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I Abstract

This paper seeks to explore the integration of spectrum and network resource management functionalities to the benefit of achieving higher performance and capacity gains in an International Mobile Telecommunications-Advanced (IMT-A) scenario. In particular, we investigate the allocation of users over two frequency bands (i.e., 2 GHz and 5 GHz) for a single operator scenario. The same type of Radio Access Technology (RAT) is considered for both frequency bands. It is assumed that the operator has gained access to a non-shared 2 GHz band and to part (or all) of the frequency pool band at 5 GHz. The performance gain is analyzed in terms of higher data throughput. The performance is heavily dependent on the channel quality for each user in the considered bands which, in turn, is a function of the path loss and the distance from the Base Station (BS). The operator will have relevant improvements when Mobile Stations are heterogeneously distributed on the cell, with variable distances from the BS. A gain up to 500 kbps (20%) was obtained with the proposed optimal solution.

II Introduction

By supporting additional system capacity and higher data rates through high speed Radio Access Technology (RAT), such as the International Mobile Telecommunications-Advanced (IMT-A) [10], users can be guaranteed universally accessible broadband services. One important enabling factor is the availability of bandwidth, which is also related to the assignment of frequency spectrum bands for IMT-A and beyond technologies [3]. This is impeded by the existing highly fragmented radio frequency spectrum that does not match the actual demand for transmission and network resources. Such fragmentation poses a challenge during dynamic spectrum use where multiple frequency bands can be assigned in support of the users and the mobile transmission system's ability to support a wide range of services across all elements of the network (i.e. core, distribution and access)[7]. In such a scenario, information about how to aggregate contiguous and not contiguous parts of the highly fragmented spectrum to be used and how to allocate users over the dedicated and shared bands of an operator, can improve the overall system capacity.

Spectrum and more recently carrier aggregation have been proposed for Long Term Evolution-Advanced (LTE-A) and IMT-A [4], [2], [1] as ways to use. Spectrum aggregation (SA) can be performed in the same or in different bands and may occur when the operator's dedicated Downlink (DL) or Uplink (UL) band is not contiguous but is split in two or more parts. Enablers of SA are the advances in the area of advances in smart antenna design, spread-spectrum technologies, software-defined radio (SDR), cooperative communications, and cognitive radio (CR) systems. Cognitive capabilities, such as sensing, access to database (in connection with geolocation), use of cognitive pilot channel (CPC), transmission power control, etc. can form a CR system capability toolbox and could facilitate coexistence/sharing in bands, where it was previously determined to be not feasible. The ITU Radiocommunication Assembly in 2007 [3] put several open and important research questions related to CR systems. The questions included the following aspects of the CR systems: definition, closely related radio technologies and their functionalities, key technical characteristics, requirements, performance, benefits, the potential applications, the operational implications, capabilities that facilitate coexistence with existing systems, possible spectrum-sharing techniques and the effect on the efficient use of radio resources. Cooperative communications and CR have become important as enablers of more energy and bandwidth for wireless networks, and thus for supporting service quality and channel capacity. Cognitive users are able to make intelligent decisions on spectrum usage and communication parameters based on the sensed spectrum dynamics and the decision of other users. Further, the dynamics of the radio environment requires new real-time decision and information exchange approaches to reduce the overhead from such signaling. The current work builds upon the advances in cooperative communications and CR and proposes an approach to maximize the overall system performance in terms of data rate, power, number of served and satisfied users, etc., which in a spectrum sharing scenario might be degraded by the reassignment of the spectrum to primary and secondary users.

In [14], it was proposed to utilize the source of diversity offered by widely separated bands as an opportunity to achieve higher spectrum efficiency by applying a General MultiBand Scheduling (GMBS) algorithm to the dedicated band and the shared bands of a single HSDPA operator during SA. But an optimal solution was not found. In this paper, the focus was on the aspects of how one operator can manage the user allocation over the dedicated and shared bands in a an optimal way achieving higher network throughput. It was shown that by allocating the user packets to the available radio resources according to the user requirements, a constant throughput gain over a wide range of active services in the cell can be achieved.

This work optimizes further the GMBS algorithm and shows that the operator applying multi-band scheduling (MBS) will have relevant improvements when the Mobile Station (MS) have heterogeneous spatial distribution in the cell (variable distances from the BS) and different channel qualities in the considered spectrum bands. Spectrum sharing mechanisms are beyond the scope of this work. Depending on the capabilities at the MSs, each user could be allocated to a single frequency band or to both the frequency bands. In the latter case, the MSs have multi-radio transceivers and can transmit and receive data on both bands. Here, the focus is only on single-band MSs that need to be allocated over one of the two possible bands. This paper is organized as follows. Section III defines the problem. Section IV proposes the GMBS as a General Assignment Problem (GAP). Section V presents the system model to test our algorithm. Section VI presents the results obtained and Section VII presents the conclusions.

III Problem Statement

The objective is to determine the best user allocation for a single operator over two (or more) frequency bands - $b \in \{0, 1, 2, \ldots m\}$ - in order to maximize the total network throughput. Two bands are analyzed. The operator has exclusive usage of the 2 GHz band and can access to the shared frequency pool at 5 GHz. The quantity of radio resources available at 5 GHz is determined by spectrum trading (or bargaining) among all the operators that have access to the common frequency pool. In this work, the part of the frequency pool assigned to the operator is assumed to be fixed. The performance gains are analyzed in terms of data throughput.

After the operator has gained access to a certain portion of the frequency pool, the problem of whether to allocate users is still to be solved. The total throughput is function of the radio channel qualities for each user in the considered bands. The Channel Quality Indicator (CQI) depends on the path loss which depends on the distance from the Base Station (BS) but also on the carrier frequency adopted on the interference that comes from neighboring cells and from the own cell. The operator applying Multi-Band Scheduling will have good improvements when the MSs have heterogeneous spatial distribution in the cell (variable distances from the BS) and different channel qualities in the considered spectrum bands.

The problem of scheduling the users in two bands (2 GHz and part or all of the frequency pool at 5 GHz) can be formulated as an GAP optimization problem [13]. The Profit Function (PF) to be maximized is the total throughput of the operator via a single objective maximization problem, fairness and Quality of Service (QoS) requirements of the service classes are not considered here. However, multiple objectives can be easily introduced and implemented in the problem, such as maximizing the total throughput while minimizing the QoS satisfaction indexes for each service class, [15]. Solving Multiple Objectives General Assignment Problem (MO-GAP) can be very difficult and usually the objectives are combined together via a linear combination, called ”scalarization” [12].

The GMBS problem can be solved considering MSs with the added capability of transmitting and receiving in multiple frequency simultaneously (multiple transceivers at the MS) or when the MSs can just chose one band among all the bands in the network and choosing one of the transceiver configurations available at the MS radio. In both cases, we have an Integer Programming (IP) problem with different constrains formulation.

In the GMBS solution proposed here, the PF depends on the ratio between the service throughput request and the real goodput available for each user (on each band). The problem is formulated with a load constrain for each band: L_b^{max} and also resource constraint based on channels available.

IV General Multi-Band Scheduling for Maximum Network Throughput

The scheduling of users over multiple frequency bands can be modeled in its most general form as a GAP Problem. The objective is to maximize the throughput and thus to maximize the exploitation of the capacity of the network. The PF is thus defined considering the ratio between the requested rate by the service flow and the rate available on a single downlink channel. This weight accounts for a real usage of the capacity considering the source traffic generator. The PF to be maximized is the following:

$$(PF)\ max \sum_{b=1}^{m} \sum_{u=1}^{n} W_{bu} x_{bu} \tag{1}$$

where x_{bu} is the allocation variable and the normalized service rate is given by:

$$W_{bu} = R_{bu}/S_{rate} \tag{2}$$

where S_{rate} is the service goodput request, and

$$R_{bu} = [1 - PER(CQI_{bu}, SIR_{bu})] \cdot R(CQI_{bu}) \tag{3}$$

is the goodput available for user *u* on band *b*, and $R(CQI_{bu})$ is the throughput on a single DL channel, and depends on the CQI value of user *u* on band *b*. PER is the packet error rate.

In each band, the network has multiple data channels. In HSDPA, each channel is identified by one of the available orthogonal codes. More than one code can be assigned to a user. A single code can be also assigned to more than one user, the users on the same code adopt a time-division multiple-access which is managed by the packet scheduler. The allocation variable, x_{bu}, is either an integer with the value 0 or 1 when only one code can be assigned to one user, or a non negative integer, i.e., $x_{bu} \in \{0, \ldots, max\_N_{codes}\}$ in the case of multi-code allocation.

Multi-code user allocation over the bands is represented by:

$$x_{bu} = \begin{cases} c & \text{if user } u \text{ has allocated } c \text{ channels on band b} \\ \vdots & \\ 1 & \text{if user } u \text{ has allocated 1 channel on band } b \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

When single code allocation is being considered, x_{bu} is equal to one or zero. We will explore in the remainder of this work single code allocation.

For a multiband MS with only one active transceiver and single code allocation, the GMBS has two constraints:

b \ u	1	2	3	...	n
1	1	0	1	...	0
2	0	1	0	...	0
3	0	0	0	...	0
⋮	⋮	⋮	⋮	...	⋮
m	0	0	0	....	0
↓	↓	↓	↓	↓	↓
$\sum_b x_{bu}$	1	1	1	1	1

Figure 1: Example of an allocation matrix X.

1. Each user can be allocated only to a single frequency band with a single code allocation. This results in the Allocation Constraint (AC) as follows:

$$(AC) \qquad \sum_{b=1}^{m} x_{bu} \leq 1, x_{bu} \in \{0,1\}, \quad \forall u \in \{0,...,n\} \tag{5}$$

2. The total number of users on each band is upper bounded by the maximum load that can be handled in the band, L_b^{max}, i.e., the Bandwidth Constraint (BC) as follows:

$$(BC1) \qquad \sum_{u=1}^{n} S_{rate}/R(CQI_{bu})x_{bu} \leq L^{max}, \quad \forall b \in \{1,\dots,m\} \tag{6}$$

3. The system has a maximum theoretical capacity:

$$(BC2) \qquad \sum_{u=1}^{n} (W_{bu})^{-1} x_{bu} \leq 331.9 \cdot 15, \quad \forall b \in \{1,\dots,m\} \tag{7}$$

   where 15 is the maximum number of parallel codes HSDPA has available and 331.9 is the the maximum data rate available per code that MS with the best Modulation and Coding Scheme (MCS) can transmit (CQI 22 is not used).

Figure 1 presents one example for the allocation matrix $X = [x_{bu}]$, with $b = \{1,...,m\}$ and $u = \{1,...,n\}$ for a given situation. If only two bands are considered one will have $m = 2$ and $L^{max} = [L_1^{max} L_2^{max}]^T$. Several testes where performed to find the best load threshold, and a top/maximum load 0.42 was found. The system reaches the maximum capacity, load wise.

The objective of the optimization procedure is to obtain the values of x_{bu}, with $b \in \{1,...,m\}$ and $u \in \{1,...,n\}$

V System Model

An High Speed Downlink Packet Access (HSDPA) radio access network is simulated for operation in the 2 GHz and 5 GHz bands in a context of multi-band user allocation.

The Resource Allocation (RA) component is responsible for allocating the available radio resources to the user traffic in a cost-effective manner, and includes a scheduling mechanism, link adaptation, code allocation policy, and Hybrid Automatic Repeat Request (H-ARQ) scheme to improve service throughput for users at the cell edge.

The HSDPA network simulated includes the following link layer functionalities:

- Multi omni-directional cell deployment model, hexagonal cells, consisting in three tiers (for interference purposes); results are presented only for the center cell;
- Near Real Time Video (NRTV) streaming traffic model from [9] with a service rate $S_{rate} = 64$ kbps;
- Radio Resource Management (RRM) schemes, including of AMC, n-parallel channel H-ARQ using chase combining and Round Robin scheduling algorithm;
- ITU-based radio propagation models. The channel loss between the MS and the BS is modeled by path loss, shadowing loss by lognormal distribution and fast fading using approximated Jakes model [16];
- The interference in the MS is calculated with the signal strength received from the neighborhood BSs and the thermal noise;
- The simulator uses as an input a BLER table provided by link layer simulations [11].

Table 1: Transport block size and bit rate associated to CQI.

CQI	Modulation	Transport Block size [bits]	R(CQI) [kbps]
CQI 5	QPSK	377	188.5
CQI 8	QPSK	396	198.0
CQI 15	QPSK	663.8	331.9
CQI 22	16-QAM	1433.6	716.8

Each Time Transmission Interval (TTI) is associated with a sub-frame duration, that corresponds to an HSDPA frame duration of 2 ms with three time slots of 0.67 ms. The HSDPA physical layer [8] provides 15 orthogonal codes available for data transmission within a sub-frame. The available data rates are summarized in Table 1. For each CQI identifier, the modulation scheme, the block sizes and the transport rate are given. The values presented in Table 1 are different from the ones presented in [8]. The physical layer procedures were changed since it was assumed that the GMBS uses single code allocation.

V.A *Resource Allocation (RA)*

The RA allocates the user packets to the available radio resources in order to satisfy the user requirements, and to ensure efficient packet transport to maximize spectral efficiency. The RA, an entity within the set of RRM algorithms, should have inherent tuning flexibility to maximize the spectral efficiency of the system for any type of traffic QoS requirements. The RA adopted here maps packets of variable size into variable

Table 2: Parameters and Models used for 2 and 5 GHz bands

Carrier frequency	2 GHz	5 GHz
Bandwidth	5 MHz	5 MHz
Path loss model:	$128.1 + 37.6Log10(d_{[km]})$	$141.52 + 28log10(d_{[km]})$
Shadowing de-correlation length	5 m	20 m

length radio blocks for transmission over the PHY layer, and the length is dependent on the channel quality. The following events are performed:

1. User packets awaiting transmission are prioritized according to the scheduling algorithm criteria;
2. A CQI identifier is selected according to the link adaptation algorithm, using the available CQI options from the PHY layer;
3. An idle ARQ channel *j* is selected to hold and manage the ARQ transmission;
4. The packet is transmitted and received at the MS. Soft retransmissions are combined with previous packet transmissions (chase combining) and the ARQ messages are generated accordingly. These are then signaled to the BS, and the ARQ processes are released if the messages are positive acknowledgments (ACKs).

V.B 2 GHz and 5 GHz usage under a common RRM approach

The 2 GHz and 5 GHz frequency bands were characterized over the same HSDPA architecture by assuming the models summarized in Table 2 [6]. We proposed to use HSDPA over the 2 GHz, but also, over the 5 GHz band and adopt a Common Radio Resource Manager (CRRM) [17] to manage the extra resources. The CRRM entity keeps track of the CQI, Signal to Interference-plus-Noise Ratio (SINR) and Packet Error Rate (PER) used in both frequencies. Coverage is worst at the cell edge at 5 GHz, as depicted by the darker filling of the 2 GHz band cell in Figure 2 since higher frequencies suffer from higher loss effects.

Figure 3 presents the algorithm to obtain the SINR in one of the frequencies. The mechanism is based on SINR measurements performed by the MS on the CPICH, and based on a prediction of received Pu/Ioc, where Pu is the received power and Ioc is the received inter-cell interference. It is important that Pu and Ioc definitions are chosen so that predicted Pu/Ioc by computation is successful and very near from real Pu/Ioc. More details are in [5]

The SINR measures are uploaded into the HSDPA Radio Network Controller (RNC) through the channel High-speed dedicated physical control channel (HS-DPCCS) then to the CRRM. To get the PER, if no transmission has been done in a given band we assume it to be 0. If a transmission has been performed, we assume the PER calculated from the average of the last transmissions that occurred within a given period.

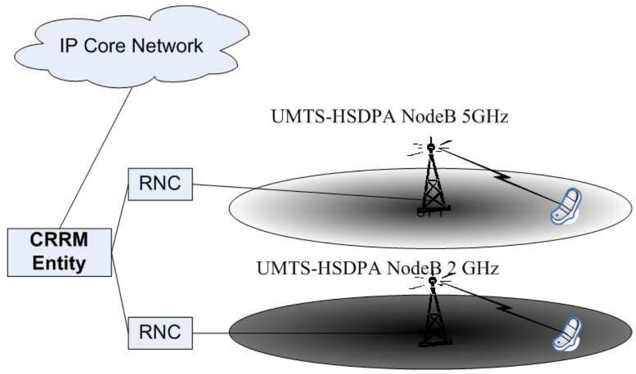

Figure 2: CRRM in the context of two separated frequencies.

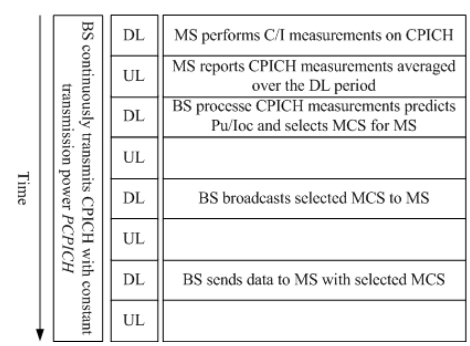

Figure 3: Obtaining SIR and MCS selection algorithm cicle.

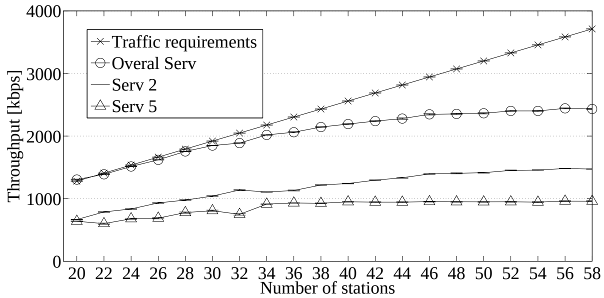

Figure 4: Average throughputs without GMBS.

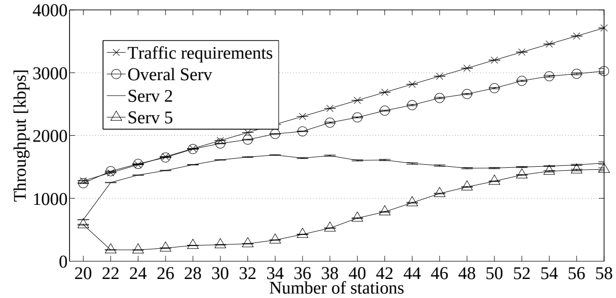

Figure 5: Average throughputs with GMBS.

VI Results

The performance of the algorithm is assessed by using the service throughput that is the total number of bits that have been transmitted and correctly received by the all users in the cell:

$$Serv\_thr_{[bits/s]} = \frac{b_{serv}(p)}{k \cdot T} \tag{8}$$

where $b_{serv}(p)$ is the number of bits received in given period *p*, *T* is the transmit time interval, and $k \cdot T$ is the total simulation time. Users are displaced in the cell with an uniform distribution within a distance of 900m with overlapping 2 Ghz and 5 Ghz coverage. The NRTV calls are modeled by a Poisson distribution, the call duration is exponentially distributed with an average of 180 s. Simulation runs are stopped when a target 95% confidence interval has been achieved. The confidence interval is represented in the graphs by the vertical bars.

Figure 4 shows the throughput results and respective confidence intervals without GMBS. The operator has the availability of two frequency bands. Each one of the two bands are managed separately; call requests are divided in the two bands and it is not possible to switch a service from one band to the other. The ”Overall Serv” throughput is the sum of the service throughput in both frequency bands. The traffic requirement is the traffic required to satisfy all the users (i.e., the NRTV required rate times the number of users in the system). When more than 32 stations are in the system, it cannot satisfy all the MS.

Figure 5 shows the results with the GMBS algorithm proposed in Section IV. As in the 2 GHz the SINR is higher and PER is lower than in the 5 GHz, in the beginning of the simulation, the system has resources for users, the constraints are not limitative and the algorithm will choose mainly the 2 GHz. When the system gets overloaded, and the constraints become limitative, the algorithm does is job of maximizing the use of resources in the optimal way.

The curves in Figure 6 enable a comparison of the results with and without the use of GMBS. The enhancement provided by the GMBS algorithm is clear when more than 32 stations are in the scenario. We assume that the systems reaches is full capacity when the overall service throughput curve stops growing (around 55-66 users). While, without GMBS, the system reaches its full capacity around 2.5 Mbps, with GMBS it reaches its full capacity around 3 Mbps. A gain up to 500 kbps may be obtained,i.e. 20% gain. This gain is achieved by dinamicaly alocating resorces to the MS that best suit the system.

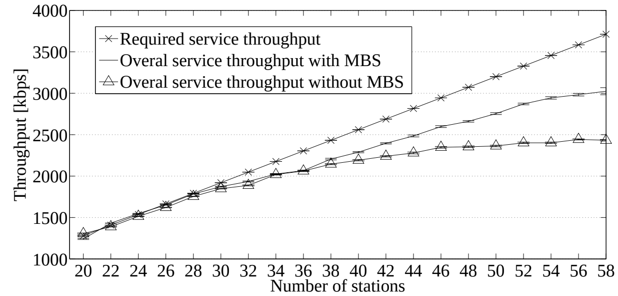

Figure 6: Service throughput with and without GMBS.

VII Conclusions

This paper proposes a resource allocation mechanism for users over two frequency bands that are accessed by a single operator. The proposal is valuable in the scope of currently on-going work within the ITU-R towards IMT-A systems, and in particular the use of SA. The hypotheses of the paper consider that SA can be successfully combined with RRM techniques for an optimized performance.

It is shown that by using the GMBS algorithm a gain up to 500 kbps=20% can be obtained. GMBS is able to support a higher number of users due to the ability of scheduling their traffic considering the respective radio channel quality in different parts of the radio spectrum. The achieved improvement is relative to a scenario where users are randomly deployed on the cell. Because the 5 GHz band has much lower coverage than the 2 GHz and the results shown here are a first step towards the analysis of the attainable gain with GMBS.

In this work, the GMBS performance was assessed in terms of the total throughput. Future work will include the QoS requirements into the GMBS formulation via a linear combination of multiple objectives (”scalarization”). The combined solution for the packet scheduler and the spectrum scheduler is foreseen to be able to greatly reduce delay and jitters, which are of paramount importance for real time services. Mobility patterns will also be analyzed, showing the effectiveness of GMBS to counter-fight shadowing in support of the aforementioned real time services.

VIII Acknowledgment

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LTE-A Long Term Evolution-Advanced
SA Spectrum aggregation
PF Profit Function
GAP General Assignment Problem
MO-GAP Multiple Objectives General Assignment Problem
CQI Channel Quality Indicator
MS Mobile Station
HSDPA High Speed Downlink Packet Access
BS Base Station
IP Integer Programming
QoS Quality of Service
GMBS General MultiBand Scheduling
DL Downlink
BC Bandwidth Constraint
AC Allocation Constraint
H-ARQ Hybrid Automatic Repeat Request
NRTV Near Real Time Video
TTI Time Transmission Interval
IMT-A International Mobile Telecommunications-Advanced
RAT Radio Access Technology
RRM Radio Resource Management
RNC Radio Network Controller
HS-DPCCS High-speed dedicated physical control channel
PER Packet Error Rate
MCS Modulation and Coding Scheme
SINR Signal to Interference-plus-Noise Ratio
RA Resource Allocation
CRRM Common Radio Resource Manager
UL Uplink