Efficient Resource Scheduling for a Secondary Network in Shared Spectrum

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***Abstract*—With limited opportunities to open up new unencumbered bands to mobile wireless services, interest in enhancing methods for sharing of spectrum between services is high. For example, the band 1695-1710 MHz is expected to be made available to 3GPP Long-Term Evolution cellular network uplinks by sharing with incumbent meteorological satellite services already in the band. The LTE networks are to be operated in a manner that ensures no loss of incumbent capability by adhering to protection requirements such as a limit on the aggregate interference power at fixed incumbent earth station locations.**

In this paper, we consider this specific spectrum sharing scenario as motivation and formulate an optimization framework for power control and time-frequency resource scheduling on the LTE uplink with an aggregate interference constraint. We design and propose a novel algorithm inspired by numerical solution and analysis of the optimization problem. Using theory and simulation, we show that our algorithm significantly outperforms more simplistic approaches, well approximates the optimal solution, and is of sufficient scope and complexity for practical implementation, even in relatively large LTE networks. Algorithms of this kind are necessary for mobile wireless networks to make the most of constrained spectrum resources in shared bands.

I. Introduction

The rapid increase in the quantity and capability of consumer mobile wireless devices has accelerated the demand for radio frequency spectrum. In recent years, to address congestion in allocated spectrum bands and allow for continued growth opportunities, national and international regulators have taken steps to identify new spectrum for use by mobile wireless services such as cellular and Wi-Fi [1]. Though growth in demand for mobile wireless has been particularly acute, myriad other systems and services already make use of spectrum in the frequency ranges that could be useful for mobile wireless.

With limited opportunities to open up new unencumbered bands to mobile wireless services, interest in enhancing methods for sharing of spectrum between services is high. The US National Telecommunications and Information Administration started several working groups to examine specific spectrum sharing opportunities. For example, in [2], the working group recommended that the band 1695-1710 MHz be made available to 3GPP Long-Term Evolution (LTE) cellular network uplinks by sharing with incumbent meteorological satellite (METSAT) downlink services already in the band. Specifically, the working group recommended that the LTE networks be deployed and operated in a manner that ensures no loss of incumbent capability by adhering to protection requirements such as a limit on the aggregate interference power at fixed METSAT earth station locations. LTE operators will be required to demonstrate that the protection criteria will be met, and should be motivated to reconsider aspects of their system design in the context of how to best make use of spectrum in a shared environment subject to interference constraints.

In this paper, we consider the specific scenario in [2] and formulate an optimization framework for power control and time-frequency resource scheduling on the LTE uplink with the interference protection constraint. We design and propose a novel algorithm inspired by numerical solution and analysis of the optimization problem. Using theory and simulations, we show that our algorithm significantly outperforms more simplistic approaches, well approximates the optimal solution, and is of sufficient scope and complexity for practical implementation, even in relatively large LTE networks.

The remainder of the paper is organized as follows. Section II discusses other relevant work. Section III describes the system model, including details of the real-world LTE and METSAT sharing scenario in III-A and formulation of the resource scheduling optimization problem in III-B. Sections IV and V detail the design of the efficient resource scheduling algorithm. Numerical results quantifying the performance of the algorithm are provided in Section VI. Practical considerations are briefly discussed in Section VII. Finally, conclusions and goals for future work are discussed in Section VIII.

II. Related Work

Many works on LTE resource allocation are available in the literature [3]. The 10 ms duration of an LTE radio frame typically requires that allocation of resources must be broken into sub-problems, favoring low complexity of implementation over better approximations of the optimal solution. Scheduling of frequency resources for the LTE uplink is itself a combinatorial optimization problem that can be impractical to solve optimally. [4], [5] and [6] propose several heuristic algorithms for frequency resource scheduling which trade between performance and algorithm complexity. LTE power allocation is often treated as a separate problem. [7], [8] and [9] examine the power control mechanisms within LTE, considering performance trades between throughput, self-interference, and energy efficiency. Because LTE generally has exclusive access to the spectrum bands they operate in, a mechanism to preclude interference to another system is not a part of these and other works on LTE resource allocation. An appropriate architecture and adapted algorithms are needed to leverage the resource allocation flexibility inherent in LTE and enable effective LTE-METSAT sharing for the scenario in [2].

The subject of avoiding interference is often treated in the literature under the topic of cognitive radio. [10] and [11] derive results for cognitive radios subject to interference constraints, including identification of frequency and power selection strategies, but only for a single cognitive radio transmitter. This does not lend insight into how resources should be allocated across multiple transmitters within the LTE network. The effect of aggregate interference due to multiple transmitters is included in [12], [13], [14] and [15], and resource allocation algorithms are developed, but all of these works assume that perfect channel state information is available. We argue that this assumption is not valid for LTE-METSAT because the networks are to operate autonomously and the number of nodes in the networks is likely to be large enough that accurate measurement and reporting of complete channel state information is impractical.

Models for characterizing probabilistic aggregate interference resulting from uncertain channel state information are developed in [16], [17], [18], [19] and [20]. Results include formulations and closed form approximations to the probability density function of the aggregate interference power measured at an arbitrary receiver as a function of the deployment and operational parameters of the cognitive network. These models do not offer a strategy for optimizing LTE resource allocations, but only provide a means to ensure interference protection requirements are met.

In [21], a general power and frequency resource optimization framework is presented that accounts for uncertain channel state information and probabilistic aggregate interference modeling. The extended problem formulation is suitable to address the LTE-METSAT problem, but scalability of their numerical search method is acknowledged as an open question in that it is unclear how the optimization problem could be solved in a practical amount of time for large networks. Similarly, [22] addresses a problem formulation that encompasses the LTE-METSAT scenario, but it is also not obvious how their use of the simulated annealing algorithm can be applied to large networks in a time-scale suitable for LTE scheduling.

In this paper, we leverage the power control capabilities of LTE, and formulate an optimization framework consistent with that in [21] to address the power allocation portion of the optimization problem with incomplete channel state information. We design an efficient algorithm that can be implemented in practice to approximate the optimal solution. We employ a frequency domain scheduling algorithm as a sub-routine in our proposed algorithm, where many of the algorithms in the literature may be applied with suitable modifications. To the best of our knowledge, this is the first work that proposes a multi-cell power and time-frequency resource scheduling algorithm that includes the aggregate interference constraint, does not require complete channel state information, and is low enough in complexity for practical implementation within an LTE network.

III. System Model

A. LTE and METSAT Sharing Scenario

Per [2], the 1695-1710 MHz band is used by METSATs for downlinking data, i.e., transmitting from the satellite to an earth station receiver at a fixed site. In a shared spectrum scenario, the service with priority status is commonly referred to as ”primary” while the service that is subject to the interference constraint is ”secondary.” For this paper, we consider the deployment of a secondary LTE network in the region around one primary METSAT site.

The LTE network will make use of the band for uplinks, i.e., transmission from the user equipment (UE) to the base station (BS). Since in this paper we are interested in resource scheduling, we assume the number and locations of the BSs and the UEs in the network operating around the METSAT site are known a priori. Consistent with LTE, we consider that each BS schedules associated UEs in time-frequency resource blocks (RBs) which are units of 180 kHz bandwidth by 0.5 ms. We include in our scheduling problem the constraint that each BS may assign each RB to only one UE, which is necessary in practice to limit interference within the LTE network. We also include the constraint that RBs assigned to any single UE in a 0.5 ms time slot must be contiguous in frequency due to the use of single-carrier frequency division multiple access for LTE uplinks. We assume any BS can make use of any RB, i.e., full frequency reuse. In addition to time-frequency scheduling, we will include LTE power control in the optimization, which allows UE transmit power levels to be varied by the BS over a large range, typically -40 to +23 dBm in 1 dBm increments. Although we assume that channel state information for predicting UE interference to the METSAT receiver is not available, we do assume that channel state information for the link between any given UE and its associated BS is available to the LTE network since this is routinely measured at the BS.

An illustration of the LTE-METSAT spectrum sharing scenario is provided in Figure 1, showing the intended transmission path between the meteorological satellite and its earth station receiver, the LTE uplinks to be scheduled, and the aggregate interference resulting from these LTE uplinks. We assume the satellite transmission is at such a distance that it has a negligible interference effect on the BS receivers. Thus we can focus the problem on the aggregate interference at the METSAT receiver.

The interference protection criteria ensures the aggregate interference power within some protected bandwidth around the METSAT center frequencies is kept below some threshold, i.e.,

$$\sum_{j \in W_p} \sum_{i=1}^{N_u} P_i g_{i,j}^1 z_{i,j} \le I_t, \tag{1}$$

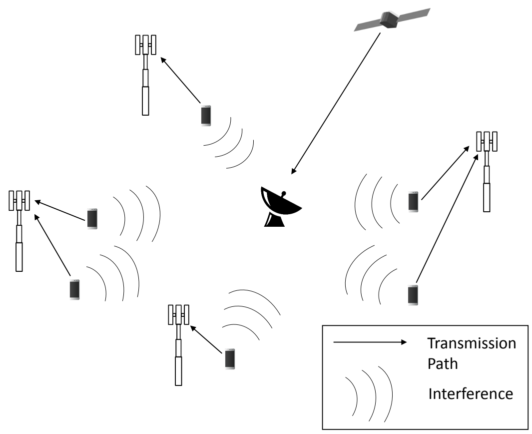


Fig. 1. Illustration of spectrum sharing between meteorological satellite downlink and LTE uplinks in 1695-1710 MHz.

where W_p is the set of RBs in any given time interval that overlap the protected bandwidth, N_u is the total number of UEs in the network, P_i is the transmit power per RB of the ith UE, $g^1_{i,j}$ is the mean channel gain between the ith UE and the METSAT receiver in the jth RB, $z_{i,j}$ is the excess gain due to shadowing and/or fading, and I_t is the threshold on maximum aggregate interference at the METSAT receiver[1]. Note that P_i does not vary by RB because power control within an LTE network is on the total UE transmit power, not on a per RB basis [9]. We assume the LTE network does not know and cannot measure $z_{i,j}$, but can estimate $g^1_{i,j}$ based on the known location of the UEs and the METSAT receiver along with a suitable propagation loss model. We can consider the effects of small-scale fading and shadowing within a resource scheduling algorithm using appropriate statistical models. With such an approach, we can only guarantee that the constraint will be satisfied probabilistically, i.e.,

$$Pr\left[\sum_{j\in W_p}\sum_{i=1}^{N_u} P_i g^1_{i,j} z_{i,j} \geq I_t\right] \leq p_t, \tag{2}$$

where p_t is a probabilistic threshold, i.e., a very small percentage of time that the primary METSAT operator can tolerate I_t being exceeded. While such a probability threshold is not specified in [2], it is a typical and often necessary criteria for spectrum sharing [23]. An appropriate value for the probabilistic threshold would likely have to be determined through coordination agreements between the METSAT and LTE operators on a site-by-site basis.

B. The Resource Allocation Problem

The problem of scheduling M RBs for N^b_u UEs associated with the bth BS to maximize their sum utility was considered in [4], where the authors showed that this problem is not only NP-hard, but MAX SNP-hard [24]. We first present an equivalent formulation for the problem that we will then use to address the more difficult interference constrained scheduling problem. Define A_i as the index of the lowest frequency RB assigned to the ith UE. Similarly, define T_i as the total number of RBs assigned to the ith UE. Thus any assignment of contiguous RBs for the ith UE can be completely specified by A_i and T_i, and we can define a utility function for any assignment to UE i at a given time interval, where that utility function is denoted $U(A_i, T_i)$. With these definitions, we formulate the RB scheduling optimization problem for a single BS as

$$\begin{aligned} \text{maximize} \quad & \textstyle\sum_{i=1}^{N^b_u} U(A_i, T_i) \\ \text{subject to} \quad & A_i \in \{1, ..., M\},\ \forall i \\ & T_i \in \{0, ..., M+1-A_i\},\ \forall i \\ & A_i + T_i \leq A_m,\ \forall i, m : A_m \geq A_i, T_m > 0, \end{aligned} \tag{3}$$

where the first and second constraints identify the range of possible integer values that can be taken by A_i and T_i, which are both upper limited by M. The last constraint ensures that any RB may be assigned to at most one UE by preventing any nonempty RB assignments to different UEs from overlapping. Note that we need not explicitly write a constraint that any UE may only be assigned one contiguous set of RBs since this is implicit in the definitions of A_i and T_i.

We now consider modifying this optimization problem to account for the interference protection constraint such that we can apply it to the LTE-METSAT sharing scenario. Let us define the aggregate interference at the METSAT receiver due to LTE uplinks operating on the jth RB as I_j. Then we have

$$I_j = \sum_{b=1}^{N_b}\sum_{i=1}^{N^b_u} P^b_i g^{1,b}_{i,j} z^b_{i,j} x^b_{i,j},$$

where N_b is the number of BSs in the network, the i subscripts denote the index of the UE, the b superscript identifies the associated BS, and the j subscript identifies the jth RB. Here $x^b_{i,j}$ is an indicator function taking on a one value when $A^b_i \leq j < A^b_i + T^b_i$ and a zero value otherwise. Obviously, the number of UEs in the network is related to the number of UEs per BS as $N_u = \sum_{b=1}^{N_b} N^b_u$. We can now consider the following aggregate interference constrained resource scheduling optimization problem:

$$\begin{aligned} \text{maximize} \quad & \textstyle\sum_{b=1}^{N_b}\sum_{i=1}^{N^b_u} U(A^b_i, T^b_i, P^b_i) \\ \text{subject to} \quad & A^b_i \in \{1, ..., M\},\ \forall i, b \\ & T^b_i \in \{0, ..., M+1-A^b_i\},\ \forall i, b \\ & A^b_i + T^b_i \leq A^b_m,\ \forall i, m, b : A^b_m \geq A^b_i \\ & Pr\{\textstyle\sum_{j\in W_p} I_j \geq I_t\} \leq p_t \\ & 0 \leq P^b_i,\ \forall i, b, \\ & T^b_i P^b_i \leq P_{max},\ \forall i, b, \end{aligned} \tag{4}$$

where P_{max} is the maximum transmission power of a UE, presumably limited by device hardware. Observe that the first

[1]For ease of reference on the notation in this paper, see Table I in Section VI which also provides numeric values used during simulation.

four lines of problem (4) are nearly identical to problem (3). The fifth line imposes the interference protection constraint, and the last two constraints limit the transmit power of any single UE to a feasible range.

Note that in problem (4) we make explicit the dependence of the utility function on the transmit power assigned to the UE. Problem (4) effectively couples the individual BS scheduling problems of (3) by the aggregate interference protection criteria. This complication cannot be avoided since the aggregate interference at the primary receiver is a result of transmissions from the entire multi-cell LTE network. Given that the original scheduling problem is hard enough that it is only treated sub-optimally in practice, the fact that our modified problem is a coupling of multiple such scheduling problems with the addition of power control motivates similar consideration.

IV. Interference Limited Power Allocation

We first consider a sub-problem that will be of use in addressing the overall scheduling problem of (4). Suppose we are given the UEs that are to operate in the band with the interference protection constraint and are only concerned with determining the power allocation that maximizes the throughput of these particular UEs in the network. Thus we need not track either the UE associations with BSs or the specific RBs and we drop the corresponding supercripts and subscripts. This sub-problem can be formulated similarly to (4) as

$$\begin{aligned} \text{maximize} \quad & \textstyle\sum_{i=1}^{N_u} U(P_i) \\ \text{subject to} \quad & Pr\{I_j \geq I_t\} \leq p_t \\ & I_j = \textstyle\sum_{i=1}^{N_u} P_i g_i^1 z_i \\ & 0 \leq P_i \leq P_{max}, \forall i, \end{aligned} \quad (5)$$

where we now write P_i as the total transmit power of the ith UE in the protected band, N_u is the total number of UEs we are considering within this sub problem, $U(P_i)$ reflects that the only variable impacting the utility function is the power allocation, and the other parameters are the same as in (4).

Because a general analytic solution to this problem is not obvious, we resort to numeric analysis. Specifically, we implement an interior-point method to solve the optimization. For the purposes of the numeric study, we consider the case of a sum-rate utility function. Also, we use a two-ray model for the mean path loss with log-normal shadowing. We use the Fenton-Wilkinson approximation as defined in [20] and also used in [21] to model the probability distribution of the aggregate interference, resulting from the sum of log-normally distributed random variables.

A wide variety of network deployments were considered for the numeric optimization. To illustrate typical results, Figure 2 plots the optimal power allocation for a simple network with three BSs and 50 active UEs connected to each BS. The BSs are located at 15, 30 and 40 km from the METSAT receiver, and each UE is randomly located within an area of 3.5 km radius around its associated BS. Each mark on the plot

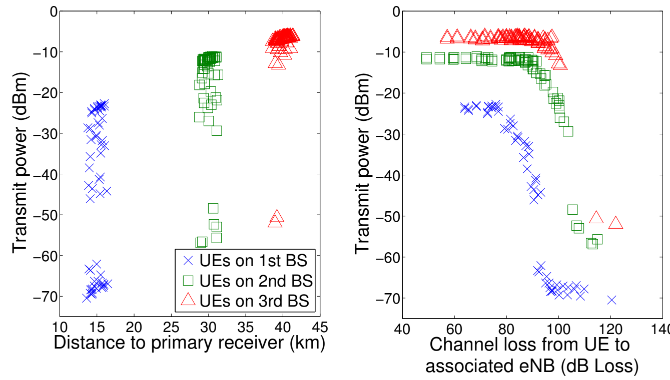


Fig. 2. Optimal UE transmit power as a function of UE distance from the primary receiver (left) and as a function of UE channel loss to the associated BS (right). Markers indicate association with the first, second and third BSs located at 15, 30 and 40 km from the primary receiver respectively.

indicates the optimal operating point for one UE. The markers identify the UE associations with the 15, 30 or 40 km BSs. We see from the plot a general tendency to assign more transmit power to UEs that are further from the primary receiver and also to those UEs with relatively less channel loss to their associated BSs. These factors are intuitive, but not sufficient to devise a power allocation strategy.

Let us define the UE gain ratio as g_i^2/g_i^1, where g_i^2 is the channel gain between a UE and its associated BS, and recall g_i^1 is the channel gain between the ith UE and the METSAT receiver (where, as already stated, we have dropped the subscript j and the superscript b). Given the aforementioned observations on the optimal power allocation, we expect that the gain ratio should be positively correlated with the optimal power assignment for a specific UE. Figure 3 examines the same three BS network considered in Figure 2, but in the context of this UE gain ratio.

We observe a very clear relationship between the gain ratio and the interference power at the METSAT receiver resulting from the optimal power allocation. First observe that UEs with the lowest gain ratios tend to have low optimal transmit power allocations, and low, approximately equal, interference contributions. Many of the assigned transmit powers are low enough that they are below the typical minimum for LTE UEs (-40 dBm). UEs with the highest gain ratios tend to receive higher transmit power allocations, and have relatively high, and also nearly equal interference contributions. The finding that many UEs should be allocated power such that their interference contributions are nearly equal is intuitively satisfying. A large number of transmitting UEs with relatively equal contributions to the aggregate interference level at the primary receiver will have an averaging effect and tend to reduce the probability that the aggregate interference will deviate far from its mean value. Thus the LTE network can operate in a way that causes a higher mean aggregate interference level and still satisfy the protection criteria, effectively allowing more total transmit power within the LTE network.

With these observations on the optimal power allocation as

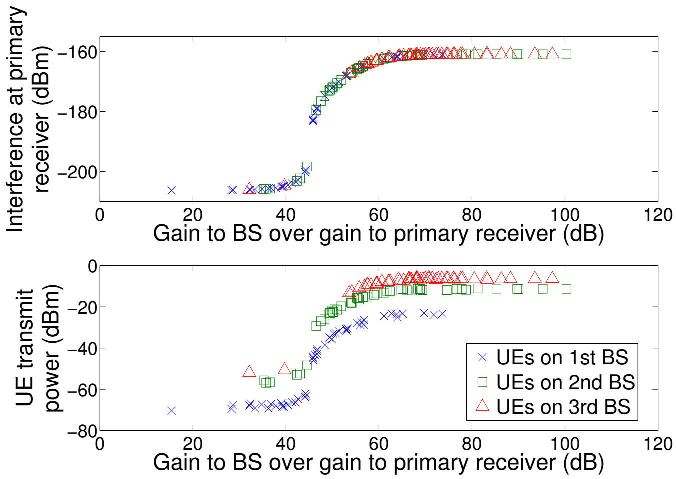


Fig. 3. Optimal UE transmit power allocation (bottom) and resulting interference power contribution at primary receiver (top) as a function of UE gain ratio. Markers indicate association with the first, second and third BSs located at 15, 30 and 40 km from the primary receiver respectively.

a function of the gain ratio, we have the basis for a specific power allocation strategy. We consider a solution to the optimization problem that has the form of assigning transmit powers to each UE such that their contribution to the aggregate interference at the primary receiver is either equal to some constant, call it μ, or it is zero. In this way, we are approximating Figure 3 by a step function. To implement this, we develop an algorithm that first sorts the UEs by their gain ratio and then searches for the transition point for the step. This transition point can be thought of as the number of UEs, L, that should be included in the nonzero power regime. The algorithm also identifies μ, the optimal interference level for the L UEs, and computes the corresponding power assignments. The pseudocode for the algorithm implemented in this specific case is provided as Algorithm 1. Here $s = (\sigma_{dB}(\ln 10)/10)^2$, σ_{dB} is the standard deviation of the log-normal shadowing, R is the achieved rate, P is the size N_u array of power assignments corresponding to L and μ, and $Q(x)$ is the tail probability for the standard normal distribution. Note that step 4 results from the choice of the Fenton-Wilkinson approximation to the aggregate interference. Other suitable aggregate interference models may be accommodated with appropriate modifications to this step. Similarly, step 7 may be modified to accomodate other utility functions.

In Figure 4, we compare the equal interference power allocation, which we dub the EIPA algorithm, to the optimal allocation. We see that EIPA closely approximates the optimal in the high gain ratio regime. Note that the results shown here are representative for a wide range of other networks which were also simulated, but whose results are omitted for brevity. In Figure 5, we compare the performance of EIPA in terms of both achieved sum-rate as well as required computation time (on a PC with a quad-core 2.2 GHz clock speed processor) for five different networks each with three BSs and varying number of total UEs. We see that EIPA comes very close to

Algorithm 1 Equal Interference Power Allocation (EIPA)

1: $L \leftarrow 1$
2: $R_{best} \leftarrow 0$
3: Order UEs by descending gain ratio
4: $\mu \leftarrow I_{th} + \frac{5}{\ln 10}[\ln(\frac{L+e^s-1}{L^3}) - 2Q^{-1}(p_{th})\sqrt{\ln(\frac{L+e^s-1}{L})} - s]$
5: $P_{new}(1:L) \leftarrow 10^{\mu/10}/g_1(1:L)$
6: $P_{new}(L+1:N_u) \leftarrow 0$
7: $R_{new} \leftarrow \sum_{i=1}^{L} \log_2\left(1 + \frac{P_{new}(i)g_2(i)}{N_2}\right)$
8: **if** $R_{new} > R_{best}$ **then**
9: $\quad R_{best} \leftarrow R_{new}$
10: $\quad P_{best} \leftarrow P_{new}$
11: $\quad L \leftarrow L + 1$
12: $\quad$ goto 4
13: **else**
14: $\quad$ **return** P_{best}
15: **end if**,

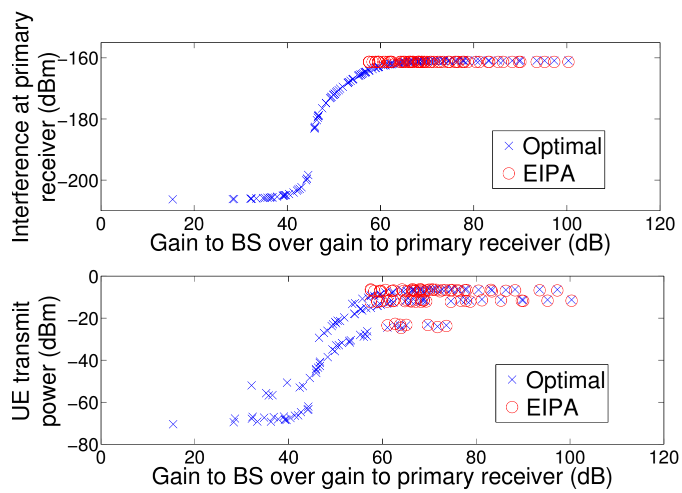


Fig. 4. Comparison of EIPA algorithm with optimal UE transmit power allocation (bottom) and resulting interference power contribution at primary receiver (top) as a function of UE gain ratio. BS associations are the same as in Figure 3, but differentiating markers have been dropped to emphasize comparison between the EIPA algorithm and the optimal.

the optimal in terms of sum-rate, achieving 98% of the optimal sum-rate or better. We see that the numerical optimization computation time grows rapidly as the size of the network increases, making it very doubtful that power allocation could be identified using numerical optimization in practice. On the other hand, the EIPA algorithm completed on the order of a millisecond or less for all networks considered and is not visible in Figure 5 due to the scale of the plot. Thus EIPA closely approximates the optimal in terms of performance and is of relatively low complexity.

V. Interference Constrained Resource Scheduling Algorithm

The EIPA algorithm starts with a group of UEs and determines the maximum transmit power each should be allowed in the interference protected band(s). This result can be used to inform a frequency domain scheduling algorithm operating at the BS such that UEs can be scheduled to meet an arbitrary objective, e.g., proportional fairness, while also ensuring

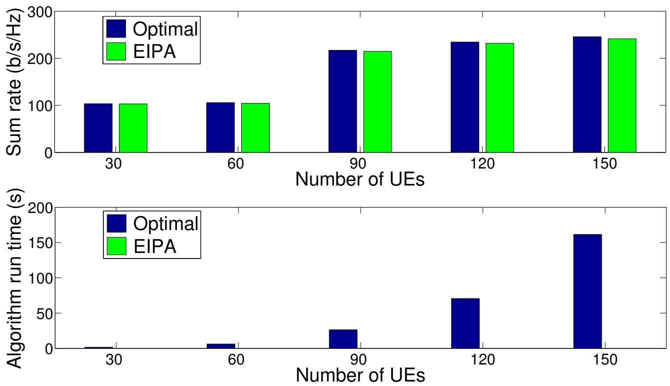


Fig. 5. Performance of EIPA algorithm compared to numeric optimization for five different networks. (Top) Achieved sum-rate. (Bottom) Time to compute power allocation. Run time of EIPA is not visible with this scale.

the interference protection criteria is satisfied. We take this approach to treat the overall resource scheduling problem.

We first use EIPA on all active UEs in the LTE network to identify the UEs that are best suited to operate in the protected band and the power limits that ensure the interference constraint will be satisfied. Then, in our frequency domain scheduler, we set the utility functions of any potential assignments in the protected band to zero for UEs assigned zero power by EIPA. This ensures that the frequency domain scheduling will not assign these UEs to the protected band. For UEs with nonzero power allocations from EIPA, we modify the utility functions for any potential assignments in the protected band based on the identified transmit power limits. Note that the frequency domain scheduler may assign RBs outside of the protected band to any of the UEs. Specifically, our interference constrained resource scheduling algorithm is summarized by the following steps:

(1) Run EIPA (see Section IV) for all UEs in the network.

(2) For UEs allocated zero power from EIPA, set their utility functions $U(A_i^b, T_i^b, P_i^b)$ to zero in the protected band.

(3) For UEs allocated a nonzero power from EIPA, modify their utility functions to reflect this maximum power level.

(4) Perform RB assignment using an LTE frequency domain assignment algorithm with the modified utility functions.

(5) Repeat step (4) at each scheduling time slot. Repeat steps (1) through (3) at an interval based on the correlation time of the UE channel state information.

Use of the EIPA algorithm to satisfy the interference constraints is the novel part of this approach since the modifications to existing frequency domain LTE uplink schedulers can be relatively straightforward. Given that EIPA equalizes the UE interference contributions to the aggregate level at the primary receiver, we dub this overall resource scheduling approach as the equal interference contribution scheduling (EICS) algorithm.

VI. Resource Scheduling Simulation Results

To evaluate the performance of EICS in the context of the LTE-METSAT sharing scenario, we consider a single representative METSAT earth station receiver with a 3 dB bandwidth of 1.33 MHz. In [2], protection zones are listed with radii ranging from 2 km to 98 km. We consider a protection zone of radius 50 km as a representative case. We also select $I_t = -121$ dBm as the aggregate interference power threshold for the METSAT receiver consistent with the thresholds identified in [2] for many of the METSAT sites. As mentioned previously, a probability threshold is not specified in [2]. We assume $p_t = 0.5\%$ for this parameter, consistent with the expectation that the METSAT operator could only tolerate exceedance of the aggreggate interference power threshold a small fraction of the time.

We consider a 5 MHz LTE network overlapping the bandwidth of the METSAT downlink with parameter selection consistent with the assumptions and analyses in [2]. BSs are placed within the protection zone, either randomly or as specified otherwise. UEs are then located uniformly within a 3.5 km radius circle around each BS. The METSAT downlink is assumed to operate at the center of the 5 MHz LTE network bandwidth and the protection criteria is active for the duration of the simulations. A proportional fair scheduler is used with target recieved power per RB of $P0 = -90$ dBm and path loss correction factor $\alpha = 0.8$. We considered Algorithm 3 from [6] which sorts all possible RB to UE assignments by their utility, and then makes assignments from the highest value to lowest, skipping those that would violate the contiguous RB constraint. We modified this scheduler to account for the interference limited utility functions as necessary for use with the EICS algorithm. UEs are assumed to have backlogged buffers with best effort traffic.

Table I identifies other parameter values used in the simulation. Most parameter values align closely with those identified in [2]. For simplicity, we ignore the effects of adjacent channel interference. This should not affect the relative performance of the scheduling algorithms. We also opt for a simple two-ray propagation model for the mean channel gain between any UE and the primary receiver. While this is a departure from the Irregular Terrain Model used in [2], it greatly simplifies the analysis and also will not affect the relative results.

A. EICS Algorithm Comparison to Optimal RB Assignment Scheduling

Here we consider the performance of the EICS algorithm described in Section V with that of the optimal solution to problem (4). We have already discussed that identifying the optimal solution to problem (4) is not trivial. It is a mixed integer programming problem with a very large variable space. We look to small-scale network deployment scenarios over which a global search for the optimal RB assignment is feasible, and defer analysis of the EICS algorithm with larger-scale scenarios to the next section. Specifically, let us consider two secondary LTE BSs, each with five associated UEs. Let us also limit our analysis to two contiguous RBs in the 5 MHz network, with one of the two subject to the interference protection constraint.

TABLE I
PARAMETER NOTATION AND SIMULATED VALUES

Parameter	Symbol	Value
LTE network bandwidth		5 MHz
Number of usable RBs	M	25
Number of BSs in network	N_b	10
Number of UEs per BS	N_u^b	varies
RB bandwidth	W_c	180 kHz
Scheduling time interval	TTI	1 ms
Number of TTIs simulated		10
Thermal noise at BS receiver	N_2	-101.5 dBm
BS to METSAT max distance	R	50 km
BS to METSAT min distance	r	1 km
UE to BS max distance	d_m	3.5 km
Std. dev. of shadowing	σ_{dB}	10 dB
Harmful interference threshold	I_t	-121 dBm
Max probability I_t is exceeded	p_t	0.5 %
Index of RBs in protected band	W_p	9 thru 17
Aggregate interference in the jth RB	I_j	computed
Maximum UE transmit power	P_{max}	23 dBm
UE transmit power per RB	P_i^b	computed
Total number of UEs in the network	N_u	varies
UE to METSAT mean channel gain	$g_{i,j}^{1,b}$	varies
UE to BS mean channel gain	$g_{i,j}^{2,b}$	varies
Random variable for shadowing	$z_{i,j}^b$	varies
Index of leftmost RB assignment	A_i^b	varies
Number of RBs assigned	T_i^b	varies

We examine five trials with random locations for the BSs and UEs in each. Figure 6 plots the performance of the EICS algorithm in comparison with the optimal for these five trials. For further comparison, a simple approach of having the entire LTE network not use, i.e., block, RBs that overlap the protected receiver frequencies was also simulated and is shown in the Figure. Also plotted in Figure 6 are the topologies of the networks for trials 1 and 3. We observe that the EICS algorithm achieves a throughput to within 99% of the optimal for trials 2, 4 and 5, 96% of the optimal for trial 3, and 88% for trial 1. We also observe that EICS can achieve up to about twice the throughput of that achieved with the RB blocking strategy.

In trials 2, 4 and 5, the EICS algorithm achieves nearly the same throughput as the optimal RB assignment strategy. The BSs are located at a distance from the primary receiver of 10 and 30 km in trial 2, 10 and 10 km in trial 4, and 15 and 18 km in trial 5. Comparison of these trials demonstrates the dependency of the results on the distances of the BSs from the primary receiver. To examine this behavior more directly, consider Figure 7 which plots the throughput of the three strategies for decreasing distances to the primary receiver. In this case, all other aspects of the simulation, such as UE distances to their associated BS and fading realizations are held fixed. The relative throughput that can be gained from the EICS and optimal strategies is decreased for networks closer to the primary receiver as this results in stricter limits on transmit powers in the protected bands

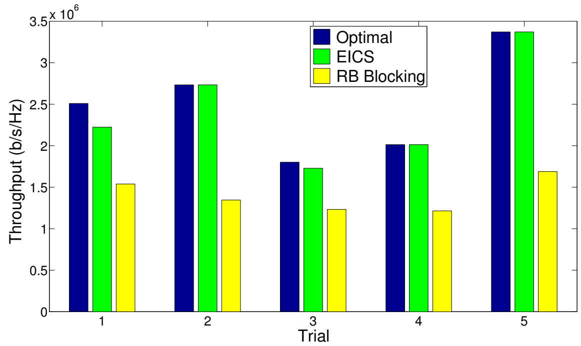
Frequency selective fading also can have a significant effect. For example, in trial 3, all five UEs connected to the UE furthest from the primary receiver happen to have deep fades on the interference protected RB, limiting the utility of the protected band to this particular network. In trial 3, we also see that the EICS algorithm doesn't achieve the same throughput as the optimal strategy. In this case, this is a consequence of the suboptimal greedy frequency domain scheduler arriving at a different RB assignment than the optimal.

In trial 1, we see the greatest discrepancy between the optimal strategy and the EICS algorithm. This is a consequence of ignoring BS associations and the number of RBs in the EIPA algorithm. Specifically, EIPA in this case determined that all of the UEs associated with the furthest BS should be permitted in the protected band, and all the UEs associated with the closest BS should not be permitted in the band in accordance with their gain ratios. The difficulty here is that all five of the UEs that are permitted in the band are associated with the same BS, and thus only one of them can be scheduled on the one protected RB during any scheduling interval. This issue will be automatically mitigated to an extent with large-scale scenarios where the number of UEs and RBs are both greater such that there is more flexibility in the scheduling and a low probability that EIPA will select UEs that are all located in the same cell. Thus we conjecture that for large-scale networks, the typical performance of EICS will more closely approach the optimal, perhaps on par with the results observed in trials 2 through 5 (within 96% to 99% of the optimal). The EICS algorithm could also be modified to address this issue, e.g., by including an iterative process between EIPA and the frequency domain scheduler, but this would come at the cost of significantly increased, possibly prohibitive, complexity.

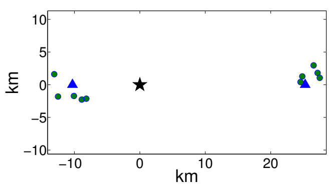
The performance of the EICS algorithm also depends on the LTE network power control parameters $P0$ and α. If these parameters are set to allow UEs to operate at higher transmit power levels, more throughput can be achieved, particularly in the bands not subject to the aggregate interference constraint. As Figure 8 shows, increasing $P0$ from the nominal value of -90 dBm increases the absolute throughput for all algorithms, but the relative throughput gains achieved with either the EICS or the optimal strategy as compared with simple RB blocking appear less and less worth the burden of their additional complexity. We note here however that to conserve the battery life of UEs and limit interference between neighboring cells in the network, LTE operators do minimize UE transmit powers via power control e.g., by keeping $P0$ small.

B. EICS Resource Scheduling Algorithm for Large-Scale LTE-METSAT Scenario

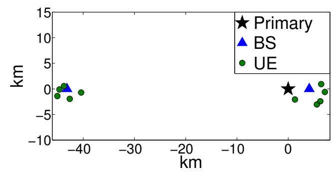
Now let us consider large-scale LTE networks with hundreds of active UEs within the protection zone. We also consider all 25 RBs in the 5 MHz network and assume that the middle 9 RBs overlap with the primary receiver band, i.e., 40% of the RBs are subject to the protection constraint. With the size of



(a) Throughput for each small-scale trial



(b) Topology of Trial 1



(c) Topology of Trial 3

Fig. 6. Performance comparison of the EICS algorithm with optimal RB assignment and RB blocking strategies for five trial topologies.

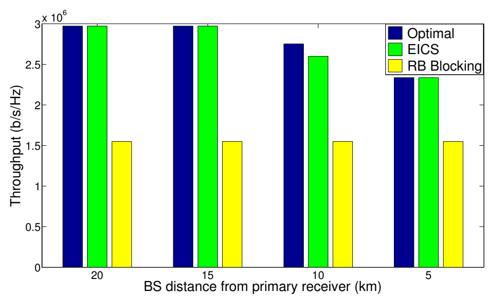


Fig. 7. Scheduler throughput versus distance of BSs from primary receiver.

the networks considered here, it is no longer feasible to identify the optimal RB assignment, but we continue to consider the RB blocking approach for performance comparison.

We once again consider five trials with random locations of BSs and UEs. Ten BSs are included in the LTE network, and 100 UEs are associated with each BS. Figure 9 plots the achieved throughput for the five trials. Here we see little variation between trials, with the EICS algorithm nearly achieving a 40% gain in all cases, on par with the number of protected RBs. The simple explanation for this lack of variation is that these networks are so large, they all have numerous UEs that can benefit from operating in the protected bands. To further highlight this, Figure 10 plots the case of a network where all aspects of the network are fixed except for the number of active UEs per BS. As the number of UEs increases, it is increasingly likely that there are UEs in the network which can put the protected RBs to good use. Thus we observe that the EICS algorithm offers the most benefit for networks with many active UEs.

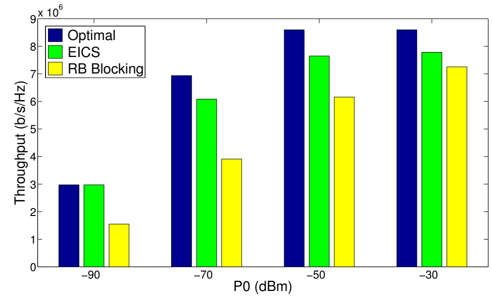


Fig. 8. Scheduler throughput versus P0 power control setting.

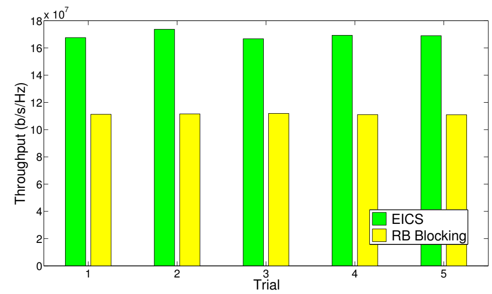


Fig. 9. Achieved throughput for large-scale trials.

VII. PRACTICAL CONSIDERATIONS

The EICS algorithm must be implemented within an LTE network in two parts. First, the EIPA algorithm must be hosted at a central node within the network that is capable of interfacing with all BSs in the vicinity of the METSAT site. This node could be the Mobility Management Entity (MME) or some other node higher in the network. Second, the frequency domain schedulers on each of these BSs must be modified to account for inputs from EIPA. The BSs must also be modified to report the relevant channel gain information of the UEs that can potentially be scheduled in the protected band to EIPA. Note that this channel gain information is already measured by the BS in current LTE networks and does not introduce any additional overhead on the spectrum resources of the network.

It is not necessary to run EIPA at each scheduling time slot, but instead, EIPA should be run often enough to account for the temporal correlation of the channel state information as well as UEs in the network going active and inactive. The coherence time [25] for pedestrian users at this frequency is on the order of 100 ms while fast vehicular users may have a coherence time of just a few milliseconds. EIPA was demonstrated to run on a PC for a network of 1,000 UEs within 1 ms. This would be sufficient to accomodate changes due to UE mobility, but the delay in the interface between the MME or other node hosting EIPA and the relevant BSs will be the limiting constraint. For example, a delay on the order of tens of milliseconds would be sufficient for pedestrian users, but would not be sufficient to address small-scale fading effects for vehicular users. In this case, a moving average of the channel state information should be passed to EIPA

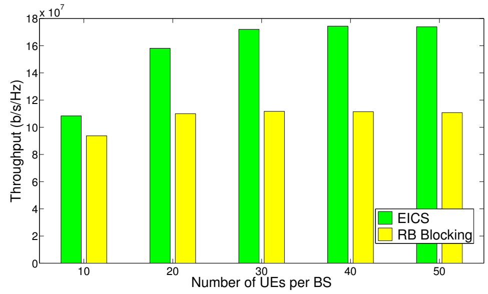


Fig. 10. Achieved throughput for variable number of UEs per BS.

such that the effects of small-scale fading are ignored and power allocation is based on the longer term state of large-scale shadowing and mean path loss.

The interface between the BSs and the MME must also be capable of handling the data reported from and to EIPA. The EIPA output consists of a simple array of integer transmit power values while each BS must return an array of channel state information for associated UEs. For 100 active UEs associated with one BS, and power limit updates every 10 ms LTE frame, overhead demand on the interface to support EICS may be up to 100 kbps. This is well within the capacity of current LTE backhaul infrastructure.

VIII. Conclusion

We have proposed a novel approach we call the EICS algorithm for LTE uplink resource scheduling in radio frequency spectrum bands that are subject to aggregate interference protection constraints. Algorithms of this kind are needed to allow networks to make efficient use of spectrum in shared environments. With the EIPA algorithm at its core, we described how the EICS algorithm could be implemented within a practical LTE network, and demonstrated its efficiency in the context of a real-world LTE-METSAT spectrum sharing scenario. Specifically, we showed that the EICS algorithm closely approached the performance of optimal scheduling, but with low enough complexity that it can be executed in a time-scale suitable for LTE scheduling. We noted that the implementation of EICS may depend on delays in the LTE network backhaul interface. The performance of EICS limited by interface delay and under various mobility models warrants further study. We also provided an optimization framework for the problem, and treated it numerically. Through further analysis of this framework, we intend to identify analytical bounds on the performance of the EICS algorithm.

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