Dynamic Spectrum Access for Primary Operators Via Carrier Aggregation in LTE-Advanced Environments*

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Abstract—**In this paper, we address dynamic spectrum access for Primary Operators (POs) for LTE-Advanced systems. We propose a dynamic spectrum access framework that exploits the capabilities of carrier aggregation to efficiently utilize the unutilized spectrum which varies with time and space when static spectrum access policies are adopted. A spectrum owner (SO) adopts an auction scheme for accessing spectrum for the dynamic requests when the overall demand is higher than the available bandwidth and uses peak-load pricing (PLP) otherwise. The objectives of the SO are to maximize its revenues and to increase the spectrum utilization efficiency as well as achieving social welfare. On the other hand, the objective of the POs is to maximize their benefits by reducing expenditures compared to the case of static allocation based on the projected maximum demand in a forecasting period. Furthermore, we introduce an accurate model for estimating the bandwidth required to satisfy the traffic demands of an operator's subscribers for a projected demand model. For the auction process, we map the spectrum access problem into a bounded knapsack problem which is solved using dynamic programming in pseudo-polynomial time. The solution uses the second price strategy, i.e. the winner pays the second highest price. Simulation results show more than 20% reduction in the required spectrum and up to 80% reduction in the average unutilized spectrum as compared with traditional static spectrum access due to the on-demand spectrum assignment.**

Keywords— Dynamic spectrum access; auction; peak load pricing, carrier aggregation; knapsack problem.

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I. Introduction

In recent years, wireless communications have expanded due to the increasing number of wireless electronic devices as well as their requests to more services e.g. video delivery services. This expansion of the data traffic demands typically exceeds the initial planning of the spectrum allocation. Hence this leads to the persistent problem of radio spectrum shortage. This triggers the telecom regulators to reconsider the traditional policies and methods of spectrum access.

Static long-term Spectrum Access (SSA) currently adopted by spectrum regulation authorities result an inefficient utilization of such a scarce resource: the wireless spectrum. Furthermore, static long-term spectrum access does not guarantee neither the highest revenue for the spectrum owner (e.g. government), nor the maximum welfare of the people, who aspire to obtain the wireless services at the lowest cost. Thus motivated, regulatory organizations are currently considering the adoption of dynamic spectrum access approaches that allow the different wireless operators to share the available spectrum based on their demands.

Such dynamic access policies would be required to take the temporal and geographical variations in the demands of different operators into account when allocating the spectrum shares of the individual operators to achieve the maximum allocation efficiency. In order to maximize the spectrum owner revenue and the users' social welfare, such dynamic spectrum access approaches typically adopt an auction or auction-like process. The auction process allows the competing operators to dynamically change their bids and the spectrum owner decides whom to grant spectrum access at which price. Such a problem has recently gained significant attention due to the win-win nature of this process.

In this paper, we present a dynamic spectrum access framework which exploits the capabilities of LTE-Advanced carrier aggregation. Carrier aggregation (CA) has been standardized in LTE Release 10 as a technology to boost the capacity by allowing flexible expansion of the spectrum. The main features of carrier aggregation are its backward compatibility with release 8 and 9 capabilities and the ability of spectrum aggregation of individual component carrier (CC) dispersed within and across different bands (intra/inter-bands). CA also allows the combination of CCs having different bandwidths. Hence carrier aggregation is considered a practical solution for the LTE spectrum fragmentation. These features offer significant flexibility for efficient spectrum utilization.

Unlike related work, the proposed Dynamic Spectrum Access framework with Carrier Aggregation (DSA-CA) for primary operators in LTE-Advanced mobile communication network is based on a *realistic and accurate* model to estimate the spectrum demands for POs. The proposed framework defines two different pricing schemes to dynamically allocate the CCs based on the supply-demand relationship. The first scheme is used when the available spectrum exceeds the PO demands. The second pricing scheme is used when the available spectrum is not sufficient to fulfill the PO demands. Hence, our framework prevents the revenue from collapsing in the abundance of supply with low PO demands. We use system-level simulation to shows the main performance improvement effects achieved by the proposed DSA-CA framework with respect to conventional static spectrum access. Our results show more than 20% reduction in the required spectrum and up to more than 80% reduction in the average unutilized spectrum.

The rest of this paper is organized as follows: In Section II, the related research is summarized. We describe the system model involving the function of spectrum owner in Section III. In Section IV, we propose the DSA-CA framework and algorithm. In Section V, we describe the estimation of spectrum demand model in LTE-Advanced environment. Simulation results are given in Section VI. Finally, Section VII concludes this paper.

II. Related Work

Dynamic spectrum access has been extensively addressed in the literature from different aspects. In this section, we summarize the closely related research efforts.

The basic dynamic spectrum access model for primary operators was presented in [1] in which a primary user, i.e. the spectrum owner, rents spectrum to the secondary users. The model can be mapped to the service providers offering service to users directly. To address this model, the paper presented a hierarchical auction which comprises of three tiers: the spectrum owner tier, the primary operators tier, and the mobile users tier. In [2], the authors seek to exploit the variation in the loads of various radio-access networks to allocate the spectrum efficiently by dynamic spectrum scheme, where the spectrum owner performs Vickery auction periodically between service providers. Meanwhile, the model in [3] proposed a dynamic spectrum allocation process, where multiple wireless service providers compete to acquire the necessary spectrum band from a common pool of spectrum by different auction mechanisms. The model in [4] proposed a real-time spectrum auction to support spectrum allocation and pricing of a large number of secondary users under interference constrains whereas the work in [5] addressed the fairness issue when the secondary users suffer from interference constrains. Similarly, the models in [6] and [7] presented frameworks for dynamic allocation based on auction that is mapped into 0-1 knapsack problem and game theory based schemes that capture the interaction among the spectrum owner, primary service providers (PSPs) and end-users in a multi-provider setting.

Out of the previously cited works, only [8] and [9] consider DSA on top of carrier aggregation, however, they do not address the primary operator spectrum allocation problem (i.e., them assume each primary operator has already been assigned its spectrum share). The authors in [8] suggested a dynamic spectrum access algorithm which works jointly with carrier aggregation. This algorithm depends on a spectrum policy server that collects data about selected enhanced Node-B’s (eNBs) to dynamically activate and deactivate the assigned component carriers as a means of bandwidth adaptation. In [9], the authors proposed a dynamic interworking carrier aggregation framework which involves every network operator releasing some of its exclusive, but excess, spectrum to another network operator for a limited time.

In this work, we follow a similar DSA model as used in [1], [6] and [7]. However, our work distinguishes itself as 1) it is the first work to consider a realistic LTE system model to estimate the required spectrum shares of operators, 2) it maps the auction problem into a bounded knapsack problem in lieu of the realistic system assumption unlike [6] and [7] that consider simplified 0-1 knapsack problem formulation, and 3) it presents an accurate system-level simulation results rather than validation of a theoretical framework as the case in all of the aforementioned works.

III. System Model

In this work, we consider a mobile cellular environment that consists of L Primary Operators (POs) in an LTE-Advanced (abbreviated LTE-A in the sequel) system and one Spectrum Owner (SO) which is responsible for spectrum management, e.g. the Federal Communications Commission (FCC) in USA and the National Telecom Regulatory Authority (NTRA) in Egypt.

We assume that the SO divides the whole service area, e.g. country, state, governorate, into smaller non-overlapping regions $J = \{1, \dots, r\}$. Each region is composed of a set of hexagonal LTE-A cells.

Each PO acquires a static portion of the spectrum to provide the basic services to its users in all regions. This static allocation is usually obtained via a licensing or an auction process which falls behind the scope of this paper. In order to increase their benefits and meet aggressive demands particularly from broadband users, POs submit requests to the SO to request additional spectrum in the regions where there is an increased demand for services which cannot be properly served by the statically-allocated spectrum alone. We assume that the SO divides the available spectrum into W equal and homogeneous spectrum chunks which, for the sake of practicality, are defined to be compliant with LTE-A component carriers (CCs) definition. The PO is interested in the quantity not the quality of CCs that will be allocated to it. The bandwidth of each CC follows the LTE Rel-8 supported bandwidth configurations, meaning 1.4, 3, 5, 10, 15, and 20 MHz. These W CCs are available in all regions.

The spectrum owner receives the spectrum requests periodically from the POs and then determines the winners set and the price to be paid by the winners. The objectives of the SO are to maximize its revenues and to increase the spectrum utilization efficiency as well as achieving social welfare. On the other hand, the objective of the POs is to maximize their benefits by reducing expenditures compared to the case of static allocation based on the projected maximum demand in a forecasting period. Another goal would be to allow the PO to attract more customers by offering attractive pricing for the periods of the day that the PO is allocated ample bandwidth.

The requests of spectrum are set for a pre-specified lease time decided and declared by the SO, e.g. 4 hours or 6 hours etc. At the end of predetermined lease time, the rights to the leased CCs are revoked and the SO decides the allocation for the next period based on the PO's bidding again and so on. This manner is conforming to the benefits for each of the SO and POs, where the POs will only lease the needed spectrum and the SO will ensure the spectral efficiency.

IV. Proposed DSA-CA Framework

In this paper, we present a DSA framework that can be applied in practice using carrier aggregation capabilities of LTE-A. By making DSA dependent on CCs in a CA-based LTE-A, we achieve dynamic reaction to the cell load. This can be achieved by a network management system (NMS) and proper signaling between the SO and the PO's by sending management messages that contain the list of allocated CCs in a given region. The PO's NMS will then activate the list of CC's in its eNBs and deactivates them at the end predetermined lease time units in a few time slots. The activation/deactivation mechanism is based on a combination of radio resource control (RRC) control messages and deactivation timers [10]. For the time being issues like handling on-going connections at the end of lease time are left for future work.

Due to the dynamic nature of the spectrum requests and the available supply, our framework follows a similar approach to that proposed in [1] which uses two different pricing schemes: *auction* and *peak-load* *pricing* (PLP) [12] schemes depending on the total spectrum requests and the available supply. Unlike [11], we consider a realistic LTE environment, hence, the underlying auction model and design is fundamentally different. *Auction* schemes have proven success when the demand exceeds the supply, and as such, are effective in selling spectrum resources when they are scarce. However, it is not suitable in the case of lack of competition between buyers due to abundance of supply. The spectrum owner uses *PLP* scheme when the sum of spectrum requests are less than the available supply. On the other hand, it uses *auction* scheme with a reserve price from the previous *PLP* when the sum of spectrum requests are greater than the available supply. The control between the two schemes is done at the SO, where the POs submit their requests of spectrum and then the SO will decide which scheme will be used. In case of the *PLP* scheme, the SO will broadcast the price per CC and the role of POs is either to accept or reject the price and in case of *auction* scheme the SO will broadcast the winner prices and their assignments after the end of the *auction*.

A. ***PLP-based Spectrum Access***

When the sum of requests of spectrum in a region is less than the available supply PLP is used. PLP is a pricing scheme with proven success in pricing the non-storable commodities whose demand varies periodically. The objectives of PLP are deriving efficient pricing, maximize social welfare and optimize the producer's revenue. According to the work of Steiner [12] who adopted the conventional welfare-maximizing approach $WE = TR + S - TC$, where WE is the net of social welfare, TR is the total revenue, S is the customers' surplus and TC is the total cost. Steiner proved that the price will be optimal if the commodity's unit (in our case the CC) will cost c during demand less than the supply, where c denotes the operating cost per unit per period [12].

B. ***Auction-based Spectrum Access***

On the other hand, when the sum of requests of spectrum in a region exceeds the available supply an auction is held. Spectrum auction is a multi-unit auction that makes POs demands its need of CCs for the predetermined time units by one request, i.e. bid in the language of auction theory, in each region. If demand exceeds the statically allocated chunk to a PO from different regions, so it must submit a bid in each of these regions.

POs do not have a hard requirement on their bids, i.e. POs prefer to obtain allocated spectrum from SO that is less than its need rather than getting nothing.

The problem described here has a very close connection to the classical bounded knapsack problem [13], where the goal is to fill a sack of finite capacity with several identical items such that the total valuation of the items in the sack is maximized. Here, the sack represents the finite spectrum capacity the SO is willing to lease to the POs in such a manner that the revenue generated from these POs is maximized. In this regard, we propose a formulation based on the "Bounded Knapsack Auction" (BKA) problem.

We denote a strategy adopted by POs by a tuple $q_{ij} = (f_{ij}, p_{ij})$ defined as an element of the bids structure Q, where f_{ij} which denotes the number of CCs required by PO i in region j is an element of the matrix F of required CCs of PO i in region j and $p_{ij} \in P$ which denotes the price per CC by PO i in region j is an element of prices matrix P .

We formulate the BKA as follows.

$$max \sum_{i}^{L} p_{ij} x_{ij}, \forall j \in J$$

Subject to

$$p_{ij} \geq c_j, \forall i \in L, \forall j \in J$$

$$\sum_{i}^{L} x_{ij} \leq W, \forall j \in J$$

$$0 \leq x_{ij} \leq f_{ij}, \forall i \in L, \forall j \in J$$

$$x_{ij}\ is\ integer, \forall i \in L, \forall j \in J$$

where x_{ij} which denotes the number of CCs to be allocated to PO i in region j is an element of the allocation matrix X and c_j which denotes the reserve price of the auction in region j is an element of the reserve price vector C , i.e. the price of the resulting from the last PLP in region j. Our goal is to solve the winner-determination problem in such a way to maximize social welfare, i.e. allocating spectrum to PO who values it the most in other words maximizing the total utility of all PO in the system, including the SO. Then, the SO determines the payments to be paid the winners. In this paper, we consider the second price bidding strategy. In second price bidding, bidders do not need to guess other bidder's bids but can offer a bid request which reflects their own valuation of the commodity [14] (in our case the CC). Each winning bidder does not pay their bidding price but pay the second highest bidding price.

Due to the close connection between bounded knapsack problem and 0-1 knapsack problem, the conventional solution's method of the bounded knapsack problem is firstly done by converting the problem into 0-1 knapsack problem and then solving the 0-1 knapsack problem. The conventional solution's method of 0-1 knapsack problem is by using the dynamic programming concept, i.e. breaking the problem into sub-problems that is solved by working backwards from the last stage. Our proposed DSA-CA is shown in algorithm 1.

V. Estimation of Spectrum Demand in an LTE-Advanced Environment

In this section, we present a methodological approach for accurately estimating the spectrum demand of POs on a certain time of day in a specific region. In order to estimate the spectrum demand of POs on a certain time of day in all regions, we provide a model for mapping the cells' traffic demand, taking into account the various LTE-A overheads, to the respective bandwidth.

Algorithm 1: Proposed DSA-CA algorithm

Input: Number of available CCs W**,** Bids structure $Q = (F, P)$
Output: Allocated matrix X and payment matrix Y
Initialize: Reserve price matrix C
for $j \in J$ **do**
  if $\sum_i f_{ij} > W$ **then**
    <u>Auction is used</u>
    for $i \in L$ **do**
      if $p_{ij} < c_j$ **then**
        $x_{ij} = 0;$
        $y_{ij} = 0;$
        Exclude index i of this operator;
    $\bar{L}$ denotes the modified number of operators.
    <u>Transform into 0-1 knapsack</u>
    Input: number of operators $\bar{L}$, price vector p_j, required vector f_j
    Output: modified price vector $\bar{p}_j$, modified required vector $\bar{f}_j$, number of modified bids $\bar{n}$
    $\bar{n} = 0;$
    for $i \in \bar{L}$ **do**
      $\beta = 0; k = 1;$
      repeat
        if $\beta + k > f_{ij}$ **then**
          $k = f_{ij} - \beta;$
        $\bar{n} = \bar{n}+1; \bar{p}_{\bar{n}j} = k * p_{\bar{n}j};$
        $\bar{f}_{\bar{n}j} = k; \beta = \beta + k; k = 2 * k;$
      until $\beta = f_{ij}$
    <u>Solve 0-1 knapsack</u>
    $A = zeros(\bar{n} + 1, W + 1);$
    for $h = 1: \bar{n}$
      for $g = 1: W$ **do**
        if $\bar{f}_{hj} > g$
          $A_{h+1,g+1} = A_{h,g+1};$
        else
          $A_{h,g} = max(A_{h,g+1}, \bar{f}_{hj} + A_{h,g-\bar{f}_{hj}+1})$**;**
    $best = A_{end,end};$
    Now backtrack to know the items in the sack;
    Set the assignments x_{ij};
    Set the payments $y_{ij} = x_{ij}$* second heights bidding price ;
  else
    <u>PLP is used, Announce the price c_j</u>
    for $i \in L$ **do**
      if operator i accepted the price c_j **then**
        $x_{ij} = f_{ij};$
        $y_{ij} = f_{ij} * c_j;$
      else
        $x_{ij} = 0;$
        $y_{ij} = 0;$
Return (X,Y);

A. Traffic Model

The cells' traffic demand varies dynamically in time and space. This dynamicity varies in accordance with the users' density distribution for each PO. The density distribution varies from region to region for the same PO. However, the user population is not active all the time and the users' activity differs from PO to another and differs in space and time with the same PO. We follow the same estimation methodology of traffic model as in [15] with additional modifications to know the generated cells' traffic demand of all POs. The following quantities are used in our modified model:

- The population densities p_d $[citizen/Km^2]$ in different deployments d, see e.g. Table I.
- The mobile subscribers' percentage m_d out of the total population in different deployment d.
- The broadband users' percentage, i.e. LTE and LTE-A users, $b_d = \sum_k s_k$ and the broadband active users' percentage$a_d$in different deployment d, where s_k denotes the fraction of broadband subscriber of the whole broadband subscribers for terminal k.
- The estimated rate r_k required for each terminal k, e.g. Table II.
- The normalized daily traffic variations curve $\alpha(t)$, e.g. Fig. 1.
- The Inter-Site Distance (ISD) of this cell.

B. Traffic Mixes

The estimated rate of each broadband user comes from different services, i.e. traffic mixes of a user. We assume that this traffic mix is the same for all users and consists of TCP services, e.g. downloading, browsing and gaming, and VoIP services with different codecs, e.g. 12.65 kbps and 6.06 kbps. The percentage of TCP and VoIP services are 80% and 20% respectively. Table III shows the percentage of each service and the average size of the application payload.

C. LTE-A Overheads

To be able to accurately transform the application/terminal bit rate into bandwidth, we need to account for the different forms of overheads added by the protocol stack comprised of TCP/IP/LTE layers and the specific structure of the LTE-A PHY later. The necessary overheads of LTE-A system composed of five types: multiple protocol layers overheads, the spectrum emission guard, reference signals overhead, control channels overhead and finally the synchronization signals overhead [16].

Protocol overheads depend on the type of the service. In case of TCP services, the different protocol layers add 18 bytes to the application layer payload and in case of VoIP services, the different LTE layers adds 9 bytes to application layer payload after header compression [17]. Table III shows the percentage of the overhead at different services. The last column of Table II provides the rates of different terminals after adding the protocol overheads. The other four overheads depend on the cell bandwidth. The emission guard overhead is the difference between the CC bandwidth and the bandwidth of the number of resource block in this channel, where the resource block consist of 12 subcarriers with a total bandwidth of 180 kHz [16]. The reference signals overhead differs based on the MIMO configuration. For 2*2 MIMO, the reference signals occupy eight resource elements per resource block [16]. The maximum control channel overhead occupies three OFDM symbols per sub-frame [16]. The synchronization signals overhead occupy two resource elements for primary synchronization signals and another two resource elements for secondary synchronization signals per frame [16]. Table IV reflects the percentage of these four overheads at different cell bandwidth and the residual spectrum after excluding the overheads.

For a given inter site distance (ISD), the hexagonal cell area is given by $\mathrm{A} = \frac{\sqrt{3}}{2}\mathrm{ISD}^2$. Thus, the users' traffic demand curve of a PO over a cell in a deployment d is determined by

$$R_d(t) = \frac{{A_d}^2}{1000^2} p_d m_d a_d \alpha(t) \sum_k \mathcal{R}_k s_k \text{[bits/s/cell]} \qquad (1)$$

At a specific average SINR and specific transmission mode we obtain the CQI from Table III in [18] and, in turn, we compute the spectral efficiency from Table 7.2.3-1in [19]. The final step is to divide the generated cell traffic demand curve (1) by spectral efficiency. The number of required CCs in this cell is obtained by dividing the cell spectrum demand by the respective number in of the last row of Table IV for the chosen CC allocation granularity.

VI. Performance Evaluation Results and Discussion

To demonstrate the effectiveness of the proposed DSA-CA framework and the bounded knapsack auction, we conducted system level simulation experiments. We next describe the network model and its assumptions, and then show the scenarios of interest and the DSA-CA bidding price parameters.

We consider a cellular network composed of three POs, i.e. $L = 3$, which we call A, B and C. The SO divides the overall service area into two regions, i.e. $r = 2$, which we refer to as R1 and R2. We consider that R1 region is composed of three LTE-A cells whereas R2 is composed of four LTE-A cells. We also assume that each PO has 5 MHz that was statically allocated in all regions.

The cells of the two regions are deployed as follows: the first region's cells and the first cell of the second region belong to dense urban deployment whereas the other three cells of the second region belong to urban deployment. Table VII shows the other simulation parameters of a specific day. This deployment is set to give a clear illustration of the gain resulting from the division of the service area into smaller regions to take advantage of the variations of spectrum demand between regions.

We assume that all broadband users of all POs have the same traffic mix as shown in Table III, and then we assume that the average SNR at all cells equals 3 dB which translates to spectral efficiency equals 1.1758 b/s/Hz at 2*2 MIMO configurations. We also assume that the operators reuse the winning CCs in the same region with factor equals one.

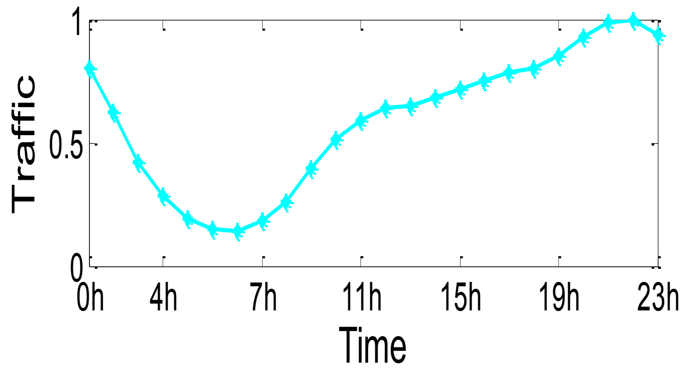

Fig 1. Normalized daily traffic variations [15].

TABLE I. POPULATION DENISITES OF DIFFERENT DEPLOYMENTS FROM EUROPE [15].

Deployment d	**Population Density p_d [citizen/ Km^2]**	**Inter-Site Distance [m]**
Dense Urban	3000	500
Urban	1000	1000
Suburban	500	1500
Rural	100	2000

TABLE II. TERMINALS AND THIER ESTIMATED RATES [15].

Terminal k	**Mixes s_k [%]**	**Rate r_k [Mbps]**	**Rate After Adding The Protocol Overhead$\mathcal{R}_k$[Mbps]**
Heavy PC Users	10	2	2.3698
Average PC Users	10	1	1.1849
Heavy Smartphone Users	25	0.5	0.5924
Average Smartphone Users	25	0.25	0.2962
Heavy Tablet Users	2.5	0.25	0.2962
Average Tablet Users	2.5	0.125	0.1481

TABLE III. PROTOCOL OVERHEAD PERCENTAGES

Users' Traffic Mixes	**80 % TCP**			**20 % VoIP**	
	30 % Downloading	***20 % Gaming***	***50 % Browsing***	***50%with Codec 12.65kbps***	***50%with Codec 6.60kbps***
Average Size of Application Payload [Bytes]	1500	500	75	33	17
Protocol Overhead [%]	1.2	3.6	24	27.27	53

TABLE IV. RESIDUAL SPECTRUM AFTER EXCLUDING ALL OVERHEADS AT DIFFERENT CHANNEL BANWIDTH

CC Bandwidth [MHz]	**1.4**	**3**	**5**	**10**	**15**	**20**
Number of Resource Blocks N_{RB}	6	15	25	50	75	100
Reference Signals Overhead (2*2)	8 signals per Resource Block (9.5%)					
Control Channels Overhead	3 Symbols per Sub-frame (21.4%)					
Synchronization Signals Overhead	4 signals per Frame (0.23%)					
Effective Residual Spectrum After Excluding all Overheads [MHz]	0.743	1.859	3.099	6.198	9.297	12.396

TABLE VII. SIMULATION PARAMETERS

Regions	R1									R2											
Cell ID	#1			#2			#3			#1			#2			#3			#4		
Population Density [citizen/ Km^2]	3000			3000			3000			3000			1500			1500			1500		
Inter-site Distance (ISD) [m]	500			500			500			500			1000			1000			1000		
Primary Operates	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
Percentage of Mobile Users [%]	35	25	20	40	20	20	35	20	25	20	30	35	20	25	40	25	25	35	20	30	35
Percentage of Broadband Users [%]	75	75	75	75	75	75	75	75	75	75	75	75	50	50	50	50	50	50	50	50	50
Percentage of Active Broadband Users [%]	10	16	20	10	16	20	10	16	16	10	10	10	10	10	10	10	10	10	10	10	10

Two particular cases of the daily traffic variations were identified, labeled scenario 1 and 2 as illustrated in Fig. 2 (a) and (b) respectively. Scenario 1 represents the case where all operators have identical or semi-identical traffic variation with time-of-day. Scenario 2 where there are shifts in the traffic demand pattern over the time-of-day. These scenarios were set to give a clear illustration of the DSA-CA effects on network performance resulting from the shifts in the traffic demand pattern over the time-of-day.

Fig. 3 and Fig. 4 show the CCs required by the three operators in the two regions in case of scenario 1 and scenario 2, respectively, where DSA-CA is held every four hours as an example. A single bar in the two figures reflects the number of CCs required by the three operators of a particular cell. The three grouped bars in (a) reflect the demand from the cells ID 1, 2 and 3 in region 1 respectively whereas the four-grouped bars in (b) reflect the cells ID 1, 2, 3, and 4 in region 2 respectively. The stairs show the CCs required to cover the demand in case of DSA-CA is held every four hours. We used conventional SSA, a dedicated spectrum configuration, as reference to evaluate the performance of the DSA-CA framework which is shown by the straight line. These two figures show the gain due to the use of the proposed DSA-CA demonstrated by the difference between the straight line and the stairs. The two figures also show the gain resulting from the division of the service area into regions that have different density in CC required as shown by the different stairs shape and their minimum and maximum values in the two regions of the two figures. Also, the gain due to the shifts in the traffic demand pattern of the different POs over the time-of-day is shown by the maximum CCs required in the second region of the two figures.

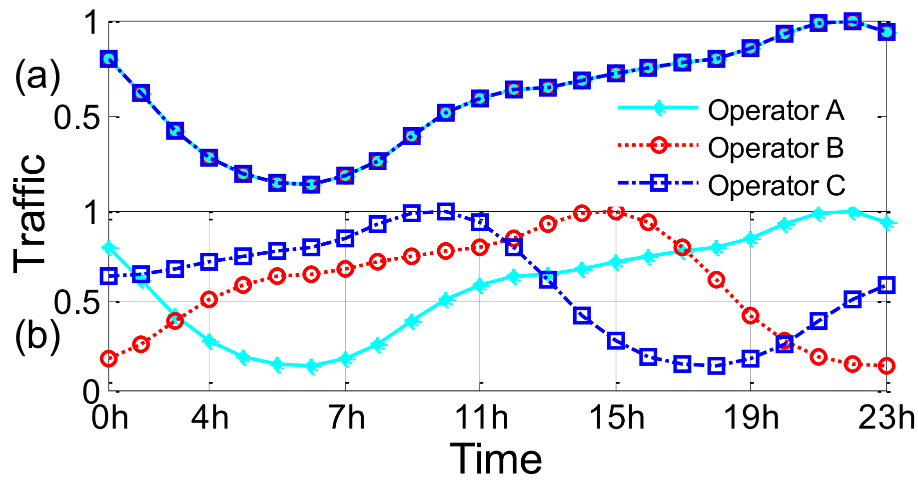

Fig. 2. Normalized daily traffic variations of (a) scenario 1 and (b) scenario 2.

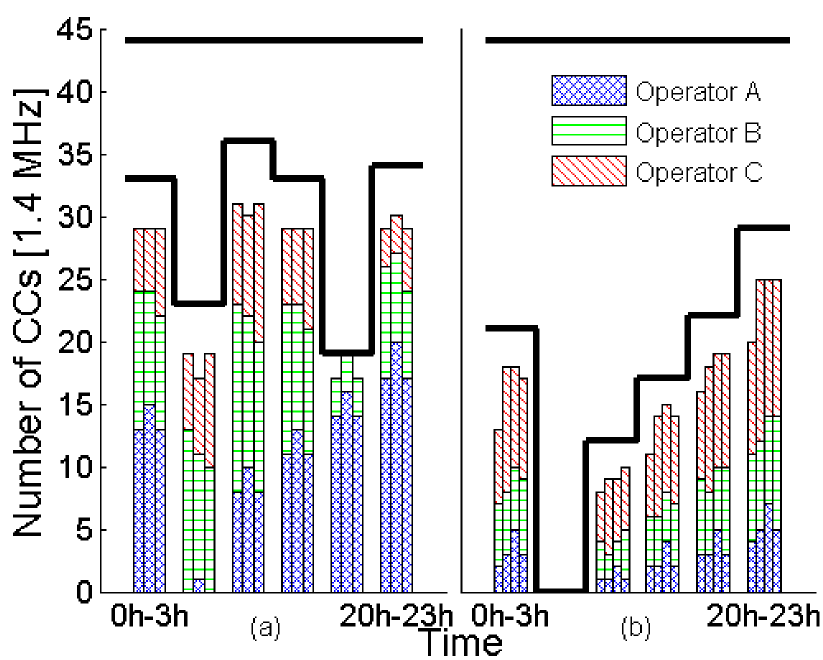

Fig. 3. The CCs required from different cells **Scenario 1** in (a) R1 and (b) R2. The black stairs show the actual CCs required to cover the demand from all cells over four-hour periods. The straight black line shows the CCs required in case of SSA

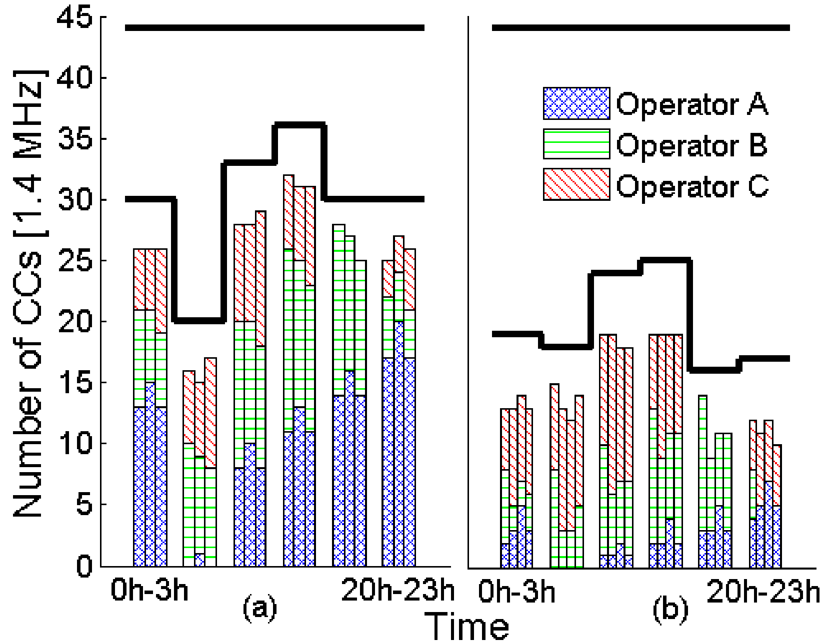

Fig. 4. The CCs required from different cells for Scenario 2 in (a) R1 and (b) R2. The black stairs show the actual CCs required to cover the demand from all cells over four-hour periods. The straight black line shows the CCs required in case of SSA

There are some factors that affect the performance of DSA-CA, e.g. the available CC sizes in the market, the predetermined leasing time units and the message overheads between POs and SO. In Fig. 5 and Fig. 6, we show these effects based on the two key performance indicators *maximum spectrum needed* to serve all demands from the different cells and *average unutilized spectrum*, i.e. the average of the unused spectrum by all POs per hour [Hz/Hr], due to the difference of demands between cells. The message overheads will decrease whenever the DSA-CA increases pre-specified lease time units. Fig. 5 shows the huge gain of DSA-CA, almost in all cases of DSA-CA, which is up to 80% reduction in the unutilized spectrum in the case of CC = 1.4 MHz and the DSA-CA is held every hour over conventional SSA. This huge gain comes from the dynamic reaction to the operators load due to DSA-CA as compared to conventional SSA. Fig. 6 shows the spectrum which should be provided by the SO to cover all demands of POs. Also, Fig. 6 shows that at scenario 1, the required spectrum quantity is close to the case of conventional SSA since the three operates have identical traffic variations with time-of-day. Meanwhile, the gain of DSA-CA become more significant (more than 20% reduction in the required spectrum) in scenario 2 in case of CC=1.4 MHz and the

DSA-CA is held every hour as compared to conventional SSA due to the time shifts in the traffic demand pattern over the time-of-day.

To gain insight about the revenue of SO, we assume all the spectrum bands are of equal value to all the POs. Note that through this simulation model, we use the notation unit instead of any particular currency. Firstly, the parameters of the auction, the *reservation price* of one CC for each POs is assumed to follow a uniform distribution with minimum 15, 40, 60 and maximum as 30, 55, 75 units in case of CC equal 1.4 MHz, 3 MHz and 5 MHz respectively. Secondly, the the price of PLP is assumed to follow a uniform distribution with minimum 15, 40, 60 and maximum 20, 45, 65 in case of CC equal 1.4 MHz, 3 MHz and 5 MHz respectively. Furthermore, we assume that the bidders use auction histories of previous rounds to submit their bids in future rounds. Thus a winning bidder (a one which won all its needs or all the market in one DSA period) will try to submit a lower bid in next DSA period so that to be greater than the last announced PLP price to increase his surplus profit whereas a losing bidder will increase his bid so that to be smaller than his maximum reservation price. The details of this price adjustment are outside the scope of this paper.

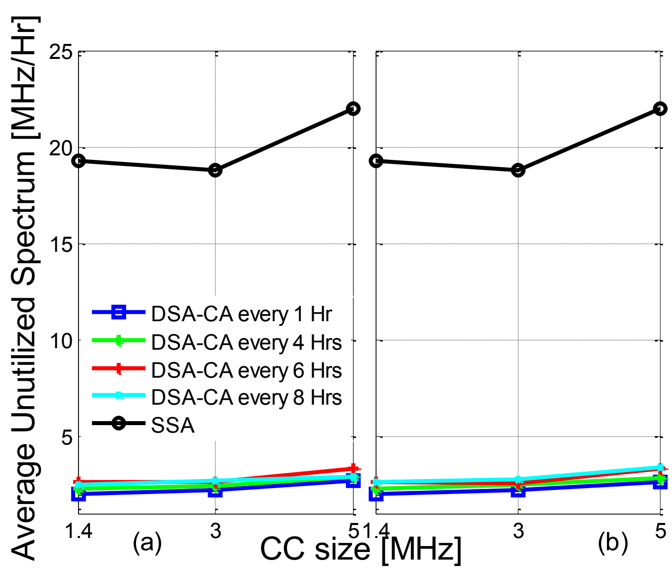

Fig 5. Average unutilized spectrum in case of (a) scenario 1 and (b) scenario 2.

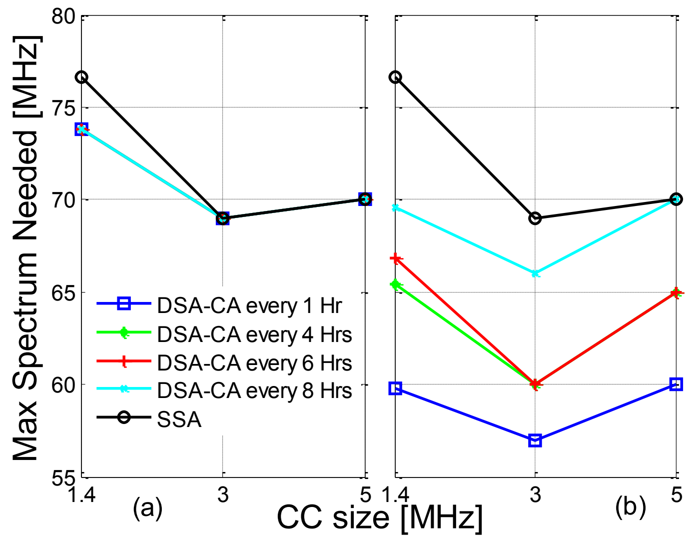

Fig. 6. Maximum Spectrum Needed in case of (a) scenario 1 and (b) scenario 2.

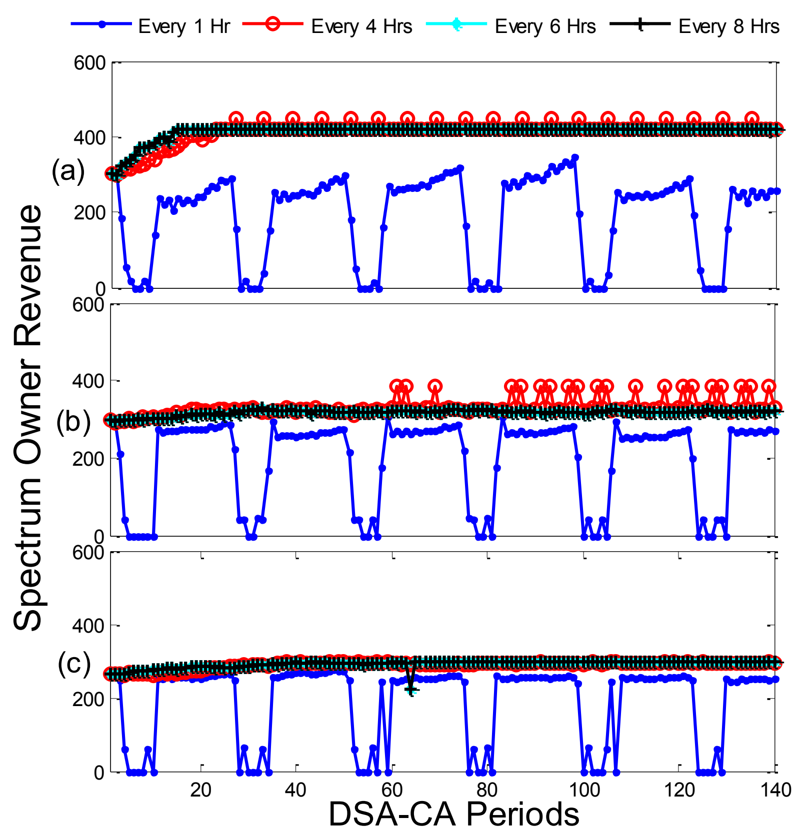

Fig. 7. Revenue of spectrum owner in case of (a) CC = 1.4 MHz, (b)_CC = 3 MHz and (c) CC = 5 MHz.

Fig. 7 shows the revenue generated by SO with the increase in the DSA-CA periods in scenario 1, where the market has 20 MHz which is divided into fourteen CCs with size 1.4 MHz, six CCs with size 3 MHz, or four CCs with size 5 MHz. Fig. 7 shows that the revenue from DSA-CA that is held every hour is lower than the revenue from DSA-CA that is held with higher time units at the three different CC sizes. This decrease in revenue is due to lack of demand from the POs who are demanding their needs every hour as opposed to an increase in demand in case of the DSA-CA that is held with higher time units which must take into account to demand the maximum number of CCs in this pre-specific lease time units. However, the decrease in revenue is acceptable as this decrement in revenue should be compared with the low average unutilized spectrum that was shown from Fig. 5 in the same case that means saving large spectrum quantity for SO.

VII. CONCLUSIONS

In this paper, we have presented a DSA-CA framework, feasible DSA for LTE-Advanced networks based on the capabilities of Carrier aggregation. We also have presented an accurate model to estimate the cell's traffic, taking into account the various LTE-Advanced overheads, to estimate the bandwidth needed. This framework presented two different pricing schemes bounded knapsack auction and peak load pricing based on the relation between the demand and the supply status to prevent the revenue of spectrum owner from collapsing in case of abundance of supply. The system level simulation demonstrated an enhanced performance compared to static spectrum access with up to more than 20% reduction in the required spectrum and up to more than 80% reduction in the average unutilized spectrum. Our future work will focus on incorporating fairness in the spectrum allocated to the different operators. Furthermore, we will thoroughly investigate the optimal size of CC and the optimal time unit for leasing from the spectrum owner's point of view. Also, it is worth defining the needed management messages to allow the dynamic switch to new CCs each lease period and the handling of on-going connections in case of used CC’s be revoked.

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