Journal of ELECTRICAL ENGINEERING, VOL. 54, NO. 9-10, 2003, 231–236

DYNAMIC SPECTRUM ALLOCATION: FROM CONCEPTS TO RECONFIGURABILITY ENABLED IMPLEMENTATION

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This paper presents the current research effort in the field of dynamic spectrum allocation (DSA) in the context of composite reconfigurable wireless networks. Concepts and implementation issues are respectively addressed. Firstly, motivations and supporting mechanisms of the DSA concept are introduced in Section 2. On this basis, some potential deployments scenarios for DSA and their associated requirements are discussed in Section 3. The enabling technologies (software defined radio, SDR) and regulatory policies supporting reconfigurable equipment are discussed in Sections 4 and 5 respectively. Section 6 addresses an architecture model supporting reconfigurable systems DSA at the network level. Finally, Section 7 discusses a potential roadmap to make DSA operations a reality.

K e y w o r d s: reconfigurable wireless networks, dynamic spectrum allocation, software defined radio

1 INTRODUCTION

Today, spectrum is allocated to the different radio access technologies in a static fashion. In this respect, some fixed spectrum portions are assigned to different standardised radio access systems that are exclusively operated either by some operators (licensed systems/bands) or by any free users (unlicensed systems/bands). This approach is sufficient to cope with interference between systems. However, with the increasing convergence between composite networks, this approach is no longer appropriate, since greater spectrum efficiency can be gained from the use of spectrum under-used by other radio systems at different times or different locations.

To gain from this diversity of spectrum usage in the systems, some new spectrum allocation concepts are investigated, such as Open Spectrum [1] or Dynamic Spectrum Allocation (DSA) [2]. With respect to this, this paper firstly presents the DSA concepts, mechanisms and results in a composite reconfigurable wireless network. Then, the paper addresses the implementation aspects of DSA. It is discussed how and where the capabilities of future reconfigurable networks can give support to the DSA schemes.

2 DYNAMIC SPECTRUM ALLOCATION CONCEPTS

Dynamic spectrum allocation schemes have the goal of increasing the spectrum efficiency. They do this by exploiting temporal and spatial variations in the traffic demands that are seen on disparate types of radio systems, such as cellular and broadcast networks (*eg* UMTS and DVB–T). The variations can be expected on most networks, due to typical patterns of user behaviour, and is dependant on the area under question. If these networks are operating in a composite multi-radio system, then this provides the ideal environment for operating a DSA scheme. The goal is to allocate the spectrum dynamically to the radio access technologies (RAT) over space and/or time, as required, whilst managing or preventing any resulting interference. Previous work performed into DSA [2] has shown the operation of a scheme called contiguous DSA, which has been further analysed and optimised for use with two RATs [3]. Further work investigates the possibilities for spectrum sharing between more RATs, through the use of a scheme called fragmented DSA.

Figure 1 illustrates the concepts of the DSA schemes. The top part of the diagram shows the concepts of spatial DSA, and the bottom half illustrates the temporal DSA concepts. The spatial DSA diagram shows a geographical region, which has been split up into 7 hexagonal 'DSA areas', labelled A1-A7. Each of these areas contains at least one DVB–T broadcast cell, and multiple UMTS cells, and potentially other RATs as well. The goal of spatial DSA is to assign each of the areas a different spectrum allocation for UMTS and DVB–T, depending on the traffic demands seen in each area.

The main limiting factor is the possibility of inter-RAN interference at the area borders. For example, consider the spectrum allocations shown in the diagram for areas A1 and A2. These allocations will produce significant amounts of interference across the borders of the area, in the overlapping region of the spectrum, as shown in the figure. Schemes have been developed to mitigate these effects. One method involves the insertion of extra

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First version of this paper was presented at SympoTIC ´03, 26-28 October 2003, Bratislava, Slovakia

ISSN 1335-3632

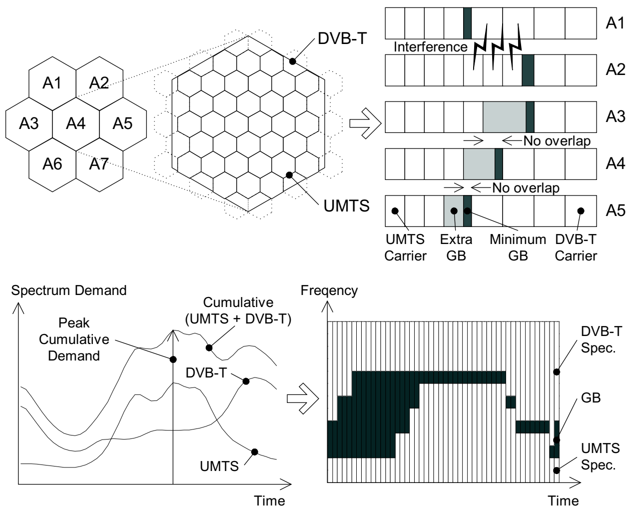

Fig. 1. Operation of spatial and temporal DSA

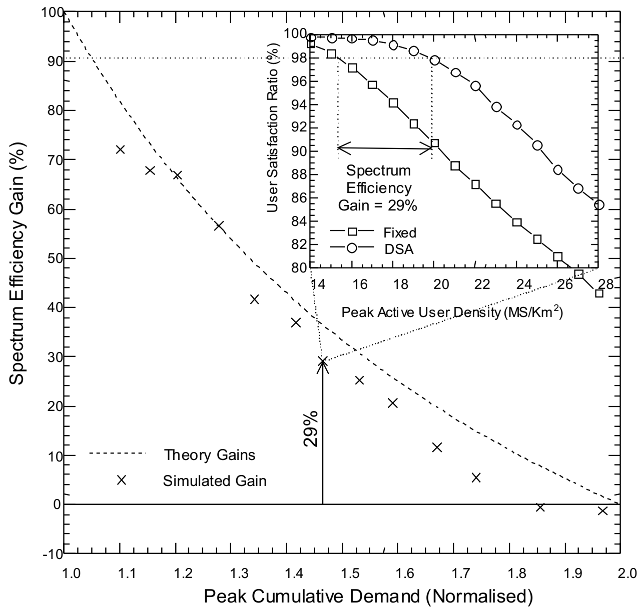

Fig. 2. Typical simulated performance of temporal DSA

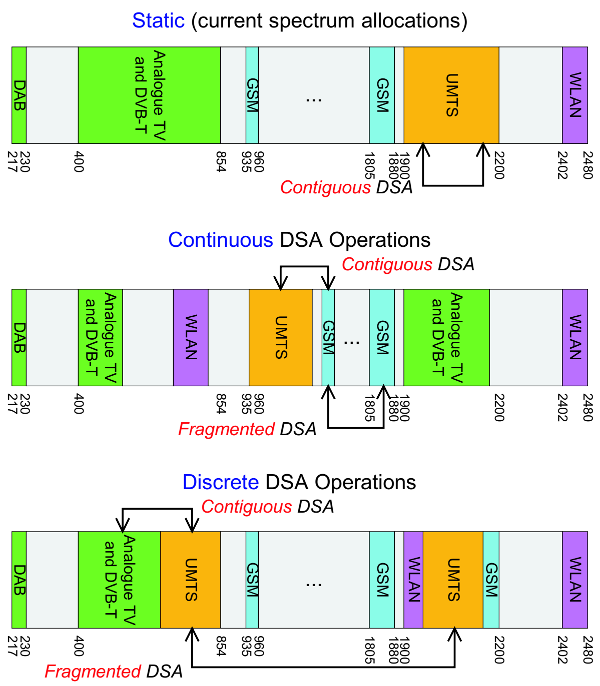

Fig. 3. DSA operations configurations

guard bands (GB) in the spectrum, such as shown in the spectrum allocations of A3, A4, and A5. This then allows the allocations to shift between adjacent areas, thereby permitting spatial adaptability of the spectrum allocations, but avoids any spectral overlap. This has the disadvantage of inserting more unused spectrum, which must be minimised to reduce the impact on the spectrum efficiency. In addition, methods are also investigated that allow spectrum allocations such as those shown for A1 and A2, but attempt to manage the interference through careful coordination of the frequency plans of the cells in the border regions.

The temporal DSA concepts are illustrated in the lower half of Fig. 1. This demonstrates how these schemes adapt the spectrum allocations over time, according to the time-varying load demands. By comparing the amount of spectrum required for fixed allocation with the amount required for DSA, the extent to which the traffic can be increased with DSA to give the same user satisfaction in the same spectrum as fixed allocation can be found. This gives an ideal theoretical value for the spectrum efficiency increase. This can be calculated for any set of traffic patterns like those in Fig. 1, which are characterised by the value of the peak of the cumulative demand on the networks, as indicated in the figure. Dynamic algorithms have been developed, such as in [3], to reallocate the spectrum between the RANs 'on-the-fly', by utilising load prediction schemes and allocation algorithms, and the simulated performance of these can be compared to the theoretical values. A typical DSA simulated performance curve can be seen inset in Fig. 2, which can be seen compared to the theoretical values in the main graph of Fig. 2.

The development of these DSA schemes motivates further investigation into system coexistence, since this could result in RATs bordering in the spectrum allocations that would not do so normally. These different radio systems have differing coexistence requirements, implying different guard bands. It is required that the DSA algorithms are aware of the guard band requirements when deciding on the allocations, to minimise the wasted spectrum.

3 DSA OPERATIONS AND REQUIREMENTS

The scalability of the temporal/spatial contiguous and fragmented DSA research concepts enables the introduction of a large scope of DSA operational scenarios. As such, different short, medium and long-term DSA deployments can be envisioned. The degree of reconfigurability requirements for the overall communications systems applying DSA depends on the envisaged scenarios. The following discusses the impact of DSA operations in the technical area — from both the physical layer and network perspectives — and in the regulatory area in the light of the rollout of different possible scenarios.

Basically, the different DSA scenarios (illustrated in Fig. 3 with example spectrum allocations for typical broadcast, cellular and WLAN systems) are characterised by the three critical features. These are the parameters "*spectrum playground*", "*frequency range*" and "*spectral resolution*" for each radio system participating in DSA.

The "*spectrum playground*" is inherently regulation related. It refers to the set of frequency bands that a system is allowed to be allocated within the spectrum. The most static approach is to operate DSA within existing assigned bands of the radio systems (Fig. 3-a) between similar radio access systems (*eg* UMTS bands). Conversely, the most flexible scenario (Fig. 3-b) would let any radio system to be operated in any part of the spectrum (in assigned or unassigned bands, owned or operated by different operators) with a fine spectral resolution (continuous DSA operation). An intermediary scenario (Fig. 3-c) could consist of allowing some pre-defined radio systems to operate on pre-defined parts of the spectrum (discrete DSA operation). Illustrations of additional scenarios can be found in [4].

The "*frequency range*" is an inherently technical related issue. It refers to the multi-band capabilities of the same equipment (end user terminal or any network access node) of a given radio system to operate from the higher bands of VHF (broadcasting at ~ 300 MHz) to the lower bands of SHF (WLAN in the 5 GHz band) to a given "*spectrum resolution*" (*ie* with accurate frequency carrier tuning). Hence, the flexibility of the DSA scenarios will depend on the operational frequency degrees supported by the equipment's capabilities.

In this respect, in terms of flexibility, the requirements of the equipment are:

- Multi-band antennas with miniaturisation constraints for small size devices (*eg* mobile handsets),
- Flexible frequency carrier tuning,
- Flexible Rx signal filtering.

In addition to this, the implementation of DSA also introduces some requirements at the system level in terms of network inter-working. The importance of the constraints applicable will depend on the amount of radio access systems competing for the spectrum access and their use at the same time or same location. In this respect, the concern of the inter-working is to ensure the support of the temporal and spatial spectrum sharing coordination processes. This interacts with the spectrum access and use (assignment and reassignment) between radio access systems owned or operated by the same or different operators, and also with potentially some different spectrum uses (*eg* commercial or non-commercial motivated radio services, etc). As such, the requirements impact the following areas:

- Spectrum pricing,
- Spectrum billing,
- Adequate interfaces between networks supporting different radio access network standards to connect rapidly the right communication equipment on the right frequency carrier. This includes the introduction of new functions to enable the decision-making, monitoring, control and management between sometimes collaborative, sometimes competitive systems.

4 RECONFIGURABLE BASED ENABLING TECHNOLOGIES FOR DSA SUPPORT

This section discusses how the flexibility demanded by the physical layer requirements mentioned in Section 3 can be handled with SDR based reconfigurable equipment. Before the full software-based reconfigurable architectures bringing digitalisation to the antenna are achieved, the way towards more flexibility relies on the following key technical areas: antenna, front end, ADC and digital signal processing. The following draws up the current technological capabilities and remaining challenges for each of these areas.

4.1 Antenna

Today, the multi-band antennas rely on the use of several resonators (*eg* Pin Diode Switch technology based). Forthcoming concerns of reconfigurable antennas rely on the design of miniature, multi-band antennas. For each of these aspects, some techniques are maturing or emerging (see Tab. 1).

4.2 Front End

Current front-end (amplifier, filtering) design is based on analogue devices (one amplifier per signal path) that are not without hindrance for reconfigurability due to the introduction of non-linearity and distortions. Due to the large amount of operations to be supported by digital filtering for multi-band scenarios, current DSP capabilities cannot handle these functions digitally.

4.3 ADC

From the fully flexible SDR architecture perspective, an ADC must sample at double rate of the maximal operating frequency of the signal with a good resolution. Hence, the higher the signal frequency, the higher the sampling rate. This approach consists of using a direct-conversion architecture from the analogue RF signal to

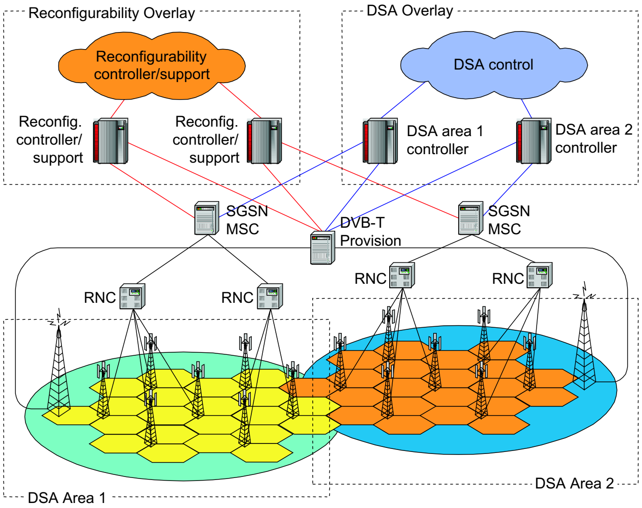

Fig. 4. Separate Reconfiguration and DSA support

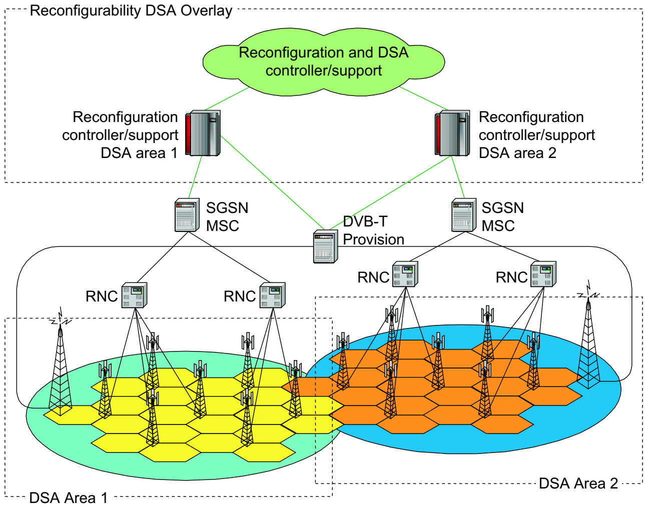

Fig. 5. Combined DSA and Reconfigurability support

baseband, so that analogue imperfections at the intermediate frequency (IF) stage are skipped. However, such an efficient architecture is not mature yet. Thus some intermediary architectures such as superheterodyne schemes (IF sampling) are proposed, although its complexity and reconfigurability have limitations.

4.4 Digital Signal Processing

Ideally, the fully flexible architecture aims at digitalising all functions from the RF to the baseband to be software-based reconfigurable. However, such a process requires a very large amount of operations per second. In comparison, for instance, in the simple case of static operations (*ie* with no multi-band capabilities), the number of operations for a 3G terminal is estimated at around 10 billion operations per second if fully software implemented [5]. This is even greater if additionally introducing reconfigurable multi-band capabilities. Digital signal processors (DSP) are good candidates for this processing. However, current DSP capabilities are beyond this required number of operations. Besides, they are power consuming, limiting their integration into handsets due to the current battery lifetime. Some alternatives, such as ASIC, FPGA or mixed ASIC/FPGA/DSP strategies are currently used at the expense of limitations in the reconfigurability flexibility.

5 REGULATORY SUPPORT FOR DSA

Current regulation policies (for both spectrum management and equipment certification) do not allow the rollout of even simple DSA schemes. However, some regulatory efforts are currently carried out to enable more flexible spectrum practices. In this respect, some new market-based tools (*eg* spectrum trading) enabling spectrum sharing are discussed at the national level (*eg* in the UK, [6]). Similarly, some active discussions on the relaxing of some important constraints on current spectrum use are discussed by the FCC in the USA [7] to enable more unlicensed practices (open spectrum).

The introduction of SDR based reconfigurable equipment, potentially reconfigurable on-the-fly over the air, requires new rules for type approval to cope with new reconfiguration procedures (software downloading) and security features. In order to support these new aspects, the European RTT&E Directive [8] and the FCC have started to propose some enhancements. The SDR Forum is also very active in this area [9].

6 ARCHITECTURE MODEL SUPPORTING DSA

This section addresses potential architecture models enabling DSA in future reconfigurable communication systems. This effort complements the discussions of DSA at the system/network level (Section 3) and includes potential architectures for specific DSA scenarios involving DVB–T and UMTS radio access technologies.

The implementation of a DSA scheme together with its required support mechanisms pose challenges comparable to those encountered for reconfigurable systems. Both these complex technologies need some kind of minimum support infrastructure, supporting decision-making as well as implementing the mechanisms for both the actual spectrum re-allocation (joint radio resource management) and reconfiguration processes.

Two main approaches can be envisaged for such a support architecture; depending on the basic principles followed, the support architecture may be implemented either as a complementary infrastructure (where reconfiguration and DSA support would be completely separated, as in Fig. 4), or conversely as a combined/integrated architecture (using the same hierarchy and sharing servers

Table 1. Current and breakthrough key enabling technologies for reconfigurable antennas

ANTENNA	Today	Breakthrough
Miniaturisation	Planar Inverted F Antenna (PIFA)	• Lengthening of current paths based antennas (*eg* Fractal antennas) • Capacitive or selfic charging based antennas (*eg* PIFA antenna)
Multi-band	Association of several resonators with the introduction of slits	• Association of several resonators with the use of particular antenna geometry (*eg* fractal antennas) • Radio wavelength adaptation with commuting or variable components (*eg* MEMS (Micro Electro-Mechanical System) or diode PIN based)
Wide-band	Planar antenna based	• Dialectical resonator • Association of several resonators frequency shifted • Independent frequency based antennas (*eg* b-conical or spiral antennas) • MEMS

and user databases, as in Fig. 5) that supports and enables a reconfigurability based joint radio/spectrum resource management.

These two approaches represent the extreme cases for such a support architecture. There are potentially other intermediate cases, comprising hybrid solutions where only limited functionality of the reconfigurability support is integrated in the DSA management structure, and the functions that remain are implemented as a (global) overlay.

7 ROADMAP TO DSA OPERATION

Given the achievable reconfigurable performance of equipment based on the current enabling technologies' capabilities, three short-term scenarios for the operation of DSA can be envisaged:

- The use of unconstrained equipment, like BSs or embedded devices (*eg* in a car). This enables the support of operations with a large frequency range with a quite good spectral resolution.
- For handsets, the current capabilities enable the support of a wide frequency range by using a limited number of predefined radio frequency carriers.
- Alternatively, handset capabilities could allow for a narrower frequency range but with a higher degree in spectrum resolution for a similar amount of complexity to the previous point.

8 CONCLUSIONS

This paper has presented an overview of the motivations, concepts and supporting adaptive mechanisms to enable the dynamic temporal and spatial spectrum allocation in composite reconfigurable wireless networks. In this respect, it has been discussed how these upcoming schemes can be envisaged in future operational scenarios in light of the current enabling technologies and regulatory policies, from both the equipment and network perspectives. As such, it has been raised that further enhancement of DSA relies on the extension of the dynamic range and frequency carrier tuning accuracy capabilities of the equipment. As SDR technology becomes more mature, it can be expected that many of the constraints on the operation of DSA will be loosened.

From the network layer, the main concern relies on the adaptability of the networks to reconfigure fully or partially some of its components to match the traffic requirements, and support policy rules enabling the interoperability between both competitive and collaborative systems.

Acknowledgements

This work has been performed in the framework of the IST project IST-2001-35125 OverDRiVE (see http://www.ist-overdrive.org), which is partly funded by the European Union. The OverDRiVE consortium consists of Ericsson (co-ordinator), DaimlerChrysler, France Telecom, Motorola and Radiotelevisione Italiana, as well as RWTH Aachen, Universität Bonn and the University of Surrey. The authors acknowledge the contributions of their colleagues in the OverDRiVE consortium.

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Received 25 September 2003

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