

# Resource Allocation with Carrier Aggregation in LTE Advanced Cellular System Sharing Spectrum with S-band Radar

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**Abstract**—Spectrum sharing is a promising solution for the problem of spectrum congestion. We consider a spectrum sharing scenario between a multiple-input multiple-output (MIMO) radar and Long Term Evolution (LTE) Advanced cellular system. In this paper, we consider resource allocation optimization problem with carrier aggregation. The LTE Advanced system has  $N_{BS}$  base stations (BS) which it operates in the radar band on a sharing basis. Our objective is to allocate resources from the LTE Advanced carrier and the MIMO radar carrier to each user equipment (UE) in an LTE Advanced cell based on the running application of UE. Each user application is assigned a utility function based on the type of application. We propose a carrier aggregation resource allocation algorithm to allocate the LTE Advanced and the radar carriers' resources optimally among users based on the type of user application. The algorithm gives priority to users running inelastic traffic when allocating resources. Finally we present simulation results on the performance of the proposed carrier aggregation resource allocation algorithm.

**Index Terms**—Resource Allocation, Carrier Aggregation, Proportional Fairness, Inelastic Traffic, MIMO radar, Spectrum Sharing, Coexistence

## I. INTRODUCTION

In recent years the bandwidth demand on cellular networks increased rapidly. This demand can exceed the network capacity due to the limited available frequency bands. A dynamic spectrum sharing among radio systems can improve the data transmission capacity by acquiring the unused spectra [1]. As a result of the high demand for spectrum by commercial wireless operators, federal agencies are now willing to share their spectrum with commercial users. This has led to proposals to share spectrum allocated for federal radar operations with commercial users. The 3550–3650 MHz band, currently used for military radar operations, is identified for spectrum sharing between military radars and communication systems, according to the NTIA's 2010 Fast Track Report [2].

In order to mitigate radar interference to LTE Advanced systems a spatial approach was proposed in [3]. Radar signals are manipulated such that they are not a source of interference to certain LTE Advanced BSs. Other related work can be found in [4].

A new feature, carrier aggregation, was added to the 3GPP LTE standard in Release 10 [5]. Carrier aggregation allows

users to employ multiple carriers to achieve higher bandwidth. A utility proportional fairness resource allocation approach is proposed in [6]. A tractable optimal solution to the optimization problem exists as the authors have proven that the optimization problem is convex. A resource allocation optimization problem with carrier aggregation is formulated in [7]. The proposed resource allocation algorithm allocates the primary carrier resources optimally among users. It then starts allocating the secondary carrier resources optimally among users. A resource allocation optimization problem is presented in [8] for two groups of users. The first group is a public safety users group and the second one is a commercial users group.

In this paper, we consider a MIMO radar sharing spectrum with LTE Advanced cellular system which has  $N_{BS}$  base stations. In order to mitigate radar interference, an interference-channel-selection algorithm is proposed in [3]. The algorithm selects the  $i^{\text{th}}$  interference channel for radar's signal projection in order to mitigate radar interference to the  $i^{\text{th}}$  BS. The  $i^{\text{th}}$  evolve node B (eNodeB) supports a number of  $L_i^{\text{UE}}$  UEs subscribing for a mobile service in its coverage area. We consider a MIMO colocated radar mounted on a ship. Colocated radars are known of having improved spatial resolution over widely-spaced radars [9]. The LTE Advanced cellular system operates in its regular licensed band and sharing the 3550–3650 MHz band with a MIMO radar in order to increase its capacity given that the two systems will not cause interference to each other. We focus on finding an optimal solution for the resource allocation (RA) with carrier aggregation (CA) problem to allocate the LTE Advanced BS/eNodeB and the available MIMO radar resources optimally among users subscribing for a service in the cellular cell coverage area. Each user is assigned a utility function based on the application running on its UE. Real-time applications are represented by a sigmoidal-like utility functions whereas delay-tolerant applications are represented by logarithmic utility functions. Real-time applications are given the priority when allocating resources.

### A. Our Contributions

In this paper we extend the spectrum sharing scenario proposed in [3] between a MIMO radar and LTE Advanced cellular system with many base stations and considered a resource

allocation with carrier aggregation approach to distribute the two carriers resources optimally among users subscribing for a mobile service in LTE Advanced cellular network.

Our contributions in this paper are summarized as:

- We present a resource allocation optimization problem with carrier aggregation to allocate the LTE Advanced and the MIMO radar carriers resources optimally among users running real-time or delay-tolerant applications.
- We propose a two-stage resource allocation algorithm to allocate the two carriers resources optimally among users. First, the LTE Advanced eNodeB and the UEs collaborate to allocate an optimal rate to each UE. Once the LTE Advanced eNodeB finishes allocating resources to the UEs, the MIMO radar carrier allocates its available resources to these UEs.

The remainder of this paper is organized as follows. Section II discusses the spectrum sharing scenario between MIMO radar and LTE Advanced cellular system using spatial approach. In Section III we present our resource allocation with carrier aggregation optimization problem using a utility proportional fairness approach. In section IV we present our two-stage distributed robust resource allocation with carrier aggregation algorithm for the optimization problem. Section V discusses simulation setup and provides quantitative results along with discussion. Section VI concludes the paper.

## II. RADAR-LTE ADVANCED SPECTRUM SHARING SPATIAL APPROACH

In order to increase the LTE Advanced system capacity, the LTE Advanced will start sharing the MIMO radar band in the 3550-3650 MHz while both systems do not cause interference to each other. Figure 1 shows a maritime MIMO radar sharing  $N_{BS}$  interference channels  $\mathbf{H}_i^{N_R^{\text{BS}} \times M_T}$  with the LTE Advanced system. The received signal at the  $i^{\text{th}}$  BS receiver can be written as

$$\mathbf{y}_i(t) = \mathbf{H}_i^{N_R^{\text{BS}} \times M_T} \mathbf{x}_{\text{Radar}}(t) + \sum_j \mathbf{H}_j^{N_R^{\text{BS}} \times N_T^{\text{UE}}} \mathbf{x}_j^{\text{UE}}(t) + \mathbf{w}(t)$$

for  $1 \leq i \leq N_{BS}$  and  $1 \leq j \leq L_i^{\text{UE}}$  (1)

where  $\mathbf{x}_{\text{Radar}}(t)$  is the signal transmitted from the MIMO radar,  $\mathbf{x}_j^{\text{UE}}(t)$  is the signal transmitted from the  $j^{\text{th}}$  UE in the  $i^{\text{th}}$  cell and  $\mathbf{w}(t)$  is the additive white Gaussian noise. In order to avoid interference to the  $i^{\text{th}}$  LTE Advanced BS, the MIMO radar maps  $\mathbf{x}_{\text{Radar}}(t)$  onto the null-space of  $\mathbf{H}_i^{N_R^{\text{BS}} \times M_T}$ .

## III. SPECTRUM SHARING THROUGH RA WITH CA

We consider one 4G-LTE mobile system cell, that can be any of the  $N_{BS}$  LTE Advanced base stations, with  $L^{\text{UE}}$  UEs/mobiles and two carriers. One of the carriers is the LTE Advanced carrier that is considered to be the primary carrier and the other one is the MIMO radar carrier considered to be the secondary carrier. Each user is allocated certain bandwidth  $r_i$  based on the type of application the UE is running. Our goal is to determine the optimal bandwidth that needs to be allocated to each user by the two carriers.

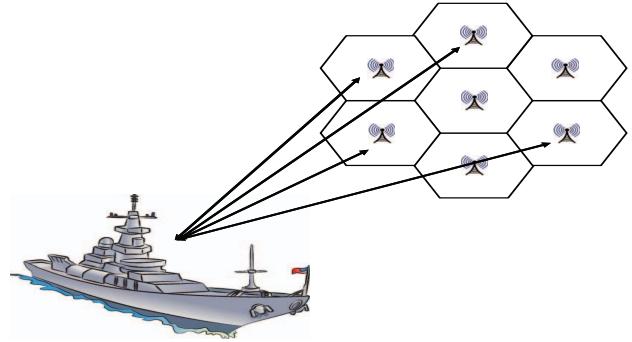


Fig. 1. Spatial spectrum-sharing scenario. LTE Advanced cellular system with a maritime MIMO radar.

Each UE has its own utility function  $U_i(r_i)$  that corresponds to the application running on the UE. We assume that the utility function assigned to the  $i^{\text{th}}$  user is a strictly concave utility function if the user is running delay-tolerant application or a sigmoidal-like utility function if the user is running real-time application:

These utility functions have the following properties:

- $U_i(0) = 0$  and  $U_i(r_i)$  is an increasing function of  $r_i$ .
- $U_i(r_i)$  is twice continuously differentiable in  $r_i$  and bounded above.

The normalized sigmoidal-like utility function used in our model, is same as the one used in [10], can be expressed as

$$U_i(r_i) = c_i \left( \frac{1}{1 + e^{-a_i(r_i - b_i)}} - d_i \right) \quad (2)$$

Where  $c_i = \frac{1+e^{a_i b_i}}{e^{a_i b_i}}$  and  $d_i = \frac{1}{1+e^{a_i b_i}}$ . Which makes it satisfy  $U(0) = 0$  and  $U(\infty) = 1$ . The inflection point of the normalized sigmoidal-like function is at  $r_i^{\text{inf}} = b_i$ . Additionally, we use the normalized logarithmic utility function, used in [11], that can be expressed as

$$U_i(r_i) = \frac{\log(1 + k_i r_i)}{\log(1 + k_i r_{max})} \quad (3)$$

where  $r_{max}$  is the maximum required rate for the user to achieve 100% utilization and  $k_i$  is a constant that varies from user to user. So, it satisfies  $U(0) = 0$  and  $U(r_{max}) = 1$ .

The first resource allocation optimization problem is the primary carrier (LTE Advanced carrier) optimization. The primary carrier allocates its resources using a utility proportional fairness approach to guarantee that no user is allocated zero resources.

The LTE Advanced carrier optimization problem, is similar to the one described in [7], can be written as:

$$\begin{aligned} \max_{\mathbf{r}_{\text{LTE}}} \quad & \prod_{i=1}^{L^{\text{UE}}} U_i(r_{i,\text{LTE}}) \\ \text{subject to} \quad & \sum_{i=1}^{L^{\text{UE}}} r_{i,\text{LTE}} \leq R_{\text{LTE}} \\ & 0 \leq r_i \leq R_{\text{LTE}}, \quad i = 1, 2, \dots, L^{\text{UE}}. \end{aligned} \quad (4)$$

where  $\mathbf{r}_{\text{LTE}} = \{r_{1,\text{LTE}}, r_{2,\text{LTE}}, \dots, r_{L^{\text{UE}},\text{LTE}}\}$  and  $L^{\text{UE}}$  is the number of mobile users in the coverage area of primary carrier and  $R_{\text{LTE}}$  is the maximum achievable rate of the primary carrier. This resource allocation objective function is to maximize the total system utility when allocating resources to each user. Furthermore, it provides a proportional fairness among utilities. Users running real-time applications are allocated more resources in this approach.

The solution of this optimization problem is the first optimal solution that gives each of the  $L^{\text{UE}}$  users the optimal rate  $r_{i,\text{LTE}}^{\text{opt}}$  only from the primary carrier and not yet the final optimal rate.

As mentioned before, once the LTE Advanced carrier finishes allocating its resources to the  $L^{\text{UE}}$  users, the MIMO radar carrier starts to allocate its available resources to the same users using proportional fairness approach to ensure a minimum user QoS.

The optimization problem for the secondary carrier (MIMO radar), is similar to the one described in [7], can be written as:

$$\begin{aligned} \max_{\mathbf{r}_{\text{radar}}} \quad & \prod_{i=1}^{L^{\text{UE}}} U_i(r_{i,\text{radar}} + r_{i,\text{LTE}}^{\text{opt}}) \\ \text{subject to} \quad & \sum_{i=1}^{L^{\text{UE}}} r_{i,\text{radar}} \leq R_{\text{radar}} \\ & 0 \leq r_{i,\text{radar}} \leq R_{\text{radar}}, \quad i = 1, 2, \dots, L^{\text{UE}}. \end{aligned} \quad (5)$$

where  $\mathbf{r}_{\text{radar}} = \{r_{1,\text{radar}}, r_{2,\text{radar}}, \dots, r_{L^{\text{UE}},\text{radar}}\}$  and  $L^{\text{UE}}$  is the number of UEs in the coverage area,  $R_{\text{radar}}$  is the maximum achievable rate by the secondary carrier and  $r_{i,\text{LTE}}^{\text{opt}}$  is the optimal rate allocated to user  $i$  by the LTE Advanced carrier in (4). Optimization problem (5) ensures a minimum rate of  $r_{i,\text{LTE}}^{\text{opt}}$  for each user and gives priority for users running real-time applications.

The final optimal aggregated rate  $r_{i,\text{agg}}$  for user  $i$  is obtained by the sum of the solution of the optimization problem (4)  $r_{i,\text{LTE}}^{\text{opt}}$  and the solution of (5)  $r_{i,\text{radar}}^{\text{opt}}$  and can be written as  $r_{i,\text{agg}}^{\text{opt}} = r_{i,\text{radar}}^{\text{opt}} + r_{i,\text{LTE}}^{\text{opt}}$ , such that  $r_{i,\text{agg}}^{\text{opt}}$  is the global final optimal solution that gives each of the  $L^{\text{UE}}$  users the optimal rate from both the LTE Advanced and the MIMO radar carriers.

#### IV. TWO-STAGE CARRIER AGGREGATION ALGORITHM

Our two-stage algorithm is a modified version of the algorithm proposed in [7]. In the first stage, the UEs and the primary carrier collaborate to allocate an optimal rate to each UE. The first stage of the algorithm starts when each UE transmits an initial bid  $w_{i,\text{LTE}}(1)$  to the LTE Advanced eNodeB. The eNodeB checks the difference between the current received bid and the previous one, if it is less than a threshold  $\epsilon$  it exists. Otherwise, if the difference is greater than  $\epsilon$ , the shadow price  $P_{\text{LTE}}(n) = \frac{\sum_{i=1}^{L^{\text{UE}}} w_{i,\text{LTE}}(n)}{R_{\text{LTE}}}$  is calculated by the LTE Advanced eNodeB. The shadow price represents the total price per unit bandwidth for all users. It depends on the users bids and the eNodeB's available

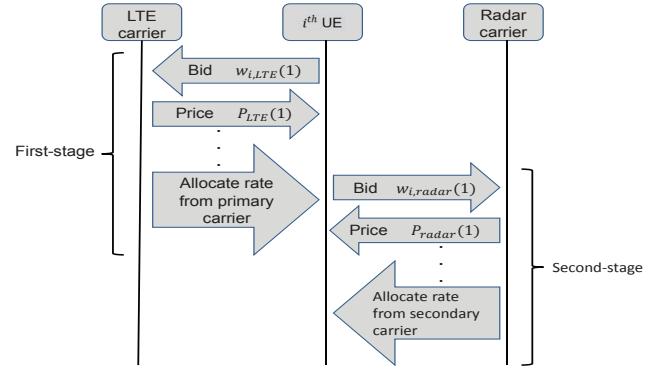


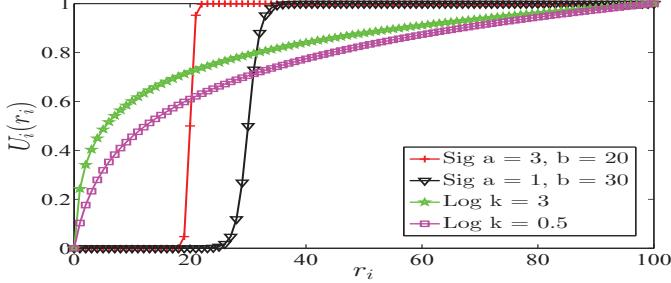
Fig. 2. Flow Diagram for the two-stage RA with carrier aggregation Algorithm.

resources. The LTE Advanced eNodeB sends the calculated  $P_{\text{LTE}}(n)$  to each UE where it is used to calculate the rate  $r_{i,\text{LTE}}(n)$  that is the solution of the optimization problem  $r_{i,\text{LTE}}(n) = \arg \max_{r_{i,\text{LTE}}} (\log U_i(r_{i,\text{LTE}}) - P_{\text{LTE}}(n)r_{i,\text{LTE}})$ . The calculated rate is then used to estimate a new bid  $w_{i,\text{LTE}}(n)$  where  $w_{i,\text{LTE}}(n) = P_{\text{LTE}}(n)r_{i,\text{LTE}}(n)$ . All UEs check the fluctuation condition and send their new bids  $w_{i,\text{LTE}}(n)$  to the LTE eNodeB. Once the first stage is finalized by the eNodeB, each UE calculates its allocated rate  $r_{i,\text{LTE}}^{\text{opt}} = \frac{w_{i,\text{LTE}}(n)}{P_{\text{LTE}}(n)}$ .

After allocating rates  $r_{i,\text{LTE}}^{\text{opt}}$  from the LTE carrier, the second-stage of the algorithm starts performing. Each UE transmits its initial bid  $w_{i,\text{radar}}(1)$  to the MIMO radar eNodeB. The eNodeB checks the difference between the current received bid and the previous one if it is less than a threshold  $\epsilon$  it exists. Otherwise, if the difference is greater than  $\epsilon$ , the MIMO radar eNodeB calculates the shadow price  $P_{\text{radar}}(n) = \frac{\sum_{i=1}^{L^{\text{UE}}} w_{i,\text{radar}}(n)}{R_{\text{radar}}}$ . The radar eNodeB sends the calculated  $P_{\text{radar}}(n)$  to the UEs. Each UE calculates the rate  $r_{i,\text{radar}}(n)$  which is the solution of the optimization problem  $r_{i,\text{radar}}(n) = \arg \max_{r_{i,\text{radar}}} (\log U_i(r_{i,\text{radar}} + r_{i,\text{LTE}}^{\text{opt}}) - P_{\text{radar}}(n)r_{i,\text{radar}})$ . A new bid  $w_{i,\text{radar}}(n)$  is calculated using  $r_{i,\text{radar}}(n)$  where  $w_{i,\text{radar}}(n) = P_{\text{radar}}(n)r_{i,\text{radar}}(n)$ . All UEs check the fluctuation condition and send their new bids  $w_{i,\text{radar}}(n)$  to the radar eNodeB. The second-stage of the Algorithm is finalized by the radar eNodeB. Each UE then calculates its allocated rate  $r_{i,\text{radar}}^{\text{opt}} = \frac{w_{i,\text{radar}}(n)}{P_{\text{radar}}(n)}$  by the radar eNodeB. The final global optimal rate  $r_{i,\text{agg}}^{\text{opt}} = r_{i,\text{radar}}^{\text{opt}} + r_{i,\text{LTE}}^{\text{opt}}$  is then allocated to each UE. Figure 2 shows a flow chart of the LTE Advanced two-stage RA with carrier aggregation Algorithm.

#### V. SIMULATION RESULTS

In our spectrum sharing model, the LTE Advanced system has  $N_{\text{BS}}$  BS, only the  $i^{\text{th}}$  BS is under zero interference from the MIMO radar due to the spatial spectrum sharing approach employed by the MIMO radar [3]. We consider this BS which has two eNodeBs, one is configured at the LTE

Fig. 3. The users utility functions  $U_i(r_i)$ .

Advanced carrier and the second is configured to use radar carrier when there is no interference from radar. In this BS we consider four UEs in its coverage area subscribing for a mobile service. The first and second UEs are running real-time applications presented by sigmoidal-like utility functions whereas the third and fourth UEs are running delay-tolerant applications presented by logarithmic utility functions. The four UEs are to be allocated resources from the LTE Advanced and the MIMO radar carriers.

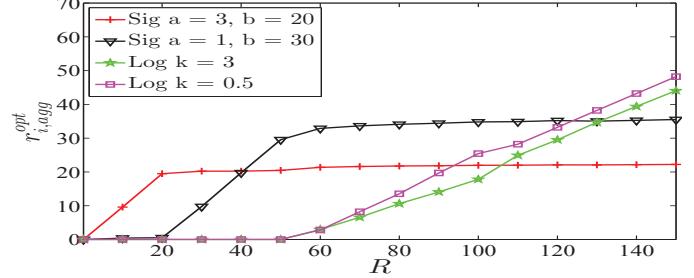
Our proposed algorithm is applied in C++ to the sigmoidal-like and logarithmic utility functions. The simulation results showed convergence to the optimal global point in the two stages of the algorithm. Each of the four UEs is allocated a final optimal rate by the two carriers. We use a normalized sigmoidal-like utility function that is expressed by equation (2) to represent the first user real-time application with  $a = 3$ ,  $b = 20$  which is an approximation to a step function at rate  $r = 20$ . Additionally, we use another sigmoidal-like utility function to represent the second user real-time application with  $a = 1$ ,  $b = 30$ . Furthermore, we use logarithmic functions to represent the third and fourth UEs delay-tolerant applications with  $k = 3$  and  $k = 0.5$ , respectively. Additionally, We use  $r_{max} = 100$  for all logarithmic functions,  $l_1 = 5$  and  $l_2 = 10$  in the fluctuation decay function of the algorithm and  $\epsilon = 10^{-7}$ . The utility functions corresponding to the four UEs applications are shown in Figure 3.

#### A. RA with Carrier Aggregation for $10 \leq R \leq 150$

In the following simulations, the total rate of the LTE Advanced carrier takes values between 10 and 70 and the MIMO radar carrier has available resources that takes values between 10 and 80. The two carriers resources are to be allocated to the four users subscribing for a mobile service in the LTE Advanced cellular cell using RA with carrier aggregation.

In Figure 4, we show the optimal rate allocated to each user by the first-stage of the algorithm when  $10 \leq R \leq 70$  is the LTE Advanced carrier available resources. The final optimal rates allocated to each user by the second-stage of the algorithm are also shown in Figure 4 for  $70 < R \leq 150$  where  $R$  is the total available resources of  $R_{LTE} = 70$  and  $10 \leq R_{radar} \leq 80$ . The LTE carrier allocates the majority of its resources to the UEs running real-time applications

until they reach the inflection rate  $r_i = b_i$ . When the LTE Advanced resources  $R_{LTE}$  exceed the total inflection rates of the users real-time applications, the LTE Advanced carrier starts allocating resources to the delay-tolerant applications.

Fig. 4. The users final optimal rates  $r_{i,agg}^{opt}$  for different values of  $R$  where  $10 \leq R \leq 70$  is the LTE Advanced carrier available resources and  $70 < R \leq 150$  is the total available resources of  $R_{LTE} = 70$  and  $10 \leq R_{radar} \leq 80$ .

## VI. SUMMARY AND CONCLUSIONS

In this paper, we presented an optimal resource allocation with carrier aggregation approach to allocate LTE Advanced and MIMO radar carriers' resources optimally among LTE Advanced users in a cell. The two systems shared spectrum through a spatial approach proposed in [3]. As a result of our analysis, we presented an iterative distributed RA with carrier aggregation algorithm for the UEs and both LTE Advanced and radar carriers. We showed through simulations that our algorithm converges to the optimal rates in its two stages.

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