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Delay Aware Resource Allocation Scheme for a Cognitive LTE Based Radio Network

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Abstract— We explore the problem of resource allocation in a Third Generation Partnership Project (3GPP) long-term evolution (LTE) based cognitive radio network (CRN). The network model consists of a number of service providers (SPs) with fixed licensed spectrum bands. The network offers the wireless services to two types of users: primary and secondary. The primary users (PUs) get prioritized access to the licensed spectrum bands. The secondary users (SUs) are served on the best-effort (non-prioritized) basis. In this paper we consider the specific design features of LTE radio interface associated with the uplink spectrum access, scheduling process, and limited control channel capacity of the LTE system. We establish the relation between the number of users in the system, and the scheduling delay (which is the largest contributor to the packet end-to-end delay in LTE network). Using these results, we propose a simple algorithm to assign the spectrum for the SUs without violating the quality of service (QoS) requirements of the PU, and implement it in an LTE-based CRN. Consistent performance of the algorithm is verified using OPNET-based simulations.

Keywords— LTE, cognitive radio network, resource allocation, packet scheduling

I. INTRODUCTION

In a CRN the wireless access is provided to the PUs and the SUs according to some predetermined user etiquette. Within a CRN, the PUs get the ultimate prioritized access to the licensed spectrum bands, whereas the SUs are served on the best-effort (non-prioritized) basis [1]. From the multiplicity of wireless standards proposed for deployment in CRN, the 3GPP LTE is considered to be the most promising mainly due to its high capacity [2]. In LTE, the available transmission resources are assigned to the users by the medium access control (MAC) schedulers located in enhanced NodeBs (eNBs). The standard specifies a general framework, and the control signalling on physical and MAC layer. The choice of the exact algorithm for resource allocation is left for the network developers (it can be based on queuing delay, instantaneous channel conditions, fairness, etc.). The scheduling process allows assigning the dedicated channels to the users based on their priority, and QoS requirements [3]. However, it introduces an additional delay in the uplink channel, which cannot be neglected in some special cases (for instance, for delay sensitive applications) [4].

In this work we present an alternative approach for resource allocation in LTE-base CRN architecture. Considering, that the end-goal of CRN is to serve as many SUs as possible without violating the QoS requirements of PUs, we propose to formulate the problem of spectrum assignment for SUs as an optimization problem with certain delay constrains on PUs. The challenge arises from the specific design features of LTE radio interface which can be formulated as follows. Because of the small subframe size, the packet transmission and buffering delays for the users in an LTE system are very small (2 ms or 10% of the packet end-to-end delay) and does not depend on the number of users in the system. The largest component of the packet end-to-end delay (more than 8 ms or 36%) results from the control signaling during the scheduling process in LTE system. This delay component depends on the number of users in the cell, and increases if the number of users exceeds the control channel capacity of the serving eNB [4, 5].

Scheduling performance for different types of the users have been studied in many papers: various multiuser scheduling strategies in the context of OFDMA downlink were described in [6 - 10]; the uplink capacity of LTE system have been investigated in [11] and [12]. Although these works provide a closer look on the capacity and coverage of LTE network depending on the channel conditions, resulting end-toend performance of wireless communication systems is evaluated only by means of simulations, and no analytical result is available. The average values of various delay components including delay due to packet scheduling have been given in [5]. However, no proper mathematical analysis confirming the delay values have been presented.

In this paper we derive the expression of the delay as a function of the number of users in eNBs, and apply this expression in resource allocation problem. We derive the algorithm for spectrum assignment for SUs, and verify the consistent performance of this algorithm under real network deployment scenarios. The rest of the paper is organized as follows. In Section II we formulate the problem of spectrum assignment for SUs in LTE-based CRN and find the relation between the scheduling delay and the number of users. In Section III we provide the example of algorithm implementation in LTE network and validate the consistent performance of the algorithm using the simulative performance study.

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II. RESOURCE ALLOCATION PROBLEM

Consider a typical cognitive radio network (CRN) model based on LTE standard network illustrated on Figure 1. It comprises a core networking part and *m* service providers (SPs) offering the wireless services via a set of respective eNBs numbered eNB₁, ..., eNB_m. Similar to the standard LTE system, this network operates on a slotted time basis: the time axis in the model is partitioned into discrete mutually disjoint intervals of length T_s {[tT_s , (t+1) T_s]}, t = 0, 1, 2, ..., with T_s denoting the subframe (in LTE $T_s = 1$ ms), and t denoting the integer values index of T_s .



Fig. 1. A typical CRN model based on LTE standard network

A CRN provides wireless access to N active primary users (PUs) and X active secondary users (SUs). PUs are the licensed network users who pay to their SPs for accessing the wireless services. SUs are unlicensed network users who access the wireless services for free. Each eNB operates on a fixed licensed spectrum band and serves a number of PUs, randomly arriving to (and leaving) the network with mean arrival rate λ_{PII} (and mean departure rate μ_{PU}). We denote the spectrum band of the eNB_i by b_i , and the instantaneous number of active PUs in eNB_i by n_i . The eNBs can also provide wireless access to SUs, randomly arriving to (and leaving) the network with mean arrival rate λ_{SU} (and mean departure rate μ_{SU}). Within a CRN the PUs get prioritized access to the spectrum band of SP (eNB) they have arrived to. The SUs are served on the besteffort (non-prioritized) basis and can be redirected to the other SP (eNB).

In this work we assume that: i) one SU can connect to at most one eNB; ii) the mean inter-arrival times of PUs and SUs (and the mean inter-departure times of PUs and SUs) are much greater than the subframe duration, i.e. $1/\lambda_{PU} \gg T_s$, $1/\lambda_{SU} \gg T_s$, $\mu_{PU} \gg T_s$, $\mu_{PU} \gg T_s$, which is quite reasonable because in real network the mean inter-arrival times (and the mean interdeparture times) of the users are usually much greater than $T_s =$ 1ms. There are two main objectives of the considered CRN. Firstly, it should provide wireless access for the SUs. Secondly, it should maintain a minimum QoS level for the PUs. Considering, that the QoS for most of the user applications is measured in terms of the packet end-to-end delay, this goal can be reformulated as follows. Maximize the number of SUs in *m* eNBs given that the packet end-to-end delay in eNBs does not exceed some predefined limit. Let x_i be the number of active SUs assigned to eNB_i. Clearly, x_i can take only non-negative integer values.

Let D_i be the average packet end-to-end delay (i.e. the time it takes for a packet to travel from the user through the network to the server, and back) in eNB_i. Let D_i^P be the maximum value of the packet end-to-end delay acceptable for PUs in eNB_i. Then the corresponding optimization problem for the CRN model illustrated on Figure 1 is given by

$$\max \sum_{i=1}^{m} x_i \tag{1a}$$

subject to:

$$D_i \le D_i^P, \quad \forall i \in \mathbf{I} \tag{1b}$$

$$\sum_{i=1}^{m} x_i \le X, \quad x_i \in \mathbf{Z}^+, \quad \forall i \in \mathbf{I}$$
(1c)

where $\mathbf{x} = [x_1, ..., x_m]^T$ is the vector of non-negative numbers; $\mathbf{I} = \{1, 2, ..., m\}; \mathbf{Z}^+$ is the set of all non-negative integers.

To solve the problem (1), we should find the relation between the number of users and the packet end-to-end delay in LTE system. According to [5], the packet end-to-end delay in LTE system is given by

 $D = D^{t} + D^{b} + D^{p} + D^{eNB} + D^{UE} + D^{c} + D^{HARQ} + D^{PS}$ (2) where D^{t} , D^{b} , D^{p} are the total (uplink and downlink) packet transmission, buffering and propagation delays between the UE and the eNB, respectively; D^{HARQ} is the total (uplink and downlink) packet delay due to hybrid automatic repeat request (HARQ) retransmissions; D^{PS} is the uplink delay due to packet scheduling; D^{eNB} and D^{UE} are processing delays of eNB and the user equipment (UE); D^{c} is the total (uplink and downlink) packet delay in core network.

Because of the small size of the subframe (the subframe duration in LTE is equal $T_s = 1$ ms), the transmission and the buffering delay components D^t and D^b are very small in LTE system ($D^t = 2$ ms, $D^b = 1$ ms). The propagation delay D^p and the delay in core network D^c depend on the distance between the UE and the eNB, and the eNB and the server, relatively, and are usually in the order of 1 ms (in case if the distance between the UE and the server does not exceed 1000 km). The components D^{eNB} and D^{UE} depend on the processing capabilities of the equipment (typically around 5 ms) [5]. The delay due to HARQ retransmissions depends on the wireless channel quality. The average value of D^{HARQ} can be estimated using [5]:

$$D^{HARQ} = P^{RTX} \cdot T^{HARQ} \tag{3}$$

where P^{RTX} is the probability of the HARQ retransmission, and T^{HARQ} is the time interval between the first transmission and respective HARQ retransmission (in LTE standard $T^{HARQ} = 8$ ms). It follows from (3) that delay due to HARQ retransmissions never exceeds 8 ms (in general $D^{HARQ} < 4$ ms) [5]. The delay component D^{PS} is associated with the scheduling process in LTE system. The scheduling process allows assign dedicated channels to the users. On the other hand, the scheduling procedure itself introduces an additional delay for all types of the network users (prioritized and non-prioritized).

In LTE the delay due to scheduling is relatively large (in general $D^{PS} \ge 8$ ms) and constitutes the biggest part ($\approx 36\%$) of the packet end-to-end delay. Unlike the other delay components, the scheduling delay depends on the number of users in eNB [4, 5].

Note, that in expression (2) D_i^t , D_i^b , D_i^p , D_i^c , D_i^{eNB} , D_i^{UE} , D_i^{HARQ} do not depend on x_i and can be directly measured at eNB_i (D_i^t , D_i^b , D_i^p , D_i^c , D_i^{eNB} , D_i^{UE} are constants, D_i^{HARQ} depends on the number of HARQ retransmissions in eNB_i). The only delay component which depends on x_i and needs to be restricted in optimization problem is D_i^{PS} . For convenience let us define

$$\Delta_{i}^{P} = D_{i}^{P} - D_{i}^{b} - D_{i}^{P} - D_{i}^{eNB} - D_{i}^{UE} - D_{i}^{c} - D_{i}^{HARQ}$$
(4)

to denote the maximum acceptable scheduling delay in optimization problem (4), which takes the form

$$\max \sum_{i=1}^{m} x_i \tag{5a}$$

subject to:

$$D_i^{PS} \le \Delta_i^P, \forall i \in \mathbf{I}$$
(5b)

$$\sum_{i=1}^{m} x_i \le X, \quad x_i \in \mathbf{Z}^+, \quad \forall i \in \mathbf{I}$$
(5c)

To find the relation between the scheduling delay D_i^{PS} and the number of users in LTE system, we start with a brief description of the scheduling process in LTE system (more detailed description of the scheduling process can be found, for instance, in [12]). The basic radio resource unit in LTE is called a resource block (RB). In frequency domain one RB consists of 12 subcarries with a constant subcarrier spacing Δf = 15 kHz. In time domain it has a length equal to one subframe with duration $T_s = 1$ ms. The number of RBs depends on the channel bandwidth. The capacity of one RB depends on the Modulation and Coding Scheme (MCS), which determines the bit rate [12, 13]. LTE resources are allocated to user equipments (UEs) for uplink and downlink data transmission in terms of RBs. Thus, one UE can be allocated only an integer number of RBs in frequency domain, and these RBs do not have to be adjacent to each other. Resource allocation (scheduling) is carried out by the MAC layer packet scheduler in the eNB, both for uplink and downlink transmissions [13]. The scheduling decisions are made based on the quality of service (QoS), user priority, fairness and instantaneous channel conditions.

The standard dynamic packet scheduling scheme can be described as follows. Within one subframe with duration equal $T_s = 1$ ms all active UEs generate the scheduling requests (SRs) and send them via the physical uplink control channel (PUCCH) to eNB using the format 1 messages. The eNB receives the PUCCH information, decodes the PUCCH format 1 messages, allocates the resources and sends the scheduling grants (SGs) to UEs via the physical downlink control channel (PDCCH) using the downlink control information (DCI) format 1 messages. The duration of this procedure is equal $T_{SR} = 4$ ms. UEs receive the PDCCH information, decode the DCI format 1 messages, and transmit the uplink data via the physical uplink shared channel (PUSCH). This procedure takes exactly $T_{SG} = 4$ ms [13].

Because of the finite capacity of the PDCCH and PUCCH, the scheduler is constrained in its freedom of how many users to address in a subframe [20]. Thus, if the number of scheduling requests (SRs) sent in one subframe is not more than the PDCCH/PUCCH capacity, all UEs generating SRs are scheduled and can transmit the uplink data. Otherwise, i.e. if the number of scheduling requests (SRs) sent in one subframe is more than the PDCCH/PUCCH capacity, the scheduling for some UEs generating SRs will be delayed for the next subframe. For delayed users the scheduling procedure will be repeated, i.e. they should send the scheduling request and scheduling grant again [4, 14].

To estimate the scheduling delay D^{PS} consider a cell consisting of a number of UEs and a eNB. The number N_{SR} of UEs generating SRs in one subframe is equal to the number of active UEs in the cell. Let C^{CCH} be the control channel capacity, i.e. the number of UEs that can be scheduled in one subframe. If $N_{SR} \leq C^{CCH}$ then all UEs are scheduled in time (8ms after sending the respective SR) [4]. The scheduling delay for all UEs in the cell in this case is given by

$$D^{PS} = T_{SR} + T_{SG}, \text{ if } N_{SR} \le C^{CCH}$$
(6)

If $N_{SR} > C^{CCH}$ then exactly C^{CCH} UEs are scheduled in time, while the remaining $(N_{SR} - C^{CCH})$ UEs are delayed for the next subframe, and therefore will experience delay equal to $2T_{SR}+2T_{SG}+T_s$ [4]. The average scheduling delay for all UEs in the cell in this case is

$$D^{PS} = \frac{1}{N_{SR}} \left[(T_{SR} + T_{SG}) C^{CCH} + (2T_{SR} + 2T_{SG} + T_s) (N_{SR} - C^{CCH}) \right]$$

$$= (T_{SR} + T_{SG}) + (T_{SR} + T_{SG} + T_s) \left(1 - \frac{C^{CCH}}{N_{SR}} \right), \text{ if } N_{SR} > C^{CCH}$$
(7)

Combining (6) and (7) we get the expression for the average scheduling delay in LTE system:

$$D^{PS} = T_{SR} + T_{SG} + \left(T_{SR} + T_{SG} + T_s\right) \left[1 - \frac{C^{CCH}}{N_{SR}}\right]^+$$
(8)

where $\lceil x \rceil^{+} = \max\{0, x\}$. For the network model shown on Figure 1 the total number of active users in eNB_i is equal $n_i + x_i$. Then the number of SRs sent in one subframe is equal $N_{SR} = n_i + x_i$.

In LTE system the value of C^{CCH} can be determined from the bandwidth of the respective eNB denoted via b_i . Recall that SRs are carried via the PUCCH using the PUCCH format 1 messages; SGs are carried via the PDCCH using the DCI format 1 messages. Thus, for eNB_i the capacity of physical control channels in uplink direction is equal to the number of PUCCH sub-channels allocated for PUCCH format 1 messages, which is denoted by $N_i^{PUCCH_{-1}}$. The PDCCH capacity of eNB_i is equal to the number of control channel elements N_i^{CCE} allocated for the DCI format 1 messages [4]. Then the PDCCH/PUCCH capacity of eNB_i given by

$$C_{i}^{CCH} = \min\{N_{i}^{PUCCH_{-1}}, N_{i}^{CCE}\}$$
(9)

The average scheduling delay in eNB_i is equal:

$$D_i^{PS} = T_{SR} + T_{SG} + \left(T_{SR} + T_{SG} + T_s\right) \left[1 - \frac{C_i^{CCH}}{n_i + x_i}\right]^+$$
(10)

And the problem (5) will take the form:

$$\max f(\mathbf{x}) = \sum_{i=1}^{m} x_i \tag{11a}$$

subject to:

$$\left[1 - \frac{C_i^{CCH}}{n_i + x_i}\right]^+ \le \frac{\Delta_i^P - (T_{SR} + T_{SG})}{T_{SR} + T_{SG} + T_s}, \forall i \in \mathbf{I}$$
(11b)

$$\sum_{i=1}^{m} x_i \le X, \ x_i \in \mathbf{Z}^+, \ \forall i \in \mathbf{I}$$
(11c)

The above problem can be cast as an integer programming problem due to the integer restrictions on bandwidth. Many efficient methods for solving such integer programming problems exist. In particular, in this work we have used branch and bound algorithm [15] to solve (11).

III. ALGORITHM IMPLEMENTATION

Assume that SPs operate on fixed licensed spectrum bands $b_1, ..., b_m$, and the number of available control channels C_1^{CCH} , ..., C_m^{CCH} remain constant. To track the number of active PUs and SUs in the proposed CRN model we utilize a modified version of the standard LTE RACH procedure [13] described as follows. For initial access to the network (i.e. at arrival or session initiation) the PU/SU generates a Primary/Secondary Service Initiation Request (PIR/SIR) and sends it in the form of an RA-preamble using the spectrum band of any eNB within CRN using the RACH procedure. When the PU/SU terminates the session or leaves the network, it generates a Primary/Secondary Service Termination Request (PTR/STR) and sends it in the form of RA-preamble to respective eNB using the RACH procedure. Recall, that one of the primary assumptions of the network model was that the mean interarrival times of PUs and SUs (and the mean inter-departure times of PUs and SUs) are much greater than the subframe duration. Based on this assumption, we propose to make each subsequent spectrum allocation within the time interval Δt such as $T_s < \Delta t < 1/\lambda_{PU}$, $T_s < \Delta t < 1/\lambda_{SU}$, $T_s < \Delta t < \mu_{PU}$, $T_s < \Delta t < \mu_{SU}$. This allows decreasing the amount of signaling without affecting the algorithm performance.

In a CRN, all PUs have the prioritized access to all spectrum bands/eNBs comprising the network and therefore they get an immediate access to any spectrum band/eNB. SUs can operate only on the spectrum bands/eNBs that have been allocated to them according to the algorithm provided on Figure 2. Within each time interval Δt all PUs/SUs initiating sessions, generate PIRs/SIRs and send them to any eNB within the network. All PUs/SUs terminating sessions, generate PTRs/STRs and send them to respective eNB. The eNBs collect all received PIRs, PTRs, SIRs and STRs, update the number of PUs and SUs, and send them to EPC. After receiving PIRs, PTRs, SIRs and STRs from all eNBs, the EPC finds the optimal solution to problem (11) given by $\mathbf{x}^* = [x_{l}^*]$, ..., x_m^* After this, the EPC redirects the SUs by sending the index and the number of admitted SUs to all eNBs within the network. At each eNB if $x_i^* - x_i(t) \ge 0$ then all SUs are granted the access. Otherwise, the eNB accepts x_i^* SUs and redirects $x_i(t) - x_i^*$ SUs to the admitting eNBs. After being located in the network, the SUs get the wireless access to the spectrum bands of admitting eNBs.

```
Proposed DSA Algorithm for LTE-based CRN
At time t:
  PUs/SUs initiating session send PIR/SIR to any eNB<sub>i</sub> in I
  PUs/SUs terminating session send PTR/STR to eNB<sub>i</sub> in I
  At all eNB; in I
     1. Update PIR_i(t), SIR_i(t), PTR_i(t), STR_i(t)
     2. Count
        n_i(t) := n_i(t-1) + PIR_i(t) - PTR_i(t)
        x_i(t) := x_i(t-1) + SIR_i(t) - STR_i(t)
     3. Send n_i(t), x_i(t) to EPC
  At EPC:
      1. Receive n_i(t), x_i(t) from all eNBi in I;
     2. Find \mathbf{x}^* = [x_1^*, x_2^*, \dots, x_m^*]^T
     3. For all i in I:
           If x_i(t) > x_i^*
           Then
              For all j in \{i+1, ..., m\}
                 If x_j(t) > x_j^*
                 Then
                    index = j
                    number = min {x_i(t) - x_i^*, x_i(t) - x_i^*}
                    x_i(t) := x_i(t-1) - number
                    x_i(t) := x_i(t-1) + number
                    Send index, number to eNB<sub>i</sub>
                 Else
                    index = i
                    number = x_i(t)
                    Send index, number to eNB<sub>i</sub>
  At all eNB<sub>i</sub> in I:
     1. Receive index, number from EPC
     2. Send index to number SUs
  At SUs:
     1. Receive index from eNB
     2. Connect to eNBindex
```

Fig. 2. Proposed resource allocation algorithm for LTE-based CRN

A. Algorithm Performance

The simulation model of the network shown on Figure 1 has been implemented based on the standard LTE platform using the OPNET simulation and development package [16]. The wireless networking part of the model consists of m = 7 SPs (eNBs) numbered eNB₁, ..., eNB₇. The core networking part consists of the EPC and the server. In the network $\Delta t = 1$ s. The radio model of the network has been developed according to the ITU-T Recommendation M.1225. Other simulation parameters are set in accordance with the requirements of the LTE specifications [13, 14]. The user traffic consists of three most frequently used network applications: VoIP, video and HTTP. All applications are simulated in accordance with the requirements in [27]. The number of the users of different types is in proportion 2:2:3 for VoIP, video and HTTP services, respectively.

We compare the performance of the proposed algorithm with the performance of two most relevant spectrum access techniques applicable to the considered system model. These techniques are a cognitive radio resource management scheme for improving the LTE efficiency described in [18] and dynamic bandwidth access scheme through pricing modeling described in [19]. In the first scheme the spectrum is assumed to be discrete: the total available bandwidth is divided into a number of sub-carriers. The sub-carriers are assigned to the users to maximize the aggregated logarithmic user utility given as a function of the user bit rate. Within the time slot a subcarrier can be assigned to at most one user [18]. In the second scheme a number of PUs provide the wireless access to a number of SUs based on their utility function, which depends on i) the amount of bandwidth which PU is willing to share with SU, ii) the signal to interference ratio of the wireless channel between the SU and PU, and iii) the offered price for the bandwidth unit [19]. In the sequel, we use the following notation to denote particular algorithms: RBA (rate based allocation) for the scheme [18]; PBA (price based allocation) for the scheme [19]; DBA (or delay based allocation) for the scheme proposed in this paper. All algorithms are simulated with identical LTE parameters and under identical network deployment scenarios (such as channel quality, traffic load, use behaviour, etc.).

The graphs on the Figures 3 and 4 show mean packet delay in the network with mean number of SUs $X = 100 \div 1000$ UEs and mean number of PUs N = 1000 UEs. For DBA we limit the maximal allowed delay to be $D_1^P = ... = D_7^P = 100$ ms for all eNBs. Results demonstrate that PBA and DBA show better performance for PUs because of the prioritized access of PUs offered in the network, whereas the delay for PUs and SUs in RBA are almost the same (the spectrum resource in RBA are assigned based on user bit rate without prioritizing). Results also show that the performance of DBA is much better than performance of RBA and PBA both for PUs and SUs which is mainly explained by the fact that the main component of delay in LTE network is related to scheduling, and the algorithm restricts the number of SUs subject to delay constrains of PUs.



Fig. 3. Mean packet delay for PUs with N = 1000 UEs



Fig. 4. Mean packet delay for SUs with N = 1000 UEs

Performance of DBA can be better demonstrated using the graphs on Figure 5 showing the mean number of SUs served by CRN with maximal allowed delay $D_1^P = ... = D_7^P$ ranging from 0 to 100 ms and X = 3000 SUs. From this graphs it clearly follows how the number of SUs served by CRN is related to the delay constraints in DBA.



Fig. 5. Mean number of served SUs with X = 3000 UEs

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