DYNAMIC SPECTRUM ALLOCATION (DSA) AND RECONFIGURABILITY

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ABSTRACT

New spectrum management rules have to be defined to maximize the use of the radio spectrum, considering the potential associated with the future introduction of SDR equipment. This challenging research has to be lead in parallel with the current research on SDR equipment design (terminals and entities in the network to support them) in order to ensure an adequate synergy between spectrum allocation algorithms and SDR equipment implementation. This paper presents the technical research to be realized within the European project OverDRiVE on Dynamic Spectrum Allocation (DSA) in a SDR context and details the objectives and the associated methodology for investigating requirements on reconfigurable radio systems to enable enhanced support for DSA.

1. INTRODUCTION

The delivery of seamless mobile multimedia services, enabled by the inter-operability of wireless heterogeneous radio access networks, addresses new challenges in terms of radio resource management. One of the keys to enabling such inter-operability is a more flexible spectrum management, providing more efficient use of radio resources. This topic is even more challenging in that it might require fundamental changes in the way spectrum is regulated and used by the operator. In addition to this new potentially "philosophical evolution", all wireless world actors must investigate jointly the reconfigurability and SDR research areas, so that flexible spectrum management becomes a reality and does not remain a utopia. Different initiatives show active worldwide research efforts into this direction (see [1]-[4]).

The provision of technical solutions for flexible spectrum management schemes can lead to a deadlock if regulatory considerations are not discussed in parallel with the reconfigurability and SDR research community. A concerted approach for the identification of future research needs is required for success.

In the context of the European research project OverDRiVE (Spectrum Efficient Uni- and Multicast Services Over Dynamic Radio Networks in Vehicular Environments), this paper presents the flexible spectrum management strategy (the dynamic spectrum allocation concept) developed in the project, and discusses OverDRiVE's approach to identify and formalise the impact of DSA on both reconfigurability and SDR equipment, capturing the reconfigurable functions to be implemented in SDR equipment. Additionally, discussions on a framework for a reconfigurable systems architecture model to enable flexible spectrum management are also included. Section 2 introduces the OverDRiVE project and presents its main objectives, and section 3 focuses on the joint DSA/Reconfigurability investigations. The operation of DSA and the associated impact in a SDR context are presented in section 4, and section 5 details the methodology envisaged for analysis of DSA requirements on reconfigurability.

2. OVERDRIVE PROJECT

The European research project OverDRiVE [5] aims at UMTS enhancements and co-ordination of existing radio networks into a hybrid network to ensure spectrum efficient provision of mobile multimedia services. An IPv6 based architecture enables interworking of cellular

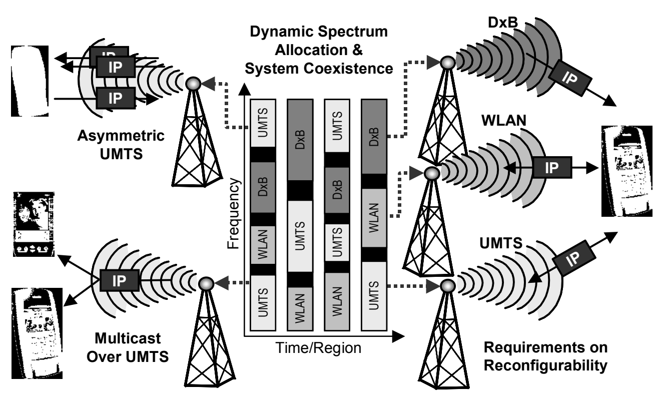

Figure 1: Support for high quality broadband services in a reconfigurable multi-radio environment

and broadcast networks in a common frequency range with dynamic spectrum allocation. The project objective is to enable and demonstrate the delivery of spectrum efficient broad-, multi- and unicast services to vehicles. OverDRiVE issues are: (i) improve spectrum efficiency by system coexistence in one frequency band and DSA, (ii) enable mobile multicast by UMTS enhancements and multi-radio multicast group management, and (iii) develop a vehicular router, that supports roaming into the intra-vehicular area network (IVAN). The project started in April 2002, and has a duration of two years.

More details on other parts of the project (e.g. Mobile Multicast or Intra Vehicular Area Network) can be found in [5] and [6]. The OverDRiVE project builds on the findings of the successful IST DRiVE [7] project, where one of the main goals was to investigate methods to improve the spectrum efficiency in a multi-radio environment through the use of new spectrum allocation methods. The method of assigning spectrum to radio systems currently used is a fixed spectrum allocation scheme, where a fixed size block of radio spectrum is allocated to a radio standard and a guard band usually separates different spectrum blocks. This spectrum can then only be utilised by the license owner. This allocation method has the advantage of simply but effectively controlling interference between differing networks using the spectrum, provided adequate guard bands are maintained, with no coordination between the networks.

However, most communications networks are dimensioned to cope with a certain peak amount of traffic called the ‘busy hour,’ during which time the peak network usage occurs. This implies that, assuming the spectrum is fully utilised during the busy hour, then the remainder of the time the spectrum is under-utilised, and therefore wasted. In fact, almost all services, such as speech, video, web browsing and multicast applications, which are envisaged as future mobile services, have distinct time-varying traffic demands, which give rise to this spectrum wastage. In addition, the demand for services on different networks depends on location, implying a spatial variation in the spectrum usage. Therefore, the radio spectrum, whilst scarce and economically valuable, is frequently underused or idle over both time and regions. This is the motivation for a more spectrum efficient technique, called dynamic spectrum allocation (DSA).

Whilst several spectrum management bodies have started mentioned issues such as spectrum trading, for example in [8] and [9], little work has previously been done on the potential for DSA to improve the spectrum efficiency, and the methods by which this may be achieved. The concept behind DSA is to allocate only the amount of spectrum to a radio access network (RAN) that is required to satisfy the short-term traffic load to a certain

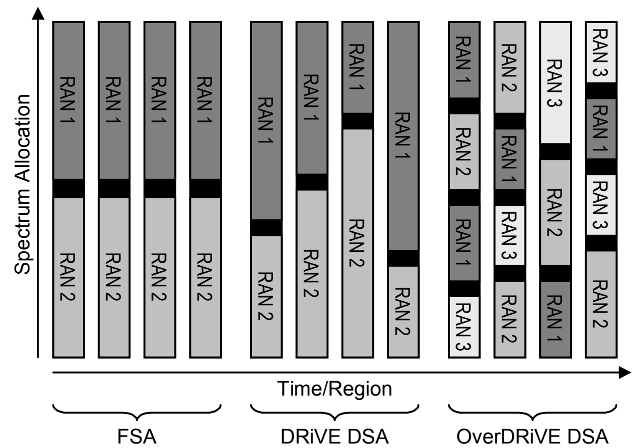

Figure 2: **DSA methods in DRiVE and OverDRiVE**

user satisfaction level within a given area. This therefore allows spectrum unused by one RAN to be given to other RANs. In the DRiVE project, a method of DSA was developed called contiguous DSA. This allocates contiguous blocks of spectrum, separated by guard bands, to the RANs, but the widths of the spectrum blocks assigned are allowed to vary to allow for changing demand. Two aspects of DSA were investigated in DRiVE, over time (known as temporal DSA) and over space (called spatial DSA). More details on the DSA results and investigations that were performed in DRiVE can be found in [10], and are summarised in [11].

The OverDRiVE project aims at taking these results further, by investigating DSA in more complex scenarios, with different allocation methods. It investigates DSA methods that do not rely on having contiguous blocks of spectrum allocated to each of the RANs sharing the spectrum, thereby making the spectrum allocations more arbitrary, and more difficult to optimise and control. Furthermore, OverDRiVE investigates the possibilities for the dynamic allocation of spectrum to be adaptive simultaneously over both time and space. A representation of fixed spectrum allocation, and DSA schemes evolving from DRiVE to OverDRiVE can be seen in Figure 2.

3. JOINT DSA/RECONFIGURABILITY INVESTIGATIONS

In the OverDRiVE project, the research task entitled “DSA requirements on reconfigurability” aims at investigating the requirements of reconfigurable radio systems to enable enhanced support for dynamic spectrum allocation. The main objectives of this are:

- The identification of DSA requirements,
- The review of the current research into the different areas of reconfigurability and SDR,
- The identification of reconfigurable aspects that are required for DSA operations.

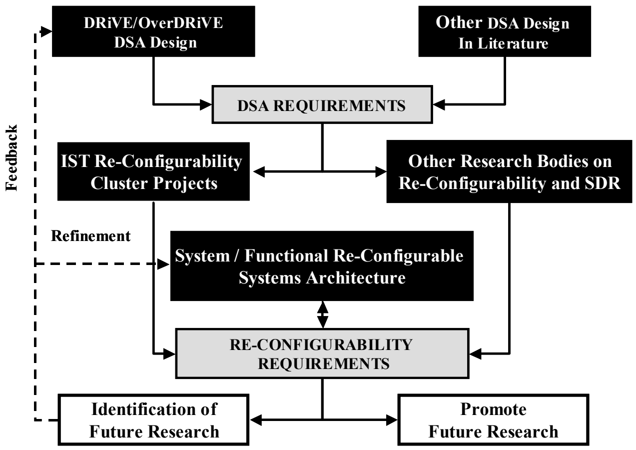

Figure 3: Approach for joint DSA/reconfigurability investigations

The aim is to identify and promote future research topics to be performed on these issues. To achieve such objectives, the approach for this follows various steps (depicted in Figure 3):

- Identify DSA requirements through both DRiVE/OverDRiVE DSA design and other schemes from the literature,
- Steer (raise awareness of) relevant research bodies/programs that investigate reconfigurability and SDR (e.g. European IST - Reconfigurability Cluster, SDR Forum…) to the areas that have been identified as requirements for DSA,
- In parallel, a reconfigurable systems architecture model oriented towards flexible spectrum management is to be developed to capture and formalise previous reconfigurability aspects in the same framework (refer to Section 5 for more details),
- Results of this will feed back into and complement research into reconfigurability (identification and promotion of future research needs) through research programs (in particular European projects),
- Use feedback from the SDR community on DSA implementation issues to refine both DSA algorithms and the reconfigurable systems architecture model.

4. DSA IN A SDR CONTEXT

This section explains how DSA schemes operate, and what impact this has in a SDR context. As described in Section 2, the DRiVE DSA scheme utilises contiguous blocks of spectrum allocated to different RANs. The RANs are separated by guard bands, and as the spectrum demands change, the widths of the spectrum blocks vary to adapt to these changes. There were two variants of this scheme, one that adapted the spectrum to time varying loads, and one that adapted it to spatial changes.

The temporally adaptive DSA algorithm, as described in [10][12], runs at set periods and the calculation of the spectrum required by each RAN is based on a prediction of the offered load until the next reallocation. From the load prediction, the RANs estimate the number of carriers they will require for the forthcoming time interval. They declare to the DSA if they have any currently unused carriers that could be reallocated, as a carrier can only be allocated to another RAN if there are no ongoing calls on it. An allocation algorithm decides how the free carriers are distributed. This spectrum allocation then applies until the next DSA run. To ensure that as many carriers as possible are free for DSA, all new calls are supported on carriers furthest away from the guard bands between RANs, and are handed over to these carriers whenever possible, making the ones nearest the guard bands free for reallocation.

For the spatial DSA, the region under question is divided up into areas where a particular spectrum allocation applies, called DSA areas. In these areas the traffic demands of different RANs should be relatively constant in space (yet may still be time variant). The algorithm used in DRiVE [10] inserts extra guard bands between the contiguous allocations, in order to allow the spectrum allocations to change by a required quantity between the neighbouring regions, without causing interference at the area borders. An optimisation scheme is run in order to select what the spectrum partitioning should be in each area, in order to maximise the performance of the system.

These methods have been shown (by simulation) to give improvements in the spectrum efficiency in the order of 30% for typical example traffic parameters. However, in order for these schemes to be operable, there are several high-level requirements that can be identified. For example, considering the network elements operating in this scenario, the radio networks must be able to utilise a variety of frequencies from an overall spectrum band, in order to perform the DSA operation. This implies that the radio systems need to be equipped with transceivers that can operate on a variety of carrier frequencies and (potentially) use different access technologies. These transceivers need to be able to be activated and tuned to a particular frequency upon command from the DSA system. It is a requirement that this can be done in a relatively short time, in order to allow regular updates of the spectrum allocations in the case of temporal DSA. For the DRiVE DSA schemes this could simply be a matter of having a set number of transceivers operating on fixed frequencies and activated or deactivated on command from the DSA. This is because with the contiguous DSA scheme there is only a certain limited set of carriers on which a particular RAN could operate. However, in the OverDRiVE scenario where the constraints on the spectrum allocations are released even further, then this might not be practical, since a transceiver may need to operate on any one out of a much larger number of frequencies. This would therefore call for the use of more complex frequency agile transceivers.

5. DSA REQUIREMENTS ON RECONFIGURABILITY

5.1. Motivation

The introduction of new concepts for a flexible spectrum management (the temporal and spatial DSA concepts of Section 4 are part of this family) in a multi-radio environment raises new research challenges at different levels of the communications systems. The DSA operations in a heterogeneous wireless network environment require the definitions or even the re-thinking of new functionalities in the existing and future systems. One of the expected new features of those functions is the reconfigurability capability. Research on reconfigurable functionalities supporting DSA is closely connected with research on the design of potential architectures supporting those functionalities. In this reconfigurability-based flexible spectrum engineering, the main challenges are to identify functions and entity classes relevant for supporting a flexible spectrum scheme. To properly carry out this study, an architecture model is needed to support and capture the interactions between the objects composing the architecture.

The architecture is expected to be composed of Functions, Entities, Components and Interfaces objects, to be defined and specified during the project. The project framework dealing with the previous topics is described in the following subsections. It is formulated as a high level view of issues to be addressed regarding respectively the flexible spectrum engineering requirements, and a reconfigurable architecture model (including discussions on Functions, Entities, Components and Interfaces). In this context, issues related to the different families of flexible spectrum engineering (encompassing the DSA concepts) are considered and discussed in the following.

5.2. Mapping DSA Requirements into Functions

Regarding OverDRiVE scenarios under investigation [13], DSA concepts (Section 4) and more generally flexible spectrum allocation schemes, the first three steps of the project framework are:

- The identification of the flexible spectrum management requirements,
- The identification of reconfigurable functions derived from the previous requirements,
- The mapping between requirements and functions.

For each requirement R_i, the mapping phase aims at associating one or several active functions F_j so that R_i is supported. Designing such reconfigurable functions F_i initially require the identification of some unit functions. Those unit functions or *primitive functions* f_i compose the pool basis on which all other functions F_i are built on. In addition to this identification, the mapping between F_i and f_i is also a research topic of the project. Regarding specific OverDRiVE scenarios and DSA concepts, some very preliminary requirements can be identified as illustrated in Table 1. Two high level sets of requirements are listed in this table: specific spectrum requirements and additional requirements directly impacting flexible spectrum management.

Spectrum Requirements
(1) Time spectrum management (2) Spatial spectrum management (3) Spectrum efficiency optimisation management (4) Scalability management
Additional Requirements
(1) Mobile and seamless connections (2) Coverage complementarity between RANs (3) Service complementarity between RANs (4) Downlink complementarity between RANs (5) Individual and System QoS optimisation

Table 1: Preliminary DSA requirements

As listed in Table 1 scalability management is important to enable the current investigated flexible spectrum management schemes to be operated by future emerging technologies and equipment. Given these flexible spectrum management requirements, some initial reconfigurable functions can be derived as illustrated in Table 2.

Physical level Functions
(1) Multi Radio Access operations (2) Multi Bands operations (3) Radio Access Technology (RAT) and frequency carrier detection (4) RAT and frequency carrier identification (5) RAT and frequency carrier monitoring (6) Variable Duplex operations (asymmetric spectrum)
System level Functions
Spectrum
(1) Spectrum availability detection (2) Fair frequency carrier distribution between RATs (3) Appropriate channel bandwidth management (4) Temporal spectrum allocation/release (5) Spectrum negotiation between operators (6) Information exchange between operators (including signalling) (7) Spectrum coexistence (guard band management in space and time) (8) Spatial area dimensioning
Vertical Handover (VHO)
(1) Transmission modes (unicast, multicast, broadcast) identification – Spectrum need for each mode (2) Simultaneous UL and DL spectrum management (3) VHO between operators – VHO between private and legacy operators (4) Group creation and management for multicast (5) Frequency planning/coordination and coverage management
Traffic Awareness
(1) Temporal traffic load statistics (2) Spatial traffic load statistics (3) Mobile nodes location (4) Mixed traffic load and spectrum needs prediction

Table 2: Potential Reconfigurable Functions

Different types of functions can be derived from Multi Radio Access and Multi Band switching operations. The user equipment needs to be able to retune to different frequencies and RATs, depending on the current allocations set by the DSA. This switching can be:

- From RAT_i to RAT_j when operating on a given frequency carrier f_c,
- From f_{c1} to f_{c2} when operating on a given RAT_i,
- From (RAT_i , f_{c1}) to (RAT_j , f_{c2}).

Additional functions can be considered in the case that RAT_i and RAT_j are supported simultaneously by the same Tx/Rx device (service complementarity case). This is one of the situations considered in the OverDRiVE scenario of a vehicle.

Different reconfigurability levels [14] are expected to emerge in the near, medium and long-term future. This impacts directly the complexity of the reconfigurable functions to be considered. One approach for full reconfigurability is software download, and it may require enhancements or the introduction of new functionalities in addition to those listed in Table 2. The need of such new functionalities and the appropriate reconfiguration management is all the more necessary for a context sensitive radio. This should be part of the project as well.

5.3. Entities

So that reconfigurable functions discussed in subsection 5.2 are supported and operated, the consideration of different *Entities* is needed. It is expected that two different types of *Entities* will be designed or enhanced to support the reconfigurable functions: the *Physical Entities* and *Virtual Entities*. Typical entities are listed in Table 3.

Physical Entities (PE)
(1) End user Terminal (2) Radio Access Network (3) Core Network (4) Backbone
Virtual Entities (VE)
(1) User (2) Operator (3) Manufacturer (4) Regulator (5) Service Provider (6) Application Content

Table 3: Identified Entities

The concept and definition of a Virtual Entity (VE) will be developed during be project. Typically, a VE could a single moral entity or the combination of one or several moral entities to achieve a given action, itself potentially enabled by one or several reconfigurable functions. The entity unit formalism enables the introduction of notions like ownership, fusion, inheritance and some others to be specified if necessary. For example, different configuration ownership has been initiated in the DRiVE project [15] and extended concepts will be further developed in OverDRiVE. In this context, a VE might own one or several PEs. Different strategies can be envisaged for that, and it will be discussed in the project.

Investigations on SDR technology for PEs as a promising enabling technology for reconfigurability will be performed in parallel. Investigations on the functions implementation feasibility into the PEs with SDR will be performed jointly with regards to other IST Reconfigurability Cluster projects. In the context of flexible spectrum management, particular attention will be given to the wireless regulators as being major players in the implications of reconfigurability in terms of SDR equipment capability and new spectrum engineering practices. In this new context, the potential new role of the operator will also be addressed. Some preliminary mechanisms for dealing with collaboration between operators have been proposed [16].

5.4. Functions Mapping into a Reconfigurable Systems Architecture Model

The interdependency between the reconfigurable functions, the entities and components are discussed in this subsection. This addresses the high level objectives of the reconfigurable systems architecture model in a flexible spectrum management context.

Current work on reconfigurable systems architecture models is being actively investigated through different European initiatives and worldwide organizations ([1], [2], [3], [4]). Those reconfigurable systems architecture model proposals often encompass numerous issues (related to all aspects of terminal and network). Consequently, specific flexible spectrum management issues are either invisible, or partially, or not at all considered in those models. So, it is very difficult to have a clear visibility on how flexible spectrum management is impacted in those generic frameworks. Alternatively, other models focus on specific issues (e.g. RF, Base Band, security) and miss some relevant points needed for an appropriate reconfigurability model of dynamic spectrum allocation.

Therefore, the main challenges in the project are to design an appropriate model enabling the capture of the overall relevant flexible spectrum management reconfigurability features into a adapted architecture, and to investigate how far this architecture model can inter-operate with/complement the existing ones. Such an architecture should define and specify as far as possible the:

- Interfaces $\mathbf{I_E}$ between identified Entities,
- Interfaces $\mathbf{I_F}$ between identified Functions,
- Interfaces $\mathbf{I_C}$ between identified Components.

This is illustrated in Figure 4. For each identified entity, the components refer to (hardware or software) elements. The identification of other relevant components will be investigated. The specification of interfaces may require the introduction of exchange rules.

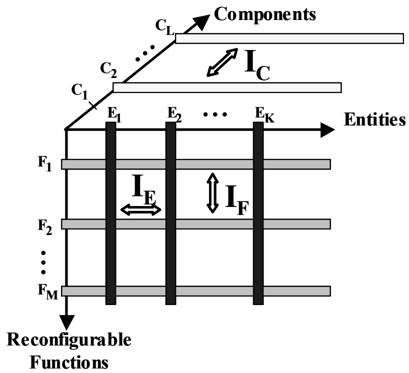

Figure 4: Functions mapping into a Reconfigurable Systems Architecture Model

In this architecture, one of the goals is to map each reconfigurable function between the different entities. One of the research challenges is to investigate how far each function (control, monitoring, decision) should be centralised within a single (or alternatively distributed between several) entity(/ies). Motivation for these choices should be rationalised and should consider the distribution strategies for the different reconfigurable functions mentioned in Table 2, considering terminal centric, network centric or terminal & network centric approaches.

In addition, different architecture models are possible depending on the degree of coupling between different radio access networks. In a flexible spectrum allocation framework, loose or tight coupling approaches can lead to different models.

6. CONCLUSION

This paper has presented the technical research to be realised within the European project OverDRiVE on Dynamic Spectrum Allocation (DSA) in a SDR context. It has detailed the objectives and the associated methodology for investigating requirements on reconfigurable radio systems to enable enhanced support for DSA. This challenging research should ensure the success of the developed new spectrum policies and allow the maximization of the radio spectrum use at the horizon of SDR equipment introduction.

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