The 13th International Symposium on Wireless Personal Multimedia Communications (WPMC 2010)

SPECTRUM AGGREGATION WITH OPTIMAL MULTI-BAND SCHEDULING

Filippo Meucci
Electronics and Telecommunication Dep.
University of Firenze
Florence, Italy

Orlando Cabral, F.J. Velez
Instituto de Telecomunicações, DEM
Universidade da Beira Interior
Covilhã, Portugal

A. Mihovska, N.R. Prasad
CTIF, Department of Electronic Systems
Aalborg University
Aalborg, Denmark

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) [1], 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 [2]. 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 [3]). 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], [5], [6] as ways to use the resources. 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 into two or more parts. Enablers of SA are the advances in the area of 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 put several open and important research questions related to CR systems [2]. The questions include the following aspects of CR systems: the definition, closely related radio technologies and their functionalities, key technical characteristics, requirements, performance, benefits, potential applications, 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 for 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. Furthermore, the dynamics of the radio environment requires new approaches to real-time decision and information exchange, 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. In a spectrum sharing scenario, these parameters may be degraded by the reassignment of the spectrum to primary and secondary users.

In [7], it was proposed to apply a General MultiBand Scheduling (GMBS) algorithm to the dedicated band and the shared bands of a single High Speed Downlink Packet Access (HSDPA) operator during SA with a Common Radio Resource Management (CRRM) architecture, as illustrated in Figure 1. Widely separated bands offer a source of diversity, an opportunity to achieve higher spectrum efficiency.

However, an optimal solution was not found in [7]. 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 whilst achieving higher network throughput. The objective is to show 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.

In this work, the GMBS algorithm is further optimized. The operator will have relevant improvements when the Mobile Station (MS) have heterogeneous spatial distribution in the cell (variable distances from the BS) and different channel quali-

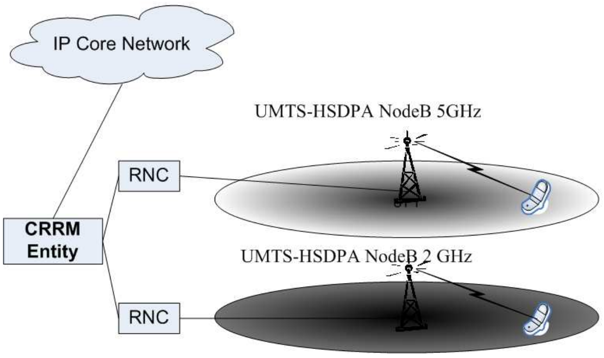

Figure 1: CRRM in the context of two separated frequencies.

ties in the considered spectrum bands. Depending on the capabilities at the MSs, each user may 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. Spectrum sharing mechanisms are beyond the scope of this work.

The remaining of the 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 discusses the results while 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 access to the 2 GHz band and can access to the shared frequency pool at 5 GHz as well. The amount 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 the 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 a 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 and on the interference that comes from neighboring cells and from the own cell. The operator applying Multi-Band Scheduling will have relevant improvements when the MSs have heterogeneous spatial distribution in the cell (variable distances from the BS) and different channel quality in the considered spectrum bands.

The problem of scheduling the users into two bands (2 GHz and part or all of the frequency pool at 5 GHz) can be formulated as a GAP optimization problem [8]. 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 [9]. Solving Multiple Objectives General Assignment Problem (MO-GAP) can be very difficult. Usually, the objectives are combined together via a linear combination, called ”scalarization” [10].

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

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 the available channels.

IV GENERAL MULTI-BAND SCHEDULING FOR MAXIMUM NETWORK THROUGHPUT

The scheduling of users over multiple frequency bands can be modelled in its most general form as a GAP Problem. The objective is to maximise the throughput and thus to maximise the exploitation of the network capacity. The PF is thus defined considering the ratio between the requested rate by the service flow and the rate available on a single DL channel. This weight accounts for a real usage of the capacity considering the source traffic generator. The PF to be maximised 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 normalised 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. Codes can be allocated to users in a flexible manner. More than one code can be assigned to a single user or a single code can be 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 a boolean value when only one

$$\begin{array}{c|ccccc} b \backslash u & 1 & 2 & 3 & \dots & n \\ \hline 1 & 1 & 0 & 1 & \dots & 0 \\ 2 & 0 & 1 & 0 & \dots & 0 \\ 3 & 0 & 0 & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \dots & \vdots \\ m & 0 & 0 & 0 & .... & 0 \\ \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow \\ \sum_b x_{bu} & 1 & 1 & 1 & 1 & 1 \end{array}$$

Figure 2: Example of an allocation matrix X.

code can be assigned to one user, or a non negative integer, i.e., $x_{bu} \in \{0, \dots, max\_N_{codes}\}$ in the case of multi-code allocation. In the remainder of this work, single code allocation is considered.

For a multi-band MS with only one active transceiver and single code allocation, three constraints can be devised for the GMBS problem:

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:

$$(AC) \qquad \sum_{b=1}^{m} x_{bu} \leq 1, x_{bu} \in \{0, 1\}, \quad \forall u \in \{0, ..., n\} \tag{4}$$

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:

$$(BC1) \qquad \sum_{u=1}^{n} S_{rate}/R(CQI_{bu}) x_{bu} \leq L^{max}, \quad \forall b \in \{1, \dots, m\} \tag{5}$$

3. The system has a maximum theoretical capacity:

$$(BC2) \qquad \sum_{u=1}^{n} (W_{bu})^{-1} x_{bu} \leq C_{max}, \quad \forall b \in \{1, \dots, m\} \tag{6}$$

   where $C_{max} = R_{max} \cdot N_{codes}$, R_{max} is the maximum bit rate at the PHY layer for a single code and N_{codes} is the maximum number of parallel codes HSDPA has available.

Figure 2 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 $L^{max} = [L_1^{max} L_2^{max}]^T$. After performing several tests (trough extensive simulation) to find the best load threshold, a load factor of 75% has been chosen. To find an heuristic that outputs this parameter it is out of the scope of this work. The objective of the optimisation procedure is to obtain the values for x_{bu}, with $b \in \{1, ..., m\}$ and $u \in \{1, ..., n\}$

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

V HDSPA NETWORK MODEL

The operation of HSDPA radio access network in the 2 GHz and 5 GHz bands is simulated for operation 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 a Hybrid Automatic Repeat Request (H-ARQ) scheme, to improve service throughput for users at the cell edge.

The simulated HSDPA network has the following characteristics:

- Multi omni-directional cell deployment model, hexagonal cells, consisting of three tiers for the purpose of computing the interference (results are however only presented for the central cell);
- Near Real Time Video (NRTV) streaming traffic model from [11], with a service rate $S_{rate} = 64$ kbps;
- Radio Resource Management (RRM) schemes, including AMC, n-parallel channel H-ARQ using chase combining and Round Robin scheduling algorithms;
- ITU-based radio propagation models: the radio channel between the MS and the BS is modelled by the propagation loss and shadowing loss, by lognormal distribution and fast fading using the Jakes model [12];
- The interference in the MS is calculated with the signal strength received from the neighbour BSs and the thermal noise;
- The simulator uses a BLER table provided by link layer simulations [13] as an input.

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 provides 15 orthogonal codes available for data transmission within a sub-frame [14]. The available bit rates are summarised in Table 1. For each CQI identifier, the modulation scheme, the block sizes and the transport rate are given.

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 maximise spectral efficiency. The RA, an entity within the set of RRM algorithms, should have

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

inherent tuning flexibility to maximise the spectral efficiency of the system for any type of traffic QoS requirements. The RA maps packets of variable size into variable length radio blocks for transmission over the PHY layer, and the length is dependent on the channel quality. The following events occur:

1. User packets awaiting transmission are prioritised 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 signalled to the BS, and the ARQ processes are released if the messages are positive acknowledgements (ACKs).

V.B MS SINR Measurements

The CRRM entity keeps track of the CQI, Signal to Interference-plus-Noise Ratio (SINR) and Packet Error Rate (PER) for every MS in both frequency bands. Figure 3 illustrates the mechanism used to sense the CQI over the various frequency bands. The sensing is based on quality measurements of the Common Pilot Channel (CPICH) channel performed by MS. The MS performs a prediction of the ratio between the received power and the received inter-cell interference. Several approaches can be followed. The MS can be either in active or passive mode. In active mode the user is continuously measuring the received CQI over both frequencies. In the passive mode, the measurements are periodically sent to the Radio Network Controller (RNC). The CQI measures are communicated to the HSDPA RNC through the High-speed dedicated physical control channel (HS-DPCCS) channel. Although the active mode has the advantage of self-detection allowing for aggressive exploitation of radio channel capacity, the passive mode could be preferred when energy saving at the MS and reduced signalling overhead is of interest. If no transmission has been previously attempted in a given band, the best CQI is optimistically assumed. Instead, if a transmission has occurred, the CQI is calculated from the average of the last transmissions within a given period, i.e., moving average calculation. More details are given in [15]

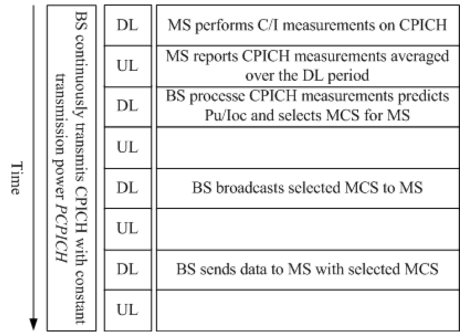

Figure 3: Obtaining SIR and MCS selection algorithm cicle.

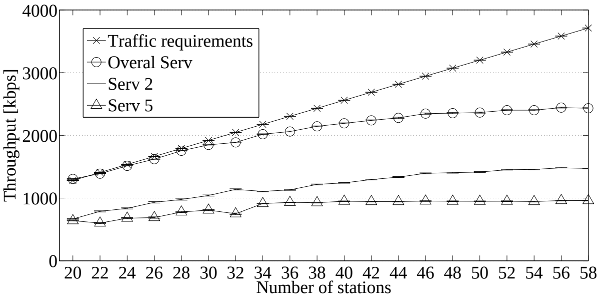

Figure 4: Average throughputs without GMBS.

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:

$$Serv\_thr_{[bits/s]} = \frac{b_{serv}(p)}{k \cdot T} \quad (7)$$

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 deployed in the cell with an uniform distribution within a distance of 900m with overlapping 2 Ghz and 5 Ghz coverage. The NRTV sessions generation is modelled by a Poisson distribution while the session 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 results for the throughput as a function of the number of stations and respective confidence intervals without GMBS. The operator has two frequency bands available, each one managed separately; session requests are divided by 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). The curves show that the system cannot satisfy the capacity request with more than 32 MSs served.

Figure 5 shows the results for the throughput with the GMBS algorithm proposed in Section IV. SINR in 2 GHz band is

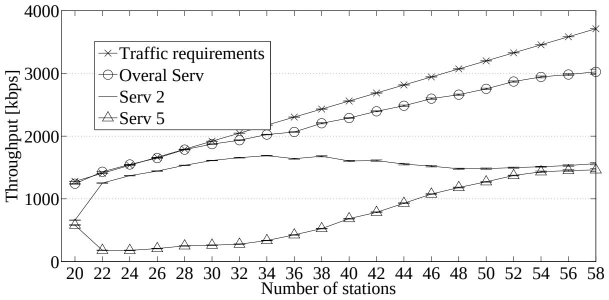

Figure 5: Average throughputs with GMBS.

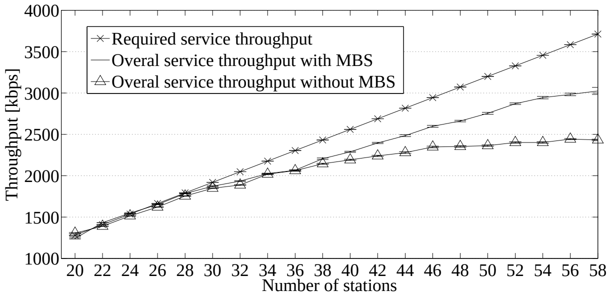

Figure 6: Service throughput with and without GMBS.

higher than in the 5 GHz band. When the system has plenty of resources, the algorithm will mainly allocate users in the 2 GHz band. As the system gets overloaded, the algorithm maximises the use of resources switching the MS between bands, in an 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 for overloaded systems (around 55-66 users). Without GMBS, the system reaches its full capacity around 2.5 Mbps. With GMBS it reaches the maximum capacity around 3 Mbps. A gain up to 500 kbps may thus be obtained,i.e., 20% gain. The gain is achieved by dynamically allocating resources (2 or 5 GHz bands channels) to the MS that best suits the system. The achieved improvement is relative to a scenario where users are randomly deployed on the cell.

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 to the use of SA. The paper assumes that SA can be successfully combined with RRM techniques for an optimised performance. 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 analysed, showing the effectiveness of GMBS to counter-fight shadowing in support of the aforementioned real time services.

VIII ACKNOWLEDGMENT

The authors would like to acknowledge the support from the following projects or grants: IST-UNITE, UbiquiMesh, OPTIMOBILE, PLANOPTI, the FCT PhD grant SFRH/BD/28517/2006, ”Projecto de Re-equipamento Cientfico” REEQ/1201/EEI/2005 (a Portuguese Foundation for Science and Technology project), FUTON (Fibre optic networks for distributed and extendible heterogeneous radio architecture, FP7 ICT - 2007 - 2015533), and EU-funded CELTIC WINNER+ project.

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