Dynamic Spectrum Allocation in Composite Reconfigurable Wireless Networks

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ABSTRACT

Future wireless systems are expected to be characterized by increasing convergence between networks and further development of reconfigurable radio systems. In parallel with this, demand for radio spectrum from these systems will increase, as users take advantage of high-quality multimedia services. This article aims to investigate and review the possibilities for the dynamic allocation of spectrum to different radio networks operating in a composite reconfigurable wireless system. The article first looks into the current interest of regulators in this area, before describing some possible schemes to implement dynamic spectrum allocation and showing some example performance results. Following this, the technical requirements a DSA system would have, in terms of reconfigurable system implementation, are discussed.

INTRODUCTION

Ever since the first radio communication transmission by Guglielmo Marconi, the radio spectrum has become the fundamental resource on which every wireless radio communication system depends. Following those early pioneering times, the use of the radio spectrum has increased dramatically. Today, the radio spectrum is heavily utilized by a variety of services based on land and sea, in air and space, for a vast array of different purposes. These services bring with them an enormous benefit to society, but also demand appropriate spectrum management and regulation mechanisms to ensure economically viable use of this limited resource. Indeed, the radio systems offering the services need to maximize their spectrum efficiency to ensure that as many users as possible can be supported, thereby increasing both user satisfaction and the revenues of the operator.

Currently, spectrum is allocated with static licenses to a particular radio standard, and is further divided into assignments to individual operators to deliver a given service. These spectrum blocks are of fixed size and separated by guard bands, and remain solely for the use of the license owner until the license expires. This effectively controls interference between different networks using the spectrum, and makes it simple to design hardware for use at a known radio frequency. While this mechanism has been utilized and proved sufficient for many years, it does have disadvantages. First, the different wireless industries that were previously disparate are now converging, and the boundaries between the services offered over different systems are becoming blurred. Even greater convergence may be seen in future years, with common core networks joining different systems together to form composite radio networks. The effect of this is that previous regulatory mechanisms that considered the different types of service separately are no longer appropriate. It has also been realized that static long-term licensing of spectrum for use by a single standard hinders fast innovation cycles, since new technologies generally move faster than regulations.

Furthermore, most communications networks are subject to time and regional variations in traffic demands, which lead to variations in the degree to which the spectrum is utilized. Therefore, a service's radio spectrum can be underused at certain times or geographical areas, while another service may experience a shortage at the same time/place. Given the high economic

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value placed on the radio spectrum and the importance of spectrum efficiency, it is clear that wastage of radio spectrum must be avoided.

These issues provide the motivation for a scheme called dynamic spectrum allocation (DSA), which aims to manage the spectrum utilized by a converged radio system and share it between participating radio networks over space and time to increase overall spectrum efficiency. Several current "hot" research topics for beyond third-generation (3G) mobile communications networks are potential enablers of DSA systems, notably composite radio systems [1] and reconfigurability [2]. Composite radio systems allow seamless delivery of services through the most appropriate access network, and close network cooperation can facilitate the sharing not only of services, but also of spectrum. Reconfigurability is also a very important issue, since with a DSA system a radio access network could potentially be allocated any frequency at any time in any location.

Given that a system to dynamically allocate and share spectrum may be desirable, we aim to address the following issues in this article: What are the regulators doing about the possibilities of DSA and converging reconfigurable systems, and the associated issues these raise? What methods can be used to determine how spectrum sharing is coordinated between sometimes collaborative, sometimes competitive systems? In addition, what are the requirements of these systems in terms of implementation and reconfigurability?

REGULATORY INTEREST IN DYNAMIC SPECTRUM ALLOCATION

Spectrum is a national resource, and consequently national regulators have the responsibility to ensure economical use of a society's spectrum resources. The governments coordinate the development and standardization of radio communication networks and services within the International Telecommunications Union — Radiocommunications Standardization Sector (ITU-R). At present, the Radio Regulations' frequency allocations differ depending on the region (Europe, North America, Asia, etc.), and are segmented into precisely defined categories of services (e.g., fixed, mobile, broadcasting, and radiolocation). The convergence of services and growing development of applications based on a combination of two or three services among fixed, mobile, and broadcasting, raises the issue of simplifying the regulatory framework to adapt to this new situation [3].

At the World Radio Conference (WRC) 2000, Resolution 737, "Review of Spectrum and Regulatory Requirements to Facilitate Worldwide Harmonization of Emerging Terrestrial Wireless Interactive Multimedia (TWIM) Applications," invited the ITU-R to evaluate the necessity to identify spectrum for TWIM, and to review regulatory methods and service definitions. In light of Resolution 737 an ITU-R Joint Task Group was formed and defined the scope of TWIM as "applications in one or more of the Mobile, Fixed and Broadcasting Services that are capable of supporting bi-directional exchange of information of more than one type (e.g., video, image, data, voice, sound, graphics) between users or between users and hosts."

TWIM was discussed at WRC 2003 and suggested as an agenda item for WRC 2010; further studies will be done until that time. There is also a new resolution for "options to improve the international spectrum regulatory framework" from WRC 2003, which proposes "to examine the effectiveness, appropriateness and impact of the Radio Regulations, with respect to the evolution of existing, emerging and future applications, systems and technologies, and to identify options for improvements in the Radio Regulations." This demonstrates international awareness that the convergence of radio systems and services will have a significant impact on the way spectrum is regulated.

Discussions have also started on a national level. For example, an independent review of spectrum management commissioned by the U.K. government states that "spectrum trading should be implemented in the UK as soon as possible." In addition, it says "broadcasters should be given the ability to lease spectrum to other uses and/or users." Outside Europe, the U.S. Federal Communication Commission (FCC) Spectrum Policy Task Force has taken a proactive role in recognizing the potential for new regulation mechanisms to be an important mechanism to allow the modernization of spectrum engineering practices to improve spectrum efficiency. A report from the Spectrum Policy Task Force states that "preliminary data and general observations indicate that many portions of the radio spectrum are not in use for significant periods of time, and that spectrum use of these 'white spaces' (both temporal and geographic) can be increased significantly." These regulatory developments show that there is a perceived need to bring regulations up to date, and these fit well with the DSA concepts presented here. However, significant changes in regulations would still be required in order to roll out even simple DSA schemes.

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World Radio Conferences are scheduled only every three to four years with the scope of the agenda established four to six years in advance. Hence, the regulatory process is slow and not tailored to cope with rapidly changing needs. For example, the 3G spectrum had to be allocated more than 10 years ago, when it was still unclear what 3G would be.

METHODS FOR DYNAMIC SPECTRUM ALLOCATION

The term *dynamic spectrum allocation* can potentially cover a range of different subject areas. Several established research fields are related to DSA, such as dynamic channel allocation (DCA), frequency assignment, unlicensed spectrum access, and spectrum coexistence.

If we are considering only a single radio network, the concept of DCA is very close to that of DSA. DCA shares the available radio resources among the base stations of a radio access network (RAN), and many different schemes have been suggested in this widely

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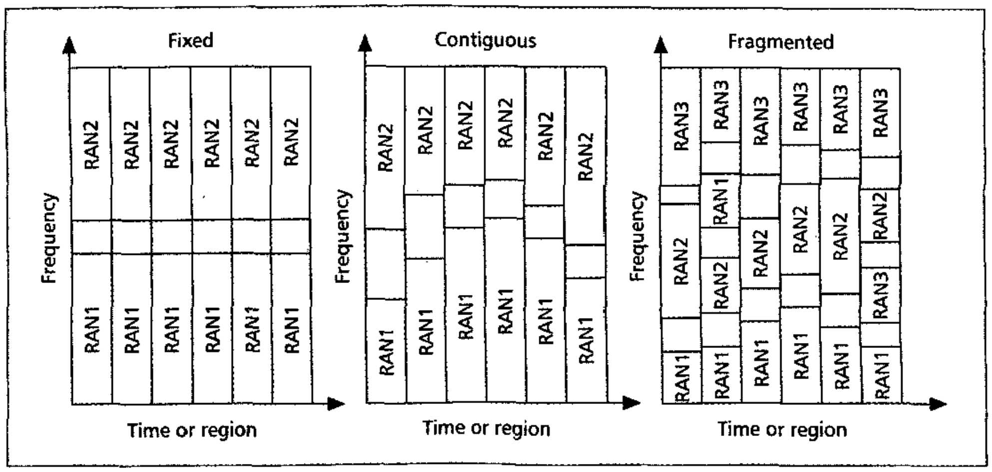


Figure 1. *Fixed spectrum allocation compared to contiguous and fragmented DSA.*

researched field [4]. The area of frequency assignment has also been studied for many years [5]. The idea behind frequency assignment is to develop techniques for finding the optimum assignment of frequencies to radio access nodes (e.g., base stations) in order to meet interference and coexistence constraints. However, we are more interested in methods that allow different radio systems with differing characteristics (e.g., broadcast/multicast/unicast, different overlapping cell sizes, various supportable services/data rates) to dynamically share a set of radio resources *between* the networks in a composite radio environment scenario.

A very relevant and active research area is unlicensed spectrum access [6]. If the spectrum is unlicensed, it is treated as an open resource any conforming device can use. However, this may not be suitable for all scenarios (e.g., where multimedia and delay-sensitive services need to be delivered). Another method of sharing the radio spectrum is to allow different networks to coexist within the same radio spectrum. This is operating successfully today, for example, with the peaceful coexistence of digital and analog TV transmissions in the same band, and can be extended to consider the coexistence of totally disparate networks through close consideration of their frequency plans [7].

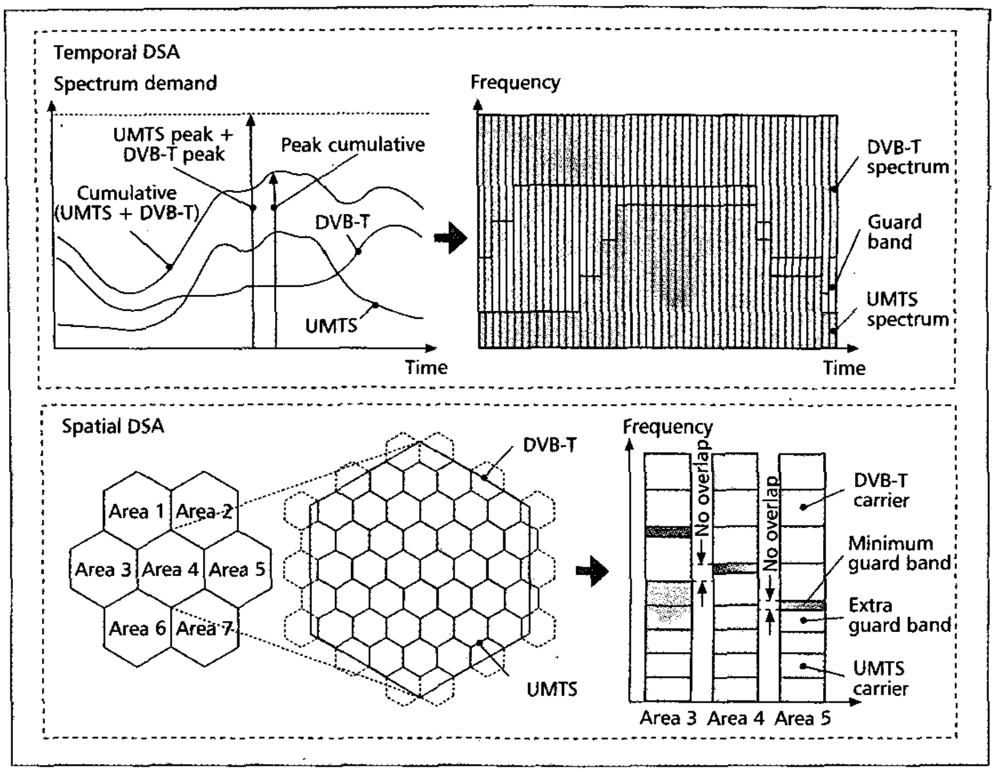
Given that there are schemes for cell-by-cell control and optimization of the radio spectrum for single networks (e.g., DCA and frequency assignment), and also ones that apply little or no control over the systems (e.g., unlicensed access or coexisting systems), we aim to focus on schemes between these two extremes. It must be remembered that we are specifically looking at schemes that share the spectrum between multiple disparate networks in a composite radio system, and we aim to share the spectrum between the networks at a RAN level, rather than with cell-by-cell coordination. We therefore concentrate on methods for permitting two or more networks to share an overall block of spectrum so that spectrum allocations can adapt to either temporal or spatial variations in demand on the networks. Two schemes to consider are shown in Fig. 1, contiguous and fragmented DSA. These types of scheme have been investigated within the European projects DRiVE, OverDRiVE [8], and TRUST [9].

Contiguous assignment uses contiguous blocks of spectrum allocated to different RANs, and these are separated by suitable guard bands, much as in fixed assignment. However, the width of the spectrum block assigned to a RAN varies in order to allow for changing demand. This scheme will only allow the spectrum partitioning of a RAN to change at the expense of the spectrally adjacent RAN's spectrum. Therefore, if a RAN wishes to increase its allocated spectrum, it will not be able to do so if the spectrally adjacent RAN will not release the spectrum, raising fairness issues. However, this still provides a scheme for allowing spectrum to be used by other RANs if it is not being fully utilized.

The second technique is called fragmented DSA. With this scheme, the spectrum to be dynamically allocated is treated as a single shared block, and any RAN can be assigned an arbitrary piece of spectrum anywhere in this block. This is advantageous if more than two RANs are sharing the spectrum, as the contiguous scheme can be restrictive in these cases. The main disadvantage with this scheme is that it becomes more difficult to control, particularly in terms of interference. This technique can potentially have many guard bands throughout the shared spectrum, and it therefore becomes very important that these be minimized and kept as small as possible, without compromising interference conditions.

OPERATION OF CONTIGUOUS DSA

As an example of the performance of a DSA scheme, we look at the operation of the contiguous DSA method described above. We consider the scenario of a converged cellular and broadcast system, for example, utilizing the Universal Mobile Telecommunications System (UMTS) 3G cellular network, and the digital video broadcasting terrestrial (DVB-T) network. These, operating in a composite radio system and working together to deliver a mix of



■ **Figure 2.** *Operation of the contiguous DSA scheme for temporal and spatial adaptability.*

The dominant services over each of the networks, e.g., voice telephony over UMTS, and video over DVB-T, determine the temporal and spatial load demands seen on the networks, and provides the variations required for DSA.

unicast and multicast services to users, provides an ideal scenario for DSA operation. The dominant services over each of the networks (voice telephony over UMTS, video over DVB-T) determine the temporal and spatial load demands seen on the networks, and provide the variations required for DSA.

TEMPORAL DSA

An example of how a temporal DSA scheme may operate can be seen in Fig. 2. This shows curves of how the loads may change on the different networks over time, and how this can correspond to changing spectrum partitioning. By comparing the amount of spectrum required for fixed allocation (given by the sum of the largest demands on the RANs, and labeled "UMTS peak + DVB-T peak") with the amount required for DSA (given by the peak cumulative demand), we can find the extent to which the traffic can be increased with DSA to give the same user satisfaction in the same spectrum as fixed allocation. This gives us an ideal theoretical value for the spectrum efficiency increase. This can be calculated for any set of traffic patterns like those in Fig. 2, and allow for interesting comparisons with algorithms developed to implement temporal DSA.

Several implementations of an iterative, real-time, temporal DSA algorithm are possible, but typical steps in the operation of the temporal DSA algorithm include:

1) Periodic triggering of DSA algorithm: Depending on the traffic patterns, typical timescales could be in the order of tens of minutes to several hours.

2) Management of the traffic on the carriers: This can include packing calls into carriers, locking off carriers from accepting new calls, or selectively dropping calls from the carriers. This ensures that as many carriers as possible can be released for reallocation by DSA.

3) Prediction of the loads on the networks: Since the DSA algorithm runs periodically, and not on a call-by-call basis, the traffic demands can change significantly during the DSA period. Prediction can be used to allocate spectrum according to the demands that are expected over the whole interval. Prediction schemes can be based on load-histories of past traffic, and time-series estimation algorithms.

4) Allocation decision: From the predicted loads, combined with the current allocations and the amount of spectrum available for reallocation, an algorithm can decide the allocations that will be applied for this interval. These algorithms have important implications for the performance and fairness of the DSA schemes.

A typical DSA simulated performance curve can be seen inset in the left curve of Fig. 3, which shows the performance for the overall system of UMTS and DVB-T for both fixed and dynamic assignment with the time varying traffic patterns from Fig. 2. The spectrum efficiency gain of 29 percent is measured as the increase in load supportable at 98 percent user satisfaction. Simulations can be performed for a range of traffic patterns (characterized by the value of the peak cumulative spectrum demand) and compared to the theoretical results. This can be seen in the main graph on the left side of Fig. 3. The comparison highlights several factors that affect

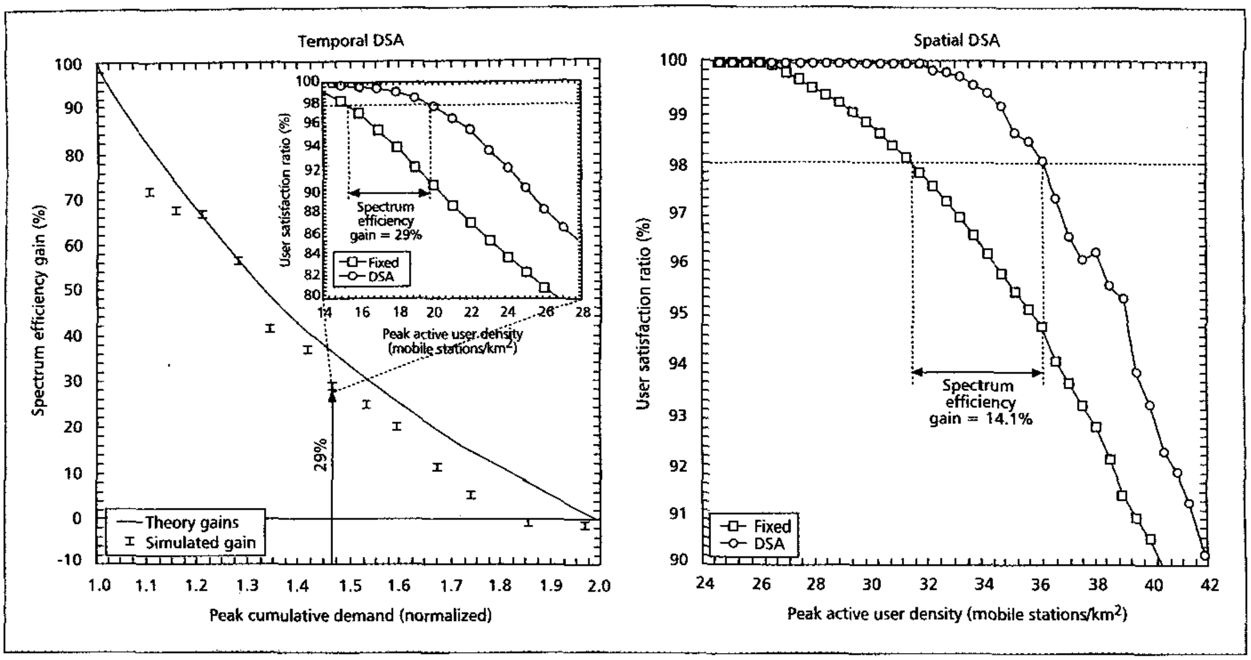


Figure 3. *Example performance of temporal and spatial contiguous DSA.*

the performance of the implemented DSA schemes. These include issues such as the overall amount of spectrum available, and to what degree it is quantized into carriers, the time interval between reallocations, the accuracy of the load prediction, and the readiness of the RANs to free up carriers for reallocation by the DSA algorithm.

SPATIAL DSA

For the spatial DSA example, we consider the same composite radio system as the temporal case, except we wish to adapt the spectrum allocations to the regional demands on the networks for a given time. The regional adaptations cannot be performed with arbitrarily fine spatial resolution, and areas of uniform spectrum allocation must be defined, called *DSA areas*. These should correspond to regions where the traffic demands of the RANs are relatively constant in space. The formation of the DSA areas in this scenario can be seen in Fig. 2, where the size of the area corresponds to a single DVB-T cell. Larger areas are also possible, comprising multiple DVB-T cells.

The goal of spatial DSA is to allocate spectrum to RANs according to the traffic demands in each DSA area. Furthermore, it is necessary to coordinate the spectrum allocation between adjacent DSA areas to avoid interference. In particular, the spectrum allocations of different RANs belonging to adjacent DSA areas should not overlap in the same portion of spectrum. In order to avoid this spectrum overlap while still allowing spectrum allocation adaptation to the traffic demand, the guard band needs to be increased to guarantee the coexistence of the different systems, as can be seen by the example allocations shown for the areas in Fig. 2. The extra guard bands represent a critical issue for spatial DSA, since it has to consolidate the need to satisfy the spectrum requirements with the necessity to limit the guard bands to the minimum possible.

The structure of an example spatial DSA scheme can be summarized in three main steps:

1) Calculate the spectrum overlap: In each DSA area this is calculated on the basis of the spectrum requirements of the RANs in its adjacent areas. This operation allows a first estimation of the size of the guard band in each DSA area, and therefore sets a limit on the portion of allocable spectrum.

2) Perform initial assignment: On the basis of these limits, calculated for each DSA area, a first spectrum assignment to each RAN can be performed, such that the overall number of satisfied users is maximized.

3) Optimization: After this spectrum assignment, actual spectrum overlap is identified and then eliminated, reducing spectrum allocations where needed.

The right curve of Fig. 3 shows the performance of the overall system of UMTS and DVB-T for both fixed and dynamic assignment. An increase of 14 percent in spectrum efficiency is shown when DSA is used over fixed allocation, in this example scenario.

DSA IMPACT ON RECONFIGURABILITY

The previous section has shown that DSA can improve spectrum usage efficiency. However, before such a system can be implemented, the technical requirements of the equipment capabilities and network interworking must be considered. This section reviews the DSA requirements and the key existing technologies to support DSA from both the physical layer — including software-defined radio (SDR) — and network perspectives. In particular, the remaining technical challenges are addressed for both

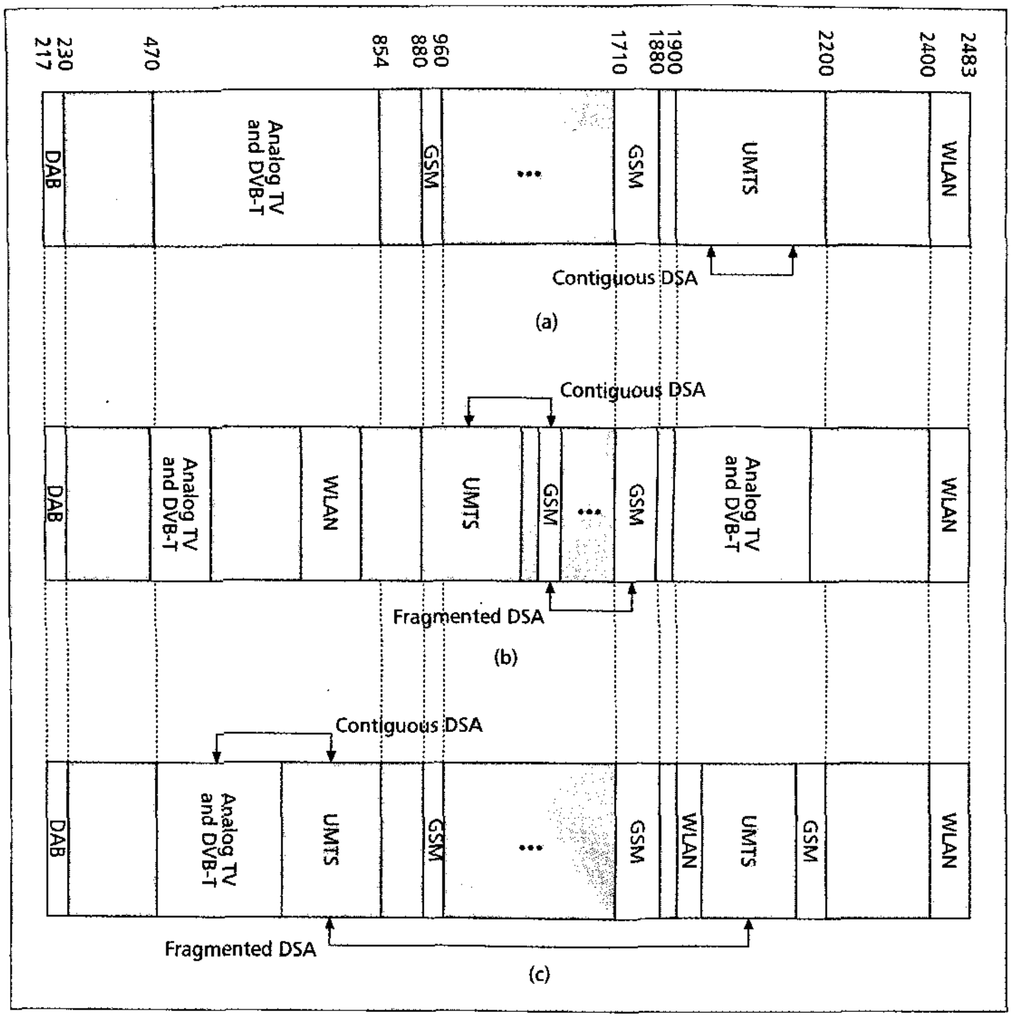


Figure 4. *DSA operation configurations: a) static (current spectrum allocations); b) continuous DSA operations; c) discrete DSA operations.*

The scalability of the contiguous and fragmented DSA concepts enables the introduction of a large range of DSA operational scenarios. The reconfigurability requirements for the overall communications systems applying DSA depend upon the envisaged scenarios.

perspectives. Finally, a possible roadmap to DSA operation is presented.

DSA OPERATIONS AND REQUIREMENTS

The scalability of the contiguous and fragmented DSA concepts enables the introduction of a large range of DSA operational scenarios. The reconfigurability requirements for the overall communications systems applying DSA depend on the envisaged scenarios. The different scenarios (depicted in Fig. 4 for the case of the European spectrum allocations for typical broadcast, cellular, and WLAN systems) are characterized by the following critical features for each system:

- The *spectrum playground* (regulation-related)
- The *frequency range* and *spectrum resolution* (technology-related)

The spectrum playground refers to the permission of the radio system to be allocated bandwidth flexibly or not within a large spectrum range. The most static approach (Fig. 4a) is to operate DSA between assigned bands of a given RAN (e.g., UMTS). In the extreme case, the most flexible scenario (Fig. 4b) would allow any access system to be operated in any part of the shared spectrum (in assigned or unassigned bands, owned or operated by different operators) with a fine resolution (continuous DSA operation). An intermediary scenario (Fig. 4c) could allow some predefined radio systems to operate in and share only some predefined parts of the spectrum (discrete DSA operations).

From the physical layer perspective, the frequency range refers to the multiband capabilities of the same equipment of a given radio system (end user terminal and network access node) to operate, for example, from the higher bands of VHF (broadcasting at ~300 MHz) to the lower bands of SHF (WLAN in the 5 GHz band), at a given spectrum resolution (i.e., with accurate frequency carrier tuning). Hence, the flexibility of the DSA scenarios will depend on the capabilities of the communication devices and access points. The requirements of the reconfigurable equipment related to multiband capabilities include:

- Multiband and integrated narrow/wideband antennas with miniaturization constraints for small-sized devices (e.g., mobile handsets)

The DSA requirements on the network include spectrum pricing, spectrum billing, and adequate interfaces between networks supporting different RAN standards to connect rapidly the right communication equipment on the right frequency carrier.

- Flexible frequency carrier tuning
- Variable duplex distances between the forward and reverse links for frequency-division duplex (FDD)-based systems
- Flexible receiver signal filtering

To simplify the access and use of networks within the coverage, a (logical) common coordination channel (CCC) could broadcast the systems available in the region as well as their currently used frequency ranges. Similarly, this CCC could be used to manage the reconfiguration processes (e.g., according to procedures such as in [10]).

From the network perspective, the network interworking constraints are mainly due to the temporal and spatial spectrum sharing coordination and configuration needed between the systems involved in DSA. The constraints depend on the number of operators and available radio access systems in the DSA area. In the simplest case a centralized entity would control the DSA regions and assign the spectrum to the different access technologies, depending on the load and resource requirements within the area. As such, the DSA requirements on the network include spectrum pricing, spectrum billing, and adequate interfaces between networks supporting different RAN standards to rapidly connect the right communication equipment on the right frequency carrier.

ENABLING TECHNOLOGIES

PHYSICAL LAYER

The required flexibility for DSA can be achieved with SDR-based reconfigurable equipment. Such reconfigurable equipment capabilities rely on the advances of SDR architectures [2]. Before the full software-based reconfigurable architecture bringing digitalization all the way to the antenna is achieved, the way toward more flexibility relies on the following key technologies: antenna, front-end, analog-to-digital conversion (ADC), and digital signal processing (DSP). Table 1 highlights the current technology and DSA-enabling breakthroughs. Additional information can also be found in [11].

Today, dual- or tri-band radio access nodes or handset products already exist. Currently, SDR is mainly used for cellular base stations (e.g., TI proposes an SDR chipset for 3G base stations) due to the lower integration constraints (e.g., size and power consumption). The technology has started to emerge in cellular handsets, although two (or more) RF paths are still required.

NETWORK INTERWORKING

On the networking side, enabling a DSA scenario requires some basic support from within the network. Entities implementing DSA and the support infrastructure for reconfiguration processes need to interact seamlessly. The actual implementation of a DSA scheme, together with the required support mechanisms, poses challenges comparable to those of reconfigurable systems. Both concepts require a minimum support infrastructure, which facilitates the decision making as well as the actual implementation of both the spectrum reallocation and reconfiguration processes. While a tight coupling of DSA and reconfiguration management would ensure speedy reconfiguration, a loose coupling would provide more flexibility for the reconfiguration. There are different ways to design the underlying support architecture, whereby the integration or implementation of the network support for reconfigurability and DSA could be separated using complementary infrastructures (Fig. 5, left). However, ideal for rapid reconfiguration would be a combined architecture (Fig. 5, right) that merges support for reconfigurability with DSA area management.

These figures depict the extreme architectural cases. However, there are potential intermediate steps, where the architectures may be constructed as hybrid solutions, and only limited functionality of the reconfigurability support is integrated in the DSA management structure with the remaining functions implemented as a (global) overlay.

A ROADMAP TO DSA OPERATION

The timeframe for the rollout of DSA relies heavily on both the complexity of the evolution of the regulation policy (for spectrum and equipment) and the technical implementation. The spectrum aspects of regulation have been discussed previously. However, the introduction of software-based reconfigurable equipment also raises a number of issues, including questions of the modus operandi, certification, reconfiguration procedures, and security features preventing impersonation and unwanted configurations of the equipment. In order to introduce such flexible equipment onto the market, new approaches for equipment certification are required. In response to this, the European RTT&E Directive and the FCC have proposed some preliminary enhancements to support this evolution.

When focusing on the technical aspects, given the achievable reconfigurable performance of the current enabling technologies and the technical constraints we have today (power consumption, compact size), three short-term scenarios for the operation of DSA can be envisaged:

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

Thus, further enhancement of DSA relies on extension of the dynamic range and refinement of spectrum resolution tuning for cost-effective equipment. As SDR technology becomes more mature, it can be expected that many of the constraints on the operation of DSA will be loosened. Eventually, this will lead to fully reconfigurable equipment, able to reconfigure to all spectrum bands with a fine resolution and use any radio access technology.

Antenna

	Today	Breakthrough	Hot research topics
Miniaturization	• Planar inverted F antenna (PIFA)	• Lengthening of current paths-based antennas (e.g., fractal antennas) • Capacitive or selfic charging-based antennas (e.g., PIFA antenna)	
Multiband	• Association of several resonators with the introduction of slits	• Association of several resonators with the use of particular antenna geometry (e.g., fractal antennas) • Radio wavelength adaptation with commuting or variable components (e.g., MEMS or diode PIN-based)	
Wideband	• Planar-antenna-based	• Dialectical resonator • Association of several resonators frequency shifted • Independent frequency-based antennas (e.g., b-conical or spiral antennas) • MEMS: Micro-electromechanical system	• Extend MEMS to support any form of antenna

Front-end

	Today	Breakthrough	Hot research topics
Filtering	• Filter rank to cover a wide range of frequencies • Tunable filters electronically controlled based on varactor	• Superconductivity-based tunable band pass filters • MEMS switch-based tunable bandpass filters	• Programmable band pass filters
Amplifier	• Specific to each band — analog RF technology based; switch between amplifiers dedicated to different bands	• Silicon — Germanium transistors • Ultra linear amplifier	• Digitalization of amplifier

Analog-to-digital conversion

	Today	Breakthrough	Hot research topics
Resolution	• Semiconductor-based — 12 bits resolution at 1.3 Gsamples/s	• Rapid single flux quantum (RSFQ) digital based on traditional semiconductor and superconductivity • Quadrature sampling — use of 2 ADCs for IQ channels • Direct conversions from antenna to baseband — CMOS-based — limited for short-range ommunications • Optical sampling	• Reduce ADC power consumption • Direct conversion with higher performance for wider coverage range

Digital signal processing

	Today	Breakthrough	Hot Research Topics
Processors	• ASIC — dedicated silicon function • FPGA — reconfigurable hardware • DSP	• Parameterization of a priori known air interface • Portable software code able to run on general purposes processors (e.g., adaptive computing machine)	• Reduce DSP power consumption • Increase number of operations in DSP • Optimization of parallel DSP architectures • Optimization of DSP/ASIC/FPGA combinations

■ **Table 1.** *Current and breakthrough key enabling technologies for reconfigurable equipment.*

CONCLUSIONS

This article has discussed the potential for utilizing dynamic spectrum allocation in composite reconfigurable wireless networks. This has been approached in three ways, first from a regulatory perspective, second from the spectrum allocation methodology and performance, and finally in terms of the main issues regarding reconfigurable system implementation.

The section on regulatory interest in DSA has shown that regulators are becoming aware of the need to adapt to the changing wireless industry, and aspects such as spectrum trading are important precursors for a DSA system. The concepts of DSA have been compared to some

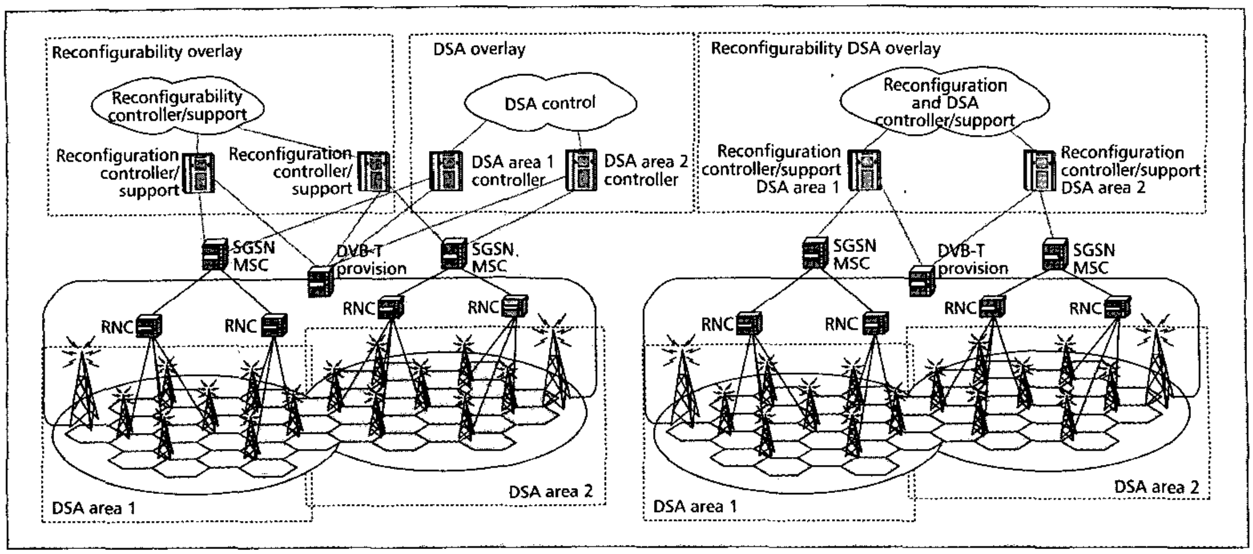


Figure 5. *Separate and combined DSA and reconfigurability support architectures.*

established research fieldd, and it has been shown that parallels exist, but DSA differs in trying to adapt the spectrum allocations of disparate radio networks according to variations in traffic demands on the networks over space or time. Example schemes to implement a spectrum allocation method called contiguous DSA have been described, and results from these schemes for both spatial and temporal adaptability of the spectrum have shown that there is significant potential for increasing spectrum efficiency. Further work will look to schemes that adapt the spectrum allocations simultaneously over both time and space. The gains in spectrum efficiency that can be made will ultimately be determined by the traffic variations seen over the networks, as well as the capabilities of the equipment being used and the regulatory restrictions.

Reconfigurable radio systems are a very important enabler for DSA. The impact of DSA on system requirements has been discussed. Several important requirements for flexible multiband equipment have been identified, including antenna aspects, the flexibility to tune to different carrier frequencies and bandwidths, and filtering issues. In addition, the various critical parts of the reconfigurable radio system have been highlighted, in terms of their current abilities and the technological breakthroughs required to enable DSA. Networking issues for reconfigurable DSA systems have also been discussed, and possible architectures have been highlighted.

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The gains in spectrum efficiency that can be made will ultimately be determined by the traffic variations seen over the networks, as well as the capabilities of the equipment being used and the regulatory restrictions.