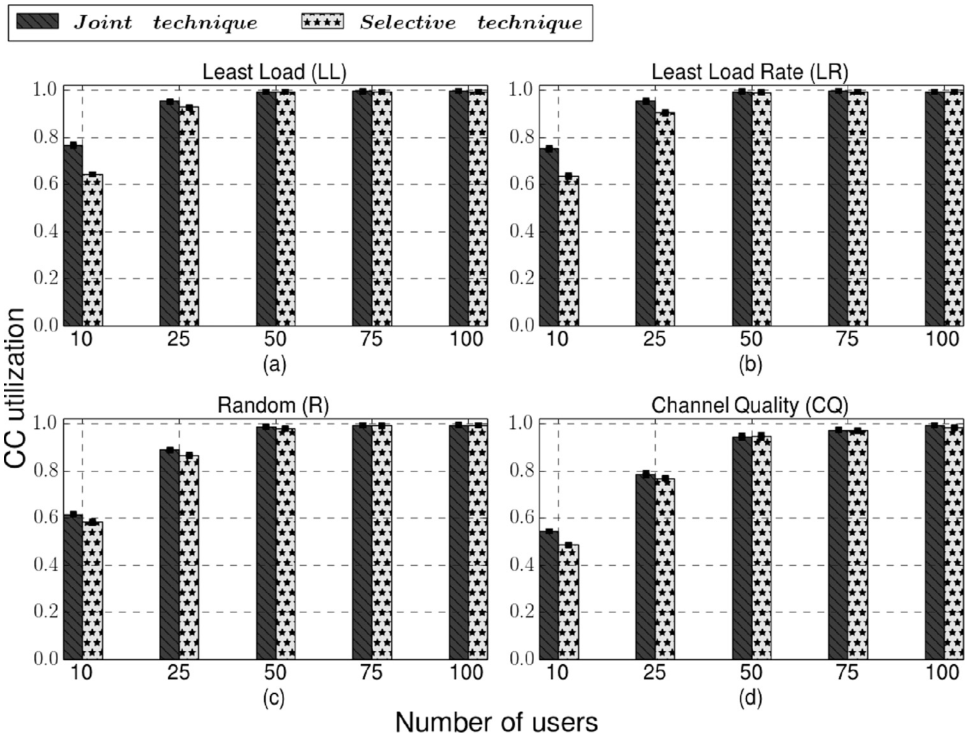

Fig. 7. Utilization of CCs for joint and selective techniques.

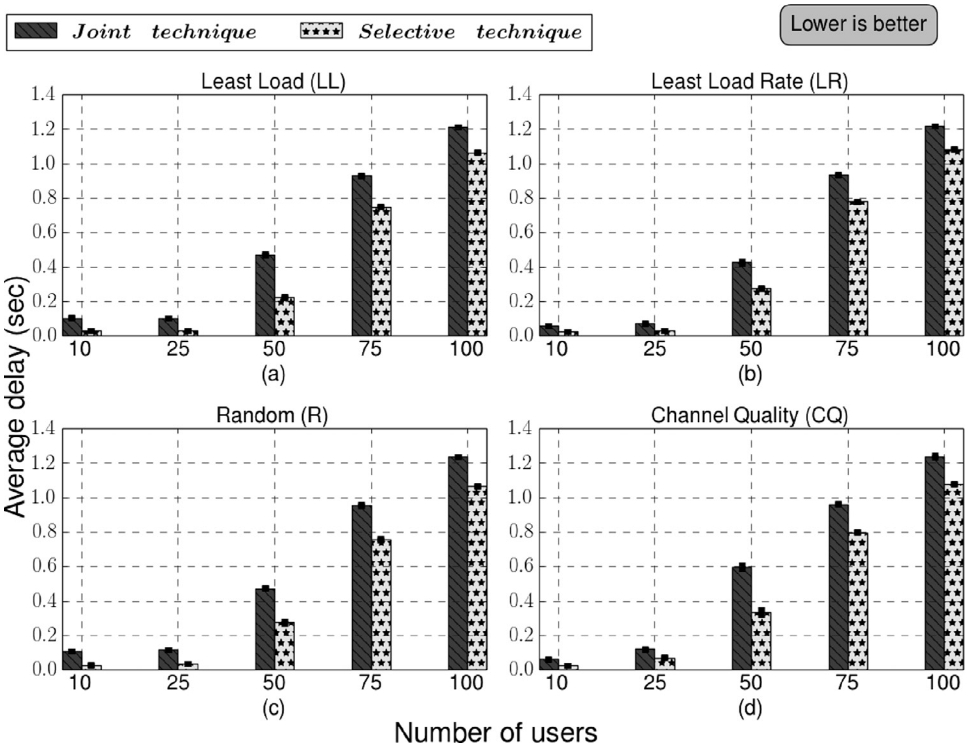

Fig. 8. Average delay per packet for joint and selective techniques.

6.3.2. Average delay

Fig. 8 demonstrates average delay per packet for the methods with joint and selective techniques. When the number of users is increasing, delay is also regularly getting higher for all cases due to a large number of packet arrivals. In all cases, selective technique is better than joint technique as shown in Fig. 8. For instance, the average delay of joint technique is between 0.06 and 0.47 s for all methods when the number of users is 50 and less. However, the average delay of selective technique is between 0.03 and 0.22 s for the same number of users. Therefore, selective technique decreases the average delay up to 50%.

When the number of users is 75 and more, the average delay is changing between 0.93 and 1.25 s for joint technique. However, the average delay is between 0.80 and 1.08 s for selective

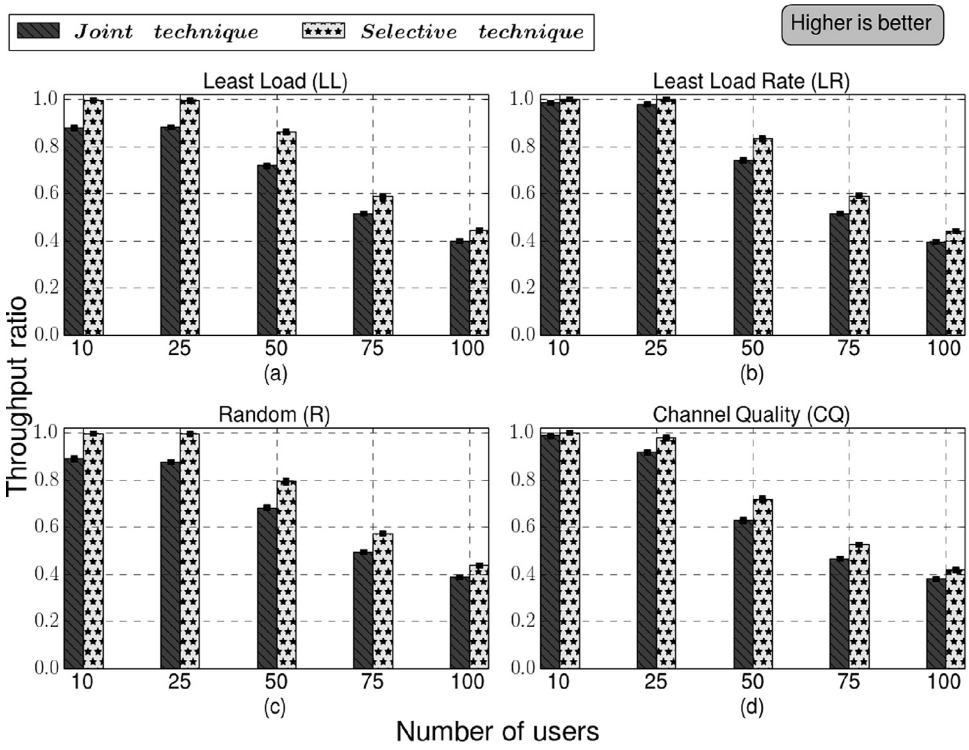

Fig. 9. Throughput ratio for joint and selective techniques.

technique. Therefore, selective technique improves the average delay up to 15% while the system is under heavy data traffic loads. It is worth to mention that while the number of users is increasing (after 50 users), the average delay gap between selective and joint is decreasing for all methods as expected. This is due to the capacity limitation of the system.

6.3.3. Throughput ratio

Fig. 9 shows throughput ratio for joint and selective techniques. Throughput ratio is gradually decreasing for all cases while the number of users is increasing. For all cases, selective technique has higher throughput ratio than joint technique. While the number of users is 25 and less, selective technique improves throughput ratio up to 14% (almost 0.87 to 0.99) in LL and R methods comparing to joint technique. Selective technique also increases throughput ratio of LR and CQ, but the improvement is not as significant as LL and R methods for the same number of the users. When the number of users is 50, selective technique improves even more (up to 18%). However, throughput ratio improvement for a higher number of users (more than 50) is not as much as for a lower number of users in LL and R methods due to carrier capacity and packet arrival rates.

Moreover, all methods with selective technique have almost optimum (=1.0) throughput ratios when the number is 25 and less. However, only LR method with joint technique has an almost optimum throughput ratio for the same number of users. It is worth to mention that LL and LR methods have almost the same and the highest throughput ratios in selective technique and LR method has the highest throughput in joint technique.

6.4. Delay and throughput ratio according to equipment types

In the following subsections, the experienced performance by each equipment type (LTE and LTE-A equipment types) for four methods with selective and joint techniques is presented according to delay and throughput ratio. Equipment based comparison is shown because we are interested in the results of how the users of different types of equipment will be affected by joint and selective techniques if there are multiple types of equipment in the system.

6.4.1. Average delay

Figs. 10 and 11 show average delays per packet which are experienced by LTE and LTE-A type equipment, respectively. When the number of users is 25 and less, delay of LTE type equipment is higher than delay of LTE-A type equipment for all methods because there is only one assigned CC to serve for LTE type equipment and multiple assigned CCs for LTE-A type equipment. Due to light packet arrival, the carriers are not busy all the time. Thus, packets of LTE-A type equipment does not experience much delay. For the same number of users, selective technique remarkably decreases average delay of LTE type equipment and slightly improves average delay of LTE-A type equipment comparing to joint technique for all methods. This shows that joint technique frequently interrupts packet transfersg for LTE type devices.

When the number of users increases to 50 and more, there are slight differences between delays of LTE and LTE-A type equipment because LTE type equipment makes carriers busier due to higher packet arrival rates. However, all methods with selective technique have up to 50% lower delays for both LTE and LTE-A type equipment because interruption of packet transfers is lower in selective technique. Additionally, the delay gap of LTE type equipment between joint and selective techniques is decreasing while the number of users is increasing. This is also true for LTE-A type equipment when the number of users is 50 and more.

6.4.2. Throughput ratio

Figs. 12 and 13 demonstrate throughput ratio which is experienced by LTE and LTE-A types equipment for joint and selective techniques. Throughput ratio of LTE type equipment is lower than throughput ratio of LTE-A type equipment for all methods because of different capacities of equipment. Throughput ratio of

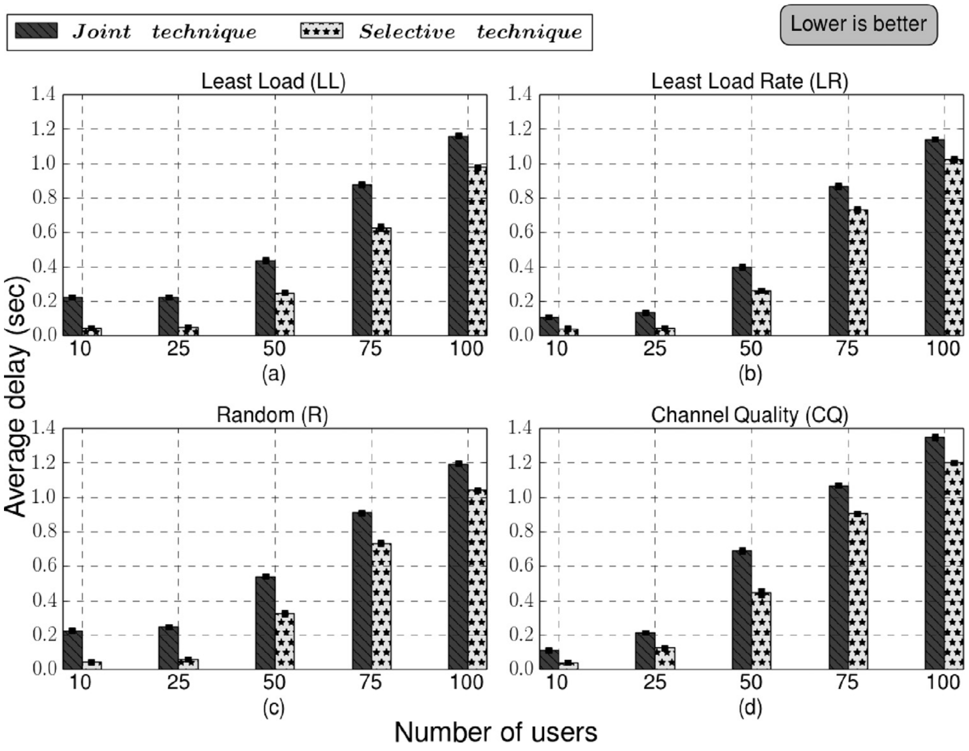

Fig. 10. Average delay per packet of LTE type devices for joint and selective techniques.

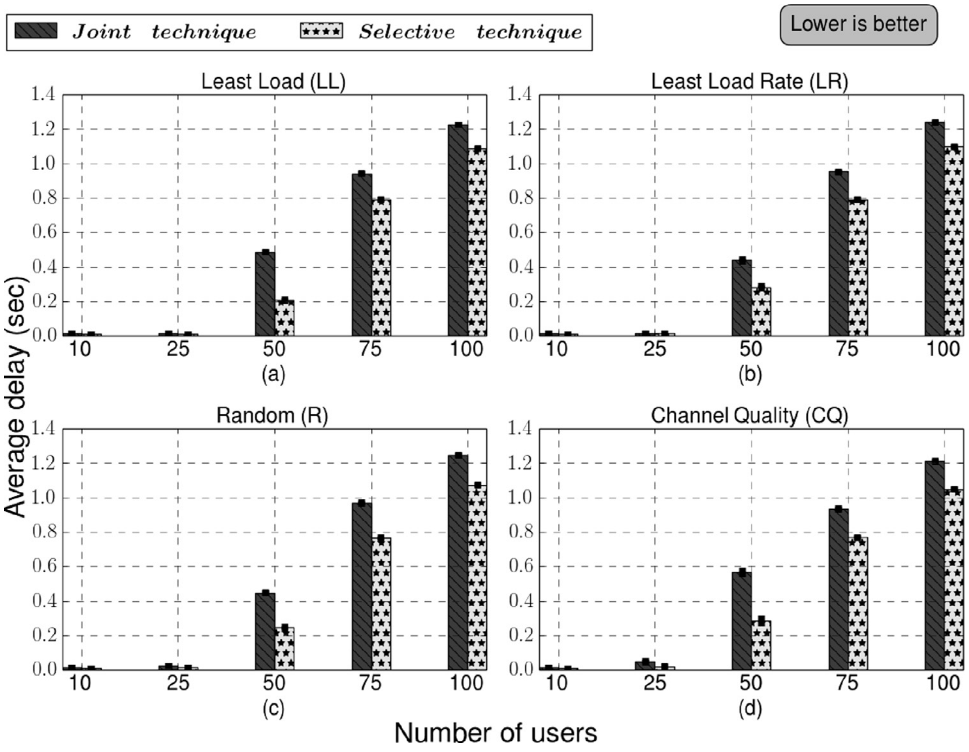

Fig. 11. Average delay per packet of LTE-A type devices for joint and selective techniques.

LTE-A type equipment is 1.0 for both joint and selective techniques when the number of users is 50 and lower. However, only LR with joint technique and all methods with selective technique have almost 1.0 throughput ratio for LTE type equipment when the number of users is 25 and less. This shows that selective technique significantly increases throughput ratio of LTE type equipment (almost up to 35%). Additionally, selective technique also improves throughput ratio of LTE-A type equipment for all methods when the number of users is 75 and more.

6.5. Summary of results

Based on the results, we make the following observations: (i) Joint technique shows that LTE type equipment traffic suffers

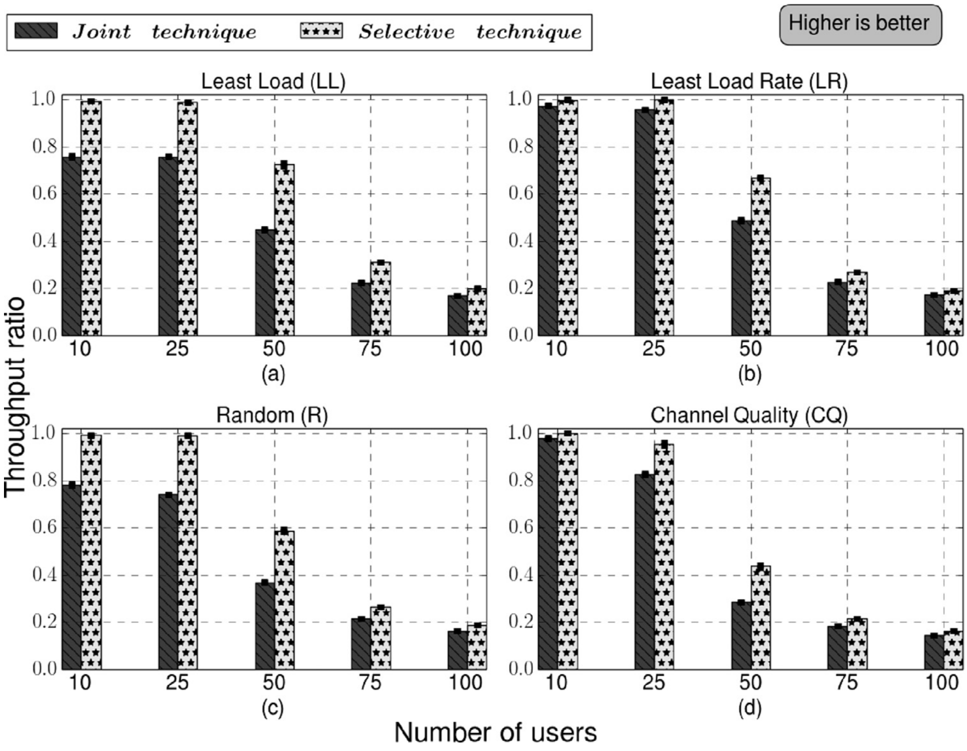

Fig. 12. Throughput ratio of LTE type devices for joint and selective techniques.

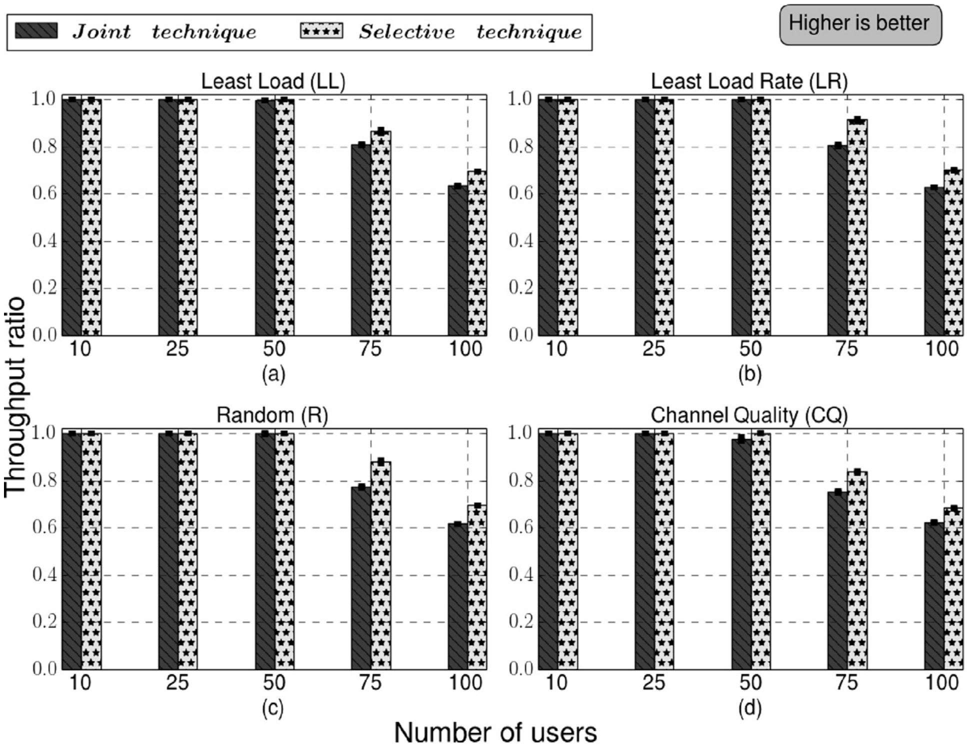

Fig. 13. Throughput ratio of LTE-A type devices for joint and selective techniques.

higher delay than LTE-A type equipment traffic due to interruptions of packet transfers; (ii) Selective technique significantly enhances the performance of LTE and LTE-A. However, the improvement in LTE type equipment is higher than the improvement in LTE-A type equipment because of the capacity of LTE type equipment; (iii) Selective technique remarkably decreases overall (up to 50%) average delay and improve (up to 18%) throughput ratio comparing to joint technique.

7. Conclusion and future works

In this paper, selective periodic component carrier assignment technique is proposed by considering the behavior of the system during component carrier assignment operations. The performances of current joint and proposed selective component carrier assignment techniques are compared by using analytic analysis based on queuing theory and an extensive simulation. Both techniques are analyzed according to not only the overall system performance but also the device based performance. Results show that the proposed technique efficiently uses system resources and improves the overall throughput ratio up to 18% and average delay up to 50% in LTE and LTE-A systems. Our proposed technique and related analysis will help service providers build efficient periodic component carrier assignment methods to improve performance metrics such as throughput ratio and delay.

Acknowledgment

This research was supported in part by U.S. NSF grants NSF-1404981.

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