AN ORTHOGONAL SPECTRUM SHARING SCHEME FOR COGNITIVE LTE NETWORKS

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ABSTRACT

Spectrum sharing has been proposed as a solution to the problem of under-utilization of licensed spectrum. It has the potential of not only increasing efficient spectrum utilization, but also of increasing revenue for cellular operators who can lease out spectrum at times of high demand to other operators. In this paper, we develop a novel architecture for spectrum sharing at the base station level for LTE-A cellular operators. The operators, acting as a primary user in their licensed spectrum, have a choice of dynamically sharing parts, or all, of their spectrum with co-located/adjacent secondary co-operators. Such an approach, as opposed to the conventional static band access, has two fold advantages. Firstly, it ensures maximum spectral utilization, thus increasing spectral efficiency. Secondly, it increases the flexibility at eNBs providing higher opportunity to use alternate channels to improve system throughput. We propose an orthogonal spectrum sharing and resource allocation scheme, focusing on rate maximization with a minimum per-user rate constraint. A linear optimization framework at the network level is developed for maximization of throughout and spectrum access cost. We study a use case with two operators and two cells, for proof of concept. We obtain analytical solutions to the rate maximization problem and show that a mutually beneficial secondary spectrum access cost exists for both operators as a trade-off with the combined system sum throughput.

1. INTRODUCTION

In wireless communication systems, Radio Frequency (RF) spectrum is one of the most tightly regulated resources of all time. With the increasing number of wireless devices, the exponentially increasing demand in data rates and the high Quality-of-service (QoS) requirements, efficient access, allocation and management of the radio spectrum resource has become a very widely addressed problem. In the recent CISCO Global Mobile Traffic Forecast Update [1], overall mobile data traffic is expected to grow to 11.2 exabytes per month by 2017, a 13-fold increase over 2012. The current fixed allocations of the spectrum, where the wireless service providers are assigned exclusive spectrum blocks, imposes severe limitations on the efficient use of the spectrum [2].

Efficient Spectrum Utilization problem has been addressed in several contexts. Deploying advanced hardware architectures such as smart antennas/MIMO, OFDMA and smart scheduling in both time and frequency have been effectively introduced as means to achieve higher data rates within the fixed allocation spectrum bands [3]. Although these technologies could provide higher throughputs for end users, the expectations for higher data rates are far more beyond what could be achieved [4]. Another path for improving spectrum efficiency is Dynamic Spectrum Access (DSA) techniques under the Cognitive Radio (CR) framework. DSA exploits white spaces in the frequency spectrum usage and secondary transmissions are scheduled on an ad-hoc basis, avoiding interference to primary spectrum users. DSA techniques include spectrum sensing [5, 6], the use of Radio Environment Maps [7, 8], and hybrid techniques [9, 10]. Although huge advancements in DSA techniques have been achieved, specially with the introduction of TV White Spaces IEEE 802.22 standard [11], the application of DSA is primarily concentrated in the 2.4GHz ISM band or the proposed 3.5GHz shared access band.

The idea of spectrum sharing among licensed cellular operators as a means of increasing spectrum utilization has been presented for 3G operators, and recently extended to 4G LTE networks. If a cell of an operator is under-loaded for a certain period of time, then a part of the spectrum will be wasted, while it could have been exploited by co-located/adjacent cells of other operators experiencing high traffic [12]. In addition, exploiting diversity between end-users and different operators' base stations may result in a higher throughput for the user with the same total bandwidth utilized but from differing operators. Inter-operator spectrum sharing for 3G systems has been discussed in [13–16]. These proposals either considered only voice applications in which the main goal was to minimize the probability of call blocking [13, 14], or their proposed models were based on the assumption that operators would only share the spectrum as a last resort [15, 16]. Most of the proposed scheduling/sharing algorithms only supported TDD systems, where sharing the spectrum merely reduces to operators sharing time slots.

With the introduction of 4G LTE cellular systems, and the shift towards complete packet-services-based networks, frequency spectrum sharing among cellular operators became a more feasible architecture. Spectrum sharing policies proposed could be generally categorized into non-orthogonal and orthogonal. The former allows several base stations to use the same transmission frequency at the same time, provided that the level of interference at the intended receivers is below a desired threshold. The latter considers mutually exclusive access to the shared spectrum and hence does not tolerate any interference [12]. Non-orthogonal spectrum sharing approaches are considered as resource allocation problems under interference constraints. Solutions presented include transmit beam-forming [17], Dynamic Frequency Selection (DFS) algorithms based on interference measurements [18], and the more complex game theoretical perspective [19]. Although non-orthogonal spectrum sharing utilizes the spectrum more efficiently, strict interference level requirements for network operators will render these algorithms less feasible.

In orthogonal spectrum sharing scenarios, operators agree to share a part or whole of their licensed spectrum on a mutually exclusive basis. Game theoretic approaches have been widely presented in both centralized and distributed scenarios . In [20], a game theoretic approach that took into consideration users throughput, blocking probability and the spectrum price was presented in which the operators are the players. [21] presented a distributed game theoretical approach for spectrum sharing, in which sub-optimum solutions are derived based on little information exchange between the operators. Other orthogonal spectrum sharing approaches presented spectrum sharing as a constrained optimization problem. In [22], a different scenario of co-existence between a CR network and three Cellular Operators was presented, in which the objective was capacity maximization. Another capacity maximization spectrum sharing algorithm for macrocells was presented in [12], in which a coordinated scheduling algorithm was designed for LTE cellular networks, with the goal of calculating an upper bound on the achievable sum capacity.

In this work, we propose a novel framework for inter-operator orthogonal spectrum sharing, where the operators have a choice of sharing parts, or all, of their licensed spectrum. The work proposes an optimized allocation scheme for resource sharing in base stations of cellular systems that guarantees maximum throughputs for end-users, minimum costs for network operators, and fairness among users. In Section 2, the proposed framework along with the system model will be presented. Section 3 will include the proposed optimization scheme for maximum throughput in the case of two adjacent cells of different operators. While in Section 4, application of the proposed optimization scheme to a realistic LTE scenario will be presented that highlights the feasibility of our proposed algorithm. Finally Section 5 will include some conclusions and suggestions for future work.

2. SPECTRUM SHARING FRAMEWORK

The proposed framework considers two cellular networks, operating in the same geographical region. In particular, for the sake of simplicity, we consider the case of two overlapping cells.

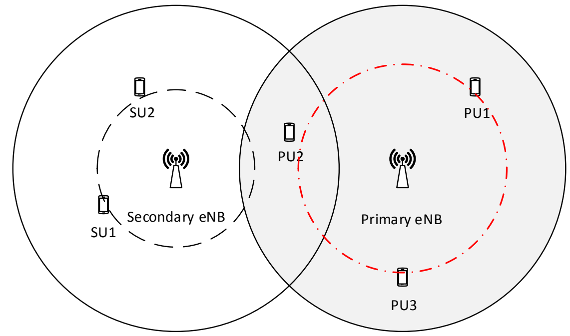


Figure 1: System Model from the perspective of one operator. The operator on the right is the primary operator any user from any other operator using the primary operator's spectrum is a secondary user. Thus the secondary users have to ensure that no interference is caused to the primary users of the spectrum. This is illustrated by the dotted circels which form the interference limits for the eNBs.

However, all considerations can be promptly extended to a more general case. We assume that the network operators own their exclusive portions of the spectrum and agree upon sharing them at an agreed cost. In this work, an orthogonal sharing scenario is considered. We consider an LTE-A network centralized Mobility Management Entity (MME) which manages a common pool of spectral resources in a specific region and is connected to several base stations or evolved Node B's (eNBs), under the control of different operators, who wish to share spectrum. When users request for resource allocations, the eNBs contact the MME. The MME performs the resource allocation optimization algorithm and assigns different portions of the combined available spectrum to different users. Operators access not only their own spectrum, but also the shared spectrum with a pre-agreed cost.

The optimization problem is developed by considering a simple case of two overlapping cells of two different operators. Each cell is assumed to have just one user for the sake of simplicity of problem formulation and proof of concept. However, this formulation can be extended to any number of users without any loss of generality as shown through simulation in Section 4.. Each user is a primary user on its own parent frequency and secondary on the frequency of adjacent operator, as presented in Figure 1. The two operators are labeled OP1 and OP2 and the corresponding users are UE1 and UE2. Let W_1 and W_2 be the bandwidth of OP1 and OP2 respectively. Let α_1 and α_2 be the fraction of the parent spectrum W_1 and W_2 used by UE1 and UE2 respectively. The remainder of the spectrum in each band i.e., $(1-\alpha_1)W_1$ and $(1-\alpha_2)W_2$, would be used by the secondary users UE2 and UE1 respectively. It is to be noted that for a multi-user case, the α's will be calculated across all users subscribing to each operator i.e., for $i \in \mathbb{N}$, α_i will be the fraction of parent spectrum used by the i-th operator.

We now introduce a *normalized cost metric weight*, $c : 0 \leq c \leq 1$. We define the normalized cost metric weight as a comprehensive metric, normalized and inversely proportional to the

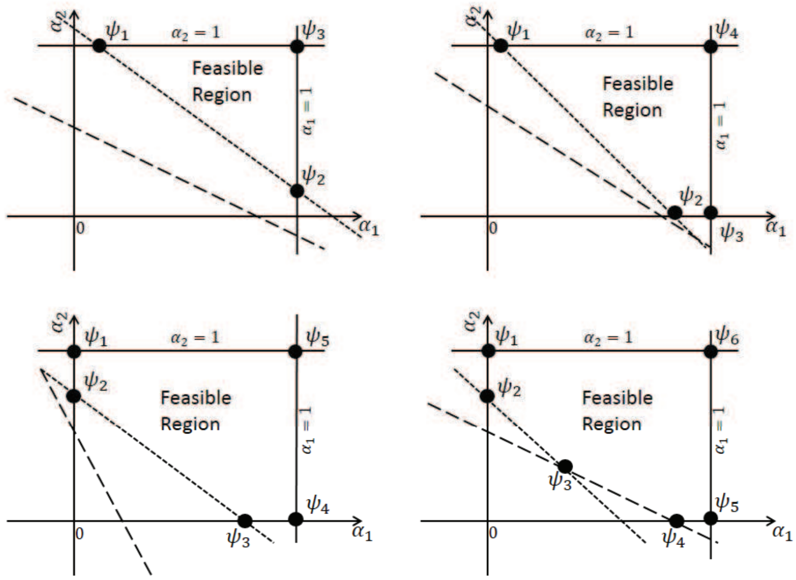


Figure 2: Sample extreme points and feasible regions

cost incurred by the operator in allocating unit spectrum to any user for the period of the scheduling interval. This cost metric weight has to take into account various parameters (e.g. the auction price paid by the operator, charges levied by the operator to the users, etc.). Development of such a cost metric is beyond the scope of the paper and a topic of research by itself, but such a metric offers immense utility and convenience in modeling the optimizing problem of network sharing. The normalized cost metric weights associated with OP1 and OP2 in allocating spectrum to UE1 and UE2 are respectively is denoted by c_1 and c_2. Further, the normalized cost metric weight associated with shared spectrum is β (i.e. when UE1 accesses OP2 spectrum or, UE2 accesses OP1 spectrum).

3. ANALYTICAL SOLUTION

In this section, we consider the overall rate maximization for framework described in the preceding section. We define the rate achievable by a user with SINR γ on bandwidth W as

$$R = W\log(1+\gamma)$$

We design a weighted rate maximization problem with a minimum rate constraint to be satisfied for each user. The optimization problem can be formulated as,

$$\begin{aligned}\max_{\alpha_1,\alpha_2}\ \mathcal{J} = {} & \alpha_1 c_1 W_1\log(1+\gamma_{11}) + \\ & (1-\alpha_2)\beta W_2\log(1+\gamma_{12}) + \\ & \alpha_2 c_2 W_2\log(1+\gamma_{22}) + \\ & (1-\alpha_1)\beta W_1\log(1+\gamma_{21}) \quad (1)\end{aligned}$$

$$\begin{aligned}\text{s.t.} & \\ & \alpha_1 c_1 W_1\log(1+\gamma_{11}) + (1-\alpha_2)\beta W_2\log(1+\gamma_{12}) \geqslant R_1 \\ & \alpha_2 c_2 W_2\log(1+\gamma_{22}) + (1-\alpha_1)\beta W_1\log(1+\gamma_{21}) \geqslant R_2 \\ & 0 \le \alpha_1 \le 1 \\ & 0 \le \alpha_2 \le 1\end{aligned} \quad (2)$$

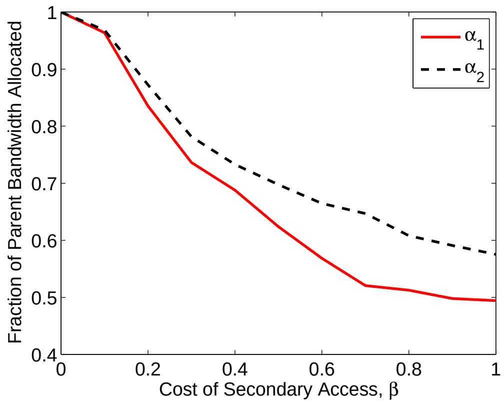
where γ_{ij} denotes the SINR for the i^{th} UE operating on the spectrum of j^{th} OP (operator).

It is important to note that the costs of accessing primary and secondary spectrum have been used as scaling factors in the objective function and rate constraints. We observe that in our problem, the objective function and the constraints are linear in α_1 and α_2. Thus, it is a linear maximization problem with linear constraints for which the optimal point lies in one of the extreme points [23]. Thus, to solve this maximization problem, the extreme points for the objective are identified and the optimal point is obtained as,

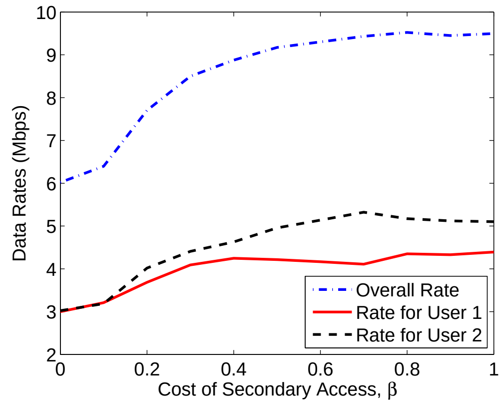
$$(\alpha_1^*, \alpha_2^*) = \psi_i \in \Psi : \arg\max_{\forall \Psi} \mathcal{J} \quad (3)$$

where ψ_i's are ordered pair of extreme points from the α_1-α_2 plane and Ψ is the set of all extreme points. Certain sample

$$I = \left(\frac{r_{11}r_{22}(r_{21} - r_{12}) + r_{12}r_{21}(R_2 - r_{22}) + r_{11}r_{12}R_2 + r_{22}r_{21}R_1 - (r_{22}r_{21}^2)}{(r_{11}r_{22} - r_{12}r_{21})(r_{11} + r_{22})}, \frac{r_{21}(R_1 - r_{12}) + r_{11}(R_2 - r_{21})}{r_{11}r_{22} - r_{12}r_{21}} \right) \quad (14)$$



(a)



(b)

Figure 3: Case 1: $c_1 = 0.5$, $c_2 = 0.7$, $W_1 = W_2 = 3$ MHz. (a) Variation of α's with cost of secondary spectrum, (b) Variation of data rate with cost of secondary spectrum.

constraint plots, the possible extreme points (ψ_i's) and the corresponding feasible regions on the α_1-α_2 plane are shown in Figure 2.

For ease of notation, we define $r_{11}, r_{12}, r_{21}, r_{22}$ as

$$r_{11} = c_1 W_1 \log(1 + \gamma_{11})$$
$$r_{12} = \beta W_2 \log(1 + \gamma_{12}) \quad (4)$$
$$r_{22} = c_2 W_2 \log(1 + \gamma_{22})$$
$$r_{21} = \beta W_1 \log(1 + \gamma_{21}) \quad (5)$$

Upon solving the constraint equations, a list of all points of intersection (A-I) are found [23]:

$$A = (0, 1 - \frac{R_1}{r_{12}}) \quad (6)$$
$$B = (\frac{R_1 - r_{12}}{r_{11}}, 0) \quad (7)$$
$$C = (0, \frac{R_2 - r_{21}}{r_{22}}) \quad (8)$$
$$D = (1 - \frac{R_2}{r_{21}}, 0) \quad (9)$$
$$E = (1, 1 + \frac{r_{11} - R_1}{r_{12}}) \quad (10)$$
$$F = (\frac{R_1}{r_{11}}, 1) \quad (11)$$
$$G = (1, \frac{R_2}{r_{22}}) \quad (12)$$
$$H = (1 + \frac{r_{22} - R_2}{r_{21}}, 1) \quad (13)$$

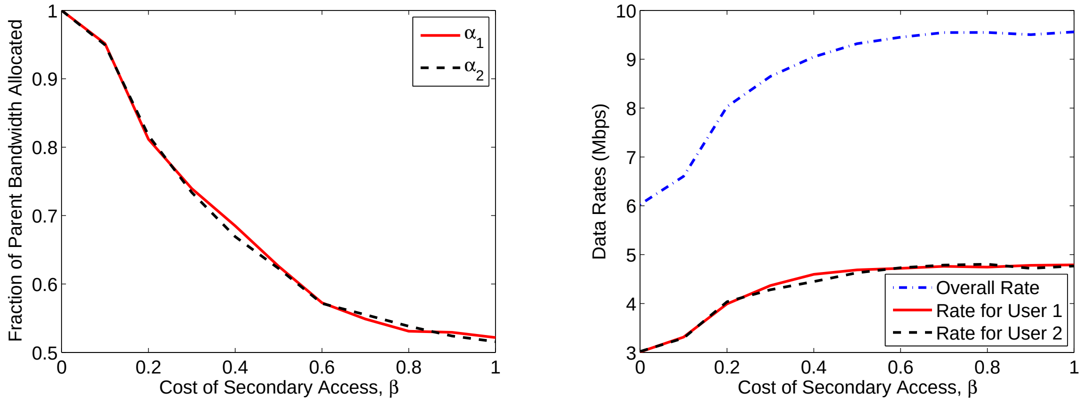
The extreme points are only those which lie in the first quadrant in the feasible region. The optimal values are chosen subject to the maximization of the objective function in (1).

3.1. Numerical Simulations of Analytical Solution

In order to obtain better insight on the behavior of the network sharing parameters, α_1 and α_2, Monte-Carlo simulations studies are carried out. One user is assumed in each network and the signal to interference ratio for each link is chosen at random in the range of -10 dB to 10 dB. In each case the shared secondary spectrum cost, β is varied from 0 to 1 and results are noted. It is noted that $\beta = 0$ implies infinite cost of secondary access, thus ruling out spectrum sharing and $\beta = 1$ implies cheapest secondary access, thus favoring complete secondary access. This can be easily extended to a multi-user case, with an aggregate rate constraint for each operator. The following use cases are discussed to highlight the dynamics of the system.

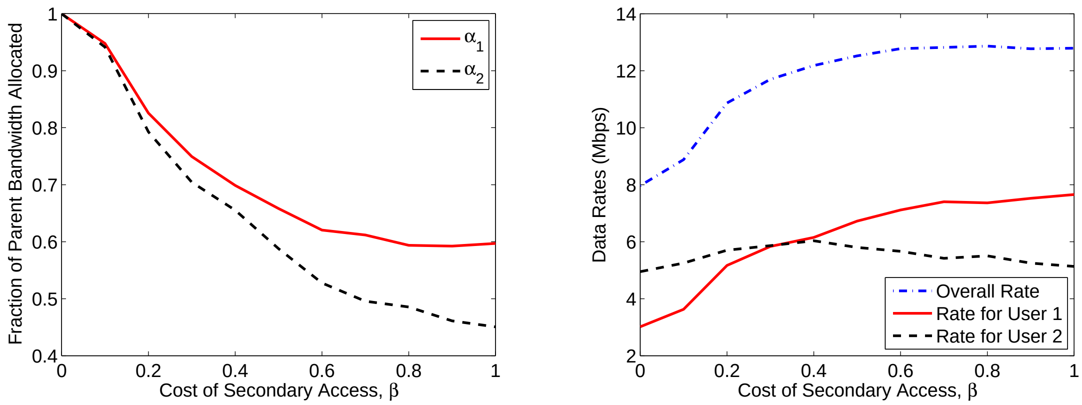
3.1.1. Case 1

In this case, the costs of parent spectrum $c_1 = 0.5$ and $c_2 = 0.7$ are chosen in an arbitrary manner. The bandwidths of both operators are chosen equal i.e., $W_1 = W_2 = 3$ MHz. This choice of bandwidth emulates a 3MHz LTE system with 15 Physical Resource Blocks (PRBs). While we note that cost of parent spectrum for operator 1 is greater than the cost of parent spectrum for operator 2 in this case, due to the symmetry of the problem, swapping the values of c_1 and c_2 would just swap the results without any further consequence. The weighted rate constraints of $R_1 = R_2 = 0.1$ Mbps are chosen. Simulations were per-



(a) (b)

Figure 4: Case 2: $c_1 = c_2 = 0.5$, $W_1 = W_2 = 3$ MHz. (a) Variation of α's with cost of secondary spectrum, (b) Variation of data rate with cost of secondary spectrum.



(a) (b)

Figure 5: Case 3: $c_1 = c_2 = 0.5$, $W_1 = 3$MHz, $W_2 = 5$ MHz. (a) Variation of α's with cost of secondary spectrum, (b) Variation of data rate with cost of secondary spectrum.

formed for 10,000 random network realizations for each value of β.

Variation of α's (averaged over all realizations) with the cost of secondary access, β is shown in the Figure 3(a). When the secondary spectrum is unaffordable, there is no sharing and users occupy the entire parent spectrum. Sharing becomes increasingly high with the decreasing price of the secondary spectrum. Since parent spectrum cost of operator 1 is higher than operator 2 in this case, we see that operator 1 tries to access more secondary spectrum as the cost of secondary access reduces.

Figure 3(b) depicts average individual rates for User 1 (belonging to operator 1) and User 2 (belonging to operator 2) and the average overall system rate achieved for different costs of secondary spectrum. Again, since the cost of parent spectrum for operator 1 is higher than the cost of parent spectrum for operator 2, User 1 is served with a lower data rate than User 2. Note that If the cost of parent spectrum for an operator is low, then it indicates that the rate levied by the operator on the user is high and vice-versa. Thus, such a user who effectively pays less for spectrum access suffers a lower data rate as compared to the user who incurs a higher cost in a shared spectrum framework.

3.1.2. Case 2

In this case, the costs of parent spectrum $c_1 = 0.5$ and $c_2 = 0.5$ are chosen to be equal for both operators, with the remainder of the parameters being identical to the previous case. The bandwidths of both operators are chosen equal, $W_1 = W_2 = 3$ MHz and the weighted rate constraints as $R_1 = R_2 = 0.1$ Mbps.

Variation of α's averaged over all realizations with the cost of secondary access, β is presented in the Figure 4(a) and the variation of data rates with the cost of secondary access is presented in Figure 4(b). As expected, the spectrum sharing and data rates would be identical in this case when averaged over large number of iterations, since the only criteria to select a secondary channel would be the availability of a better channel.

3.1.3. Case 3

In this case, the costs of parent spectrum $c_1 = 0.5$ and $c_2 = 0.5$ are chosen to be equal for both operators. However, the bandwidths of the operators are chosen as, $W_1 = 3$ MHz and $W_2 = 5$ MHz ($W_2 > W_1$) and the weighted rate constraints as $R_1 = R_2 = 0.1$ Mbps. Again, by symmetry of the problem, reversing the bandwidths of the operators would simply reverse the results.

Variation of α's with the cost of secondary access, β is shown in the Figure 5(a) and the variation of data rates with the cost of secondary access is presented in Figure 5(b). As the cost of the secondary access decreases, both the operators increasingly access secondary spectrum. However, we draw attention of the readers to the variation of data rates in Figure 5(b). When the cost of shared spectrum is high, the User 2 (of operator 2 with higher bandwidth) gets higher overall bandwidth and hence enjoys a higher data rate. However, with the cost of the secondary spectrum decreasing, secondary access predominates the primary access (as seen in Figure 5(a)) and since $W_2 > W_1$, User 1 (of operator 1) gets higher data rates. Note that the cost of parent spectrum is the same in this case and if they were to be different, the intersection would happen at a different cost of secondary spectrum.

From the preceding discussions and results, it can be seen that the framework developed in this paper can be used to numerically optimize the cost of secondary spectrum. An optimal β value can be chosen for a mutually beneficent sharing scheme, depending on the costs and bandwidths of parent spectrum. Note that this framework focuses on maximizing the data rate for all users and does not blindly maximize the cost subject to a minimum rate constraint. The choice of the secondary access cost is crucial in all the use cases. This formulation provides a theoretical framework for the numerical optimization. This can easily be extended for a multi-user case where the rate constraint can be replaced by overall minimum demand of the network. This will be demonstrated in the next section, where we carry out simulations for an extension of this problem to an LTE framework. Furthermore, this scheme can also be extended for a multi-operator case, with the addition of sharing parameters and fractional bandwidths.

4. SPECTRUM SHARING FOR AN LTE NETWORK

The spectrum sharing framework discussed in Sections 2 and 3 can be extended to a multi-operator LTE-A system. In LTE, the smallest allocable resource unit is called the physical resource block (PRB). At the eNB level, a resource allocation algorithm runs at every transmission time interval (TTI) and assigns PRBs to the UEs. In the case of orthogonal network(spectrum) sharing, the inter-operator scheduling becomes a joint allocation problem which can be handled by a central entity like an MME. The scheduling algorithm takes into account the individual UE's minimum rate constraints and instantaneous achievable rates [24] and aims to maximize the sum throughput of the system. Since the resource allocation in LTE is discrete in the form of PRBs, in the ensuing discussion, the rate maximization from Section 3 is reformulated as a PRB assignment problem with a modified objective function.

We define a system for two LTE operators covering two adjacent cells. Let $\mathbb{I}_1, \mathbb{I}_2$ denote the set of PRBs in operator 1 and 2's network respectively. Also, let $\mathbb{J}_1, \mathbb{J}_2$ denote the set of users in operator 1 and 2's network respectively. For a total of $I \in \mathbb{I}_1 \bigcup \mathbb{I}_2$ PRBs and $J \in \mathbb{J}_1 \bigcup \mathbb{J}_2$ UEs in the combined network, the assignment problem then calculates the optimum rate assignment matrix $\mathbf{X}_{I\times J}$ whose elements are $x_{i,j}$ for $i = 1, ..., I; j = 1, ..., J$. The value $x_{i,j} = 1$ signifies that the i-th PRB in the system is assigned to the j-th UE. We assume that Carrier Aggregation is available as a standard feature in LTE-A. This will enable users to aggregate non-contiguous PRBs from different bandwidths in the shared network i.e., a user in operator 1's network can use PRBs from both $\mathbb{I}_1$ and $\mathbb{I}_2$. Suppose the achievable rates for the j-th UEs on the $i-$th PRB is $R_{i,j}$. We model the cost for primary and secondary spectrum access with the variable $\mathcal{C}_{i,j}$ as follows:

$$\begin{aligned}
\mathcal{C}_{i,j} &= c_1 \ \forall i \in \mathbb{I}_1,\ j \in \mathbb{J}_1 \\
\mathcal{C}_{i,j} &= c_2 \ \forall i \in \mathbb{I}_2,\ j \in \mathbb{J}_2 \\
\mathcal{C}_{i,j} &= \beta \ \forall i \in \mathbb{I}_1,\ j \in \mathbb{J}_2 \\
\mathcal{C}_{i,j} &= \beta \ \forall i \in \mathbb{I}_2,\ j \in \mathbb{J}_1
\end{aligned}$$

where c_1, c_2 and β are identical to Section 3.

The joint problem at any given scheduling instant i.e., TTI t is defined as:

$$\max_{x_{i,j,t}} \ \sum_{j=1}^{J} x_{i,j,t}\mathcal{C}_{i,j}R_{i,j,t} \tag{15}$$

$$\text{s.t.} \ \sum_{j=1}^{J} x_{i,j,t} \in \{0,1\}, \tag{16}$$

$$\sum_{i=1}^{I} (x_{i,j,t}R_{i,j,t}) > R_{j,t}^{\min}, \tag{17}$$

$$\sum_{i=1}^{I} (x_{i,j,t}R_{i,j,t}) < R_{j,t}^{\max}, \tag{18}$$

The constraints are given by equations (16)-(18) where, $R_{j,t}^{\min}$ is the minimum rate guaranteed to the j-th user and $R_{j,t}^{\max}$ is a limit on the maximum rate per user set by the operators. The first constraint ensures that a given PRB is assigned to a single UE in the network. The second constraint ensures that the minimum rate guarantees of the individual UEs are satisfied. The third constraint is based on a maximum rate limit as decided by the network and this constraint is designed based on the current demand of the UEs within the network. Once the assignment matrix $\mathbf{X}_{I\times J}$ is obtained, the α's can be evaluated as follows:

$$\alpha_1 = \frac{1}{|\mathbb{I}_1|} \cdot \sum_{j\in\mathbb{J}_1} \sum_{i\in\mathbb{I}_1} x_{i,j,t}$$
$$\alpha_2 = \frac{1}{|\mathbb{I}_2|} \cdot \sum_{j\in\mathbb{J}_2} \sum_{i\in\mathbb{I}_2} x_{i,j,t}$$

The problem described in equation (15) belongs to a class of NP-Complete binary integer assignment problems [25]. It is a general scheduling and rate maximization problem which can be solved by any scheduler proprietary to an LTE service provider. The novelty in this scheduler comes from the use of a weighted linear function as the objective to achieve cost optimization and throughput maximization. The weighing factor $\mathcal{C}_{i,j}$ is based on the price of spectrum as decided by each operator for spectrum sharing. When an UE j uses PRB i which is a part of its own licensed band, then the price paid for that spectrum is set by its own operator i.e., c_1, c_2 as opposed to the scenario where the UE uses unlicensed spectrum where the price associated is represented by β. From discussions in Section 3., we have seen that depending on the cost set by the operators an optimum β can be chosen to facilitate spectrum sharing. In this section we perform simulations to show that the theoretical results discussed in Section 3. hold for a general LTE network. The simulation parameters are summarized in Table 1.

Table 1: Simualtion Parameters

Channel Model	COST-Hata Model
Center Frequency of Operator 1	1800 MHz
Center Frequency of Operator 2	1900 MHz
Sub-carrier separation (Δf)	15 kHz
LTE system bandwidth (Operator 1& 2)	3 MHz (15 PRBs)
Number of cells in network	2
Radius of each cell	2 km
Height of base-station	80 m
Height of UE	10 m
eNB transmit power (maximum)	40 dBm
$\sigma_{\text{Shadowing}}$	7 dB
Simulation time	50 TTIs
Operator 1's cost, c_1	0.5
Operator 2's cost, c_2	0.7
Secondary Access cost, β	0.3
Minimum rate per UE, $R_{j,t}^{\min}$	0.1 Mbps

The cost for secondary access is chosen as $\beta = 0.3$ as it can be observed for Figures 3(b),4(b) and 5(b) that this point offers a suitable cost versus rate trade off for secondary spectrum access given the choice of system parameters. As discussed before, β is inversely related to the spectrum price. The linear weighted problem formulation to factor in the spectrum price leads to a reduction in complexity as a linear problem is solved. Since this is an integer assignment problem, standard binary integer programming solutions can be used for solving it. The COST-Hata Model is used for modeling path-loss. For each eNB, an uniform power distribution scheme is used i.e., the total available transmit power is divided equally among the available PRBs. A frequency reuse factor of 1 is considered. We discuss the cases for two operators and a single user per operator (similar to Section 3.) and the multi-user extension with 2 users per operator.

4.1. Single User Case

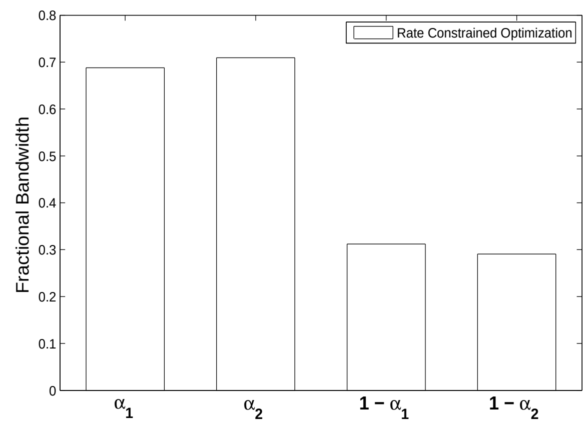


Figure 6: Average α factors for Operators 1 & 2 over 50 TTIs.

Figure 6 illustrates the spectrum sharing between operator 1 and 2 over 50 TTIs. The average α values are shown. This case corresponds to *Case 1* in Section 3.. It can be seen that given $\beta = 0.3$, $\alpha_2 > \alpha_1$. This reflects the result in Figure 3(a) i.e., the simulation confirms the theoretical result. The result is not unexpected as the cost for spectrum access is cheaper for operator 2 than opertor 1. Hence operator 2 uses a greater fraction of the parent spectrum and in turn operator 1 uses a greater fraction of shared spectrum.

Figure 7 shows the sum throughput of the two users over the simulation duration of 50 TTIs. The average throughput of user 2 is greater than that of user 1. This again reflects the result shown in Figure 3(b). With a lower spectrum access cost in general over parent and shared spectrum, user 2 always has an advantage over user 1 in terms of accessed spectrum given a particular cost. Thus the average throughput is greater than user 1. Another interesting feature is apparent when the instantaneous rates for the users are observed over the simulation duration. It can be seen that when the instantaneous rate of user 1 increases, the corresponding rate for user 2 decreases. This reflects the spectrum sharing between the two users. When one user uses more resources, the other user gets a smaller share of the total bandwidth and consequently lower instantaneous rate. Thus this

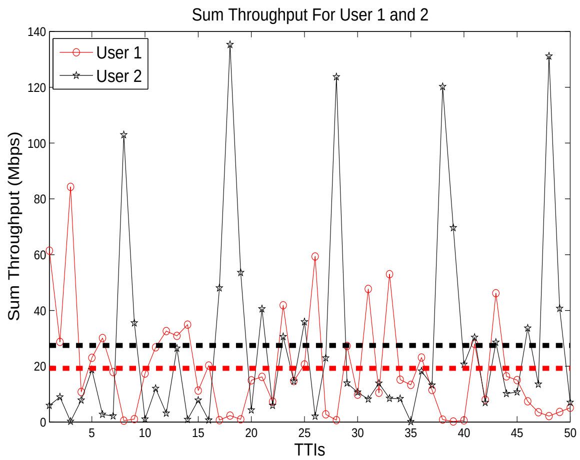


Figure 7: Sum Throughput of User 1 and 2 over 50 TTIs. The dotted lines are the average sum throughputs of the users over the entire simulation duration.

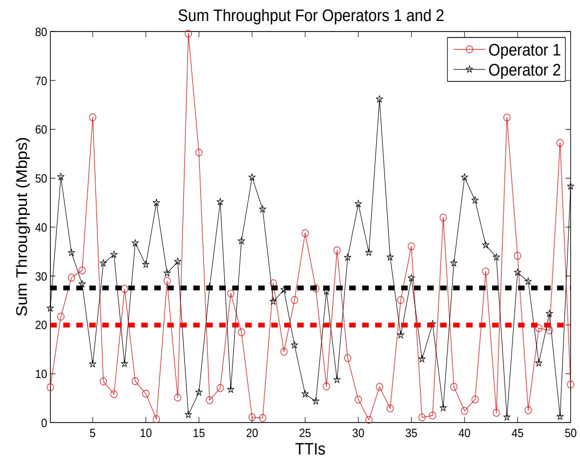


Figure 9: Sum Throughput of Operators 1 and 2 over 50 TTIs. The dotted lines are the average sum throughputs of the users under operators 1 and 2 over the entire simulation duration.

simulation shows the instantaneous spectrum sharing achieved by the proposed resource allocation scheme. It is to be noted that the instantaneous rates are dependent on the channel conditions at the given time.

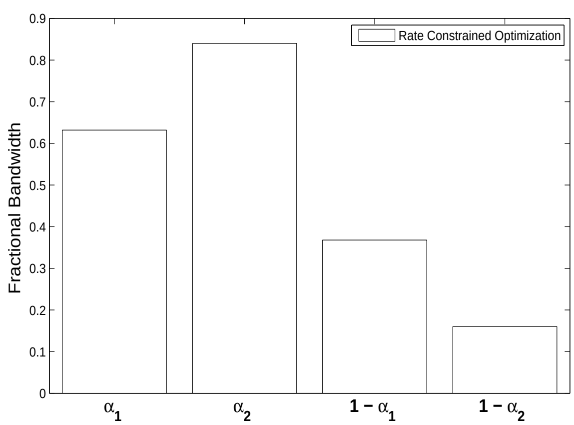


Figure 8: Average α factors for Operators 1 & 2 over 50 TTIs.

4.2. Multi-user Case

Next, we look at the extension of the problem to the multi-user case. In this paper we have assumed that each operator in this scenario has two users in their respective cells. This assumption, while simplistic, makes the results tractable. Also, it is easy to see that the assignment problem in 15 is easily extendable to large number of users by increasing the size of the sets $\mathbb{J}_1, \mathbb{J}_2$. Figure 8 shows the α factors in the multi-user case. Here the α's are calculated across all users under the control of the given operator and the subscripts on α's specify the *operator* and not the individual users. It can be seen that under the given parameters the result of analytical solution $\alpha_2 > \alpha_1$ is validated by the figure. Thus the problem formulation proposed in Section 3 is *scalable*.

Figure 9 shows that the spectrum sharing holds under the multi-user assumption. The average rate of operator 2 is higher than operator 1 and the sharing effect i.e., increase in instantaneous rate of users under operator 1 leading to decrease in the rate of users under operator 2 holds true. From the simulation results it can seen that the weighted linear optimization problem designed for inter-operator spectrum sharing achieves its purpose of selecting the optimal bandwidth fraction for parent and secondary network access and also a mutually beneficial secondary spectrum access cost can be designed.

5. CONCLUSION

In this paper, we have proposed a model for multi-operator orthogonal spectrum sharing. The problem has been formulated as a weighted linear optimization which achieves rate maximization. Analytical solutions have been obtained for a two-operator, single user scenario. The proposed model's novelty lies in the fact that it includes the price for primary and secondary shared spectrum access as a scaling factor in the objective function. From the analytical results we have shown that, given a cost for primary spectrum access, it is possible to select a mutually beneficial secondary spectrum access price as trade-off against the achievable rate of the combined system. The problem formulation was then extended to a general LTE network and through simulations, it was shown that the analytical results hold in the case of both single and multi-user scenarios. Since the problem involves the solving of a linear maximization which in turn leads to a search of an ordered set of extreme points, the complexity is low compared to non-linear solutions.

Future work relating to this problem would be to analyse a non-orthogonal sharing sharing model with power control. In this case the role of the central entity for scheduling can be compromised and local scheduling at the eNB of each operator can be achieved with downlink power control. The problem in that case, however, becomes non-linear. Downlink power control is not featured in current LTE releases but is expected in future releases to enable dynamic Spectrum access and cognitive applications. A mode selection problem can be devised based on the orthogonal and non-orthogonal sharing modes with the ability to dynamically select modes depending on which one offers the best sum-rate at a given scheduling instant.

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