# IST-2003-507581 WINNER

## D6.1

# *WINNER Spectrum Aspects: Methods for efficient sharing, flexible spectrum use and coexistence*

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**Abstract:** This report describes spectrum sharing and coexistence issues relevant to WINNER and reviews the possibilities of flexible spectrum use as well as their implications on the design of the WINNER system concept.

**Keyword list:**

Spectrum sharing, co-existence, dynamic spectrum allocation (DSA), flexible spectrum use (FSU)

**Disclaimer:**

# Executive Summary

IST 6th framework project WINNER aims at defining a system concept for a new radio system supporting very high data rates up to 1 Gbit/s as well as increased overall radio system performance. This sets tight challenges both to the radio network solutions and radio interface techniques.

The purpose of this document is to describe spectrum sharing and coexistence issues relevant to the WINNER system concept. The possibilities of flexible spectrum use (FSU) as well as their implications on the design of the WINNER radio interface and network topology are reviewed.

Motivation for spectrum sharing and flexible spectrum use is given with a brief recap on the WINNER system concept vision, reviewing different spectrum access possibilities between multiple radio services as well as between multiple WINNER operators. Opportunities for secondary spectrum use are identified. This work investigates in the area of recent and on-going research activities on spectrum sharing, and methods for FSU like dynamic spectrum allocation (DSA), joint and common radio resource management and software defined radio (SDR).

An overview on the existing and emerging radio services and legacy systems in the considered WINNER spectrum range is presented identifying the properties of the services or systems that may encourage or discourage spectrum sharing between them and WINNER systems. Implementation and deployment aspects that are related to spectrum sharing and FSU are also discussed.

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# Abbreviations

| | |
|---|---|
| ACI | Adjacent Channel Interference |
| AP | Access Point (=Base Station) |
| ASE | area spectral efficiency |
| AWGN | additive white Gaussian noise |
| BER | bit error ratio |
| BS | Base Station |
| CS | Central Station |
| DAB | Digital Audio Broadcasting |
| DSA | Dynamic Spectrum Allocation |
| DVB-T, S, C, H | Digital Video Audio Broadcasting (Terrestrial, Satellite, Cable, Handheld) |
| EIRP | Equivalent Isotropically Radiated Power |
| ENG | Electronic News Gathering |
| ERC | Electronic Radiocommunications Committee |
| FCC | Federal Communications Commission |
| FSA | Fixed Spectrum Allocation |
| FSU | Flexible Spectrum Use |
| FWA | Fixed Wireless Access |
| GPS | Global Position Satellite |
| IA | Interference Area |
| ITU | International Telecommunications Union |
| IP | Integrated Project |
| ISM | industrial, scientific, medical |
| ISOP | Interference Scenario Occurrence Probability |
| ld | ‘logarithmus dualis’, logarithm to base two |
| MT | mobile terminal |
| OB | outside broadcasting |
| P-MP | point-to-multipoint |
| PSD | power spectral density |
| RAN | Radio Access Network |
| RAT | Radio Access Technology |
| RPE | Radiation Pattern Envelope |
| SDR | Software Defined Radio |
| SFN | Single Frequency Network |
| SNR | signal to noise ratio |
| TS | Terminal Station |
| UWB | Ultra Wideband |
| WINNER | Wireless World Initiative New Radio |

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|---|---|
| WLAN | Wireless Local Area Network |

# Table of Contents

# 1. Introduction

IST 6th framework project WINNER aims at defining a system concept for a new radio system to be deployed within a time frame of about 10 years. WINNER system concept has to support much higher data rates than the current systems and their evolutions as well as increased radio system overall performance. This sets tight challenges both on the radio network solutions and radio interface techniques. Despite of the technical challenges, the overall system development has also to result in acceptable solutions from the viewpoints of economics as well as standardisation and regulatory processes. As spectrum is a very scarce resource, WINNER system needs to be capable of efficient and flexible use of spectrum. Efficient spectrum use is one of the crucial design targets of the WINNER system concept that is taken into account and sought after already from the beginning of the design process.

The overall spectral efficiency of a system can be improved with good coexistence properties, good spectrum sharing capabilities, as well as with flexibility in the spectrum use. WINNER systems need to be able to coexist efficiently with each other and with different radio services in the same or adjacent frequency bands without a need for wide guard bands or restrictive technical or usage limitations. Capabilities to share spectrum with other systems will significantly increase the efficiency as well as acceptability of the system. The overall spectral efficiency of the WINNER system can be also increased with a flexible use of spectrum that adapts to the spatial and temporal variations in the traffic and environment characteristics. The flexibility and scalability of the system is important also in order to simplify the network deployment under spectrum arrangements that may vary from region to region. Built-in capabilities for flexibility and sharing may significantly ease the task of spectrum identification for the system.

The purpose of this document is to describe sharing and coexistence issues relevant to the WINNER system concept, review flexible spectrum use methods, as well as to present what requirements these issues imply for the design of WINNER radio interface and network topologies.

The document is organized as follows:

- In the rest of this chapter, further motivation for spectrum sharing and flexible spectrum use is given with a brief recap on the WINNER system concept vision, a review on different spectrum access possibilities between multiple radio services as well as between multiple WINNER operators, and a discussion on the opportunities on the secondary spectrum use. Finally, the chapter is ended with a brief survey on the recent and on-going research activities on the sharing, flexible spectrum use and, in general, optimised utilisation of spectrum.
- Overview on the existing or emerging radio services and legacy systems in the considered WINNER spectrum range is presented in Chapter 2. In the overview, such properties of the services or systems that may encourage or discourage spectrum sharing between them and WINNER systems are emphasized.
- The methods for coordinated and un-coordinated spectrum sharing are described in Chapter 3, based on existing literature, and their inherent advantages and disadvantages are discussed.
- In Chapter 4, the different scenarios for spectrum sharing in the context of WINNER system are discussed. The scenarios for spectrum sharing between different radio services or systems are addressed in Section 4.2. The spectrum sharing between multiple WINNER operators as well as between different WINNER system modes of the same operator is considered in Section 4.1.
- The coexistence issues between systems allocated on the same or adjacent frequency bands are considered in Chapter 5. The purpose of the chapter is to recognize aspects that need to be taken into account in the WINNER system design as well as in the spectrum requirements so that unnecessarily wide inter-service guard bands or areas are avoided without too strict technical or usage restrictions.
- Implementation and deployment aspects that are related to the spectrum sharing and flexible spectrum use are discussed in Chapter 6. The requirements imposed on the signalling and the possibilities and limitations of software defined radios (SDR) are discussed as implementation issues in this chapter. The network deployment is addressed in respect to the gradual re-farming of legacy system spectrum as well as to the regional variations in the spectrum arrangements.
- The document is summarized and the main conclusions are presented in Chapter 7.

## 1.1 Vision for WINNER System Concept

The key vision for the WINNER system concept is a ubiquitous radio system that covers the full range of the scenarios from short-range communications to wide-area applications, as depicted in Fig. 1. The WINNER concept is based on common radio access technologies that will adapt to different scenarios instead of vertical integration of multiple systems optimised for specific scenarios [64].

WINNER system capabilities will extend up to 1 Gbps cell throughput in indoor and outdoor applications at low mobility, and in the other end to urban, sub-urban and rural coverage with peak data rates per user in the range of 1 Mbps to 100 Mbps at high velocity. Such wide range of capabilities calls for extensive scalability and flexibility in the system. WINNER system will adopt new technologies to achieve these goals including, e.g., new network topologies like multi-hop concepts that enhance the scalability [64].

The system scalability and adaptability needs to be achieved in economically sound manner. This means that the easiness of implementation and re-configurability, cost efficient RAN deployment, and stepwise increasing complexity and performance characteristics allowing also for simple and cheap WINNER equipment, are emphasized in the system design. Therefore the WINNER system will be based on a minimum number of variants for radio interface elements that can be combined in the most appropriate way to efficiently support any given scenario. The radio interface elements will have high commonality and may comprise one generic modulation scheme, multiple access scheme, etc. In other words, WINNER RAN will consist of different combinations of radio interface elements, or modes, adapted to the local traffic and environment conditions [64].

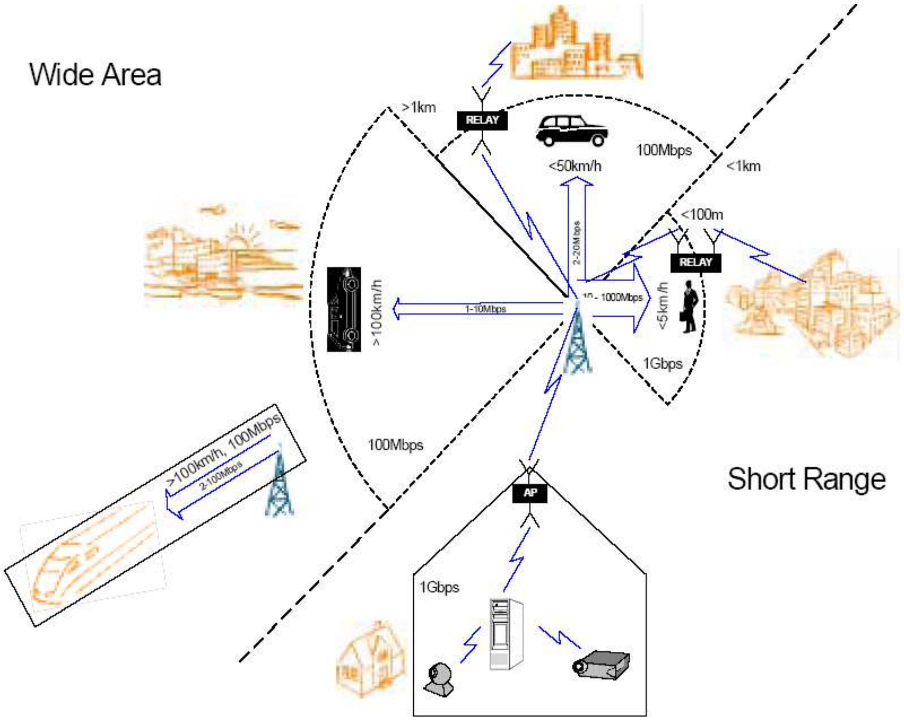

Fig. 1 Multitude of scenarios covered by WINNER system concept [64].

## 1.2 Coexistence and Spectrum Sharing

A large number of wireless applications and services has been developed and deployed in the recent years. Moreover, many of these applications are being improved and many new radio access technologies (RAT) are developed, aspiring to get access to the radio spectrum. As there are hardly any free frequency bands available, new RANs are expected to be able to share the spectrum and to co-exist with existing services. We define these two concepts for the following:

***Coexistence***: The concurrent operation of different services or RANs in the same or in adjacent frequency bands without causing degradation to any service, with emphasis on the indicated limitations in terms of, e.g., frequency separation, physical separation, and transmission powers.

***Sharing***: The use of a same frequency band by different RANs or services, either with coordination or possibly without any coordination between the systems, with emphasis on the spectrum access schemes and methods.

Efficient sharing capabilities are required as most frequency bands that are well-suited for WINNER systems are already allocated and used to some extent by existing services. Therefore, WINNER systems may not get sufficient dedicated frequency bands of its own, but will have to be able to use the same bands with other services. Of course, it must be guaranteed that existing services are not significantly negatively affected. Sharing of the same frequency band by different services or technologies is only possible through well-defined limitations on e.g. spectrum use, output power level, equipment density, transmission masks, etc. Technical requirements which facilitate sharing capabilities are, e.g., transmitter power control, low level protocols, and dynamic frequency selection [108].

Spectrum sharing includes the common use of bands between new technologies with existing ones, as well as between several other new technologies that are deployed in parallel in the same bands. An example for a new technology which shares bands with many existing ones is UWB, while WLAN and Bluetooth are a typical example for technologies which are deployed at the same time and make use of overlapping frequency bands.

Future networks will very likely have to be able to coexist with some services and systems using the same or adjacent frequency bands. The deployment of these networks should be easy from the spectrum coordination point of view and thus, the required coordination for transmitters and systems should be kept to a minimum. Coexistence of different services on adjacent bands is facilitated by grouping the services according to their power levels and interference sensitivity.

The issue of coexisting systems is closely related to DSA, since it is concerned with different radio systems sharing the same block of spectrum. However, in coexistence the concern is finding the effect on the performance of the systems when they are simply both operating in the same spectrum band. This can either be investigated for systems operating on exactly the same frequencies, i.e. the co-channel case, or when the systems are operating in adjacent frequencies, i.e. the adjacent channel case. An interesting study of this concept deployed in 3G systems (UMTS Terrestrial Radio Access Network – UTRAN) and digital video broadcasting (DVB-T) is presented in [52].

## 1.3 Opportunities for Secondary Spectrum Utilization

Recent measurements of the spectrum occupancy as a function of time and frequency indicate that great parts of the spectrum, although dedicated to some service, are actually not used for significant periods of time. In these measurements, the received power at some location is measured and plotted over time and frequency. Spectrum is regarded as unoccupied when no power is detected at a certain time and frequency. Note that detecting whether a frequency band is in use is not a trivial task. Especially spread spectrum systems can operate at signal powers well below the noise level and may thus not be detected by simply measuring the power level.

Measurements like those reported by Shared Spectrum [98] in Fig. 2 suggest making use of the “spectrum holes”. However, although the measurement of the power spectral density over time in a limited frequency range seems feasible, it is by far more complicated to identify a spectrum hole that can be used by a non-primary system without causing interference to the primary system. A basic problem of these measurements in the time-frequency plane is that the spatial dimension is missing. Although a frequency band is unused at the location where the measurement is taken, at another location within the range of the secondary transmitter, it might be heavily used. On the other hand, there might be areas where a certain frequency band is not used over a very long time.

We might thus speak of temporal and spatial spectrum holes. Of course, there is no clear distinction and most spectrum holes will be a combination of both, but often either the spatial or the temporal component will dominate. Possible examples for both cases are:

- Temporal holes: Sporadic use of the spectrum by certain services. Services, e.g. military use, that use the spectrum in a sporadic manner, i.e. only a few times per day, are possible candidates for spectrum sharing.
- Spatial holes: Some services use spectrum only in reduced geographical areas like e.g. WLAN in central urban areas or at airports.

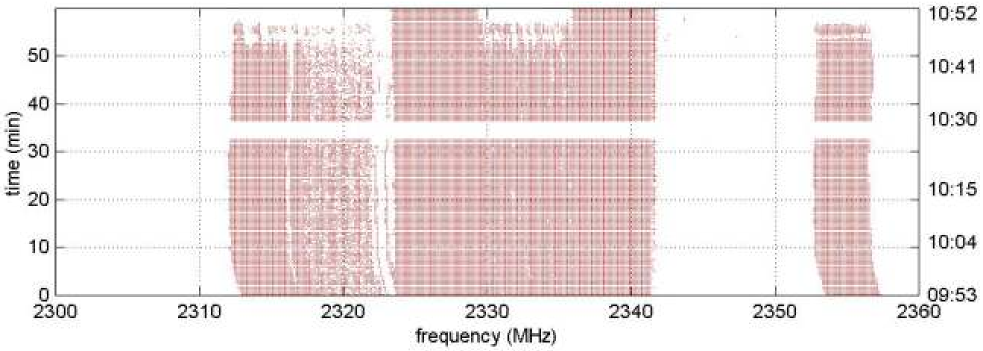

Fig. 2 Measurement about the spectrum occupancy. (taken from [98]).

If no coordination between the primary and the secondary system is possible, the extent to which spectrum sharing is possible depends strongly on the characteristics of the primary system. Properties of the secondary system that favour uncoordinated spectrum sharing are:

- Directivity of radio emissions, like e.g. in satellite links, radio links or fixed wireless access with directive antennas. The more directive, the better.
- Bidirectional links with fixed transmit powers. This makes it much easier for the secondary system to locate primary transceivers and estimate the path loss between primary (victim) receiver and secondary transmitter.
- Very narrowband or very broadband systems. If the primary system is narrowband, the influence of a broadband, low-power system might be negligible and vice versa.

Properties of the primary system which make uncoordinated spectrum sharing difficult are:

- Broadcast systems or uni-directional links. In broadcast systems, generally no temporal holes are present and, what is more important, it is impossible for a secondary system to determine the locations of the receivers.
- Varying transmit power, e.g. power control in CDMA.
- Adaptive modulation with power control.
- Spread spectrum with low SNR.
- Mobility of terminals.

This list suggests that, one of the systems that are less adequate for uncoordinated secondary spectrum use is IMT-2000. This is not surprising as it is designed to use its transmit power efficiently and is highly adaptive.

Another aspect that has to be considered in this context is the coverage area. Wide-range radio networks influence or might be influenced by a great number of actors. These RANs normally use dedicated frequency bands below ≈2 GHz, due to the propagation conditions (satellites do not fit into this classification). On the other hand, short range radio networks cover only the range of few individuals and thus the possibility to interfere or be victim of interference are drastically less than for wide-range systems (Nevertheless, as often various RATs are located in the same device, interference is not automatically prevented). Short-range systems typically use frequencies above 2 GHz and operate often in shared frequency bands. Due to the limited propagation, interference issues are limited in space. This reasoning leads to the distinction between wide-range and short-range RANs and the tendency to operate wide-range RANs in dedicated spectrum at low frequencies and short-range RANs in shared spectrum at high frequencies.

## 1.4 Spectrum Access Scenarios

Currently, fixed spectrum allocation, assingments and licensing is the prevailing method in granting access to spectrum. In the context of spectrum access for WINNER systems we have to consider far more general spectrum access scenarios and have to account for the expected changes of paradigms in spectrum regulation policy. Recently, more flexible spectrum access scenarios have been studied in several projects. Dynamic spectrum allocation between RATs was considered in OverDRiVE [62]. In SCOUT [55], various spectrum management scenarios are described. This is done in the context of flexible spectrum use in cellular systems and the spectrum management is considered from the view of different network operators.

We may distinguish four basic possibilities to coordinate the access to spectrum between different radio services:

1. Fixed assignment: This is the way access to spectrum is managed nowadays. For each service or RAT a fixed frequency band in a specific geographical area is allocated, and some technical rules are established in order to prevent interference. If frequency bands are shared, detailed rules on a number of parameters like transmit power, antenna radiation patterns, etc. are established before deployment.
2. Central Radio Controller: In this scenario, the access to the spectrum is controlled by a central controller which serves a certain frequency band and geographical area. Access to a spectrum range is solicited to and granted by this controller. This controller thus acts like a real-time regulator, in that it is a centralized, independent entity which grants access to spectrum immediately.
3. Primary system: The spectrum access is controlled by the incumbent operator, who has obtained a license for a frequency band. This operator may make parts of his spectrum available to secondary users when it is not in use. In this scenario, WINNER may act as primary or as a secondary system. This can be indicated over a broadcast signalling channel, or with signalling between the RAN controllers of the different RATs. In this scenario we might further distinguish between intra-operator and inter-operator coordination:

   3a) Coordination inside an operator: the operator has the freedom to use his licensed spectrum for more than one RAT. Frequency is assigned dynamically among the RANs according to the traffic load.

   3b) Coordination between different operators: The operator, which controls the access to spectrum, might decide to cede spectrum access to another operator for a certain time in a certain area.
4. No coordination: In a certain frequency band, various RANs may access spectrum without central coordination. No communication between different systems is established. An important distinction in this case is if all spectrum users have access on equal terms or not:

   4a) No priority. No RAN is privileged in accessing the spectrum. This is the situation nowadays in e.g. the ISM bands.

   4b) With priority. A primary RAN is defined which has preference in accessing the spectrum. In this case, at least the secondary systems have to be equipped with some mechanism that detects the presence of the primary RAN.

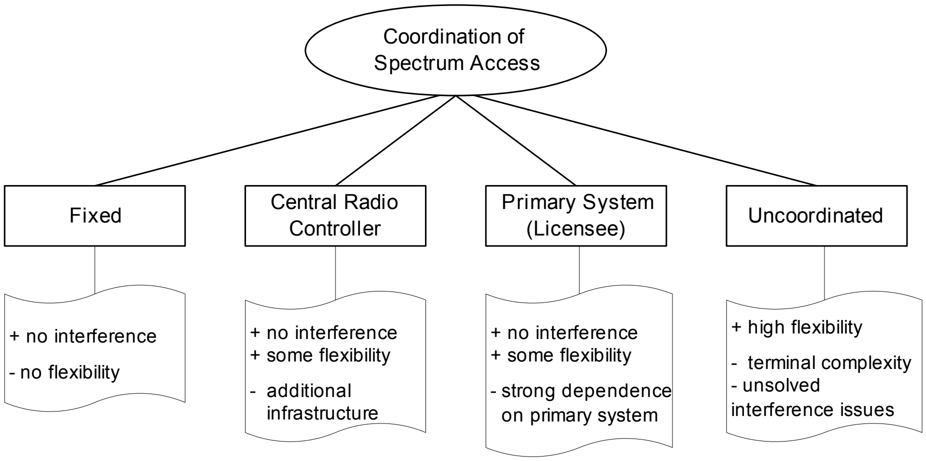

Fig. 3 Methods to coordinate spectrum access.

The same spectrum access scenarios can be applied within a system or RAT among different operators, or in principle, between WINNER modes operated by the same operator.

## 1.5 European Research Projects

Spectrum sharing and flexible spectrum use has been considered in several research projects. In this section, a brief survey on recent and on-going public research activities in Europe is given.

### End-to-End Reconfigurability (E²R)

E2R is an Integrated Project of the 6th Framework Programme of the European commission, addressing the core of the strategic objective "Mobile and wireless systems beyond 3G" and is part of the Wireless World Initiative (WWI). The key objective of the E2R project is to devise, develop and trial architectural design of reconfigurable devices and supporting system functions to offer an expanded set of operational choices to the users, applications and service providers, operators, regulators in the context of heterogeneous mobile radio systems. The E2R project consortium is composed of major manufacturers, operators, academia and regulators and aims at bringing the full benefits of the valuable diversity within the Radio Eco-Space, composed of a wide range of systems such as Cellular, Wireless Local Area and Broadcast [72].

The E2R Project is structured in six technical work-packages (WP), corresponding to six main research fields. "Evolution of Radio Resource and Spectrum Management" work package (WP5) aims at developing the mechanisms for dynamic allocation of radio resources. This requires research into combining reconfigurable technology and support structures (from pure terminal perspectives, e.g. Cognitive Radio, to network oriented perspectives, e.g. Joint Radio Resource Management (JRRM) and flexible network planning) with novel resource management techniques that are capable to control the complete spectrum in a local area. Deployment of such technology requires a new approach to regulation and economics of spectrum. Hence the second major aim of this research is to develop, based on the results of the system research (which will be in tight collaboration with national regulatory bodies and operators), new options and mechanisms to enable more progressive spectrum regulation and market-based approaches, and to facilitate a more efficient resource usage [72].

The WP5 of E2R project has rather overlapping goals with WP6 (T6.5 and T6.6) of the WINNER project. Both belong to the 6th Framework Programme of the European commission so a cross-programme co-operation between the work packages will be organised.

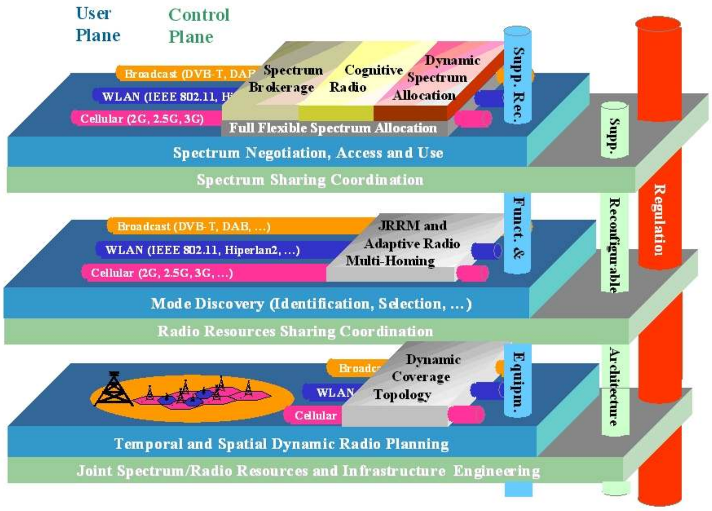

Fig. 4 Mechanisms for dynamic allocation of radio resources (taken from [72]).

## IST DRiVE

The European project DRiVE (Dynamic Radio for IPServices in Vehicular Environments) [53] investigated novel methods for dynamic spectrum allocation (DSA) in a multi-radio environment.

The overall objective of the DRiVE project was to enable spectrum-efficient high-quality wireless IP in a heterogeneous multi-radio environment to deliver in-vehicle multimedia services, which ensure universally available access to information and support for education and entertainment. The project aimed at investigating methods of increasing the spectrum efficiency and capacity in a multi-radio environment, operating in an integrated all-IP network, utilising new dynamic spectrum allocation schemes and new traffic control methods [53]. To achieve these objectives the DRIVE project addressed the convergence of cellular and broadcast networks to lay the foundation for innovative IP-based multimedia services. Two key issues were tackled in the DRiVE project:

1. Inter-working of different radio systems (GSM, GPRS, UMTS, DAB, DVB-T) in a common frequency range with dynamic spectrum allocation.
2. Co-operation between network elements and applications in an adaptive manner.

The work package 1 of DRiVE (dynamic radio aspects) developed methods for dynamic spectrum allocation and for co-existence of different radio technologies (GSM, GPRS, UMTS, DAB, DVB-T) in one frequency band to increase the total spectrum efficiency. Dynamic Spectrum Allocation can be defined as a method that allocates only an amount of spectrum to a radio access network (RAN) to satisfy short term traffic needs with certain user quality of service, and hence, balancing the load between underused spectrum/RAN and overused spectrum/RAN.

Different services such as speech, video, web browsing and multicast applications may have very distinct time-varying traffic demands. Also the demand for different services on different networks depends on location, leading to a spatial variation in the spectrum usage. Therefore, two main methods of dynamic spectrum allocation were investigated during the DRiVE project. One section investigated changing the spectrum allocations over time, known as temporal DSA, and the other over space, called spatial DSA.

The temporal and spatial DSA work indicated that around 30% increases in spectrum efficiency could be gained when DSA is compared to fixed spectrum allocation (FSA), although the actual value does depend on the traffic patterns used. These two main sections on DSA have described how spectrum allocations can be dynamically changed either over time or over regions [77].

The work carried out in DRiVE project can serve as a foundation for the research on sharing and flexible spectrum use done in WINNER WP6. Similar techniques as proposed in DRiVE can be applied to WINNER air interface modes.

### IST OverDRiVE

The European research project OverDRiVE (Spectrum Efficient Uni- and Multicast Over Dynamic Radio Networks in Vehicular Environments) [60] is the follow-on project of DRiVE and aims at UMTS enhancements and coordination of existing radio networks into a hybrid network to ensure spectrum efficient provision of mobile multimedia services. An IPv6 based architecture enables inter-working of cellular 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 multi- and unicast services to vehicles. The key OverDRiVE research issues are: (1) improve spectrum efficiency by system coexistence in one frequency band and by DSA, (2) enable mobile multicast by UMTS enhancements and multiradio multicast group management, and (3) develop a vehicular router that supports roaming into the intra-vehicular area network [60]. The work on OverDRiVE project was started in late 2002 and finished in 2004.

The OverDRiVE project is divided into four work packages, which are hierarchically subdivided into several tasks. The work package 1 (Spectrum Efficient Radio Resource Management) is direct continuation to the work done in DRiVE project and investigates new and advanced methods for dynamic spectrum co-ordination in old and new frequency bands and the co-existence (with regard to interference and sensitivity) of different radio services such as UMTS and DVB-T in one frequency band. It also develops enhancements for UTRAN to provide spectrum efficient multicast and asymmetric services [60].

The DSA work in OverDRiVE takes the results on contiguous DSA from DRiVE, and works on more complex allocation schemes that are not limited to allocating contiguous blocks of spectrum to each RAN, giving more flexibility in sharing the spectrum. OverDRiVE also investigates issues of spectral coexistence over DSA areas, allowing areas with differing allocations to be compatible at the borders, providing a further step towards DSA that is both temporally and spatially variable [60].

Other study areas of OverDRiVE include: UMTS enhancements, co-ordination of existing networks to provide mobile multimedia, software defined radio vs. reconfigurability vs. DSA, IPv6 based architecture to enable networking of cellular and broadcasting type networks (DVB-T), mobile multicast (grouping).
The work carried out in OverDRiVE project can also serve as a foundation for the research on sharing and flexible spectrum use done in WINNER WP6. Similar techniques as proposed in DRiVe and OverDRiVE can be applied to WINNER air interface modes.

### IST TRUST & SCOUT projects

The European research project SCOUT [55] is follow-on project of IST TRUST. The top-level goal of the SCOUT Project is to provide and validate concepts for networks supporting reconfigurable mobile equipment and concepts for terminal reconfiguration that are intelligently customised and managed when used by mobile users for a wide range of wireless access technologies. Also it is aiming to extend the All-IP mobile networks for supporting reconfigurability functions in the equipment by researching the system concepts in the network and technologies required to support users within such networks including:

- Reconfigurability of all layers for cellular and ad-hoc hybrid networks and to support self organization.
- Quality of Service - To support Quality of Service for reconfigurable terminals in IP-based mobile networks.
- *Spectrum issues* - To investigate the spectrum and air interface management for reconfigurable systems.

In order to fully exploit the flexibility provided by the re-configurable terminals and networks capabilities, further research on advanced RRM, combining both classical RRM and advanced spectrum management, are investigated in the SCOUT project. The research aims at providing efficient solutions for RRM in a composite radio environment, supporting multiple RATs in different network topologies (hierarchical, decentralized) and moreover being potentially managed by the same or different operators. This includes *spectrum management for asymmetric regular traffic*, inter-system handovers measurement and criteria, design of potential collaborative RRM schemes considering *solutions of spectrum sharing between operators, and flexible spectrum allocation* in a context of re-configurable equipment and self-organizing networks.

The results from SCOUT project especially on spectrum issues can be also utilized in WP6 and applied to WINNER air interface modes.

### IST EVEREST project

The objective of the newly established European research project Everest (Evolutionary Strategies for Radio Resource Management in Cellular Heterogeneous Networks) is to devise and assess a set of specific strategies and algorithms for access and core networks, leading to an optimised utilisation of scarcely available radio resources for the support of mixed services with end-to-end QoS mechanisms within heterogeneous networks beyond 3G [63].

The provision of beyond 3G heterogeneous network topologies is conceptually a very attractive notion; however, it is a challenge to accomplish an efficient network design. In this context, RRM strategies are responsible for an utmost efficient utilisation of the air interface resources in the available RANs. EVEREST will provide tangible contributions towards a heterogeneous realisation of 2G/2.5/3G (e.g. GERAN, UTRAN) and 3.5G networks with the inclusion of newly emerging RANs (e.g. WLAN for vertical coverage extensions). The potential inclusion of location information in RRM design, as well as some forms of *RAN sharing*, will be considered as additional examples of the medium and long term research focus of EVEREST [63].

The research challenges, to be tackled by EVEREST project, can be summarised as follows:

- To identify, propose, simulate, assess and validate advanced RRM algorithms for GERAN and UMTS as well as novel radio concepts beyond 3G.
- For heterogeneous networks, to develop Common RRM (CRRM) algorithms between access technologies focused on UTRA and GERAN. Both for tight and very tight coupling will be considered.
- To consider other technologies that can be a complement to GPRS/UMTS, such as:
    - WLAN for indoor hotspots
    - Different types of repeaters, acting as coverage extensions
    - To support end-to-end QoS in a heterogeneous wired and wireless mobile environment. To this end, the investigation about the relationship between the core network Bandwidth Broker (BB) and the RRM & CRRM entities for a plethora of RANs (UMTS, GERAN and WLAN) becomes of prime importance.
    - To demonstrate the benefits of the developed RRM and CRRM algorithms by means of multimedia IP based applications over a real time testbed.

The expected research results from the EVEREST project can be summarised as follows:

- Further progress on the definition of advanced RRM mechanisms leading to an optimized usage of the different Radio Access technologies

- Acknowledge and contribute to the definition of useful Common RRM strategies, where a pool of resources belonging to different technologies are commonly considered and commonly optimized.
- Providing end-to-end QoS in an IP mobile access network. Define the interactions between a BB and the radio entities, in order to provide the adapted QoS to the service and to use in an optimal way the heterogeneity of the IP access network.

The work in Everest project has just started and it remains to be seen how much synergies between the Everest project and WINNER WP6 can be finally achieved.

## 1.6 International Research Forums

In this section, a brief summary about research activities in different open research forums related to spectrum sharing and flexible spectrum use is presented.

### Wireless World Research Forum

Major objectives of the Wireless World Research Forum (WWRF) are:

- to develop and maintain a consistent vision of the Wireless World
- to generate, identify, and promote research areas and technical and society trends for mobile and wireless systems towards a Wireless World
- to identify and assess the potential of new technologies and trends for the Wireless World
- to contribute to the definition of international and national research programs

A new work group structure for the WWRF was created in the late 2003. Two interesting work groups were added then, namely WG6: Reconfigurability and SIG1: Spectrum Topics. These groups can partly address similar issues as studied in WINNER WP6. One of the new research items of WG6 is "Support for Dynamic Spectrum Allocation in Reconfigurable Access Networks". This research item will study how to implement flexible spectrum allocation schemes in composite radio environments. The research will consider scenarios where the delivery of seamless mobile multimedia services, enabled by the inter-operability of wireless heterogeneous radio access networks, will open new challenges in terms of radio resource management, whereby the key that enables such inter-operability is the availability of a more flexible spectrum management making more efficient use of the available radio resources. Apart from the obvious changes that DSA schemes would require in terms of spectrum regulation, there are also the technical challenges towards the actual management of dynamic spectrum allocation schemes. In [81] the research requirements into mechanisms to manage dynamic spectrum allocation are outlined. The objectives are given to sketch an initial approach how DSA processes, enabled through reconfigurable technologies, can be managed.

Part of the work proposed for WWRF WG6 is already included in the work plan of the IST project 'End-to-end Reconfigurability' (E2R) and is currently under investigation (i.e. reconfiguration management and dynamic resource allocation). First results are expected to be published before end of 2004.

### SDR Forum

The SDR Forum is an international, non-profit organization dedicated to promoting the development, deployment, and use of software defined radio (SDR) technologies for advanced wireless systems. SDR is defined as a collection of hardware and software technologies that enable reconfigurable system architectures for wireless networks and user terminals. Radios built using SDR concept can allow multimode/band, multifunctional wireless devices that can be adapted, updated or enhanced by using over-the-air software upgrades [91].

The mission of the SDR Forum is to accelerate the proliferation of SDR technologies in wireless networks to support the market needs. SDR Forum aims to:

- Develop requirements and/or standards for SDR technologies to be adapted to existing and evolving standards for wireless systems
- Cooperatively address the global regulatory environment by closely working with regulatory agencies around the world
- Provide a common ground to codify global developments by industrial or governmental players

### 4G mobile Forum

Fourth Generation Mobile Forum (4GMF) is the first international technical body focusing on the next generation broadband wireless mobile communications which converge wireless access, wireless mobile, wireless LAN and packet-division-multiplexed (PDM) networks. The integrated 4Gmobile system provides wireless users affordable broadband mobile access solutions for the applications of secured wireless mobile Internet services with value-added quality-of-service (QoS) through application layer all the way to the media-access-control (MAC) layer and physical (PHY) layer. The 4GMF is launched on a new different platform so as to complement (and not to compete) with WWRF, Darpa XG, mITF, K4G, J4G, FuTURE, F4G, B3G, 802.20, etc.

The mission of 4GMF is to provide a technical forum to promote the exchange of technology advancement resulted from academic and industry research and develop efforts to facilitate the realization of the 4G Mobile Vision. The objective is to define the Open Wireless Platform Architecture supporting the convergence of broadband wireless mobile and wireless access.

- With this technology, one integrated terminal with one global personal number can access freely any wireless air interfaces, and the radio transmission modules are fully software-definable, reconfigurable and programmable.
- The All-IP will be terminated at the wireless end-terminal to enable End-to-End direct signaling and QoS guarantee.
- The network layer and the lower layers will be combined together to construct the common broadband wireless super-engine of this 4Gmobile -Open Wireless Architecture.

### IEEE 802.20

On 11 December 2002, the IEEE Standards Board approved the establishment of IEEE 802.20, the Mobile Broadband Wireless Access (MBWA) Working Group. The mission of IEEE 802.20 is to develop the specification for an efficient packet based air interface that is optimized for the transport of IP based services. The goal is to enable worldwide deployment of affordable, ubiquitous, always-on and interoperable multi-vendor mobile broadband wireless access networks that meet the needs of business and residential end user markets.

The MBWA scope is the specification of physical and medium access control layers of an air interface for interoperable mobile broadband wireless access systems, operating in licensed bands below 3.5 GHz, optimized for IP-data transport, with peak data rates per user in excess of 1 Mbps. It supports various vehicular mobility classes up to 250 km/h in a MAN environment and targets spectral efficiencies, sustained user data rates and numbers of active users that are all significantly higher than achieved by existing mobile systems.

### Mobile IT Forum (Japan)

Mobile IT Forum was inaugurated on June 25, 2001. The aim of Mobile IT Forum (mITF) is to realize Future Mobile Communication Systems and Services such as the fourth-generation mobile communications systems and mobile commerce services. At an early date by performing research and development activities on Future Mobile Communications, making studies on its standardization, conducting coordination with related bodies, collecting information, and carrying out promotional and educational activities, and thereby contribute to a healthy utilization of radio spectrum.

### 4G committee (Korea)

Next Generation Mobile Communication (NGMC) Forum was established on September 29, 2003. Its objectives include, e.g., studies on spectrum use. The activities of the Forum for the attaining objectives are arranged in three working groups. One of them is Spectrum Working Group that analyzes trends of spectrum utilizations in mobile communications, proposes spectrum utilization plans for the activation of mobile communications, and discusses about B3G spectrum.

### FuTURE (China)

Future Technologies for Universal Radio Environment (FuTURE) is a part of China’s 863 Program for 10th 5-year plan ( 2001-2005). Its objective is to aim at the development of mobile telecommunication in 2010, studying the future technology used in radio environment, and to establish a universal radio experience environment that can meet the future application demands and development trends towards years of 2005 to 2010. Considered technical challenges include also Cooperative Networks with dynamic spectrum usage, and SDR terminal and base station with reconfigurable RF and base-band technologies.

## 1.7 Activities in Standardisation Bodies

Recent activities in standardisation bodies that are closely related to sharing and flexible spectrum use and present significant advances in the sharing or flexible spectrum use methods are summarized in this section.

### 3rd Generation Partnership Project (3GPP)

**RAN sharing**

The interest in network sharing in 3GPP has emerged as a consequence of limited spectrum resources, licensing, and the cost of infrastructure deployment and site availability for different operators. Sharing the same radio access networks or radio spectrums is further emphasised for future WINNER networks as it could be difficult to assign the required large bandwidths per operator based on traditional fixed spectrum assignment rules. Therefore, in the future an operator may be faced with the challenge to offer services over a complex set of shared and non-shared networks of different radio access networks. This will put new requirements on radio resource management in terms of handling, e.g., network selection, user mobility, load/bandwidth sharing, and the availability of the services.

In 3GPP the network sharing issues are dealt with in technical reports TR22.951 [4] and TR 23.851 [5], especially concentrating on the architectural aspects of network sharing.

**Inter-working between heterogeneous networks and Common Radio Resource Management**

In 3GPP the inter-working between heterogeneous networks can be realised by means of different levels coupling. The inter-working between cellular UTRAN (WCDMA) and GERAN (GSM/GPRS) is readily standardised with a tight coupling between the networks. However, more alternatives are given for inter-working between WLAN and UTRAN networks where loose (common authentication mechanisms), tight (similar to UTRAN-GERAN inter-working) and very tight (WLAN as sub-system within UTRAN) coupling schemes are standardised. The standard documents describing most of the inter-working procedures between UTRAN and GERAN networks are TS 22.129 [6], TS 23.009 [8], TS 23.060 [9] and TS 25.304 [10], while UTRAN-WLAN inter-working for different coupling scenarios is described in the 3GPP technical report TR 22.934 [7].

Clearly some form of overall resource management is needed to get the best out of the mixture of radio resources. Common Radio Resource Management (CRRM) has been introduced in 3GPP to perform these tasks. CRRM can be defined as a centralised or distributed intelligent entity having knowledge about the channel (spectrum) occupancy in all participating radio access systems, where the resource utilization information is shared between nodes. CRRM may give support for inter-system handovers strategies to flexibly transfer users and their services to another access when appropriate. CRRM architectures and functionality are described in 3GPP TR 25.881 [11] and 3GPP TS 25.891 [12].

# 2. Overview on existing services in 3.4-5 GHz range

According to IR6.1 [70] the assumed frequency range for WINNER research purposes is the 3.4 – 5.0 GHz range. That frequency range is used as a starting point for the research work, allowing some narrowing down of the otherwise numerous options. The same spectrum range is used here in the following initial examinations. It should be noted, that the WINNER system concept should be able to operate fully anywhere between 2.7 and 5.0 GHz and it should be able to utilise any available Mobile Service bands even below 2.7 GHz.

This sections aims to describe the current and future radio systems allocated in this range according to the ITU and CEPT allocations for sharing purposes. Firstly the services in Europe and China are briefly described. The use of spectrum in other regions is very similar (according to Table 2.1) and therefore the conclusions drawn from the European spectrum allocation can be generalized to quite some extent. Finally some initial study of co-existence is presented for the Fixed Service in the Frequency Range 3.6 – 4.2 GHz.

The investigations in this chapter are carried out with the objective of starting an evaluation of the possibilites for spectrum sharing and coexistence. For this purpose, some exemplary frequency bands are considered in more detail. The selection of these frequency bands is solely for research purposes and it is not intended to suggest that these frequency bands should be considered for the WINNER system. This question is outside the scope of the project.

The following table shows the current services in the 3.3-5GHz range in the world according to the ITU Radio Regulations [73]. The primary service is printed in capital letters, while possible secondary services are printed in lower-case. The secondary service is allowed to operate if no interference is caused to the primary service.

Table 2.1 ITU spectrum allocations in the WINNER target frequency band.

| Band (GHz) | Region 1 | Region 2 | Region 3 |
|---|---|---|---|
| 3.3 - 3.4 | RADIOLOCATION | RADIOLOCATION, Amateur, Fixed, Mobile | RADIOLOCATION, amateur |
| 3.4 - 3.5 | FIXED, FIXED-SATELLITE (space-to-Earth), Mobile, Radiolocation | FIXED, FIXED-SATELLITE (space-to-Earth), amateur, Mobile, Radiolocation | |
| 3.5 - 3.6 | | FIXED, FIXED-SATELLITE (space-to-Earth), MOBILE (apart from aeronautical), Radiolocation | |
| 3.6 - 3.7 | FIXED, FIXED-SATELLITE (space-to-Earth), Mobile | | |
| 3.7 – 4.2 | | FIXED, FIXED-SATELLITE (space-to-Earth), MOBILE (apart from aeronautical) | |
| 4.2 – 4.4 | AERONAUTICAL RADIONAVEGATION | | |
| 4.4 – 4.5 | FIXED, MOBILE | | |
| 4.5 – 4.8 | FIXED, FIXED-SATELLITE (space-to-Earth), MOBILE | | |
| 4.8 – 4.99 | FIXED, MOBILE except aeronautical mobile, Radio Astronomy | | |
| 4.99 - 5 | FIXED, MOBILE except aeronautical mobile, RADIO ASTRONOMY | | |

## 2.1 Spectrum in Europe

In Europe, CEPT aims to harmonize the European frequencies use across all members countries beyond 2008 [32]. The following table shows the current services in the 3.3 – 5GHz range in Europe. The same notations (upper-case / lower-case) as before are applied. Some of these services and their characteristics are described below.

Table 2.2 Spectrum allocation in Europe according to ERO [30].

| Band (GHz) | Service (Europe) | Description |
|---|---|---|
| 3.3 – 3.4 | RADIOLOCATION | Radiolocation (military) (2.9 – 3.5) |
| 3.4 – 3.5 | FIXED | Radiolocation (military) (2.9 – 3.5) |

| | | |
|---|---|---|
| | FIXED-SATELLITE (space-to-Earth)<br>MOBILE<br>Amateur<br>Radiolocation | Amateur<br>Fixed links<br>SAP/SAB and ENG/OB (3.4 – 3.6)<br>Point-to-Multipoint (3.4 – 3.8) |
| 3.5 – 3.6 | FIXED<br>FIXED-SATELLITE (space-to-Earth)<br>MOBILE | SAP/SAB and ENG/OB (3.4 – 3.6)<br>Point-to-Multipoint (3.4 – 3.8)<br>Fixed links |
| 3.6 – 4.2 | FIXED<br>FIXED-SATELLITE (space-to-Earth) | Point-to-Multipoint (3.4 – 3.8)<br>FSS Earth stations<br>Point-to-Point |
| 4.2 – 4.4 | AERONAUTICAL RADIONAVIGATION | Altimeters<br>Earth exploration-satellite |
| 4.4 – 4.5 | FIXED<br>MOBILE | Point-to-Point (4.4 – 4.8)<br>Defence systems (4.4 – 5)<br>SAP/SAB and ENG/OB (4.4 – 5) |
| 4.5 – 4.8 | FIXED<br>FIXED-SATELLITE (space-to-Earth)<br>MOBILE | Point-to-Point (4.4 – 4.8)<br>Defence systems (4.4 – 5)<br>SAP/SAB and ENG/OB (4.4 - 5)<br>FSS Earth stations |
| 4.8 – 4.99 | FIXED<br>MOBILE except aeronautical mobile<br>Radio Astronomy | Defence systems (4.4 - 5)<br>SAP/SAB and ENG/OB (4.4 - 5)<br>Passive sensors (satellite)<br>Continuum measurements (4.8 - 5)<br>VLBI observations (4.8 – 5.03) |
| 4.99 – 5. | FIXED<br>MOBILE except aeronautical mobile<br>RADIO ASTRONOMY | Defence systems (4.4 - 5)<br>SAP/SAB and ENG/OB (4.4 - 5)<br>Continuum measurements (4.8 - 5)<br>VLBI observations (4.8 – 5.03) |

### Radiolocation

Spectrum allocated to the radiolocation service is used by radars with installations on land, on ships and on aircrafts. In general, the predominant use by mobile radars is on ships and aircrafts.
The radar service uses the 3.3 – 3.5 GHz band. For airborne radars the upper limit is 3.41 GHz. In the 3.3-3.4 GHz band this service is the primary service. In the 3.4-3.5 GHz band it is the secondary service, and it is expected not to be used beyond 2008.

### Fixed Satellite Service (FSS)

This service is primary in the 3.6-4.2 GHz band for coordinated earth stations in FSS, (regulated in [35]) and with priority for civil networks. It is the primary also in the 4.5-4.8 GHz band for space to earth communications (not to be implemented in NATO Europe).

One of the services using this band is Very Small Aperture Terminal (VSAT). Small aperture refers to the size of the antenna diameter, which is from 1 up to 3.8 meters. Originally VSAT networks appeared in USA at the beginning of 1980s and were refers to private networks for the data transmission from a master station through satellite towards several receiving stations. VSAT networks are one of the fastest growing sectors in satellite communications. The bands of operation are:

| Standards | Up-link (Earth to Satellite) (GHz) | Down-link (Satellite to Earth) (GHz) |
|---|---|---|
| C-band | 5.925–6.425 | 3.7–4.2 |
| Extended C–band | 6.725–7.025 | 4.5–4.8 |
| Ku–band | 14–14.5 | 10.95–11.7 |

The system has a EIRP at the antenna from 40 to 70 dBW.
Two types of VSAT architecture are found today:

- Star (point-multipoint, the most common architecture: two VSAT stations can only communicate through the hub (relay station)). This hub is the earth station where all the providers (e.g. TV) are connected and transmit their contents through the hub to the satellite. The satellite broadcasts the content to all the VSAT terminals (e.g. TV receptors).

- Mesh (point-to-point): two VSAT stations can communicate without the hub directly throught the satellite, so a multiple access should be implemented (normally FDMA and TDMA together). The hub has the control of the network and still has the capability to switch-off a part or the totality of the network.

### SAP/SAB and ENG/OB

The service is allocated in the 3.4-3.6 GHz band as the primary system, for coordinated SAB/SAP applications for occasional use. The service has also primary status in the 4.4-5 GHz, also for coordinated SAB/SAP applications for occasional use.

SAP stands for Services Ancillary to Programme making, and SAB stands for Services Ancillary to Broadcasting. For SAP and SAB the use of radio microphones, OB (outside broadcast) links and talkback equipment is necessary. This equipment is used for the transmission of sound signals and programme signals, e.g. within a broadcast studio or for OB productions, and for the connection between OB vehicles and studios or transmitter sites as well as between different production sites or broadcast studios.

Current ENG/OB (Electronic News Gathering/Outside Broadcast) systems use FM modulation between 14 and 25 MHz of bandwidth (20 MHz for the majority of the systems) [75].

### Fixed links

This service is allocated in the 3.4 – 3.6 GHz band as a primary system including point to multipoint. It is regulated by EN 301 751, EN 301 753, ERC REC 14-03.

Fixed wireless access (FWA) systems use the 3.4-3.8 GHz band as a primary system. It is regulated by EN 301 751, EN 301 753, ERC REC 13-04, ERC REC 14-03, and the 3.6-3.8 GHz band includes also point-to-multipoint.

The most representatives services are HIPERMAN and 802.16. The WI-MAX organization, similar to the well-known Wi-Fi, is working towards interoperability profiles definition for 802.16 and ETSI HIPERMAN.

### Aeronautical Radionavigation

This service has primary status in the 4.2-4-4 GHz band and is used for airborne radio altimeters. (ARNS: Aeronautical Radio Navigation Service). This use will continue and will expand in the future as the number of aircraft in use increases.

Also the standard frequency and time signal-satellite service may be authorised to use the frequency 4.202 GHz for Space-to-Earth transmissions confined within the limits of a 2 MHz band.

### Defence systems and mobile communications

This service operates in the 4.4-5.0 GHz band as a primary system. This frequency range is an harmonised military band for fixed and mobile systems. In general it is for military use in Europe, but the band can be shared between civil and military users according to national requirements and legislation. The priorities in respect of preferred channels or sub-bands are to be determined after further discussions between interested parties.

### Radio astronomy (VLBI)

The service is allocated in the 4.8-5 GHz band for continuum measurements and Very Long Baseline Interferometry (VLBI).

Radio astronomy antennas measure quite weak radio signals typically of the order of -290 dBW/m$^2$/Hz or less from the universe, using wide bandwidths to achieve the necessary sensitivity. Radio astronomy continuum measurements routinely detect tiny changes in the noise floor of the order of –60 dB.

Since radio astronomy consists of making precise measurements of noise-like signals close to the sensitivity limit of the radio telescope, interference by other emissions in the band is almost inevitable. A new wireless system that pretends to use this band will have to avoid emissions nearby the radio astronomy stations according with the policies of the recommendation [ITU-R RA.1031-1]. The radio astronomy stations are normally placed far away from other terrestrial wireless systems [75].

### Space research (passive) and earth exploration-satellite service EESS (passive)

This service operates in the 4.95-4.99 GHz as a secondary system.

Passive sensing instruments operating in the earth exploration-satellite, by their nature are very sensitive to any emissions within the sensor band. It operates by integrating a very low signal over time across a relatively large bandwidth. EESS (passive) also uses bands 50 to 60 GHz, 23.6 to 24 GHz, 31.3 to 31.8 GHz that are out of the scope of this document.

Many EESS (passive) sharing studies and sharing agreements have been completed based on specific system noise temperatures, noise floors or interference environments. Passive microwave radiometry is a tool of fundamental importance for the Earth exploration-satellite service. The EESS operates passive sensors that are designed to receive and to measure natural emissions produced by the Earth's surface and its atmosphere. The frequency and the strength of these natural emissions characterize the type and the status of a number of important geophysical atmospheric and surface parameters (land, sea, and ice caps), which describe the status of the Earth/Atmosphere/Oceans System, and its mechanisms:

- Earth surface parameters such as soil moisture, sea surface temperature (SST), ocean wind stress, ice extension and age, snow cover, rainfall over land, etc. Regarding SST, uses also the band 4.2-4-4GHz as a secondary system. Recommendation ITU-R SA.1624 gives general policies about sharing between this service with Aeronautical radionavigation (airborne altimeters).
- Three-dimensional atmospheric parameters (low, medium, and upper atmosphere) such as temperature profiles, water vapour content and concentration profiles of radioactively and chemically important trace gazes (for instance O3, SO2 and ClO).

Microwave observation techniques below 100 GHz allow studying the Earth's surface and its atmosphere from space-borne instruments even in the presence of clouds, because they are almost transparent at these frequencies [75].

## 2.2 Spectrum in China

The following table gives a brief overview about spectrum allocation in China.

Table 2.3 Spectrum allocation in China.

| Band (MHz) | Service (China) | Band (MHz) | Service (China) |
|---|---|---|---|
| 1710-2010 | FIXED<br>MOBILE<br>SPACE | 3300-3400 | RADIO DETERMINATION<br>Amateur<br>Fixed<br>Mobile |
| 2010-2160 | FIXED<br>MOBILE<br>SPACE | 3400-4200 | FIXED<br>SPACE (Fixed) (Air to Surface)<br>Mobile |
| 2160-2300 | FIXED<br>MOBILE<br>SPACE | 4200-4400 | AERIAL RADIO NAVIGATION |
| 2300-2450 | FIXED<br>MOBILE<br>RADIO DETERMINATION<br>SPACE<br>Amateur | 4400-4990 | FIXED<br>MOBILE<br>SPACE |
| 2450-2500 | FIXED<br>MOBILE<br>RADIO DETERMINATION<br>SPACE | 4990-5000 | FIXED<br>MOBILE (Except Navigation Mobile )<br>RADIO-ASTRONOMICAL<br>Space (No Power Supply) |
| 2500-2655 | FIXED<br>MOBILE (Except Navigation Mobile)<br>RADIO DETERMINATION<br>SPACE | 5000-5150 | AERIAL RADIO NAVIGATION<br>SPACE |
| 2655-2690 | FIXED<br>MOBILE (Except Navigation Mobile)<br>RADIO DETERMINATION<br>SPACE | 5150-5250 | AERIAL RADIO NAVIGATION<br>SPACE |
| 2690-2700 | RADIO-ASTRONOMICAL<br>SPACE (No Power Supply) | 5250-5650 | SPACE<br>RADIO DETERMINATION |

| | | | |
|---|---|---|---|
| | | | RADIO NAVIGATION |
| 2700-2900 | RADIO DETERMINATION<br>AERIAL RADIO NAVIGATION<br>SPACE | 5650-5850 | FIXED<br>SPACE<br>RADIO DETERMINATION<br>MOBILE<br>Amateur |
| 2900-3100 | RADIO DETERMINATION<br>RADIO NAVIGATION | 5850-5925 | FIXED<br>SPACE (Fixed) (Space to earth)<br>RADIO DETERMINATION |
| 3100-3300 | RADIO DETERMINATION | 5925-7075 | FIXED<br>MOBILE<br>SPACE (Fixed) (Space to earth)<br>Radio Determination |

## 2.3 Emerging Services

Apart from the already existing services, new radio technologies are being developed and some of them might be in operation at the time of the deployment of WINNER systems. Naturally, these evolving technologies do not yet have regulatory status in ITU-R or Europe and their system properties are subject to change.

### Ultra Wide Band (UWB)

Ultra Wideband Radio is a wireless technology for transmitting large amounts of digital data over a wide spectrum of frequency bands with very low power. According to the American Federal Communications Commission (FCC) definition, UWB uses an ultra wide fractional bandwidth of at least 20 percent, or alternatively a bandwidth of 500 MHz or more. But the main characteristic is that UWB transmit ultra low power spectral density so that the signal in a narrow band is below the noise floor. In 1973 the first US patent was awarded for UWB communications. UWB was firstly developed by military groups in US. The first steps towards development of commercial communication devices appear in the 1990s [65].

Several European projects inside FP5 has studied aspect of UWB: whyless (www.whyless.org), "Ultra-wideband Concepts for Ad-hoc Networks" (UCAN., www.ucan.biz) and "Ultra Wideband Audio Video Entertainment System" (ULTRAWAVES, www.ultrawaves.org). Within the FP6, the projects "Pervasive Ultra-wideband Low Spectral Energy Radio Systems" (PULSERS, www.pulsers.net) and "My personal Adaptive Global NET" (MAGNET,www.telecom.ece.ntua.gr/magnet/) are working on studies of UWB regarding its definition, test and analysis of coexistence with the current services.

The areas of application of UWB are systems with high/very high data rate (VHDR) requirements in the short range, and precise localization and tracking features by exploiting the inherent properties of very wideband signalling systems. For example UWB can rate up to 100 Mbit/s in 10m., and localization accuracy of less than 1m. So possible uses are [64]:

- Hot-spot Wireless Personal Area Network (WPAN)
- Intelligent Wireless Area Network (IWAN) , for example in-house network, as wireless High Definition Television
- High Data Rate in Peer-to-Peer Networking, e.g. wireless high definition TV
- Sensor, Positioning and Identification Network (SPIN)
- Military applications, due to the low probability of intercept and detection.
- Radar, obstacle avoidance in unmanned vehicles. High precision altimeters.

UWB technology can use many different types of modulations, which can also be combined: pulse position modulation, pulse phase modulation, pulse amplitude modulation, frequency sweep, direct sequence and orthogonal frequency division modulation. The typical pulse used for UWB is known as Gaussian doublet. This is sent in a train of pulses where the start of each pulse is pseudo randomly modified for avoiding the frequency peak at the repetition period.

The frequency band between 3.1 and 10.6 GHz was identified for communication and measurement systems with a tight spectral mask by the FCC. Under the FCC UWB regulatory regime, the amount of spectral power that can be transmitted is limited by the mask, see Fig. 5. The major reason for the low allowed power output in the frequency bands 0.96-1.61GHz is due to the potential impact of interference to existing services, such as mobile telephony, GPS, and military usage.

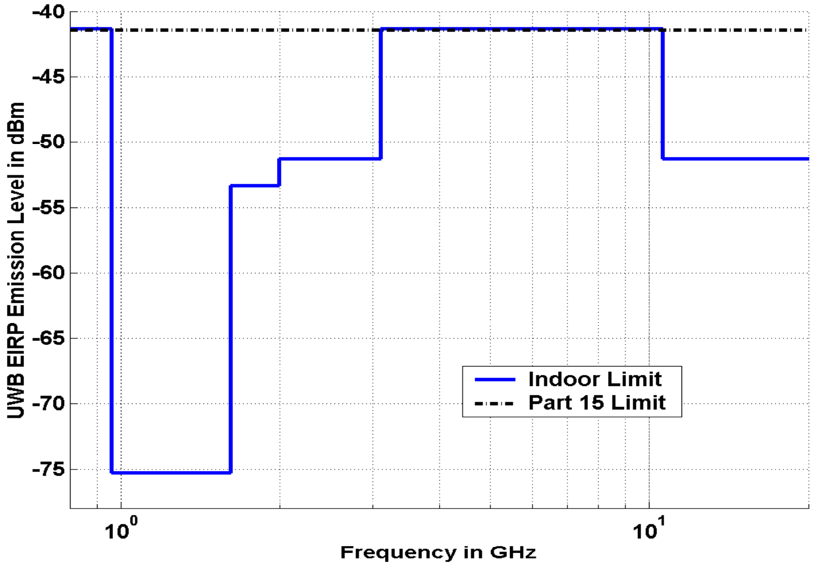

Fig. 5 FCC mask for spectral power transmission [39].

IEEE 802.15.3a intends to standardize a high data rate WPAN, up to 10m in the 3.1-10.6 GHz band, which is one of the applications of UWB. In March 2003 more than 30 proposals were submitted to TG3a, and 7 were initially chosen. After a “down selection procedure”, 2 merged proposals have remained [44]:

- Direct Sequence Ultra Wideband (DS-UWB)
- Multi-Band OFDM (MB-OFDM)

The main aspects of each one specified in the following table.

Table 2.4 Main characteristics of DS-UWB and MB-OFDM.

| | DS-UWB | MB-OFDM |
|---|---|---|
| No. of bands | 2 | 3 (1st generation bands)<br>10 optional bands |
| Bandwidths | 1.386 GHz, 2.736 GHz | 528MHz |
| Frequency ranges | 3.2 – 5.15 GHz<br>5.825 – 10.6 GHz | Group A: 3.168-4.752 GHz<br>Group B: 4.752-6.072 GHz<br>Group C: 6.072-8.184 GHz<br>Group D: 8.184-10.296 GHz |
| Modulation scheme | BPSK, QPSK, DS-SS | TFI-OFDM (with 128 point FFT), QPSK |
| Coexistence method | Null band for WLAN (~5GHz) | Null band for WLAN (~5GHz) |
| Multi access method | Ternary CDMA | Time-frequency |
| No. of simultaneous piconets | 8 | 4 |
| Error correction codes | Convolutional, Reed-Solomon code | Convolutional code |
| Code Rates | 1/2 @ 110 Mbps<br>RS(255/223) @ 200 Mbps<br>RS(255/223) @ 480 Mbps | 11/32 @ 110 Mbps<br>5/8 @ 200 Mbps<br>3/4 @ 480 Mbps |
| Chip time/symbol period | 731ps (low band), 365.5ps (high band) | 312.5ns (OFDM symbol) |

Coexistence issues need to be carefully taken into account to guarantee the specified quality of service for all the existing radio services sharing the same spectrum. With a bandwidth of at least 500MHz, the overlapping of UWB signal with the other RF systems is evident. Coexistence issues have been studied by various institutions and industrial players and reports can be found from public sources. Measurements

have been done using high power UWB transmitters that exceed the radiation limits given by the FCC. However, using these interference sources the cumulative impact of high density of UWB devices can be demonstrated. From these studies, UWB seems to be a promising technology that could coexist with the present WLAN and RF systems and standards.
UWB will be on the same spectrum initially identified for WINNER (3-5GHz band). The mechanism of impact of UWB for WINNER systems is expected to be similar as for the current mobile systems. However, the magnitude of the impact will most likely be orders of magnitudes higher in the case that the UWB devices emit the higher power spectral density in this band that is allowed under the FCC regime. (see spectrum mask in Fig. 5).

## 2.4 Fixed Service in the Frequency Range 3.6 – 4.2 GHz – A Closer Lock

According to the ERO Frequency Information System (EFIS) [30], in the band 3600 – 4200 MHz in Europe (ECA), there are two primary services allocated: fixed, fixed-satellite (space-to-earth). It should be noted that for ITU region 1, there is additionally a Mobile service allocated on a secondary basis. Also, there may be other secondary allocations in European countries, e.g. in Finland the Amateur service.

The band 3.6 – 4.2 GHz has been selected for a more detailed investigation on sharing possibilities for several reasons:

- With 600 MHz, it is the widest contiguous band inside the WINNER target spectrum range.
- No safety-of-life services like aeronautical radionavigation, or other sensitive services like radio astronomy or radio determination are allocated in this band.
- No primary allocation for the mobile service is present, in many countries there is no mobile allocation at all. As mentioned in section 1.3, spectrum sharing with a mobile service is especially difficult.

For these reasons, spectrum sharing is considered to be most easily feasible in this band.

### 2.4.1 Users and relevant standards or recommendations

The exact definition of the “fixed service” has been subject to considerable debate [31]. The principle question is whether transportable stations should be considered as “mobile” because they can be moved easily from one place to another or as “fixed” because during operation they are not in motion. Such equipment is often referred to as “portable”, however in the ITU classification there exists no portable service and therefore they have to be treated as either fixed or mobile services. In the following, transportable stations will be considered as belonging to the fixed service because during operation there are not moving [31]. Typical examples are stations for ENG and OB.
The principal users of the fixed service are [31]:

1. **Telecommunication network operators**: Radio links form part of public telecommunication networks. High capacity trunk lines are normally cheaper to deploy with optical fibre, whereas radio links provide the possibility of rapid deployment and it is thus expected that they will not be replaced completely by optical fibre.
2. **Television network operators**: Partly for their radio links used for the contribution and distribution of programmes to their own broadcast transmitters and partly for their additional ancillary broadcasting requirements comprising ENG and OB.

There is a multitude of relevant standards and recommendations for fixed radio systems in the 3.6 – 4.2 GHz band. The following table shows the most relevant ETSI standards and ERC and ITU recommendations.

Table 2.5: Standards for fixed radio systems in the 3600–4200 MHz band.

| | Fixed Radio Systems; P-MP equipment, [*multiple access method*], P-MP digital radio systems in frequency bands in the range 3 GHz to 11 GHz |
|---|---|
| EN 301 021 | TDMA |
| EN 301 080 | FDMA |
| EN 301 124 | DS-CDMA |
| EN 301 253 | FH-CDMA |
| EN 301 744 | DS-CD/TDMA, P-MP digital *packet* radio systems |
| | |

| | |
|---|---|
| EN 301 751 | Fixed Radio Systems; Point-to-Point equipments and antennas; Generic harmonized standard for Point-to-Point digital fixed radio systems and antennas covering the essential requirements under article 3.2 of the 1999/5/EC Directive |
| EN 301 753 | Fixed Radio Systems; Multipoint equipment and antennas; Generic harmonized standard for multipoint digital fixed radio systems and antennas covering the essential requirements under article 3.2 of the Directive 1999/5/EC |
| IEEE 802.16a | Broadband Wireless MAN |

Table 2.6: CEPT/ERC recommendations.

| | |
|---|---|
| ERC REC 12-08 | Harmonised radio frequency channel arrangements and block allocations for low, medium and high capacity systems in the band 3600 MHz to 4200 MHz |
| ERC REC 13-04 | Preferred frequency bands for fixed wireless access in the frequency range between 3 and 29.5 GHz |
| ERC REC 14-03 | Harmonised radio frequency channel arrangements and block allocations for low and medium capacity systems in the band 3400 MHz to 3600 MHz |

Table 2.7: ITU-R recommendations.

| | |
|---|---|
| ITU-R F.382 | Radio-frequency channel arrangements for radio-relay systems operating in the 2 and 4 GHz bands |
| ITU-R F.635 | Radio-frequency channel arrangements based on a homogeneous pattern for radio-relay systems operating in the 4 GHz band |
| ITU-R F.758-3 | Considerations in the development of criteria for sharing between the terrestrial fixed service and other services |

### 2.4.2 Methods to assess the severity of interference

In ERC Report 99 [29], a number of different methods have been defined to assess the severity of interference:

- Interference Area (IA)
- Interference Scenario Occurrence Probability (ISOP)
- Monte Carlo (MC)
- Worst Case (WC)

In fixed wireless systems, the occurrence and level of interference depends mainly on the placement of the terminal stations (TS) and the central stations (CS), as well as on the antenna gains.

The **Interference Area** (IA) is defined as the area, in which unacceptable interference occurs, relative to the area of the cell or sector.

The **ISOP** (Interference Scenario Occurrence Probability) is defined as the probability that at least one terminal is placed in the IA. This measure is related to the number of terminals deployed in a cell, and possibly to the cell planning methodology. In [29], this method is used to evaluate guard bands between frequency bands belonging to different operators.

The **Monte Carlo** method is used in [29] to evaluate the interference probabilities between terminals, since the placement of terminals is rather random.

The **Worst Case** method derives system deployment parameters to ensure that the interference is in all cases below a given threshold.

#### The Interference Scenario Occurrence Probability (ISOP)

The ISOP is the probability that a TS or CS experiences unacceptable interference. In the scenario where the CS is affected by harmful interference, an assessment based on the ISOP is probably not adequate since in this case a whole cell could be blocked. Therefore, for the CS a worst case analysis is preferred. In the CS to TS interference case, an ISOP of 1% means that on average one terminal out of hundred faces interference problems.

#### The Interference Area

The IA is the quotient of the area, in which interference exceeds a set threshold and the area of the whole cell or sector. This is equivalent to the probability that a single terminal placed anywhere in the cell will suffer from unacceptable interference. The IA is computed for specific antenna patterns, channel assignments and guard bands. This measure is related to the ISOP, however, it does not depend on the number of deployed terminals.

### 2.4.3 Case study: Rudimentary coexistence analysis for fixed radio systems

The fixed radio systems according to the ETSI standards in Table 2.5 do not specify the equipments in such detail that terminals from different manufacturers are interoperable, i.e. there is no common air interface. This implies that the susceptibility for interference will vary among systems from different manufacturers. In the following, we will take as an example the standard EN 301 021, which applies TDMA as the multiple access scheme. The technical parameters of the other ETSI standards in Table 2.5 do not differ substantially, so that the main conclusions drawn for this particular standard can be generalized to standards with other multiple access schemes.

**Channel Arrangements**

For the channel arrangements, i.e. the centre frequencies, bandwidths and duplex arrangement, various solutions exist. Some possible channel spacings are recommended in CEPT/ERC/REC 12-08 E [21], which in turn refers to ITU-R F.635 and ITU-R F.382. Annex A of [21] recommends a channel spacing of {15, 20, 30, 40} MHz, while Annex B recommends a spacing of $N \cdot 0.25\,\mathrm{MHz}$, with $N \in \{1, 2, \ldots, 200\}$. For the channel arrangements, also several possibilities depending on the channel spacing, are recommended.

**Transmit power ranges**

The maximum transmit power at the point C’ in Fig. 6 according to [34] is 35 dBm. No specifications about EIRP or antenna gains are given, thus any calculation including the radiated power is necessarily based on some assumptions. Automatic power control is optional but not mandatory.

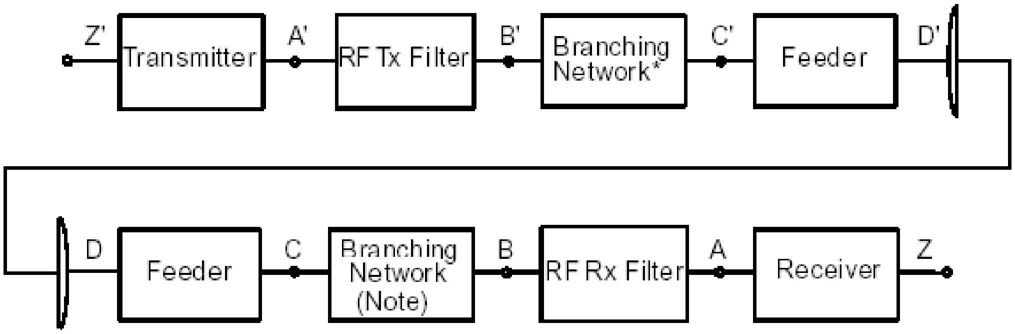

Fig. 6 Radio frequency block diagram of EN 301 021 [34].

**Spectrum density masks**

The standard [34] defines eight “system types” which represent different bitrates and modulation types. The spectrum density, as exemplarily depicted in Fig. 7, masks depend on this system type and on the chosen channel spacing.

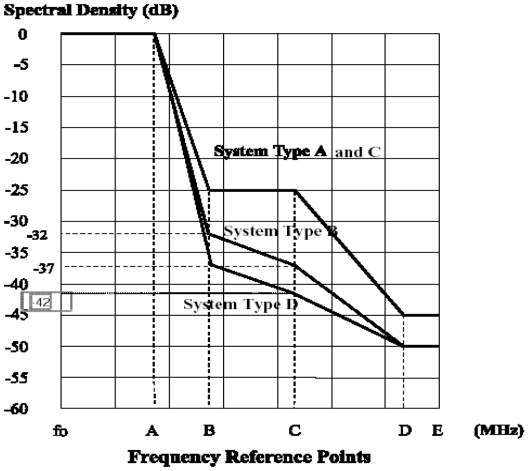

Fig. 7 Power spectrum masks for system type A, B, C and D. fo denotes the actual carrier frequency and the frequency reference points are further specified in tables in [34].

**Interference sensitivity**

The standard [34] distinguishes three types of interference:

- Adjacent channel interference
- Co-channel interference
- CW interference

For issues of spectrum sharing, the sensitivity to co-channel interference is the most relevant one. Co-channel sensitivity is defined as the resistance of the receiver with respect to an unwanted signal of the same type at the same frequency, but with less power. The standard defines the co-channel interference sensitivity with the following procedure:

Two transmitters are connected to the receiver under test, like depicted in Fig. 8.

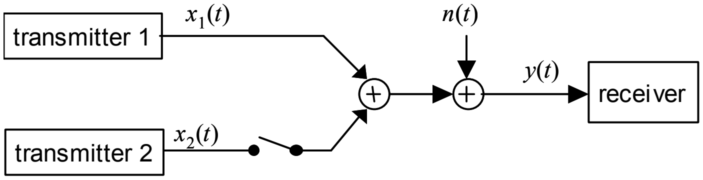

Fig. 8 Setting for test of interference sensitivity.

In first pass, the power of transmitter 1 $S_1 = \mathrm{E}\left[|x_1(t)|^2\right]$ is adjusted such that the SNR $\gamma_1$ at the receiver corresponds to the BER $P_b(\gamma_1) = 10^{-6}$. The SNR is thus given by $\gamma_1 = S_1/N$, with $N = \mathrm{E}\left[|n(t)|^2\right]$. Then, the signal of transmitter 2 is injected with power $N_2 = \beta \cdot S_1$, where $\beta = 10^{-23\,\mathrm{dB}/10}$ for system type A, C and E. The SNR at the receiver is now

$$\gamma_2 = \frac{S_1}{N + N_2}$$

At this SNR, the BER shall not be greater than $10^{-5}$, i.e. $P_b(\gamma_2) \le 10^{-5}$. From Fig. 9 we see that this method to define the sensitivity against interference is very specific to the considered system as it depends on the slope of the $P_b(\gamma)$ curve. A system which employs strong channel coding would probably not fulfill this requirement since the BER curves for coded systems are much steeper.

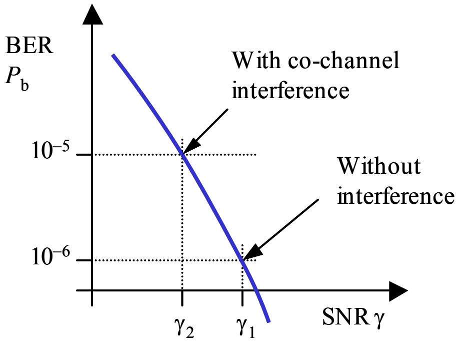

Fig. 9 SNRs and BERs for testing the sensitivity to co-channel interference.

A way to estimate coarsely the permitted interference level is via Table 8 of EN 301 021. There the receiver signal level for a performance at $P_b = 10^{-6}$ is defined to lie between –90 dBm and –60 dBm. The interfering signal has to be at a level 23, 30, or 37 dB below, depending on the system type. To fulfil this requirement in all cases, the interference power at the receiver must not exceed –127 dBm.

### Rudimentary Coexistence Analysis

The interference limit for FWA systems is estimated in [28], Table 7 as $P_{r,i} = -146$ dBW / MHz. This is the maximum interference PSD that is allowed at the receiver's antenna. As an orientative level for the transmit power, we might select the maximum power of an UMTS data terminal. This power is limited to 0.25 W and the bandwidth is assumed as 5 MHz, which gives

$$P_t = \frac{0.25\ \text{W}}{5\ \text{MHz}} \overset{\Delta}{=} -13\frac{\text{dBW}}{\text{MHz}}$$

Assuming one interfering UMTS terminal transmitting at its maximum power, the required attenuation between the UMTS terminal and the FWA receiver is then 133 dB. This allows to roughly estimate the necessary distance $d_{\min}$. The antenna gain of the UMTS terminal is assumed to be 0 dBi and the boresight gain of the FWA antenna according to [28], Table 7 as 18 dBi. Assuming that the attenuation is only due to free space loss and spherical diffraction, we get from (9.9)[1]:

$$A_{\text{fsl}} + A_{\text{sp}} + A_{\text{fm}} = P_t - P_r + G_t + G_c = 133\ \text{dB} + G(\varphi)$$

where $G(\varphi)$ is the FWA antenna gain as a function of the azimuth angle, with $G(0) = 18$ dBi. For this gain, the RPE defined in ETSI EN 302 085, range 1, class TS2 is assumed.
A further assumption is $A_{\text{fm}} = 10$ dB.

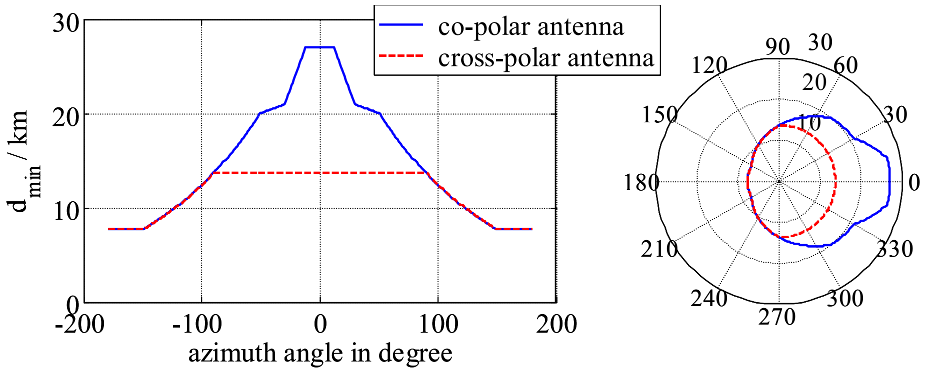

Fig. 10 Necessary distance from FWA terminal in order to avoid unacceptable interference. The attenuation consists of free space loss and spherical diffraction.

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[1] A more detailed explanation of this equation is given in section 9.2.

Instead of considering only free space loss and spherical diffraction, a possibly better estimate for the path loss is given by the extrapolated Okumura model:

$$A_{50} + A_{\text{fm}} = 133 + G(\varphi)$$

With the parameters that lead to (9.11) and the same assumptions as above, we get the minimum distance as depicted in Fig. 11.

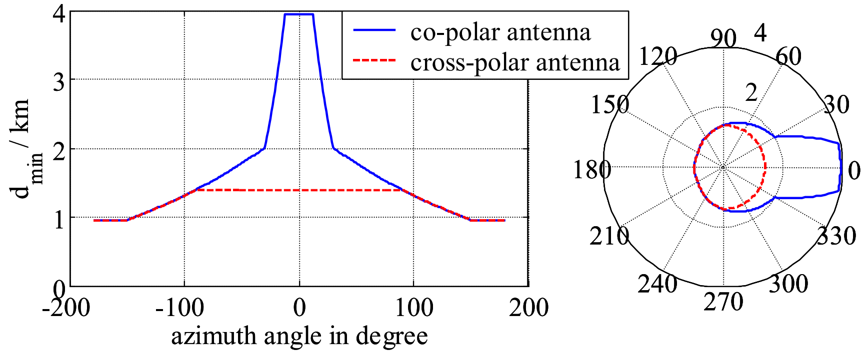


Fig. 11 Minimum distance from FWA terminal to avoid unacceptable interference. The attenuation is calculated with the extrapolated Okumura model.

The results in Fig. 10 and Fig. 11 differ considerably, which demonstrates their strong dependence on the chosen propagation model. Additionally, it must be noted, that all channel models are a more or less coarse approximation of the real-world phenomena in radio propagation and can never capture the actual propagation conditions in a particular case.

Furthermore, it must be emphasized that the results in Fig. 10 and Fig. 11 only meant to give a first indication, since they are are based on a set of assumptions, some of which are nothing more than best guesses, and thus should in no case be taken as basis for any decision.

# 3. Sharing Methods

## 3.1 Coordinated Sharing

Current deployed RANs support one single Radio Access Technology (RAT), even though they sometimes share some common supporting infrastructure, like the same antenna or antenna mast, in GSM and UMTS. In other cases, like GPRS and WLANs they are fully isolated, and communication between them is performed via an external, fixed data network. This isolation and single technology characteristic will be one of the main differences between the current, or legacy, RANs and the new ones, which are the subject of the WINNER project, and other related Integrated Projects. In the WINNER project, mechanisms for cooperation between the radio segments of different RANs will be proposed and analyzed and new RANs will incorporate flexible, multi RAN supporting RATs. This cooperation is expected to enhance the functionality, performance, flexibility and radio coverage with respect to the single RAN case. In WINNER terminology "different RANs" encompasses not only RANs of different types, but also multiple, independent RANs of the same type.

Therefore future radio access deployment concepts will take advantage of a reduced mutual interference resulting from coordination of the shared radio medium across base stations (BS). Rather than being an admission control only, this coordination will result in an improvement of the overall system capacity with centralized or decentralized organization. This will comprise in the domains of time, frequency and code and will take overall traffic load and its geographical distribution into account.

The scarcity of available radio spectrum limits the capability of RANs in carrying of modern multimedia enhanced services introducing constraints in terms of QoS. One possibility to alleviate this limitation is the development and deployment of flexible, optimized mobile radio networks which will be able to adapt to the spatial and temporal variation in capacity in demand in order to increase the overall spectral efficiency of the joined set of radio networks. One such coordinated sharing scheme is dynamic spectrum allocation (DSA) among different RANs.

### 3.1.1 Dynamic Spectrum Allocation (DSA)

Currently the available radio spectrum is divided into fixed and nonoverlapping blocks assigned to different services and standards. Guard bands are introduced between frequency bands allocated to systems that would otherwise interfere with each other due to out of band emissions. The static spectrum usage paradigm ensures predictable and negligible interference between different RANs. Since the RANs operate in non-overlapping spectrum the necessity of investigations into coexistence is kept to a minimum. The IST project DRiVE, the predecessor to OverDRiVE, was one of the first projects to investigate DSA, and thus provides the main input for the foundation work upon which the OverDRiVE DSA work is built.

The main goal of DSA is to allow a controlled amount of spectrum sharing between a defined set of radio systems, such that these systems obtain the optimum amount of spectrum available to them, either at a particular time, or in a particular location, depending on their current traffic/load demands. Therefore DSA investigates adapting spectrum allocation to time varying and spatially varying loads in a coordinated manner. The next section describes the different methods identified for implementing a time-variable DSA scheme.

#### 3.1.1.1 Different Spectrum Partitioning Schemes

Several basic schemes for implementing temporal dynamic allocation of spectrum have been identified in DRiVE. The first two schemes are called contiguous and fragmented DSA. These two schemes apply to scenarios where the DSA is performed in an area of approximately uniform geographic spectrum demand, i.e. the spectrum allocation is changed over time, and these allocations apply over a set of geographical area. In contiguous DSA scheme, each RAN or RAT uses a single contiguous frequency band only, whereas with fragmented DSA, multiple bands can be used. Thereby fragmented DSA conceptually has the flexibility of using more and smaller spectrum holes. The scheme offering ultimate flexibility is a cell-by-cell DSA scheme, and this scheme changes the spectrum allocation over time, and is also not constrained to any particular area of uniform spectrum demand, see Fig. 12.

The minimal coordination among RANs is needed in contiguous DSA scheme, whereas in fragmented DSA the coordination is much higher. For better spectral efficiency the means of allocation of fragments of spectrum among different RANs in an effective manner is a challenging problem. Existence of more guard bands in fragmented DSA compared to contiguous DSA increases the number of inter-RAN interference possibilities and at the same time this will reduce the spectrum efficiency. In cell-by-cell DSA scheme highest degree of flexibility is allowed thus giving best possible performance in terms of spectral efficiency. But this comes with a greater price of maximum amount of coordination among RANs.

*The Contiguous DSA Scheme*

The first scheme considered is contiguous DSA, and this can be seen as an evolution between fixed and fragmented assignment. Contiguous assignment uses contiguous blocks of spectrum allocated to different RANs, and these are separated by suitable guard band, which is very much like fixed assignment. However, the width of the spectrum block assigned to a RAN is allowed to vary in order to allow for changing demand, by adding more carriers at the end of the allocated block of spectrum. The basic operation of this type of scheme can be seen in Figure 12 and [50]. This technique has several advantages. Firstly, it is seen as the simplest spectrum allocation system possible after fixed assignment, as it maintains several of the FSA advantages such as easily controlling interference between the RANs as only one guard band is required between each RAN, and it can be ensured that this is always of an adequate size. This technique also needs a minimum of coordination between the RANs, as the only aspect that controls the spectrum partitioning is the location of the main guard band. However, this technique does have some disadvantages. 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 then it will not be able to do so if the spectrally adjacent RAN will not release the spectrum, which therefore introduces further constraints on the spectrum allocation procedure. However, this still provides a scheme for allowing spectrum to be used by other RANs during times when it is not being fully utilised.

*The Fragmented DSA Scheme*

Another allocation technique is called fragmented DSA. With this scheme, the spectrum to be dynamically allocated is treated as a single pool, and any RAN can be assigned an arbitrary piece of spectrum anywhere in this pool. The operation of this technique can be seen in Fig. 12. This technique is no longer as constrained in its spectrum allocations as the contiguous scheme, but this does serve to introduce some extra disadvantages. In general, the primary advantage of this scheme is that the size of one RAN's spectrum is not dependent on its current adjacent spectrum neighbours. Therefore the spectrally adjacent RAN does not have to necessarily give up its spectrum to give more to its neighbour. This would be of increasing advantage if more than two RANs were sharing the spectrum, as the contiguous scheme could potentially stop one RANs spectrum expanding as its spectrum neighbour would not release spectrum, even though a third RAN had free bandwidth to give up elsewhere in the spectrum. This technique could therefore produce greater allocation flexibility, but it does have disadvantages. The main disadvantage is that now the scheme becomes more difficult to control, particularly in terms of interference. This technique can potentially have many guard bands throughout the shared spectrum. Since guard bands are essentially unused spectrum and could potentially significantly reduce spectrum efficiency, it becomes very important that guard bands are kept as small as possible, without compromising interference conditions. These disadvantages could be mitigated by schemes that keep the guard bands minimal, such as having adaptive guard bands where certain cells close to a strong interferer (e.g. a UMTS system with small cells being interfered from a large celled DVB-T broadcast system) are forbidden from using frequencies close to the allocated spectrum of the interferer, whereas cells further away are permitted to use these frequencies. To summarise the total frequency band that covers all the spectrum fragments is naturally larger than in the sum of the size of all fragments. This requires a larger frequency band to be covered by the RAT using fragmented DSA. Since the goal is to dynamically include and exclude or shift fragments, this also requires increased frequency agility of base stations and terminals. Both requirements lead to additional costs. In essence, the fragmented scheme may give more allocation flexibility over the contiguous scheme, but this must be traded off against the need to more carefully control the use of the spectrum, leading to more complex systems, and larger amounts of information to be exchanged between RANs and network elements.

*The Cell-By-Cell DSA Scheme*

The final technique is a fully dynamic cell-by-cell assignment scheme where the individual base stations of each RAN could be allocated any part of the spectrum. This means that each individual base station of a RAN can be operating on completely different frequencies, and cells of one RAN could be using the same frequencies of other cells of another RAN in another location. A representation of this scheme can be compared to the other schemes in Fig. 12. This scheme would overcome the constraint of the other temporal DSA schemes that the spectrum partitioning chosen needs to apply over certain defined areas, preferably with relatively constant spatial traffic demands. This gives this scheme the advantage of not only adapting to time-varying spectrum demands, but also spatial demands.

In the three DSA schemes stated above, interference constraints need to be considered between each cell pair consisting of two cells belonging to different RANs. This will therefore lead to more complex interference control issues, as simple guard bands between RANs no longer apply. Ultimately, since interference from multiple cells can aggregate, interference constraints between cell *groups* would have to be considered.

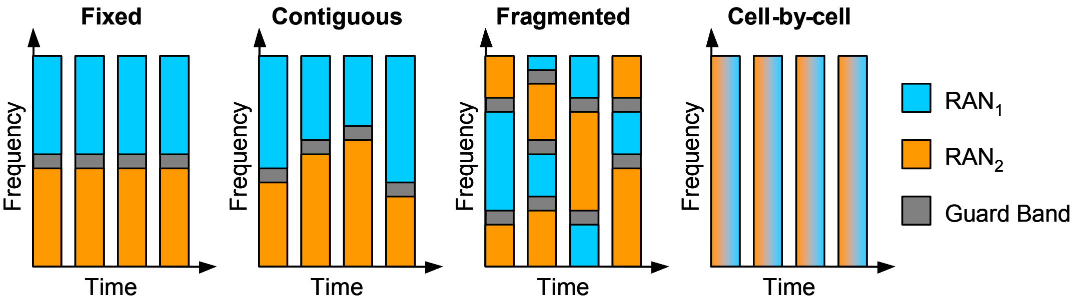


Fig. 12: Basic operation of fixed, contiguous, fragmented, and cell-by-cell DSA.

### 3.1.2 Investigation of contiguous DSA Scheme

The spectrum allocation technique investigated below is the contiguous DSA scheme. It would be also possible for the DSA to operate with more than two RANs sharing the spectrum, and this could be achieved with some modifications to the algorithms presented here.

As already started, contiguous allocation still uses continuous blocks of spectrum allocated to different RANs, and these are separated by at least a suitable minimum guard band. However, the actual width of the spectrum block assigned to a system is allowed to vary in order to allow for increased or decreased demand. Each RAN has a ‘starting point’ in the spectrum, and carriers are added from this point at each spectrum reallocation, as the demand increases, such that the gap between the RANs decreases. Once the demands on the RANs becomes large enough such that the spectrum blocks allocated to the RANs are only separated by the minimum guard band, then any further increase in spectrum can only be done at the expense of the width of the adjacent blocks of spectrum. In these cases of spectrum contention, specific carrier allocation algorithms need to be used to decide which RAN should be awarded the carrier. It is assumed that the size of the guard band is not based on current interference measurements, but on a known, worst-case, interference value, see Fig. 13.

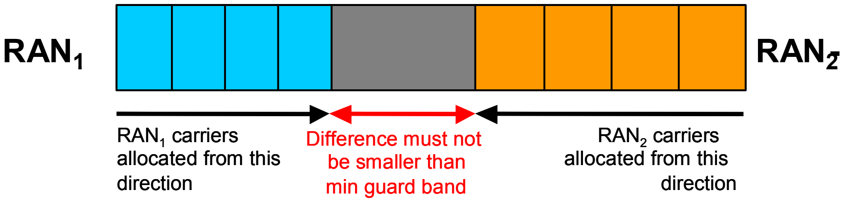


Fig. 13: Dynamic allocation of contiguous spectrum for each RAN.

#### 3.1.2.1 Contiguous DSA Algorithm Constraints & Assumptions

In addition to the assumptions on the DSA operation the algorithm has several practical constraints placed on it, which help to define how the DSA algorithm must perform. Firstly, the algorithm must take a short time to decide on the spectrum allocations, such that the time of DSA calculations is not so long that significant changes in spectrum demand have occurred. State of the art frequency planning algorithms run for up to several hours for the generation of a frequency plan for some hundred cells, even if each has only a single transceiver. Calculation times of hours are certainly not acceptable, because the real loads on the RANs would deviate unacceptably from the loads used in the calculations for such long time horizons. Acceptable calculation times of the DSA are assumed to be in the order of minutes.

The second constraint is related to the continuity of services whilst DSA is performed. It is assumed that a carrier can only be taken out of service from one RAN and allocated to another if there are no ongoing calls currently on that carrier. In other words, the DSA cannot drop calls currently in progress, in order to perform reallocation of spectrum. This is seen as an important constraint for operators who would be concerned that changing their allocated spectrum may cause forced terminations of service. Therefore, in order to achieve maximum reallocation flexibility in DSA it must be possible to move the ongoing calls through frequency, in order to free up the carriers near the spectrum borders between RANs. This assumes that schemes are in place to allow ongoing calls to be handed over from one carrier to another without interruption to the on going call, much like is done in frequency hopping with GSM. It should also be possible for calls to be handed over to other access networks, if these services could be supported on the other RAN, in order to free carriers for reallocation. One such scheme is that all calls are supported on carriers furthest away from the spectrum borders between RANs, and are handed over to these carriers whenever possible, see Fig. 14.

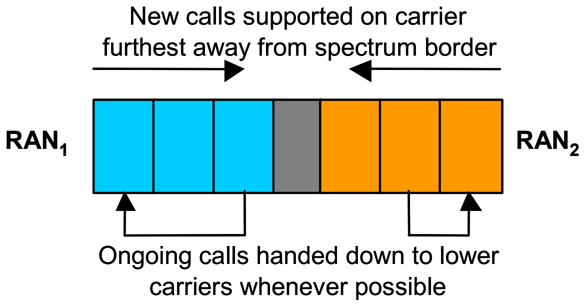


Fig. 14: Allocation of calls to carriers within a RAN, for maximum DSA flexibility.

Thirdly, it is assumed that each of the transceivers in the base stations of the RANs has a finite activation/retune time. This means that upon command from the DSA the BS takes a certain amount of time to tune the transceiver to a specific frequency and activate it. This sets a lower limit on the time between successive re-allocations by the DSA. The finite processing time of the DSA algorithm and the finite activation/retune time of transceivers limit the updating intervals of frequencies. The DSA gain vanishes if the updating intervals are so large that the average spectrum demand in each RAN is about the same in each interval. As the update interval cannot be made arbitrarily small, the DSA can follow the temporal fluctuations of the traffic demand only down to a limited time resolution. The temporal characteristics of the traffic demand are in general not the same for different time scales.

Therefore, the DSA algorithm has a lower limit on its reallocation time, set by the finite activation time of transceivers, and the finite processing time of the algorithm, but it also needs to be run over a long enough interval in order to adapt well to the long-term fluctuations in the traffic demands seen on the RANs, without being too long that the changes in the fluctuations are not being sufficiently served by the DSA.

#### 3.1.2.2 Top Level Algorithm

A basic top-level version of the contiguous DSA algorithm developed can be seen in Fig. 15. There are three main important sections to the operation of the algorithm, and these are the DSA triggering, the load measurement and prediction, and the spectrum allocation procedure [53]. The operation of each of these will be discussed in turn.

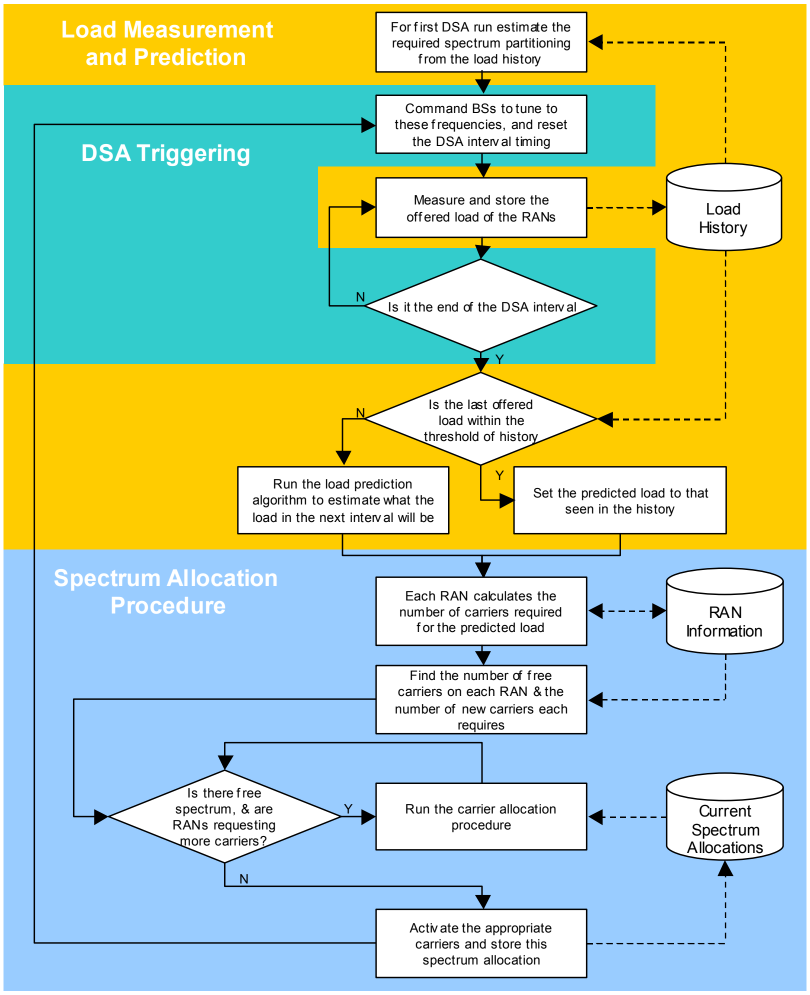


Fig. 15: Top-level algorithm flowchart.

### 3.1.2.3 DSA Triggering

The algorithm runs at set periods, within the constraints outlined previously, for each RAN in the system at the same time. This aspect has important impacts on the ability of the DSA to follow traffic fluctuations, and on the accuracy of the load prediction.

### 3.1.2.4 Load Measurement & Prediction

One of the most important parts of the DSA algorithm, with regards to the ability of the DSA to perform optimally is the load prediction. A load prediction function is required as the DSA is not able to allocate and de-allocate spectrum on a call-by-call basis. For this reason, the spectrum partitioning chosen by the DSA needs to apply for a set period of time into the future determined by the DSA interval. These allocations therefore need to take into account not only the load that was seen in the previous DSA interval, but also the load that is expected in the forthcoming interval. This gives rise to the need for load measurement and prediction functionality in the algorithm.

There are three main functions in this part of the algorithm. These are the load measurement, the load history and the prediction algorithm. The load measurement part simply records the loads that are seen on the RANs during the DSA intervals. The measurements from this can be stored in different ways. For example, the load measurements could be stored as the average load that is seen on a RAN during a particular DSA interval, or alternatively the peak load seen during the interval could be stored, or some other statistical measure for example peak to mean ratio. The load statistics that are seen are recorded in a load history, which is a database of past and present loads on the network. The load history forms a major part of the operation of the algorithm, and it relies on the assumption that the traffic patterns seen for the RANs will be repeating and predictable from one week to the next. For example, it is likely that the traffic patterns seen on a Tuesday will be very similar to those seen the previous Tuesday and the one before that. Therefore, by maintaining a load history for each day of the week, it should be possible to predict, with reasonable accuracy, the load on the networks. In order to be as accurate as possible load histories would need to be maintained for different days of the week, or at the very least different for weekdays and weekends. In addition they would need to be adaptable to seasonal variations, or slow long-term changes in the loads, such as the number of subscribers increasing over time. There are many different ways to account for these variations, under given circumstances.

The final part of the load prediction needs to look at both the load seen during the last DSA interval, and the load history, and make an estimate of what the load will be during the forthcoming DSA interval. The basis for the prediction can either be the load history or a time series prediction algorithm. The load prediction system needs to look at the load seen during the last DSA interval, and compare it to the same time period in the history. If the load is within a certain threshold of the history then it is assumed that the load is approximately following the historical patterns, and the estimation for the next DSA interval is taken as the value for that time period stored in the history.

The problem with using the load history as the basis for the load prediction is that it is not adaptable to unexpected changes in the traffic demand. As the load history cannot adapt to these changes then the DSA would not attempt to increase the spectrum allocations to those RANs with the increased demand. However, the load seen on the RANs would be diverging from that in the load history, and once it has diverged by a set threshold then this signals that the history is no longer a reasonable basis for prediction, and a time-series prediction algorithm should be used. The time-series prediction algorithms make a simple estimate of what the load will be in the forthcoming DSA interval, from the measurements of the load that were taken on the RANs for several measurements into the past. This is one of the main differences between using a history and using a time-series algorithm. The time series algorithm only considers measurements from very recently into the past, whereas the history considers a much more distant time horizon into the past. The four prediction schemes used in DRiVE are presented below. The following terms apply in the equations used for these schemes:

$\hat{y}_{t+1}$ = predicted $y$ value (i.e. predicted load), $y_t$ = current $y$ value, $y_{t-n}$ = $y$ value $n$ samples into the past,
$x_t$ = current $x$ value (i.e. current time), $x_{t-n}$ = $x$ value $n$ samples into the past

*Current value prediction scheme*

This is the most basic prediction scheme, sometimes referred to as naïve prediction. All this scheme does is take the value of the load seen during the last interval as an estimate of what will be seen in the next one. This can perform well if the time between predictions is very short, and if the load does not change very rapidly from interval to interval. The equation can be seen in (3.1) below.

$$\hat{y}_{t+1} = y_t \tag{3.1}$$

*Moving average prediction scheme, n samples past*

This scheme takes the value of several samples into the past, denoted by $n$, and averages them as an estimate of the forthcoming value. This can be a good scheme for data that fluctuates rapidly, where a degree of smoothing is required for the data. It generally does not perform well for data that is already smooth. The equation can be seen in (3.2) below.

$$\hat{y}_{t+1} = \frac{\sum_{i=0}^{n-1} y_{t-i}}{n} \tag{3.2}$$

*Linear regression prediction scheme, n samples past*

This scheme takes the data from the previous $n$ samples, and attempts to fit the best possible straight line through the points. This straight line is then used to estimate what the value will be for the next time interval. The number of samples into the past used is a trade off against the accuracy of the best-fit line, and the adaptability to sudden changes. This scheme is good for data that generally changes linearly, but can have problems such as overshooting or undershooting at peaks or troughs in the data. The equations for this scheme can be seen in (3.3), (3.4), and (3.5) below.

Where

$$\hat{y}_{t+1} = a + b \times x_{t+1} \tag{3.3}$$

$$a = \frac{\sum_{i=0}^{n-1} y_{t-i}}{n} - b \times \frac{\sum_{i=0}^{n-1} x_{t-i}}{n} \tag{3.4}$$

$$b = \frac{n \times \sum_{i=0}^{n-1} (y_{t-i})(x_{t-i}) - \left(\sum_{i=0}^{n-1} x_{t-i}\right)\left(\sum_{i=0}^{n-1} y_{t-i}\right)}{n \times \sum_{i=0}^{n-1} {x_{t-i}}^2 - \left(\sum_{i=0}^{n-1} x_{t-i}\right)^2} \tag{3.5}$$

*Exponential regression, n samples past*

This scheme takes the data from the previous *n* samples, and attempts to fit the best possible exponential curve through the points. This exponential line is then used to estimate what the value will be for the next time interval. The number of samples into the past used is, as before, a trade off against the accuracy of the best-fit line, and the adaptability to sudden changes. This scheme is good for data that generally changes exponentially, and is better performing than the linear scheme at peaks in the data. The equations for this scheme can be seen in (3.6) to (3.9) below.

$$\hat{y}_{t+1} = p \times q^{x_{t+1}} \tag{3.6}$$

Where

$$p = 10^a \text{ and } q = 10^b \tag{3.7}$$

and

$$a = \frac{\sum_{i=0}^{n-1} \log(y_{t-i})}{n} - b \times \frac{\sum_{i=0}^{n-1} x_{t-i}}{n} \tag{3.8}$$

$$b = \frac{n \times \sum_{i=0}^{n-1} (\log(y_{t-i}))(x_{t-i}) - \left(\sum_{i=0}^{n-1} x_{t-i}\right)\left(\sum_{i=0}^{n-1} \log(y_{t-i})\right)}{n \times \sum_{i=0}^{n-1} {x_{t-i}}^2 - \left(\sum_{i=0}^{n-1} x_{t-i}\right)^2} \tag{3.9}$$

#### 3.1.2.5 Spectrum Allocation Procedure

Once the DSA has been triggered and the load that will be seen in the forthcoming interval has been estimated the spectrum allocation procedure will be completed. The above is done for each RAN in the system, and after this the spectrum allocation appropriate for these conditions needs to be determined. This part of the algorithm is important in terms of the distribution of the spectrum to the RANs. This needs to be as fair as possible in its allocation of the spectrum, as otherwise certain RANs may be favoured over the others. There are two main aspects to this part of the algorithm, and these are the RAN carrier declarations and the allocation algorithm.

The purpose of the RAN carrier declarations is for the RANs to tell the algorithm how many carriers it will require during the next DSA interval, and to state how many unused carriers it currently has. The first thing that each RAN does is to tell the DSA how many of its allocated carriers are currently unused, i.e. have no ongoing calls on them. These carriers are logged by the DSA as being available for reallocation. From the predicted load that is expected during the next interval, the RANs make an estimate of the number of carriers they will need to support the predicted load, using knowledge of the load that a certain number of carriers can support at a sufficient satisfaction ratio. The RANs compare the number of carriers they think they will require during the next interval with the number of carriers they currently have with ongoing calls on them. This results in the number of extra carriers that the RAN would like the DSA to allocate to it for the next DSA interval.

The output from the carrier declaration section is the unused carriers that are available in the spectrum, and also the number of extra carriers that each RAN requires. The purpose of the carrier allocation section is therefore to decide which RANs are allocated the free carriers. Obviously, if there is enough free spectrum available to satisfy the requirements of all the RANs, then the solution is trivial. However, the difficulties arise when there is insufficient spectrum to satisfy the RANs fully. In these instances an allocation algorithm needs to be used that attempts to share out the free carriers as fairly as possible to the RANs. Following this part of the algorithm, all that remains is to activate the selected carriers in the RANs, and reset the DSA interval and begin the cycle again.

## 3.2 Uncoordinated Sharing

In uncoordinated sharing scenarios, no communication between the systems that share the same frequency band, is established. This is typically the case when one of the considered systems is a legacy RAN which does not have any means to exchange information with other systems. In this setting, a system which is affected by interference cannot give feedback to the system which is causing this interference. The transmit decision is taken in one system while the effects of this transmission affect the other system. Two schemes aiming at avoiding intolerable service degradation to any sharing partner can be described:

1. The involved systems are capable of estimating the level of interference they cause to others. This would enable the systems to limit their emissions to levels that with sufficiently high probability do not interfere with other systems. This scheme relies on the predictability of the generated possible interference.
2. All systems are designed to cope with possible interference from other systems and there is a set of transmit rules defined so that no system causes harmful interference to others. This scheme is better suited for deployment scenarios where the generated possible interference is less predictable, e.g. due to transmitter and receiver mobility, in particular when the distance between interfering transmitter and victim receiver can vary over several orders of magnitude.

Another important distinction is about the access priorities to the spectrum:

**Priority access**: the spectrum is dedicated to the primary system (usually the license owner). A secondary system may only access the same spectrum as long as it does not cause significant interference to the primary system. This case corresponds with case 1 from above.

**Equal right access**: several systems with equal rights to access the spectrum operate in the same band. No priority about access rights exists. This situation is typical for unlicensed bands like the ISM band and corresponds to case 2 from above. Of course, some technical rules are set to prevent unfair use of the spectrum.

In the following, uncoordinated sharing with priority access is considered. The challenge of this setting is that the secondary system(s) do not obtain any feedback from the primary system, but they must ensure that they do not cause significant interference to the primary system.

### 3.2.1 Introduction and General Concept

Current "interference management" is based on static transmit power masks and allocation of a frequency band to a service with a predefined RAT or RAT group. This approach successfully prevents interference, however, in many situations it does not lead to the most efficient use of the spectrum, because it does not take into account the temporal and spatial variations of the actual radio environment. A fundamental observation about the interference potential of any radio emission is that its impact on any radio service depends on the interference level at the *victim receiver's antenna*. The impact also depends on the capabilities of the receiver to "suppress" or cope with interference. However, the ability to suppress interference is limited by fundamental limits (see chapter 9.1), which cannot be overcome by any measures taken at the receiver. Completely unpredictable interference, i.e. interference resembling white Gaussian noise, cannot be suppressed at all. It has the same effect as thermal noise. It thus lowers the SNR at the receiver, and thus the limits depicted in Fig. 52 apply. Note that this also holds for "smart" or "cognitive" radios.

The fact, that the relevant location for the effect of interference is the receiver, motivated the FCC to pursue the idea of new concepts about interference management [38]. Fig. 16 is taken from this reference for illustration.

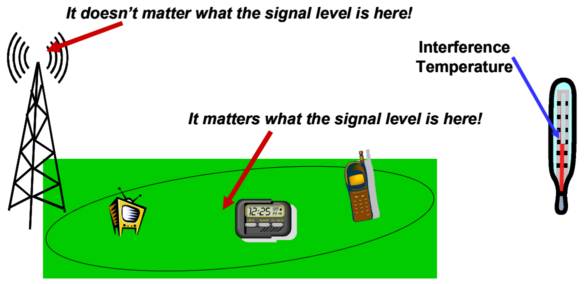


Fig. 16 Motivation for definition of "interference temperature" (taken from [38]).

Provided, the influence interference can be described in a quantitative way and can be measured, a more flexible concept of interference measurement could be based on real-time measurements taking into account the actual RF environment. This concept would allow a secondary user to assess – before transmitting – if his signal would cause "harmful" interference to the primary system. The idea for this concept is motivated by the desire to allow spectrum to be utilized by secondary users while guaranteeing that no harmful interference is generated that affects the licensee. One of the main idea expressed in the FCC Report [38] is that the influence of interference is determined at the receiver and not at the transmitter. Thus, interference management that is based on signal and interference levels at the receiver input can be more exact and realistic. On the one hand it would open opportunities for secondary users which would be allowed to transmit as long as they do not cause "harmful" interference. On the other hand it can give more certainty to primary users that the pre-established limits are met than in the case of an unlicensed secondary usage that is just based on regulation of rather static transmit parameters of the unlicensed devices.

The current situation, as observed by the FCC, is depicted in Fig. 17: over time, the noise floor can rise unpredictably due to additional interfering signals which might stem from out-of-band transmissions of new users and further aggregation of unlicensed devices. As a result, the coverage of the licensed signal could accidentally be reduced unexpectedly. The idea to counteract this situation is to place an interference cap called interference temperature which is to be respected by all, esp. unlicensed, devices. However, in practice traditional spectrum management has already achieved interference control that has been satisfactory to primary spectrum users. Therefore it is suspected that the main aim of the considered new approach is to achieve a similar level of interference control and primary user satisfaction despite the intended introduction of new unlicensed secondary services.

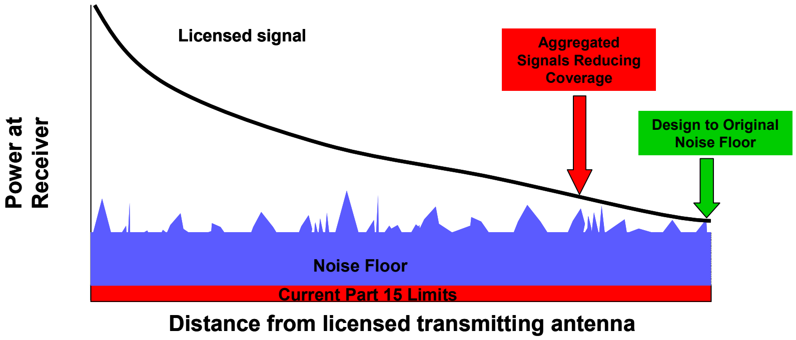


Fig. 17 Aggregation of noise floor due to uncontrolled deployment of unlicensed devices (taken from [38]).

This new management idea is partially illustrated in Fig. 18, where all noise and interference stemming from secondary sources are limited by a maximum interference temperature. The maximum aggregate interference power is defined by $P_{\mathrm{it}}$, which is related to the interference temperature $T_{\mathrm{it}}$ by

$$T_{\mathrm{it}} = \frac{P_{\mathrm{it}}}{k \cdot f_{\mathrm{B}}} \quad (3.10)$$

where $f_{\mathrm{B}}$ is the bandwidth and $k = 1.38 \cdot 10^{-23}$ J/K is Boltzmann's constant. Rather than a new concept, the term "interference temperature" thus is an equivalent name for interference power or power spectral density.

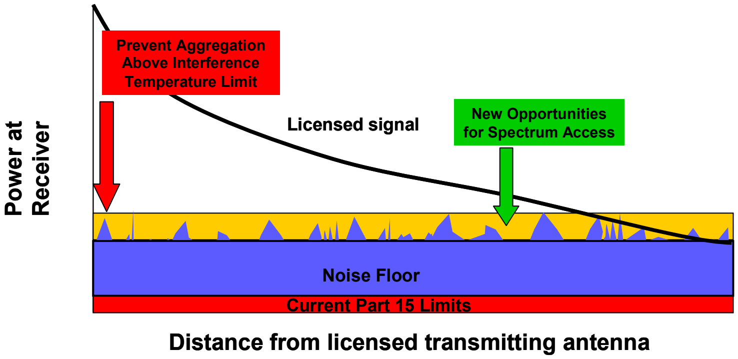


Fig. 18 Noise floor with interference temperature limit (taken from [38]).

### 3.2.2 Open Questions and Limitations

This initial description of the idea for a concept regarding secondary spectrum access based on interference temperature measurements leaves open some key questions that need to be resolved before any further steps can be taken:

1. How and where should the interference power be measured? The only relevant location, as correctly suggested by Fig. 16, is the antenna outputs of *all* receivers belonging to the primary system. It is not clear how a secondary system can obtain this information.
2. How often should be measured? There might be “temporal holes” in a certain frequency band, but it is difficult to predict when the primary system is going to access these frequencies.
3. Fig. 18 suggests a distinction between the licensed signal and everything else, which is to be considered as noise plus interference. This is an obvious distinction for the primary system, but it is not obvious for the secondary systems.

The main question which is left open in [38], also visible in Fig. 16, is where to measure the interference temperature. A secondary system which is to be deployed in the same frequency range as an established system can only take measurements in its own devices using its own antennas, whereas interference happens at the primary system’s receivers. This discrepancy obviously causes a plethora of problems, some of which have been described in the reply comments to the FCC report [84][97][104][105] and are mentioned in the following:

**Hidden terminal problem**

The transmitter (A) in Fig. 19 of the primary system is shadowed to the secondary transceivers ($b_1$, $b_2$). Although both $b_1$ and $b_2$ are sensing the channel, they do not detect the presence of A’s signal and thus decide to transmit whereupon they cause harmful interference to the mobile terminal a.

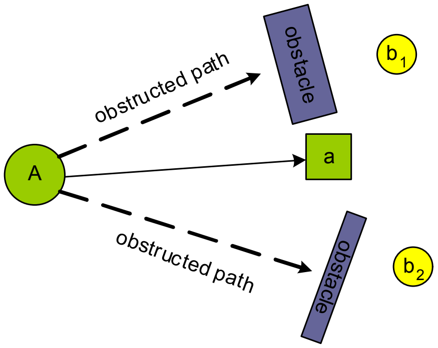


Fig. 19 Obstructed path problem.

This problem and many related ones is due to the inability of the secondary transceivers $b_1$ and $b_2$ to “sense” at the location at the mobile terminal a.

### A concept based on path loss estimation

As was outlined above, the relevant location for the measurement of the interference power is the receiver's antenna. A concept, which under certain conditions outlined below, predicts the interference that a secondary transceiver would cause to a primary receiver, has been presented by, among others, Shared Spectrum Company [98]. It assumes that the primary system is bidirectional and uses the same antenna and frequency band for transmission and reception. The transmit power of the primary system is assumed to be known. In this case, receivers and transmitters of the primary system are at the same location, which makes it possible for the secondary system to detect the presence of a primary *receiver*. As outlined in Fig. 20, the secondary transceiver B observes the transmissions from primary transceiver A and based on its measurements decides whether to transmit or not.

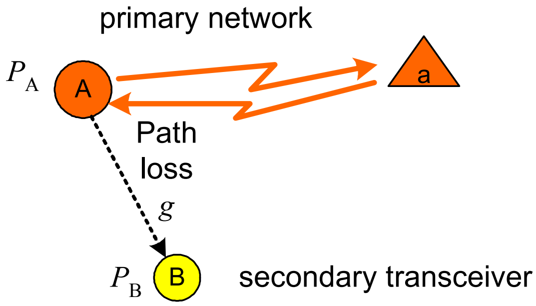


Fig. 20 Concept to estimate the path loss between primary and secondary transceivers.

The assumptions on the primary network are:

1. The transmit power $P_A$ is the primary transmitter is known in advance.
2. The maximum allowable interference power $P_{it}$ at location A is known in advance.
3. The primary system is bidirectional and uses the same antenna (array) and frequency band for both directions (TDD). Thus, transmitter and receiver are co-located.

The secondary node *B* measures the received power $P_{A,m}$ of transmitter A and combines this with the knowledge of the transmitted power $P_A$ to estimate the path loss:

$$\hat{g} = \frac{P_{A,m}}{P_A}$$

As the transmit power $P_B$ of B is attenuated by *g*, it is limited by

$$P_B \leq \frac{P_{it}}{g}$$

This measurement has to be repeated for each primary transceiver.

In addition to the above stated conditions, additional assumptions about the temporal component of this system concept must be made:

1. Transceiver A must transmit sufficiently long to allow for a measurement of B. B must have some knowledge about the duty-cycle of A, otherwise it may decide to transmit while A is receiving. In the other hand, B must listen sufficiently long in order not to miss a transceiver which is only transmitting form time to time (but may be receiving all the time).
2. In case the node A has been idle for a time longer than the observation window of B and then suddenly switches on, B has to perceive this and immediately stop transmission or lower its power. The time scale, on which this has to happen, depends strongly on the primary system.

The timing issues can be resolved by an RTS/CTS like handshake as it is used with 802.11. If all these conditions are fulfilled, this concept almost completely solves the problem of the unknown receiver location, including the "hidden terminal problem". It also takes into account the antenna gain and directivity of the primary system. An important advantage of this concept proposal is that the secondary receiver is not required to distinguish between the primary signal and the rest (which appears to the primary receiver like interference). Such a requirement to separate the signals would bring about the need to demodulate – at least partially – the licensed signal.

A serious drawback of this concept is that each secondary transceiver only can predict the interference power due to its own transmission. If another secondary transceiver is already transmitting at its allowed power limit, the interference power at location A might already have reached its permitted limit.

Thus, this concept fails to estimate the actual interference power which contains the influence of all transmitters of the secondary system as well as other possible sources of interference.

It should be noted that in this survey no reliable mechanism has been identified which is able to guarantee under all circumstances that the aggregate interference from secodary devices will be strictly limited to some pre-defined threshold.

### 3.2.3 Equal Right Access

In frequency bands, which are used by several systems without any prioritisation, all systems access the spectrum on a equal rights basis. This is the current situation in the ISM bands around 2.4 and 5.2 GHz, which are mainly used by WLAN and WPAN applications. The issue of coexistence between different systems has been investigated intensely in the 2.4 GHz ISM where the simultaneous presence of WLAN and WPAN systems like IEEE 802.11a, g and Bluetooth, respectively, raised concerns about mutual interference. This problem is aggravated by the fast growth of both markets and the fact that often both Bluetooth and WLAN are located in the same devices, like laptops or PDAs.

The basic problem of uncoordinated sharing of two systems with the characteristics of IEEE802.11 and Bluetooth is illustrated in Fig. 21. The WLAN system operates in 20 MHz wide channels and uses CSMA for the multiple access while Bluetooth applies frequency-hopping. Based on the characteristics of both schemes and dependent on the actual deployment scenario, collision probabilities and their impact on the perfomance of each system can be derived [27], [109]-[111]. The mutual impact of this interference depends on many factors as e.g. the packet lengths, the hopping-pattern, the transmit powers, the distances between interferer and victim, etc.

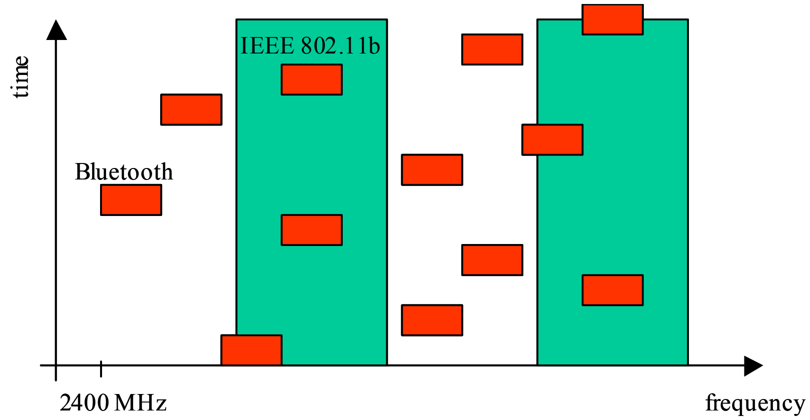


Fig. 21 Coexistence problems between IEEE 802.11b and Bluetooth.

It is obvious from Fig. 21 that without coordination between both systems, the possibilities to improve the coexistence are limited and have to be based on estimations of channel occupancy. The basic mechanism to adapt the Bluetooth system to alleviate interference are:

- Adaptive frequency hopping: Based on measurements and statistics of packet errors, some channels are declared as occupied and henceforth are excluded from the hopping pattern [26][42].
- Adaptive packet selection and scheduling: Bluetooth uses different packet length and grades of protection. By selecting the most adequate packet type for the next hop as a function of the channel conditions, the performance can be improved without changing the hopping pattern [101].

It is clear that these mechanisms can help to improve the coexistence between the two considered systems. However, they are very system-specific and restricted by compatibility and regulatory requirements and must be seen more as a timely patch to current problems than as a solution for the future.

Beside these mechansims it is obvious that adaptive transmit power control, which assigns only the necessary transmit power to each terminal, can greatly improve coexistence, apart from prolonging the battery life.

Another mechanism, which is employed by HIPERLAN/2 systems in the ISM band, is dynamic frequency selection (DFS) [37]. This mechanism basically avoids intra-system interference that may occur if two WLAN access points (AP) operate in the same channel and are located closely. However, it is also used to avoid interference to nearby radar systems and in this regard is not related to equal rights access. DFS is mainly based on received signal strength measurements during idle channel conditions. Measurements are carried out by the AP, which can solicite additional measurements from the terminals.

Since the measurements can be taken on the channel in use or on another frequency, it is possible to perform distributed measurements on a given channel without transmitting on the same frequencies. The measurement results are collected by the AP, which decides whether to use the measured channel or to move to another carrier frequency.
As can be seen in Fig. 21, DFS cannot work efficiently with interference from spread-spectrum or frequency-hopping systems.

More research-oriented methods for minimizing interference in a wireless communications system is the research line on interference avoidance followed by C. Rose, D. Popescu et al. [86],[88],[89]. These ideas have their origin in codeword optimization for CDMA and are currently extended to a more general context. Minimization of interference and thus maximization of system throughput is described as a distributed algorithm. However, information about the other system is still needed and thus some kind of coordination is assumed.

A conclusion that we can draw from this short review of coexistence issues in the ISM band is that uncoordinated sharing mechanisms for equal right access can alleviate mutual interference and improve coexistence. However, the existing mechanisms are highly system-specific and only can decrease interference, but not eliminate it. This means that all systems in such an environment must be prepared for unpredictable interference.

## 3.3 Time frame for optimum joint spectrum and traffic load reallocation

The optimisation of the usage of the available spectrum can be roughly divided into two parts:

- Long-term spectrum allocation which reacts to long term changes in traffic patterns or trends, and where the spectrum reallocation rate may vary from several minutes to several hours. The available spectrum (frequency/time) can be reassigned from low loaded services/systems/modes to high loaded services/systems/modes according to the temporal and/or spatial changes in the average traffic demand.
- Short-term traffic allocation which attempts to further optimise the overall system capacity by reallocating services or users between all available systems according to short term fluctuation in the instantaneous traffic demand. The aim is to optimise the quality of service of both users and the entire system, e.g., by maximising the user throughput and/or minimising the blocking probability for new incoming services. The allocation of users/services may be performed instantaneously at user arrival rate (optimal system/cell selected for any new active user) or at the rate of few seconds, e.g., by utilising load triggered inter-system or inter-mode handovers or cell reselections.

### 3.3.1 Long-term Spectrum Reallocation

Almost all radio systems face time and region dependent load characteristics. Most services have a predictable load pattern with time periods of both peak and low traffic loads. With fixed assigned spectrum, bandwidth is reserved to handle the peak-load periods with some level of quality of service. However, most of the spectrum will be unused for long periods of time during the low-load intervals. The dynamic and flexible spectrum use prevents this situation by enabling other services to dynamically utilise the unused spectrum.

Spectrum adaptation strategies can be grouped into three different categories:

- Spatial/Geographical adaptation: spectrum allocations are adapted to follow regional fluctuations in traffic demands of the services supported by each radio access network
- Temporal adaptation: attempts to adapt to time-varying loads seen on the radio access networks sharing the spectrum
- Spatiotemporal adaptation: adapts to changing demands for the spectrum jointly over both time and space.

The DSA methods introduced in Section 3.1.1 can take advantage of the day-time varying traffic demand and the traffic demand variations over different regions, e.g. between city centres and suburban areas.

### 3.3.2 Short-term Traffic Reallocation – Load Balancing

An overview of the short-term spectrum allocation meaning is given in this section. More detailed investigation on the inter-operability of heterogeneous networks is carried out in WINNER WP4 "Radio Access Systems", [68] and [69].

Short-term spectrum allocation attempts to further optimise the overall system capacity by reallocating services or users between all available resources (air interfaces, cells, uplink/downlink, layers: cellular, LAN, PAN, etc.) according to the short-term fluctuation in the instantaneous traffic demand. Reallocation of the actual spectrum resources at this rate would make the management of the overall system prohibitively complex. The aim is to optimise the quality of service of both users and the entire system, e.g., by maximising the user throughput and/or minimising the blocking probability for new incoming services. The allocation of users/services may be performed instantaneously at user arrival rate (optimal system/cell selected for any new active user) or at the rate of few seconds, e.g., by utilising load triggered inter-system or inter-mode handovers or cell reselections.

Future mobile networks will not consist of just one radio access technology, such as WCDMA or GSM/EDGE but will contain several different radio access technologies possibly with cells on several hierarchical layers, e.g. macro, micro and pico layers. By exploiting several radio access technologies, the network can benefit from the individual coverage and capacity characteristics of each technology, resulting in most economic solution providing the most appropriate radio bearers for the variety of different services. However, in order to utilise the existing resources most efficiently, the traffic management within different systems and cell layers becomes necessary and beneficial. Fig. 22 illustrates an example of the variety of radio access technologies possibly available in the same geographical area. It is obvious that efficient inter-working mechanisms are required in order to jointly optimise their spectrum use.

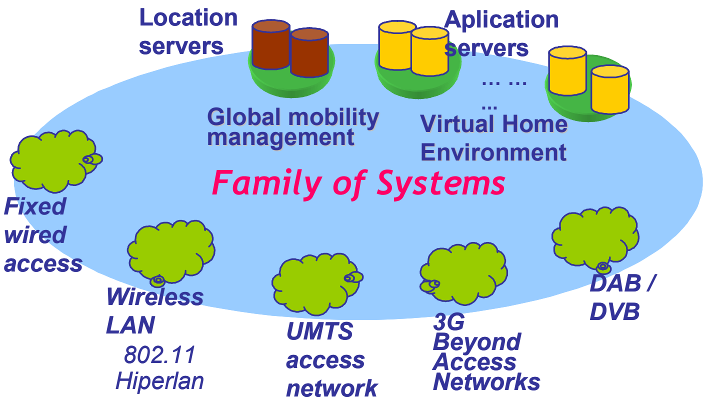


Fig. 22. An example of the variety of different radio access technologies available.

In the existing radio access networks the management of the radio resources between the systems is performed mostly in a distributed way with radio network controllers of different systems managing the resources independently. Moreover, in this scheme the efficiency of the resource management functions is limited by the area under control of the radio resource controllers (BSC, RNC etc.). This shortcoming is especially important in the handover decision, where the information that can be taken into account to perform the handover is limited to the resources under the control of each radio resource controller. It would be beneficial to have some knowledge of the available quality of service of all available radio access technologies when deciding on where to serve a new multi-mode terminal asking for resources (Fig. 23).

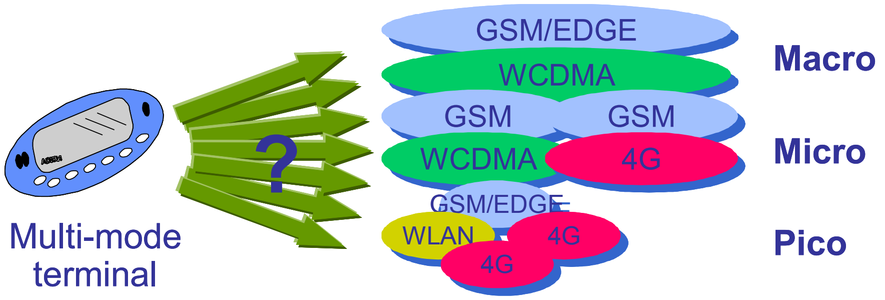


Fig. 23. To which system should this new multi-mode terminal be directed?

### Traffic reallocation between systems at user arrival rate

The uniform distribution of traffic is desirable to maximise the trunking gain in the network and to minimise the probability of making needless traffic reason handovers, see Fig. 24. This also results in more uniform distribution of interference. Uniform traffic distribution can be achieved from knowing, e.g., the load status of each cell. This would require obviously some sort of information sharing between network elements.

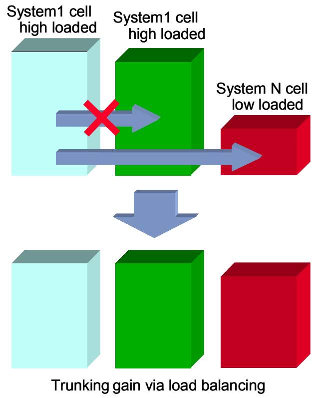


Fig. 24. Trunking gain via load balancing [100].

Without information sharing only very little or no information about the target cell status can be obtained. So, a handover or call setup attempt can fail due to high load in the target cell just not being known. In this case, the user equipment (UE) either remains in its original cell, or is dropped or blocked.

In order to achieve the trunking gain some of the mobiles must be triggered to make handovers to other systems or layers due to higher load in the current cell. However, continuous load balancing actions among systems/carriers without common control might lead to huge number of handovers between systems or carriers, and the capacity would potentially be reduced due to the higher amount of handover signalling (and possibly due to high number of required compressed mode measurements for example in WCDMA cells). Therefore, some mechanisms must be introduced to cope with this issue [99].

In future wireless systems the mobile location plays also an important role in the handover control. In addition to signal level measurements the location information received from the terminal can be of great help when deciding on the best available cell or radio access during the handover. According to WP1 the WINNER system must support precise location information.

### Common/Concurrent/Joint Radio Resource Management

Clearly some form of overall resource management is needed to get the best out of the mixture of radio resources. Common Radio Resource Management (CRRM) has been introduced in 3GPP (3GPP TS 25.881 and 3GPP TS 25.891) to perform these tasks.

CRRM can be defined as a centralised or distributed intelligent entity having knowledge about the channel (spectrum) occupancy in all participating radio access systems, where the resource utilization information is shared between nodes. CRRM may give support for inter-system handovers strategies to flexibly transfer users and their services to another access when appropriate.

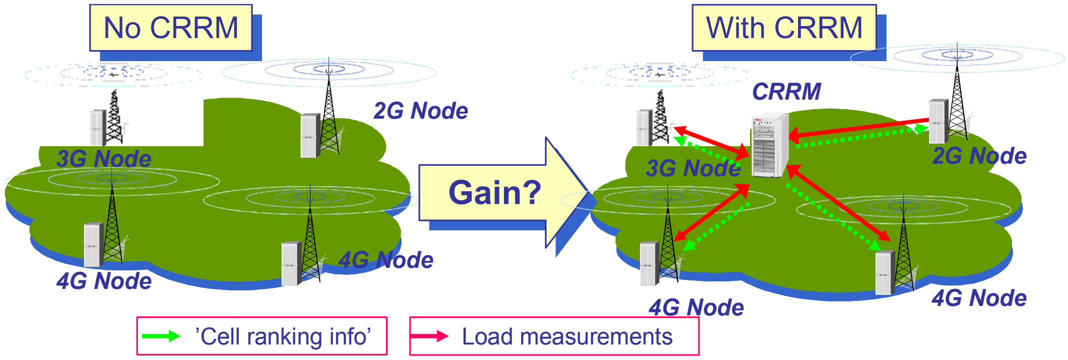


Fig. 25. Inter-working in heterogeneous networks with the aid of distributed or centralised Common Radio Resource Management

Methods very similar to CRRM concepts have been developed in other projects for inter-working between heterogeneous networks. For example, Joint RRM (JRRM) was introduced in IST SCOUT project [55] for inter-working between HIPERLAN2 and UMTS. More information of other inter-working methods can be found in [68].

### 3.3.3 Dynamic Spectrum Reallocation vs. Short-term Load Balancing

It can be clearly deduced from the previous sections that the spectrum reallocation based on the varying traffic needs, and more instantaneous load balancing using e.g. inter-system or inter-mode handovers are somewhat competing approaches. Let's assume for a moment that a service (with small bandwidth need) can be supported in all available systems and/or air interface modes and some of the available systems are becoming congested. In such a case, both approaches can achieve more or less the same spectrum usage optimization goal by either reallocating more spectrum for the congested systems from the less congested ones or moving some users from the congested to less loaded systems. Thus, the gains achieved separately from both approaches are not purely additive but rather overlapping.

However, there are clearly many situations when both approaches are needed in order to optimize the use of spectrum resources:

- Some specific (wide band) services cannot be supported in one system/mode while another system is optimized for it. Spectrum reallocation is needed (if free spectrum available) in case of congestion, in order to accommodate blocked or dropped services.
- Dynamic spectrum reallocation cannot be as dynamic and instantaneous than the load balancing at user arrival rate. Load balancing and common radio resource management algorithms are needed in order to further optimize the spectrum use especially during the busy hour.
- Minimum spectrum granularity: The reallocation of spectrum resources is most likely not going to be fully dynamic with infinitely small bandwidth tuning step. The minimum resolution for the tuning can be even in order of several MHz's. This obviously depends on how a specific radio interface studied in WP2 is able to adapt to changing bandwidth.
- …

One of the goals for WP6 (T6.5 and T6.6) is to find a good trade off or balance between both approaches.

# 4. Sharing Scenarios

This section focuses on the identification, design and evaluation of mechanisms and algorithms for advanced spectrum management that can flexibly and dynamically share the spectrum between the WINNER system mode(s) and also between several radio systems. The investigation is focused on how the system can adapt to changing demands for the spectrum over both time and space.

## 4.1 Intra-WINNER sharing scenarios

### 4.1.1 Basic Assumptions

#### 4.1.1.1 WINNER Air Interface modes

It is foreseen that a single WINNER air interface mode is not sufficient for achieving the high spectral efficiency and peak bitrate targets set for next generation wireless systems with power consumption characteristics suitable for portable user terminals [64]. A dual-bandwidth approach for beyond 3G systems was recently proposed in [87] to cope with these somewhat conflicting demands. In the proposal peak bitrates are provided on a wideband channel, but due to challenges in e.g. arranging cellular re-use, uplink range, mobile terminal power consumption and scheduling of a wide array of data rates, a more narrowband channel format is also defined. The dual-bandwidth system is seamlessly linked together through flexible scheduling capable of apportioning capacity across the two bands.

Similar multiband approach can also be adapted for the WINNER system concept. Reasons to have more than one WINNER modes include among others:

- Range and terminal power consumption: combination of long range with good error performance and high spectral efficiency (high data rates) is very difficult to achieve with a single, wide bandwidth carrier.
    - One WINNER mode can be more optimised for small cells (hot spots) while another mode may be more robust and suitable for wide area (vehicular) communication.
- Support for a wide range of data rates: Filling a single wideband carrier with small packets can be difficult in practice and can lead to very inefficient use of resources. Flexibility in resource allocation: smaller amounts of data can be send on a mode specifically designed for that purpose.
- Variety of different services: different WINNER air interface modes maybe optimised for distinct service types, e.g. multicast/broadcast/unicast.
- Support for multi-hop communication: wireless feeder concept (see Section 4.1.1.3).

Based on the reasoning above it is assumed that at least two intra-winner modes are needed to be deployed. At least one wideband WINNER air interface with ~50-100MHz bandwidth and one narrowband WINNER mode with ~2.5-20MHz bandwidth are needed in order to fulfil both wide area and hotspot service needs. Wideband mode(s) would enable ~1Gbit/s operation in hot-spots while narrowband mode(s) would enable wider coverage, vehicular support and lower terminal power consumption.

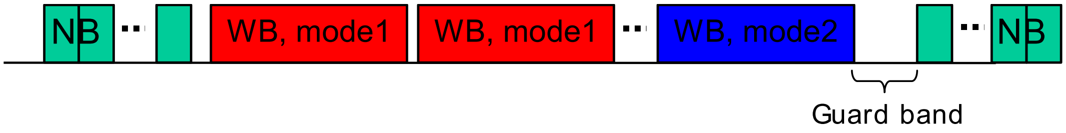


Fig. 26. An example of possible spectrum allocation between different WINNER air interface modes.

#### 4.1.1.2 Spectrum Asymmetry

Different services may have very distinct needs for capacity in up- and downlink transmission directions, causing very different traffic asymmetry between the transmission directions. Fig. 27 illustrates the interaction of the service and traffic asymmetries and how they affect on the spectrum asymmetry.

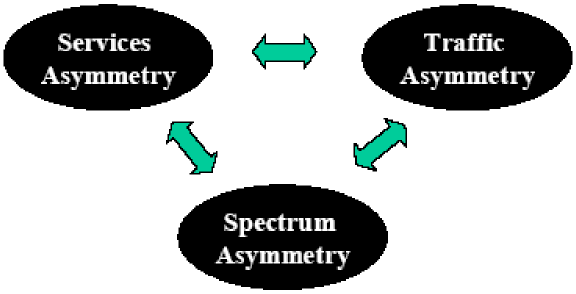


Fig. 27. Scope of Asymmetry and cross interactions [61]

The traffic asymmetry can be divided in to three levels of asymmetry: the user (single link), the cell (several local links) and system (several links on a large area) levels [61]. The differences between these cases are the nature and the quantity of the traffic sources. In addition to this, for each of these views, the asymmetry can have different meanings depending of the time scale under consideration. Table 4.1 shows the connection between the traffic asymmetry level, its origins and the rapidity of the traffic asymmetry variations. For the WINNER system [71] the range of single service traffic symmetry (not including broadcast or one-way services) is expected to be 10:1 to 1:10., while the symmetry of the long term aggregate user traffic within the system is expected to be 1:2 to 2:1

**Table 4.1. Traffic asymmetry levels**

| Traffic Asymmetry | Traffic Source | Traffic Asymmetry Variations |
|---|---|---|
| **User/Link** | One single user whose service is composed of one or several applications | High |
| **Cell** | Several users. Each user has his own service profile | Medium |
| **System** | Several cells distributed over a large geographical area | Low |

The single user source traffic asymmetry changes more rapidly than at the cell or system level. The variation of the asymmetric traffic degree at the system level can be rather slow mainly due to the fact that the statistics is collected over a large number of users (in time and space) profiles and over a large set of cells. This tends to smooth variations even for short time window observations. In contrary, at the user level, statistics is collected on the basis of the call duration (rather short time window) [61].

Different techniques can be envisaged to handle these different asymmetric factors and variations occurring at these different levels. Hence, it is expected that some techniques are more applicable to the link level (to deal with rapid variations) whereas some other techniques are expected to be more appropriate for the system level (to deal with slow variations). However, the techniques should be rather tightly interconnected and coordinated at all levels.

#### 4.1.1.3 Coverage/Capacity Extension of Cellular Networks with Multi-hop Relaying

Future generation wireless systems will likely incorporate multi-hop system providing adequate coverage and performance for very high bit rate services. Extending the cellular coverage and capacity by multi-hop links or relaying can be seen as complementary (or even alternative) to narrowband/wideband method discussed earlier in this section. In Fig. 28 an example of coverage/capacity extension of cellular networks with multi-hop relaying is depicted.

In WINNER WP3 new cellular-multi-hop deployment concepts will be developed with the aim to fulfil the requirements of the identified user and usage scenario. The development will be based on conventional single hop concepts, on relay station based concepts with either a homogeneous radio interface or heterogeneous radio interfaces and on the combination of these three basic approaches. Further the coordination of the sharing of the radio medium across base stations (including relays) to improve the mutual interference situation will be taken into account. This development includes the identification of functional elements and the characteristics of the newly identified radio interfaces (WP2). Furthermore, the characteristics of the identified candidate bands (from WP6) will be taken into account.

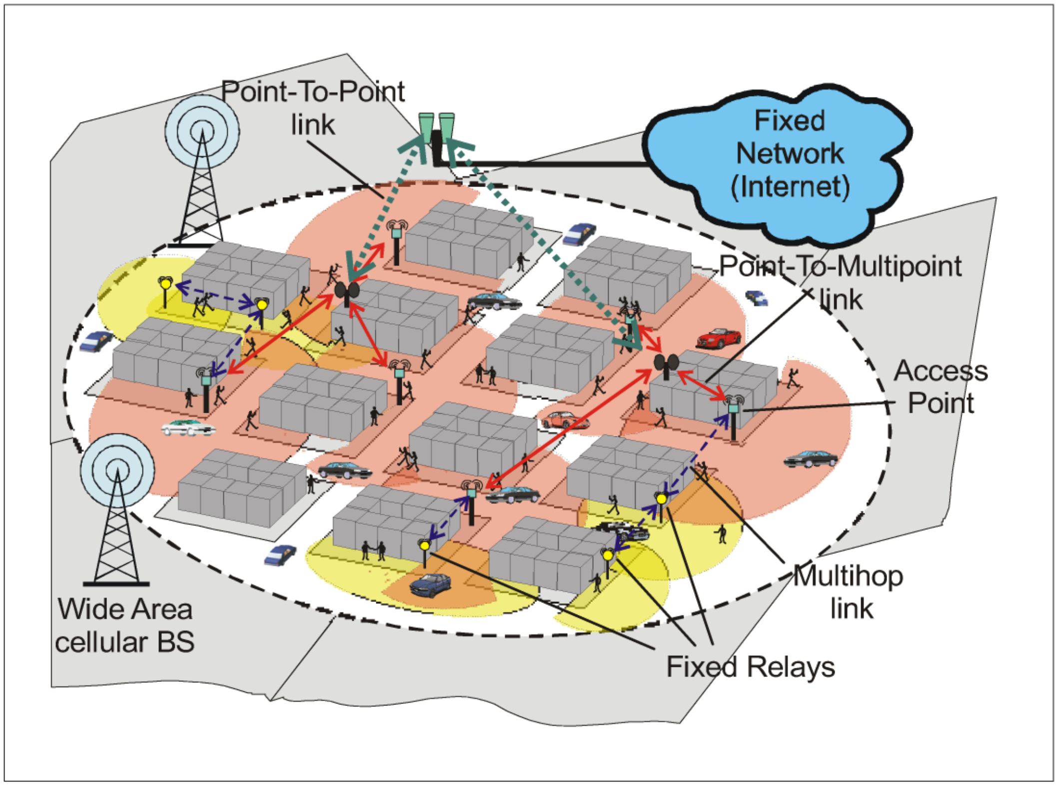


Fig. 28. Example scenario of Coverage/Capacity Extension of Cellular networks with Multihop Relaying [106].

WP3 is also considering a so called wireless feeder air interface mode specifically designed to support other WINNER air interface modes. Some cost reduction of the wireless feeder infrastructure versus wired feeding are expected. Wireless feeder is a (highly directional) link from a base station steered towards another base station and not towards a final user. However, in rural areas the wireless feeder mode could be also used to provide umbrella coverage for some nomadic fixed users similarly to "Wireless MAN" concept [25]. The radio interface mode of the wireless feeder can be different (differently parameterized) from the mode used for the last hop, so that the base station node of the last hop can be seen as a "heterogeneous relay station". Wireless feeder air interface mode can be also different for NLOS (urban coverage) and LOS (rural coverage) [67].

*Spectrum needs of relay based deployment concepts:*

Homogeneous relaying concept means that the very same radio interface mode is used for all links between relaying nodes and the end users. However, the systems based on homogeneous relay concept can still use a different spectrum band for the links between relay stations than for the last hop link between the end user and the relay station. This gives the possibility to use a shared spectrum band for the last hop connection, while using dedicated spectrum for multi-hop links, exclusively [67].

For the case of heterogeneous relay (feeder) systems it depends strongly on the scenario requirements, whether to employ dedicated or shared bands. It can be assumed, that in any case the "feeder-link" is based on strongly directed antennas with the consequence that the link is resistant against interference by other networks nearby. Thus the feeder link can also take place in shared bands for some scenarios [67]. It can be further assumed to have different bands for the feeder systems as they might face different regulatory requirements due to the directional characteristic of the link and the stationarity of transmitters and receivers. Thus they might be allowed to transmit with higher power than links connecting the user with the BS. This should be taken into account by WP6 for spectrum requirements. The higher power can be used to overcome long distances in rural areas.

One of the important issues to be studied is to find solutions on how to optimize the spectrum used both in the primary links (between the cellular base station and the fixed relaying stations or relaying mobile stations) and in the secondary link (between the relaying node and end users) in case of both homogeneous and heterogeneous radio interfaces jointly with spectrum used for wide area coverage.

### 4.1.2 Spectrum Sharing and FSU between WINNER modes

The efficiency of a WINNER system utilising flexible spectrum use methods can be influenced by several factors, dictating several challenges in the system design in terms of more flexibility in network control to optimise the use of spectrum, radio and network resources. In depth investigation of dynamic spectrum allocation functionality and required modifications and/or adaptation on the proposed WINNER air interfaces is given in this section.

The usability of dynamic flexible spectrum use algorithms for spectrum rearrangements are constrained by several factors:

- Distinct time and/or space varying load patterns are required for different services per mode
    - Distinct traffic patterns in adjacent regions, for example urban / suburban areas
    - Distinct time varying traffic patterns for different services within the same geographical area
    - Distinct traffic patterns for different transmission directions (uplink and downlink)
- Traffic patterns and trends must be at least somewhat predictable based on e.g. load history from previous days, weeks and months. Actual load measurements can be utilised to further improve the estimation accuracy by using time-series prediction, for example, to overcome the effect of unexpected traffic peaks
- Spectrum reallocation period must be short enough to follow changing spectrum demands of different services and air interface modes. However, the reallocation frequency is obviously limited by the signalling it requires. Fast traffic variation between air interface modes should be optimised by using some short-term traffic balancing methods introduced in Section 3.3.2. Although, this approach may require similar amount of signalling.
- Spectrum granularity must be high enough. The minimum amount of spectrum for reallocation must be relatively small compared with the total spectrum available for the WINNER air interfaces

All the constraints mentioned above must be met in order to achieve significant gains from the use of dynamic spectrum sharing algorithms.

#### 4.1.2.1 Spectrum allocation between different air interface modes

Different spectrum allocation schemes for DSA, such as contiguous, fragmented and cell-by-cell schemes, were studied in OverDRiVE project [62]. These schemes are briefly introduced in section 3.1.1. In those studies the contiguous scheme resulted in the lowest performance since it only allowed the spectrum partitioning of a RAN to change at the expense of the spectrally adjacent RAN's spectrum. With fragmented scheme, the spectrum to be dynamically allocated was treated as a single pool, and any RAN can be assigned an arbitrary piece of spectrum anywhere in this pool resulting in more flexibility. The main disadvantage is that now the scheme becomes more difficult to control, particularly in terms of interference. Also this technique can potentially have many guard bands throughout the shared spectrum.

In the studies carried out in OverDRiVE project an assumption was made that neither centre frequencies nor bandwidths of different carriers could be changed 'on the fly'. The carrier frequency raster and the bandwidths of studied systems were limited to those given in their respective standards. If more flexibility was allowed for contiguous allocation scheme, the same capacity gains, as in case of fragmented scheme, would have been achieved without complicated guard band control.

The impact of unequal sized bandwidths (for example WLAN vs. GSM band, 25MHz vs. 200kHz, respectively) was also investigated in OverDRiVE project and it was found out that the gains were greatly reduced if the bandwidths of systems were unequal. This applies directly to WINNER concept and the achievable gains can be strongly compromised if the bandwidth of the air interface mode requiring much larger bandwidth cannot be adjusted with smaller steps than with the size of the whole carrier.

Some spectrum waste could occur, for example, if the bandwidth released from a number of narrow band mode carriers could not be fully used by new wideband mode carrier. Also it would be difficult to reassign the spectrum for the mode with higher bandwidth as it would be required the NB mode to release at least WB MHz / NB MHz carriers (100/10 = 10, for example). This would be less fair for the WB mode. Therefore, it would be indeed better to enlarge/shrink the bandwidth of WB mode carrier gradually so that for example 1 NB mode carrier would be released at the time.

As the goal of WINNER project is to design a new single radio technology with several possible air interface modes, there are no limitations or restrictions to carrier frequency or bandwidth dictated by any legacy radio access networks. Fragmentation of the spectrum should be avoided by default as the control would be much more complicated with several guard bands needed, etc. Therefore, the contiguous spectrum allocation policy should be considered as the target for the flexible spectrum use concepts among WINNER modes.
Fig. 29 illustrates an example of possible reallocation of WINNER spectrum between different time instants or between two (adjacent) regions. In the example one of WB mode2 carriers was replaced by six NB carriers while two WB mode2 carriers' bandwidth were reduced (and centre frequencies shifted) to accommodate two more NB carriers.

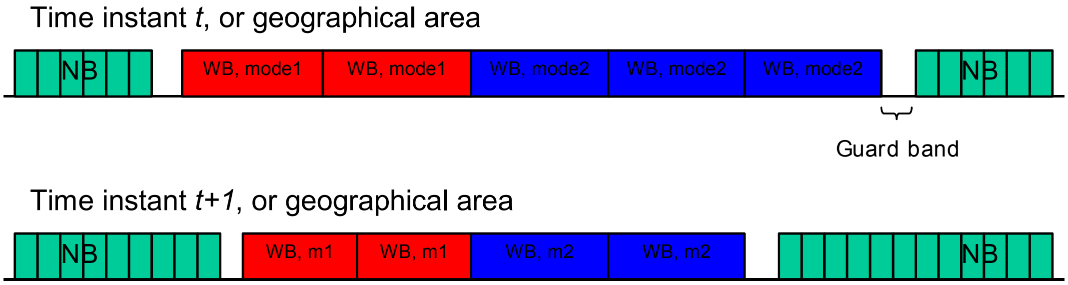


Fig. 29. Example of possible reallocation of WINNER spectrum between different time instants or between two (adjacent) regions.

In order to fully gain from the flexible spectrum use methods the WINNER radio interfaces should be designed such that the centre frequencies and bandwidths of the carriers could be reassigned as freely as possible depending on the needs dictated by the reallocation algorithms, noting the constraints of other requirements like cell search procedures.. It was shown in the OverDRiVE project that one of the most important factors for the performance of flexible spectrum use is the relative granularity of the system (minimum bandwidth step for reallocation vs. the total available bandwidth). The larger the size of the total available spectrum or the smaller the bandwidth tuning step, the less effect the quantization has on the performance.

Let's now consider an example in Fig. 30 where the bandwidth range for WB mode is between 100MHz (max) and 70MHz (min) with corresponding FFT sizes between 2048 and 1408, for example, and with tuning granularity of 10MHz. Assuming the bandwidth need begins to decrease from 300MHz (3 full carriers) the bandwidth of carrier(s) is reduced by steps of 10MHz until the bandwidth need for WB mode is decreased below 210MHz. After that one of the carriers is dropped and the WB mode is operated with 2 full WB carriers (3*70MHz = 210 => 2*100 = 200MHz). New adapted carrier frequencies and bandwidths are signalled to users at any time the algorithms are triggered. Tuning algorithm can be designed so that only one of the carriers needs to be reconfigured at the time the algorithm is triggered.

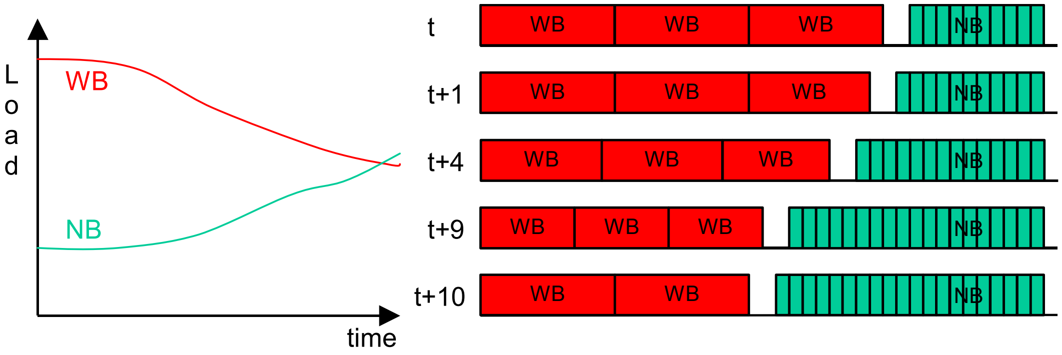


Fig. 30. Example of bandwidth tuning as a function of traffic demand.

The possibility to freely modify centre frequencies and bandwidths can pose some disadvantages on the functionality of the whole system. It could be indeed challenging to change the carrier frequency and/or the bandwidth (FFT length of the WB carrier adjusted adaptively, for example) of WINNER carriers with on-going calls on them without any loss of service. Suitability of such terminal reconfigurability scenario to WINNER RAT should be studied in WP2-4. However, it is foreseen that the possibility to adapt the bandwidth is at least required for proper functioning of the algorithms. The bandwidth change almost always implies the change of centre frequency, as well. In Section 6.2.5 a more detailed discussion about the implications of FSU and DSA on the implementation of the WINNER system is conducted.

#### 4.1.2.2 Optimisation of spectrum use by dynamic spectrum reallocation between different WINNER modes

Different service types, e.g., multicast, broadcast and unicast services may have correlation properties of the traffic distribution characteristics in both temporal and spatial domains that are particularly useful for DSA. Both spatial and temporal spectrum reallocation between the bands possibly allocated to different usage scenarios, e.g., wide-area use, hot-spot use and peer-to-peer use is needed in order to optimise the usage of the WINNER spectrum pool.

There are several scenarios where the spectrum optimisation by reallocation of WINNER air interface modes is emphasised:

- Regional variation: Need for more WB carriers can be high especially in densely populated areas (city centers) while in suburban and rural areas where the traffic demand is not necessarily as high the released bandwidth could be used more effectively for NB mode carriers to provide better coverage, for example.
- Temporal variation: The demand for different services such as speech, video conferencing, web browsing and multicasting may have distinct time-varying patterns on different geographical areas.
- Service requirements: Some services may be served in all air interface modes while other services can be served only in some specific modes. The services may have different regional variation. Therefore, inter-mode handover cannot be utilized to balance the load between the modes in case of congestion. Spectrum reallocation can be used to borrow capacity from less loaded modes. Some services may be prioritized to be served in some specific mode when possible while they could be served also in other modes. Although, inter-mode HO can be utilized in such a case for load balancing the spectrum reallocation is still preferred. Traffic characteristics of 'Feeder' mode and 'last hop' mode can be very similar. More feeding capacity is required as more hotspot capacity needed. Thus, dynamic spectrum reallocation may be performed jointly for both modes. However, there can be exceptions in some scenarios, such as the nomadic user case introduced in Section 4.1.1.3.
- Terminal capabilities: Some low end terminals may be capable to use only some of the WINNER modes such as NB mode. If the traffic caused by such users is high compared to the total traffic the demand for NB carriers may be higher and vice versa.
- Coverage area: The coverage of different air interface modes may vary significantly depending on carrier bandwidth, frequency, transmission power, number of antennas, etc. For example, some end users may have only NB coverage available in certain areas while others may have access to all modes. Thus, the spectrum demand for different air interface modes may vary

depending on the region and/or temporal variation. Use of inter-mode HO for balancing the load between modes is also limited to the WB coverage area only in such case

**DSA Regions**: The concept of DSA areas will be introduced in more details in Section 5.1.1. It seems inevitable that similar concept is also needed for WINNER in order to minimise co-channel interference from adjacent regions with distinct spectrum allocation among different WINNER modes. Guard bands are needed to prevent different air interface modes to overlap on the same spectrum and at the borders of neighbouring areas similarly as shown in Section 5.1.1. Guard bands can be gradually shrunk with increasing distance to the adjacent region border. New spectrum allocations in the centre of DSA region should not cause any significant interference to other modes at the border of neighbouring DSA region. Obviously, the design of DSA region scenarios depends on the radio interfaces. In the extreme case the DSA regions are not required at all, if for example all winner modes are designed for reuse one, and reuse one can be supported even between winner modes.

The optimal sizes for WINNER spectrum reallocation regions together with minimum guard bands and minimal distances between different WINNER modes should be studied. As already shown in OverDRiVE project smaller DSA regions should approximate the spatial distribution of spectrum demand [62]. However, smaller regions increase the percentage of the total area that can be expected to suffer additional degradation due to DSA border interference. Optimum trade-off between these two should be found by an optimization process.

The final goal for FSU in WINNER should be to make control of reallocation areas also as automatic as possible, in order to minimise the need for network planning. Also temporal and spatial adjustments of the spectrum need to be done jointly.

**Functionality during congestion**: The performance of WINNER system during the congestion is one of the important topics that should be covered. The methods and algorithms should be designed so that spectrum reallocations are not triggered when all available modes are in congestion or at least high loaded. Only short-term load balancing actions should be taken in such case. The spectrum reallocation should not have any negative impact on the overall performance.

**Spectrum Granularity**: The effect of spectrum reallocation granularity on the performance of FSU algorithms must be taken into account in the algorithm studies. As mentioned in the earlier subsection the higher the spectrum granularity the more gains are expected. However, higher granularity requires also possibly higher tuning rate in order to achieve the high gains. High tuning rate incurs inevitably some detrimental effects such as more signaling towards end users and more carrier reconfigurations (bandwidth and centre frequency changes)

**Traffic Asymmetry**: The handling of traffic asymmetry between transmission directions (uplink/downlink) should be jointly optimised with the spectrum reallocation. In FDD case the effect of asymmetry is inherently included in the spectrum optimisation process. TDD option requires additionally reallocation of the uplink/downlink switching point according to the changes in traffic demand in the transmission directions. Different switching point between adjacent cells/regions incurs similar DSA border effects as spatial spectrum reallocation. It should be studied whether the regions for both spatial spectrum and uplink/downlink switching point reallocation (TDD case) can be the same. Methods considered in WP6 for handling the traffic asymmetry should be mostly centred on system (and cell) level asymmetry (see Section 4.1.1.2) while user/link and cell level asymmetry could be dealt with in other WPs.

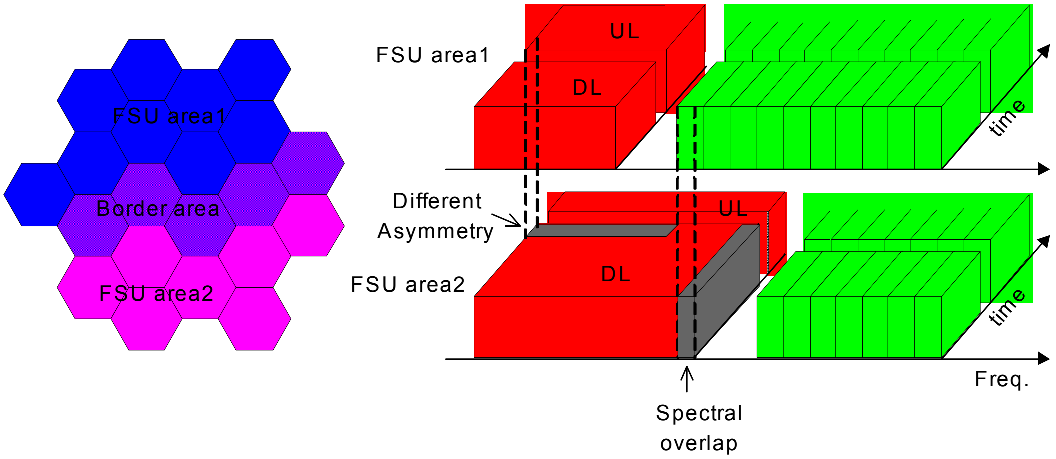


Fig. 31. Example of combined spatial reallocation of spectrum and TDD UL/DL switching point.

**Short-term vs. long-term**: Section 3.3 discussed about fundamental differences between long-term spectrum reallocation and short-term load balancing methods. It was claimed that spectrum reallocation based on the varying traffic needs, and more instantaneous load balancing using e.g. inter-system or inter-mode handovers are somewhat competing approaches. There were listed, however, some situations when both approaches are needed in order to fully optimize the use of overall spectrum resources. Special care should be given to optimum co-operation between short-term load balancing and long-term spectrum reallocation algorithms as the algorithms and methods are developed.

**Radio Resource Management**: Spectrum reallocation methods demand some support from cell level radio resource management, in addition to short-term load balancing. One of the requirements is the carrier freeness. Carriers next to adjacent mode band should be kept as free as possible, at least when close to reallocation event. End users connected to the reallocated carriers should be transferred to other carriers using e.g. inter-mode handovers in order to free spectrum for reallocation.

Control, management and actual implementation of the algorithms require also special focus. Some issues to be studied are listed below:

- Signalling needed between network elements: base stations, mobile nodes, servers, etc.
- Centralised vs. distributed control and management of resources
- Trade-off between achievable gains and implementation complexity (processing time and power, signalling overhead, reconfiguration breaks)
- Reallocation intervals and triggering events, load measurements, load history, load prediction, etc.

### 4.1.3 Spectrum Sharing and FSU between Multiple WINNER Operators

Current 2G and 3G systems were mostly designed under the principle "one operator, one radio access network". The GSM network has some possibilities of infrastructure sharing, but it does not support true radio access network sharing. The initial design of 3GPP system has followed the same principle. The interest in network sharing between operators in 3GPP has emerged as a consequence of limited spectrum resources, licensing, and the cost of infrastructure deployment and site availability for different operators. In 3GPP the network sharing issues are dealt with in technical reports TR22.951 [4] and TR 23.851 [5], especially concentrating on the architectural aspects of network sharing.

There are several network sharing scenarios identified in 3GPP. The identified scenarios range from simple infrastructure sharing that does not provide any improvement in trunking efficiency to full spectrum sharing with full trunking efficiency gain. Infrastructure sharing enables operators to reach significant savings in roll-out costs by sharing the RAN elements, but *without* sharing their respective licensed radio frequencies. Full spectrum sharing is achieved if a number of operators decide to pool their allocated spectrum bands and share the total spectrum. Fig. 32 illustrates the case where a number of operators may connect their respective core networks to any radio network controller of any operator (only one radio network controller depicted for simplicity) [4].

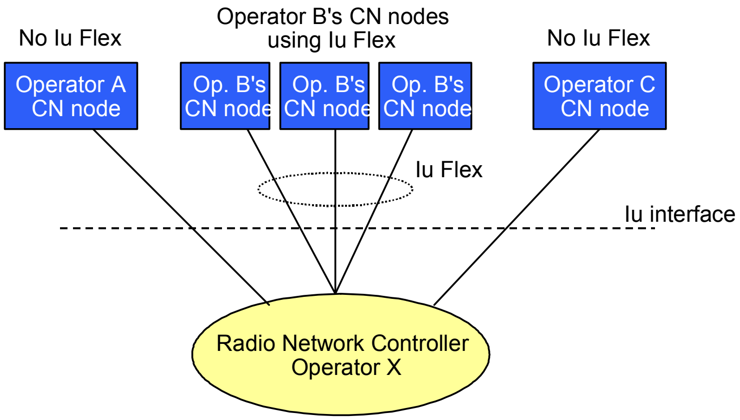


Fig. 32. Common spectrum network sharing between multiple operators [4].

Sharing the same radio access networks or radio spectrums is emphasised for future WINNER networks as it could be difficult to assign the required large bandwidths (up to 100MHz) per mode and per operator based on traditional fixed spectrum assignment rules. Therefore, in the future an operator will be forced to offer services over a complex set of shared and non-shared networks of different radio access networks. This will put new requirements on radio resource management in terms of handling, e.g., network selection, user mobility, load/bandwidth sharing, and the availability of the services. Some initial scenarios, methods and rules for sharing the network (WINNER air interfaces) between different operators are studied in this section.

In the optimal case, at least from the spectrum reallocation point of view, the operators would share all of the available carriers and modes without any dedicated operator specific bands. Unused bandwidth should be offered (leased) to other operators that require more capacity at certain time or at certain location. This would provide full flexibility to utilise the spectrum the most optimal way. There would be no artificial spectrum holes due to spectrum reserved for some operator with low traffic demand. Operators could have agreed on some minimum/maximum share of the bandwidth per operator in case of congestion (= total bandwidth / number of operators), but could freely lease capacity from others' territory if necessary provided that such capacity is available. Operators may have specialised to different services that have different spatial and temporal trends which can provide even more room for spectrum optimisation between operators.

The deployment of all spatial and temporal spectrum reallocation methods described in earlier sections is rather straightforward in case of full spectrum sharing and does not necessarily require much added complexity due to multiple operators, especially if all/some operators are using the same hardware. In case the full spectrum sharing arrangement as advertised above is not possible due to excessive complexity, regulation rules, operators' unwillingness to share their traffic information, or any other reason, the overall spectrum efficiency is inevitably compromised. In the worst case when the dynamic spectrum reallocation is only performed within one operator domain the gains are expected to be much more modest than if the spectrum reallocation was performed over the total available bandwidth. Fig. 33 illustrates an example case where the operators do not collaborate at all. It can be seen from the example that the spectrum is wasted due to required guard bands between modes.

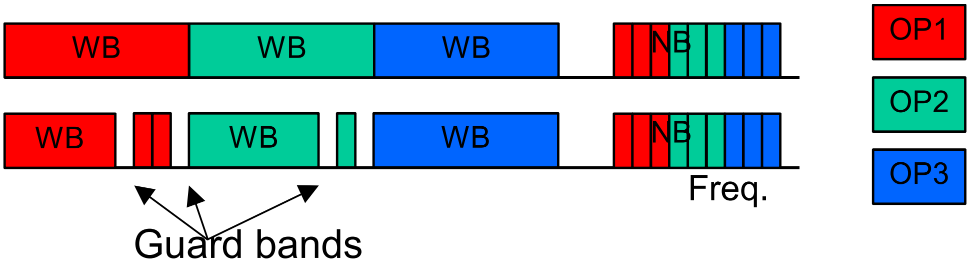


Fig. 33. Example of spectrum reallocation only within single operator domain.

The minimum requirement for FSU to achieve proper gains without full spectrum sharing between the operators (single hardware) is that the operators need to agree on shifting their centre frequencies to pack the operator specific air interface modes if any of the operators is reallocating its spectrum between air interface modes (see the example in Fig. 34). This is done in order to avoid spectrum holes and/or need to apply fragmented spectrum reallocation (see Section 3.1.1.1).

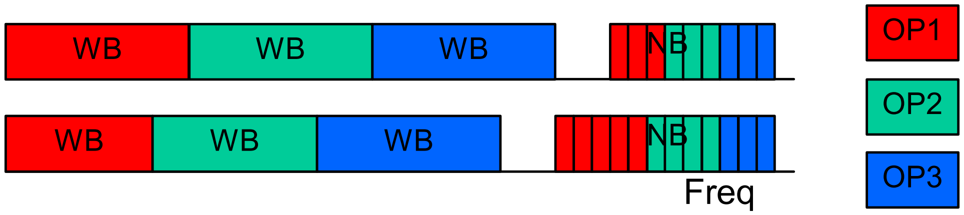


Fig. 34. Example of coordinated spectrum reallocation between operators.

## 4.2 Inter-system sharing scenarios

This section deals with spectrum sharing scenarios between a WINNER system and existing (legacy) systems, which are at least partially operating in the same frequency bands. On the one hand, spectrum sharing between WINNER systems and other systems could be more efficient, in case the other systems have more different traffic load time variations from the WINNER system than among the modes within the WINNER system. On the other hand, the possibilities for efficient spectrum sharing may be more limited due to the possibly very distinct properties of the “sharing partner”, i.e. the system which operates on the same frequencies as the WINNER system. The legacy system under consideration may be very dissimilar to a mobile communication system. This can be seen when considering the radio systems, which already operate or at least have spectrum allocated in the target WINNER frequency band:

- Radiolocation
- Amateur radio communication
- Satellite communication
- Fixed wireless access
- Fixed radio links
- Transportable stations for ENG and OB
- Aeronautical radionavigation
- Radio astronomy

The very distinct nature of most of these services in comparison to a mobile communications system makes it probable that these will be operated by distinct operators, thus further reducing the possibilities of coordination between the WINNER and the legacy system(s). This also practically excludes sharing possibilities of infrastructure elements like the radio network controller (Fig. 32) or base stations.

Spectrum sharing with a legacy system operating in the same frequency band requires that the WINNER systems is capable of protecting the legacy system from harmful interference. The level of interference that a legacy system can tolerate depends strongly on its air interface properties and thus it is difficult to define generic interference thresholds. As in intra-system sharing, the possible gains are determined by the system flexibility and especially the granularity of its frequency bands.

### 4.2.1 Inter-system sharing between WINNER and legacy systems that belong to one operator

Spectrum sharing between systems belonging to the same operators allows coordinating to some extent the system parameters and the spectrum use of both systems. Although the systems may be quite dissimilar, detailed information about the existing system will result beneficial for the WINNER system. The more knowledge the WINNER system has about the sharing partners, the better it can adapt its transmission parameters, thus utilizing the unused spectrum while at the same time protecting the other systems from interference. Fig. 35 illustrates the growing opportunity for controlled spectrum sharing if detailed information about the primary system is available.

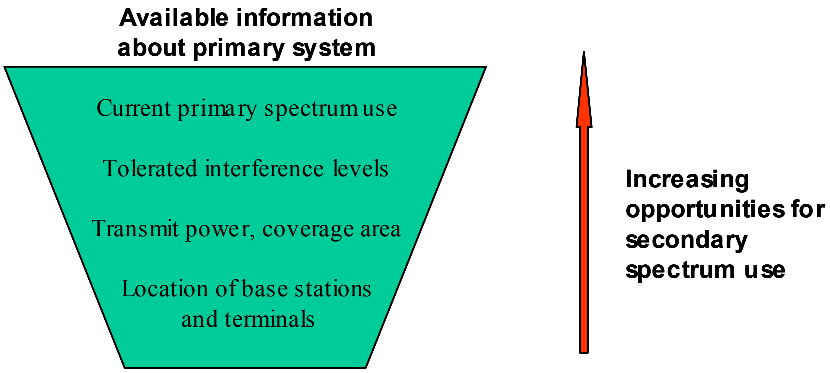


Fig. 35 The possibilities for secondary spectrum use increase with the amount of available information about the primary system.

If the same operator controls the WINNER and the legacy system, it can be expected that the WINNER system has real-time information about the location, coverage area, the traffic load and the acceptable interference levels of the legacy system. If the legacy system experiences a traffic load which is not uniformly distributed over e.g. one day and is different from the load distribution of the WINNER system, complementary use of the spectrum applying DSA might be possible. An example, which illustrates this principle, is the spectrum sharing concept between DVB-T and UMTS/GSM as it was investigated in the project OVERDRIVE [60] (see also [51], [52]). The traffic loads during one day of the broadcasting system and the mobile communication system are quite complementary, as can be seen in Fig. 43. This allows to make a much more efficient use of the radio spectrum by applying temporal DSA. This example implicitly takes for granted that the spectrum utilization of the DVB-T system is proportional to the user demand, which is of course not generally the case. It assumes that some TV channels are switched off due to low demand during the morning and early afternoon, thus making spectrum available during this time for the GSM or UMTS system. This scenario seems much more realistic if the TV broadcast system is controlled by the same operator as the mobile communications system, or if there exist some adequate agreements between both operators.

If the legacy system operated by the WINNER operator is also a mobile communications system, a much higher degree of coordination is possible. Depending on the user demand and the flexibility of the legacy system, a gradual substitution of the legacy system might be feasible. This is viable for FDMA as well as for CDMA legacy systems: in FDMA systems the total bandwidth can be reduced by removing carriers, while in CDMA systems the interference tolerance automatically increases with decreasing system load. A tight cooperation with the legacy systems is possible if the terminals offer the capability of inter-system handoff. This would allow a very efficient spectrum use by DSA and load balancing.

### 4.2.2 Inter-system sharing between WINNER and legacy systems belonging to distinct operators

In the sharing scenario between a WINNER system and legacy systems, which are controlled by different operators, the possibilities for efficient spectrum sharing are limited by the possible lack of coordination between both systems. Nevertheless, depending on the properties of the legacy system, spectrum sharing is possible to some extent. More details on uncoordinated sharing are specified in the sections 1.3 and 3.2. The possibilities for uncoordinated sharing with controlled interference depend strongly on the properties of all involved systems and have therefore to be investigated for each legacy system separately. Some initial steps are sketched in 2.4.3, which will have to be investigated in some more detail.

### 4.2.3 Opportunities for WINNER

Nearly in all spectrum sharing scenarios, the WINNER system is at the same time originator of interference and victim of interference from all other systems. If the other system is only transmitting (e.g. satellite uplink) or receiving (e.g. satellite downlink, radio astronomy) in the shared frequency band, the WINNER system acts either only as victim or only as interferer, respectively. When sharing spectrum with legacy systems, it cannot be expected that these systems are well prepared for coexistence with a WINNER system. On the other hand, the WINNER project has the opportunity to develop mechanisms that facilitate an efficient coexistence with legacy and emerging systems. These mechanisms should have a two-fold objective:

1. Confine the interference to other systems to a tolerable limit
2. Efficiently use the available spectrum, which is not used by other systems

In line with the first objective, the WINNER system can take advantage of the fact that the base station has complete control over the spectrum usage in its coverage area. Provided enough information about location and interference thresholds of other systems is available, the BS can create exclusion zones where neither the BS nor the terminals exceed certain power levels. This requires either that the BS can control the terminals with a signalling channel in another frequency band or that the terminals do not transmit while they are outside the coverage area (following the well known "receive before transmit" principle). By applying adaptive beamforming and provided that localization information is available, the BS can even adapt to slowly moving legacy systems.

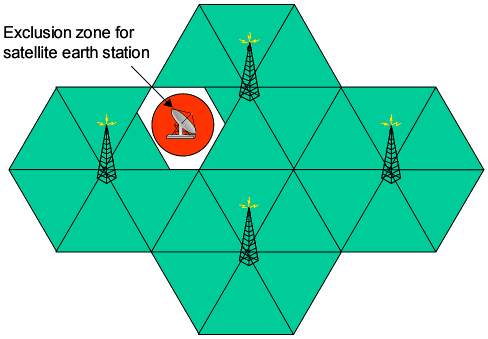


Fig. 36 Possible reduction of coverage in selected sectors to ensure coexistence with satellite station.

A WINNER system, which is in the role of a primary spectrum user, may help to increase the total intensity of spectrum use by concentrating its own transmissions in a frequency band as narrow as possible and thus leaving parts of its dedicated spectrum free. The WINNER system would thus create spectral holes or “whites spaces” in its frequency bands, which could be used by secondary systems. Of course, there have to be some well-defined etiquette, so that the primary system can retrieve ‘its’ spectrum. In order to allow other systems to access the free spectrum, the WINNER system could communicate the free bands via a broadcast signalling channel. In order to retrieve these bands, the secondary devices will have to free these channels within a predefined time period. In this way, secondary spectrum use can be made possible in a controlled manner and unpredictable interference can be avoided.
There may be various motivations for implementing such mechanisms in a primary system: it may be advantageous from a regulatory point of view or there may be beneficial agreements with secondary users, etc.

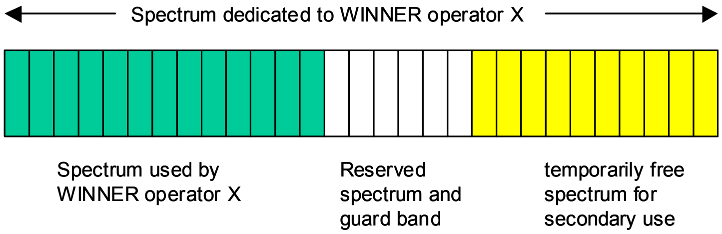


Fig. 37 Possible controlled secondary spectrum use.

Another opportunity is to take advantage of the capabilities of the terminals and their spatial distribution to collect information about the current radio frequency environment. The terminals could measure the received PSD and communicate their results to the BS, where they can be processed further. This would add to the cellular communication system similar functionalities as currently under discussion for sensor networks. The processed information about the received PSDs could be utilized to obtain a detailed observation of the radio frequency environment. This information may be used to better control possible interference to and from other cells or systems.

# 5. Coexistence and Methods to Improve Coexistence

## 5.1 System Coexistence of Multi Radio Networks

Given the constraints of high cost and limited availability of radio spectrum, efficient spectrum usage is key to the economic success of future cellular systems. One novel concept to use available resources more efficiently is the combination of existing radio systems into a coordinated, hybrid system, in order to combine the strengths and capabilities of the individual systems. Additionally, while ideally transparent to the user, the combination of systems adds a degree of freedom in the sense that at any time, the most spectrally efficient transport system can be chosen, depending for example on QoS requirements and traffic characteristics. If additionally the allocation of spectral resources to the individual systems were flexible, currently under-utilised spectrum can be reused by another, presently overloaded system, thus again increasing overall spectral efficiency.

The IST project DRiVE presented a concept of using available resources more efficiently by combining existing radio systems into a coordinated hybrid system in order to attain maximum flexibility in using available resources. This system offers the user an integrated transport system, which can adapt to both per session QoS demands and overall system load status by dynamically choosing the most suitable RAN for the request, and by dynamically allocating spectral resource to the participating systems (DSA).

The radio system studied in the DRiVE and OverDRiVE projects is based on the assumption of a large degree of flexibility in the allocation of spectral resources to different radio systems. Exploiting this flexibility, adaptation mechanisms are suggested that leverage spatially and temporally variable load conditions in order to optimise overall spectral efficiency. While it was shown that there is a potential benefit from this optimisation, this benefit is limited by additional radio interference that directly results from the flexible spectrum allocation. This additional interference can lead to a decrease in individual system capacity, thus consuming part of the gains predicted in the DSA investigations.

DSA generates issues of system coexistence. This includes the challenges involved in ensuring the compatibility of different regions with differing spectrum allocations, and methods to mitigate unwanted interference. In addition, investigations into the determination of required guard bands and coordination distances for differing systems sharing a unified radio spectrum, have been performed.

Two main aspects of radio interference are taken into account in the OverDRiVE coexistence work; Radio systems that were previously spectrally separated by the traditional, static spectrum regulation, can now operate in adjacent frequency bands, thus creating previously irrelevant adjacent channel interference scenarios. OverDRiVE looked into requirements for spectral and spatial separation, to ensure that systems can coexist without excessive capacity degradation. Borders between DSA regions are of special interest; these borders represent areas where radio cells with different spectrum allocations will overlap. In those regions, the different radio systems can potentially create co-channel interference in the overlapping frequency channels.

### 5.1.1 DSA Area Border Coordination

A further coexistence issue arises in the case where regionally adaptive spectrum allocations are permitted, and different areas have different allocations. This presents the problem of what effect the different spectrum allocations will have at the borders of these areas. By determining the amount of capacity loss by having bordering DSA areas, then it can be determined what effect this would have on the overall performance, for a particular size of DSA area.

Fig. 38 illustrates the types of interference encountered in the scenarios under question. Always present is normal intra-system interference, shown as type ① in the figure, which is not influenced by the DSA. In the case where there are no DSA areas, i.e. no borders between differing areas, then the dominant source of additional DSA-related interference is adjacent channel interference leaked across the guard band by one system into the other. This is shown as interference type ② in the figure. This type of additional interference is discussed in section 5.2 and it has been shown that it can be managed using a combination of a reasonably wide guard band and suitable frequency channel allocation in order to guarantee a minimal spatial separation between victim and adjacent channel interferer.

The introduction of the DSA areas, and the associated border, creates additional sources of interference, shown as types, ③, ④ and ⑤ in Fig. 38. Since, in this case where the DVB-T system in the lower DSA region is reusing a frequency channel assigned to the UMTS system in the upper DSA region, there is no attenuation of the interferer power by the receiver filter, this can be assumed to be the most critical source of additional interference, shown as type ④. As mentioned in [77], the co-channel part of this additional interference was assumed to be avoided by introducing a wide guard band however, this is spectrally ‘expensive’, since a DSA area is assumed to have a homogeneous spectrum allocation, and thus the wide guard band needs to be present over the whole DSA area. This illustrates a complicated trade-off; small DSA areas are desirable, since they allow close adaptation to the regionally varying traffic characteristics. However, small DSA areas introduce the coexistence problem at DSA area borders to a large percentage of the total covered area. Additionally, the preferable method for coping with the border effect may vary with the size of the DSA area. A more detailed exposition of the DSA area border problem, including simulation results, can be seen in [49].

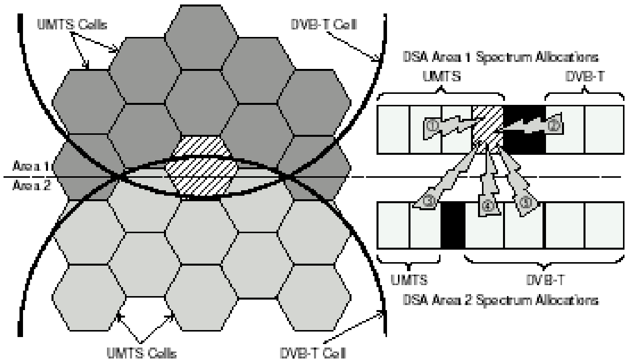


Fig. 38: DSA Border Interference Scenario.

## 5.2 Guard Bands for Spectral Coexistence of Radio Systems

As discussed before, new spectral neighbourhoods emerge when using DSA. This poses requirements regarding the protection of one system from the co- and adjacent-channel interference generated by the other system. In the literature the guard band spacing and its effect is studied for coexisting DVB-T and UMTS radio systems in the DRiVE project [48]. The resulting spectrum neighbourhood of powerful DVB-T transmitters and UMTS requires guard bands between the dynamically assigned spectral regions, and thus decreases the overall spectral efficiency of the coexisting radio systems. However, the overall spectrum efficiency of the coexisting systems is still much larger then the spectral efficiency of each system in isolation.

## 5.3 Spectral Coexistence

In the hybrid system considered in DRiVE, DVB-T and UMTS are spectral neighbours and therefore any out-of-band energy emitted by one system due to transmitter imperfections will interfere with the adjacent system. Fig. 39 shows such an Adjacent Channel Interference (ACI) scenario. The transmitter (TX) masks are defined in the relevant standards for DVB-T and UMTS [13],[14]. ACI degrades the Signal to Noise Ratio (C/I) in the victim system, and therefore potentially decreases system capacity and Grade of Service (GoS) in the victim system. Therefore, guard bands are used between the interfering systems operating in adjacent regions. In this context, a guard band is assumed to be the gap between the upper spectral border in the channel raster of one system, and the lower spectral border of the second system’s channel raster. Generally, the level of ACI is a time varying stochastic process due to station mobility, power control and handover. In practice, ACI is only one of several causes that create interference between radio systems. Additional effects may even dominate, but are difficult and computationally expensive to model in a multi-cellular environment with many simultaneous victims and interferers.

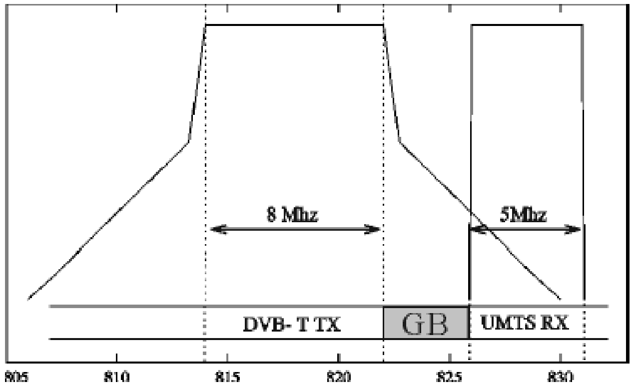


Fig. 39:Mask and Filter in an ACI Scenario.

The studies performed in DRiVE have shown that coexistence of DVB-T and UMTS is possible. While the high power of the DVB transmitter creates considerable adjacent channel interference in a neighbouring UMTS channel, with a combination of guard band and minimum spatial separation of the DVB transmitter and victim UMTS cells occupying the adjacent channel a satisfactory GoS can be obtained.

## 5.4 Guard Bands and Coordination Distances

Mobility, propagation, and deployment restrictions limit the use of the frequency bands for radio communication systems. There are already many different systems deployed in such bands, which have launched commercial services. New systems' owners have to prove their systems can coexist with existing systems without causing interference to these systems in the same or adjacent bands. Regulatory decisions protect existing services, and, hence, new systems can gain frequency bandwidths only if they do not cause interference to existing systems. Since DSA leads to dynamic neighbourhood relations between different radio systems, protection requirements of the participating systems have an impact on the efficiency of DSA. If the radio access technologies’ spectrum bandwidths are not fixed in the frequency band allocated to the DSA system, network operators have to protect different systems involved in DSA to manage efficiently the dynamic frequency allocations. Hence, network operators will be able to provide seamless services to the different customers and efficiently manage the spectrum. In order to avoid interference between radio access technologies’ frequency allocations, minimal guard bands separation/minimum frequency separation and minimal distance protection have to be defined. Technical studies on the use of the radio spectrum generally imply the use of software tools enabling the performance of compatibility studies.

### 5.4.1 Minimum Frequency Separation for System Coexistence

This section will outline in more detail the methods by which the types of interference that have been discussed in previous sections can be modelled. At the assignment of frequency bands for radio systems the simultaneous, undisturbed service of mobile radio systems, which are operating in adjacent frequency bands has to be ensured. Thereby in respect to efficient use of spectrum, the required guard band between coexisting systems have to be reduced to a limit that the QoS guaranteed by the service provider is just not yet jeopardised. Especially this task will become important when planning future systems that are based on different mobile system standards that have to reside in an appropriately chosen frequency band. Particularly the interferences due to simultaneous operation of the systems as a function of the transmitted power, attenuation and carrier frequency have to be taken into account.

#### 5.4.1.1 Definition of Minimum Frequency Separation (MFS)

The unused frequency band between two different radio systems intended to decrease the possibility of mutual interference is referred to as minimum frequency separation (MFS), Fig. 40. Thus MFS can be derived from the following equation [79].

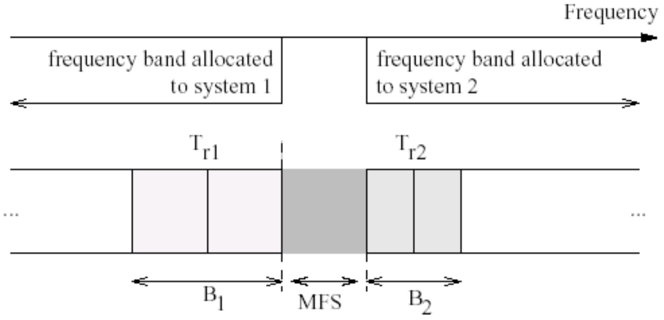


Fig. 40: Definition of MFS.

$$MFS = (Tr_2 - \frac{B_2}{2}) - (Tr_1 + \frac{B_1}{2}) \tag{5.1}$$

Where, $T_{rx}$ stands for the carrier frequency of system $x$ and $B_x$ for the bandwidth requirement of a carrier in system $x$.

## 5.5 Interference Modelling Issues

The general situation of interference can be investigated using an example scenario where a mobile station (*V, victim receiver*) with links to its base station is interfered by mobile stations of a system in an adjacent frequency band, see Fig. 41.

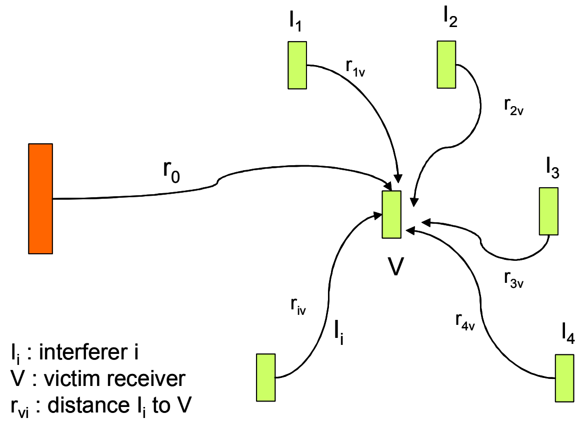


Fig. 41: Example Interference Scenario.

The unwanted emissions of the interfering stations ($I_i$) and their impacts at the victim receiver ($V$) need to be assessed. Depending on the distances between the interferers and the victim appropriate propagation models have to be chosen to assess the attenuation on the respective paths. The interfering station with the minimum distance to the victim receiver is the dominant interferer. As under special circumstances interfering stations with greater distances will contribute to noticeable interferences the number of interferers taken into account can be varied.

The carrier to interference ratio (C/I) measured at the victim receiver depends on both the user path length and the interference path lengths. To estimate this the distance between the transmitter and the receiver on the user link and as well as between the interfering stations and the victim receiver and density of active users are important parameters. The user path length can be determined assuming that there is exactly one receiver within the coverage radius of the victim link base station. All mobiles are uniformly distributed within the considered scenario with the victim link base station in the centre. More than one interfering mobile station can be taken into account depending on the active user's density. In the case that interferer is a base station it is assumed by approximation that the base stations of a single system operator are equally operated and it can be assumed only one interfering base station is located within the interference scenario.

In order to assess the influence of the interference power and the wanted power at the receiver and thus C/I the propagation loss on the interference path and the user path have to be calculated. Methods have been developed to determine the properties of radio channels, which take the main physical effects into account in the form of models. They simulate various characteristics of a channel, i.e. the propagation coefficients and fading behaviour. Especially the fading needs to be considered in mobile communications scenarios. In view of permissible level of unwanted emissions, it suffices to take the fading due to shadowing into account and to calculate the median path fading value. This slowly varying signal length can be described by log normal distribution. Respective values for variance of the distribution are known from measurements and are dependent on topography and morphology.

### 5.5.1 Transmitter and Receiver Characteristics

For the efficient use of radio spectrum it is essential to know the power density spectrum emitted by interfering stations. The impact of the emissions at the receiver depend on the interfering frequency, receive band, interference power and on the receiver characteristics. Apart from that the duty-cycle pattern of transmitter activity as well as the amplitude probability distribution during active transmit periods, which is influenced by the modulation method, need to be considered. Therefore, the transmitter and receiver characteristics of the different systems have to be taken into account. For this purpose the permissible interference power and acceptable received signal levels of each system as defined in standards needs to be considered when specifying spectrum masks.

The mask for the interfering transmitter represents the maximum permissible emission levels as a function of the frequency. To define a mask for the emissions, the different sources of out-of-band emissions are combined in one mask. The most important sources of out-of-band energy are as follows;

- Effects of modulation process
- Rise and fall times of the transmitted signals (switching transients)
- Inter-modulation products
- Wideband noise

To assess the receiver characteristics appropriate masks need to be developed which models the effects of adjacent and co-channel interferences with taking into account inter modulations and blocking characteristics.

### 5.5.2 User and Interference Path Length

The C/I measured at the victim receiver depends on both the user path length and the interference path lengths. To estimate the distance between the transmitter and receiver on the user link Fig. 41 as well as between the interfering stations and the victim receiver, the density of active users is an important parameter. The user path length can be determined assuming that there is exactly one receiver within the coverage radius of the victim link base station. All mobiles are uniformly distributed within the considered scenario with the victim link base station in the centre. More than one interfering mobile station can be taken into account depending on the active user's density. In the case the interferer is a base station it can be approximated that the base stations of a single system operator are equally distributed.

### 5.5.3 Propagation Models

In order to assess the influence of the interference power at the receiver and thus the carrier to interference ratio C/I the propagation loss on the interference path and the user path have to be calculated. There exists a huge literature base on the properties of radio channels, which take the main physical effects into account in the form of models. In addition WINNER is also performing characterisations of the radio channel that is intended to be used with the WINNER system. They simulate various characteristics of a channel, i.e., the propagation coefficients and fading behaviour. Especially, the fading has to be considered in mobile communication scenarios.

## 5.6 System Coexistence by Fair Spectrum Sharing Schemes

In this section, a different type of spectrum coexistence mechanism is highlighted and described, for completeness. This type of scheme is very specific to certain systems. It outlines the requirements of a spectrum pooling system, and shows the closest scheme available in the literature.

### 5.6.1 Spectrum Pooling Technique

As described in [17][18] spectrum pooling is a resource sharing strategy with the highest priority for the owner of the license. The owner allows prior specified candidate renters to use its spectrum. The selection of the frequency ranges at which, the different applications are considered to be supported depend on the physical characteristics of the frequencies. For example, communications at high speed are best suited for frequencies below 2GHz. Spectrum pooling is a technique that investigates the dynamics of occupying and releasing the spectrum. The owner’s allocated spectrum is divided into equal sized blocks (sub bands), which can be used by renters when not in use. If the license owner needs spectrum either he search for available free sub bands or either block the renter’s use and obtain the spectrum. Although the mechanism is assumed as real time operation, the difficulty arises since for real time the components require ‘tight coupling’ of the spectrum users. However the real time possibility may be better achievable considering only DSA among WINNER modes.

# 6. Implementation & Deployment aspects of sharing and FSU in WINNER concept

## 6.1 National variations in spectrum arrangements

Though the regulators aim at universal harmonized use of frequencies, many current services have different frequency bands in each country or region. Besides the increased complexity of equipment this entails. This also becomes an interference problem in the borders of the countries. The WINNER system must work with the different country variations regarding the spectrum availability, dealing with one of the scenarios described below.

Normally the country borders are located at rural areas where the traffic demand is low, so few radio frequency channels are needed. Then, an agreement can be made between operators in order to use different frequencies channels. However, sometimes large/medium cities are near a frontier and the spectrum is fully used and there is no room for such arrangements.

In current mobile systems (e.g. GSM), operators of different countries agree with the use of different frequency bands at borders. For e.g. GSM the frequency plans are adapted to the available frequency bands in the border areas. So far the frequency planning is a long term process and in particular cross border coordination is not an automated process. This forces to not change the radio frequency planning very often. However, this is contrary to the techniques of DSA in future systems, so this is not longer a good solution. Also, spectrum sharing makes these arrangements in the frontiers more complicated.

In current mobile systems (GSM, UMTS), operators agree with the use of different frequency bands at borders. This forces to not change the radio frequency planning very often. However, this is contrary to the techniques of DSA in future systems, so this is not longer a good solution. Also, spectrum sharing makes these arrangements in the frontiers more complicated.

### 6.1.1 Scenarios

The following scenarios can take place in the future. Fig. 42

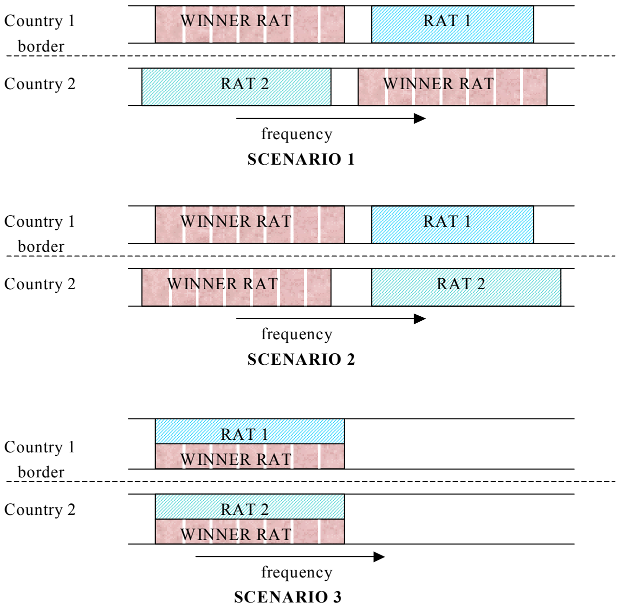


Fig. 42 Scenarios of possible country variations in WINNER.

1. Each country uses different frequency bands for WINNER as a primary system. In this situation the WINNER and other RAT interfere each other on the borders, and coordination can be difficult or impossible because systems operate in different countries.

Global harmonization solves this problem. But in case this is not possible, traditionally the way to solve this problem by the regulators was limiting the power transmitted from one country to the other. Operators have to place the access points far away from the border and/or limit the power of these access points.

The DCA technique plays an important role for mitigating this problem, allowing the use of the most suitable band in order to minimize the interference. Mobiles will sense the level of interference in order to dynamically use the better frequency bands (and modes) for reducing the interference.

2. Each country use the same proprietary frequency bands for WINNER, but the radio-frequency channels have non-aligned centre frequencies. This is normally due to the fact that the beginning of the band is different in each country, or simply because for the FSU it is needed to move the centre of the channels (see section 4.1.2.1); or even though if the centre frequency is the same, they can use different modes where each mode uses different bandwidth. In TDD modes, due to a lack of uplink/downlink switching point synchronization, interference arises among mobile terminal close to each other.

3. Each country uses the same frequency bands for WINNER, but the bands are not dedicated to WINNER, and must be shared with another primary RAT (in a coordinated manner, e.g. DSA described in chapter 3.1.1, or in a non-coordinated manner). WINNER system is not allowed to cause interference to the primary systems of either countries.

   Several problems arise in this situation:
   - If sharing is made in a non-coordinated manner, the methods that WINNER will use for not interfering the primary RAT, could not be suitable for the characteristics of the primary RAT of the other country.
   - If the spectrum sharing/DSA is used in a coordinated manner (e.g. central controller), probably this coordination can not be done between WINNER and the primary RAT of the other country.

The different DSA implementation options have been introduced in section 3.1.1, and the border effects in section 5.1.1. The IST-OVERDRIVE project studied the interferences between adjacent cells in contiguous or fragmented DSA schemes.

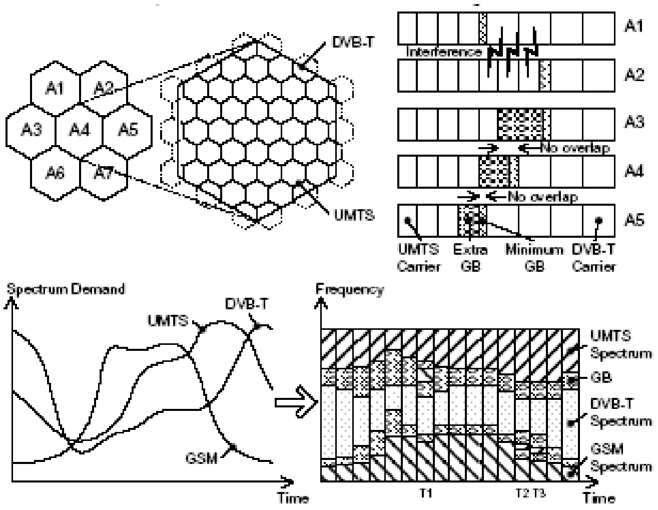


Fig. 43 Operation of spatial and temporal DSA [Taken from IST-OverDRIVE].

Basically, the method is to enlarge the guard bands in order that the gaps were suitable for both adjacent cells. Another possibility is the Cell-by-cell DSA scheme presented in 3.1.1.1, though this needs further study.

However DSA is made in a coordinated manner, so that interference is avoided among different RANs inside a country, but coordination may not be possible between RANs of different countries, so special care must be taken in border countries that use DSA for managing the spectrum.

### 6.1.2 Detection of bands of operation (roaming)

In case of roaming, when a user terminal is switched on in a different country, it must detect the availability, band and mode of operation of a WINNER access point. In WINNER RATs, this is a bit more complicated than in current GSM/UMTS systems due to the assumption that it can operate in a large range of bands (potentially in the band of existing 2G and 3G systems and in a WINNER primary band) and in different modes (hybrid TDD/FDD with variable bandwidth and carrier raster). DSA generally leads to an even wider band of possible operation, because WINNER with DSA may share spectrum with a number of other systems.

In current system, the detection is done by the user terminal with a frequency scanning, looking for significant power in downlink channels, and detecting the synchronization channel (FCCH, SCH, CPICH) and decoding the information. Obviously, this can be done equally in WINNER, but a problem arises due to the fact that there will be a lot of bands of operation, with many possible RATs. The user terminal may have to spend a lot of time cell searching. In a normal situation, all bands are used and normally not for WINNER, but for e.g. GSM/UMTS. Then, the user terminal will detect power in these bands and so it will try to synchronize without success because it is used by a different RAT (GSM, UMTS, WLAN…). As WINNER can operate with different modes, different bandwidths, and different carrier raster the user equipment will spend a lot of time in each channel looking for all the combinations. For reducing this time some other techniques should be use as:

- A physical channel inside a WINNER channel (like SCH, CPICH in UMTS) must be present for quickly detection and synchronization. This physical channel must be equal for the different WINNER modes and overall for different bandwidths, it would be convenient that this channel had the same narrow bandwidth regardless of the bandwidth of operation.
- Another possibility is having a common frequency channel (Pilot Channel) in a standard fix frequency that informs about the WINNER (and general radio frequency systems) arrangements in this location. This channel can be use also for other purposes as sharing needs, central controller for spectrum, or/and mobile reconfigurability for the standards (SDR download). This Pilot Channel can be implemented for example only in airports and main motorways in country borders for the reconfigurability or everywhere in the country for the central spectrum controller.

## 6.2 Control and Management of available resources

The control and management regarding the spectrum use can be carried out by the Radio Resources Management (RRM) entity. In future deployments several sub-networks with different RATs will have to co-exist and cooperate for optimising networks resources and services delivery, and to offer ubiquitous coverage. The inter-working and especially the tight cooperation between them are of great importance. Different approaches have emerged for the control of the resources (Combined, Joint, Concurrent and Layered RRM). Here a brief description is presented. They are commonly useful for RATs belonging to the same operator. But in a future RAT like WINNER this schemes of cooperation must be valid also between different operators.

When the integration between different technologies is high, the use of spectrum is more efficient. On the other hand, a higher level of integration requires a bigger effort in the definition of interfaces and mechanisms able to support the necessary exchange of data and signalling between different radio access networks.

### 6.2.1 Co-operation between Different (WINNER) Networks and RATs

The ETSI/BRAN has defined different interworking topologies between UMTS and WLAN, and similar work is on-going within the 3GPP (TS 25.331). Different approaches can be taken, depending on the level of integration that is necessary or possible to achieve between different RATs. The co-operation between RATs can be Loose or Tight coupling (Also we can separate this in Tight Coupling and Very Tight Coupling) [59] [68].
Fig. 44 shows the different couplings between RATs taking as an example the UMTS topology.

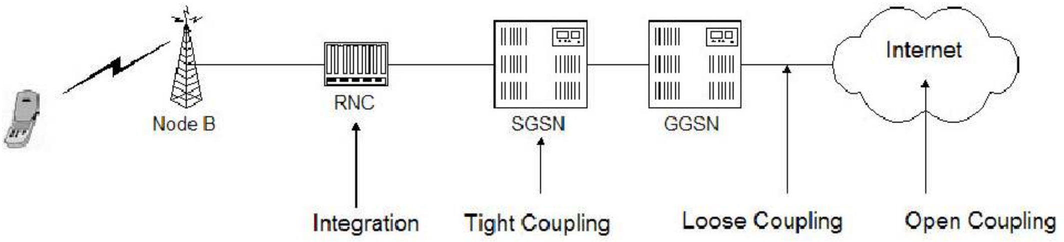


Fig. 44 Degree of coupling in function of RATs attachment point [68].

#### 6.2.1.1 Open Coupling or no coupling

In this scenario there is no real integration because both RATs are considered as two independent systems. Separate authentication procedures are used and vertical handover will not be possible. This scenario corresponds normally to the coupling between the same RAT and different operators.

#### 6.2.1.2 Loose Coupling

According to [36] loose coupling is defined as utilization of a generic RAT as an access network complementary to current 3G access networks, utilizing the subscriber databases but without any user plane Iu interface, i.e. avoiding the SGSN, GGSN nodes. In this scenario there is no possibility of making network initiated vertical handover between the RATs. But it uses the same subscriber database for both RATs .

As network initiated vertical handover can not be made, load balancing can only be made at user arrival rate. Both RATs must inform in the broadcasting channels the presence of the other RATs and neighbouring cells (type of RATs, frequency, CDMA codes, etc.) and its status (i.e. traffic load, and the available of type of services and QoS). The mobile terminal after scanning the available RATs with their status and the required service by the user, will decide the most appropriate target cell and RAT.

But in case the spectrum must be released (i.e. for DSA, to be use for other RAT), current user traffic can not be moved to another RAT without dropping the call. If this traffic cannot be reallocated to other frequency or cell inside the same RAT, it has to wait to the end of the on-going calls before releasing the spectrum (inefficient), or to drop the call (unacceptable). A more acceptable approach could be to share this spectrum between the new and old RAT (gradual DSA). The on-going calls will suffer a lot of interference until they can be reallocated, but could be acceptable. Anyway for DSA a tight coupling between RATs is desired.

#### 6.2.1.3 Tight Coupling

In the tight coupling, as shown in the Fig. 44 , the RATs' networks are connected to the rest of the UMTS network (the core network) in the same manner as other UMTS radio access technologies (UTRAN, GERAN) using, e.g., the Iu interfaces or any other standardized interface. For example Fig. 45 shows a tight coupling between UMTS and GSM.

One of the most relevant aspects is that the vertical handover can be supported. In the tight coupling scenario, the interface between different radio access networks is located in the Core network ( i.e. SGSN) and the vertical handover is managed by the core (i.e SGSN).
In this scenario the network can move user traffic from one RAT to another if for example spectrum must be released. The load balancing can be made also at user arrival rate as before but in this case the network has more control and can move one income call from one RAT to another regardless of the initial RAT where the mobile is camped.

#### 6.2.1.4 Very Tight Coupling

In the very tight coupling or integration, the RAT network is connected to the RAN of the UMTS. Then The RNC of UMTS (for example) controls not only its own node B but, other RATs access points. WINNER RATs act as another base station or Node-B. In this new scenario the interworking is provided within the radio access network, near the RNC and involves the Iur interfaces.

### 6.2.2 Combined RRM (Centralized)

Combined RRM will refer to a cooperation approach where the resources are managed centrally for all the involved RATs by a single functional entity.
Two examples of combined RRM are:

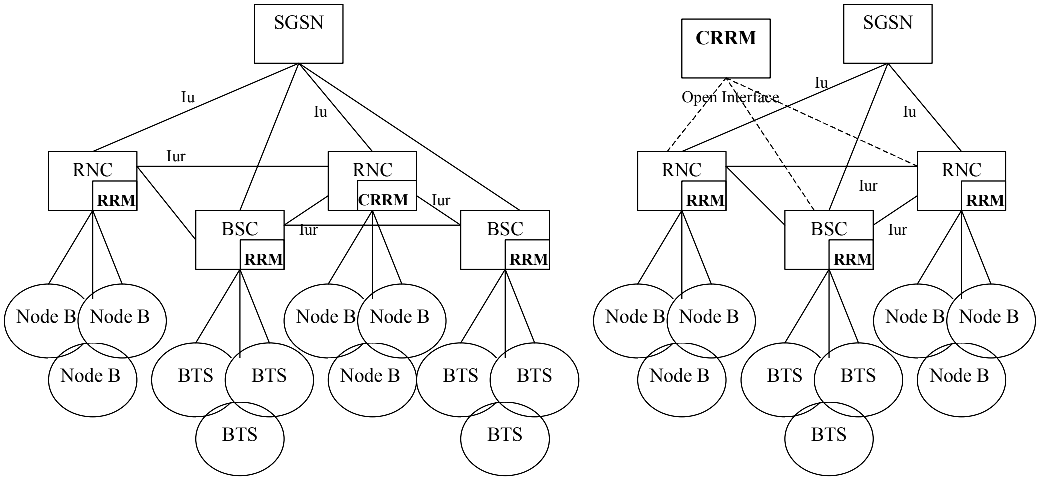
- Common Radio Resource Management (CRRM) defined within 3GPP to allow inter-working between UMTS and GSM/GPRS networks.
- Joint Radio Resource Management (JRRM) as defined in the IST SCOUT project for inter-working between HIPERLAN2 and UMTS.

#### 6.2.2.1 Common RRM

CRRM (Common Radio Resource Management) is one resources management solution developed within the 3GPP UTRAN and GERAN groups to make UMTS and GSM/GPRS networks cooperate. CRRM is a mechanism for intelligent distribution of traffic among these systems. With this scheme, the RNC/BSS exchange cell load information in order to balance the load / reassign spectrum.

Each RAN (RNC/BSS) has a RRM entity, which is responsible for RRM inside one radio resource. The radio resource has un RAT and one or several frequencies inside a region. This RRMs are coordinated by a controller, called CRRM. This is responsible of a certain number of RRM entities. The target of CRRM is the load balancing of the overlapping and neighbour RATs. It must direct users in idle and connected mode to the most suitable RAT.

The CRRM entity can be a stand-alone server (Fig. 45b) (TR 25.891) or can be integrated in one UTRAN/GERAN node (Fig. 45a) (TR 25.881), or even integrated in each UTRAN/GERAN node (CRRM and RRM at the same time). In this last approach the control becomes distributed. The main benefit of this integrated CRRM solution is that it has limited changes to the current UMTS/GPRS network, because there are interfaces among RNCs and BSCs. If The CRRM is implemented as a separate node, new interfaces have to be standardized. However integrated CRRM is only suitable if the RATs are connected in a tight coupling, because if not, no interfaces are present among the RNCs.



**a) CRRM integrated** **b) CRRM server**

Fig. 45 The Common RRM Architecture.

So the stand alone node solution is a more general approximation, and more suitable for adding future RATs to the net. Also this is better if several operators need to cooperate with the spectrum resources (shared or rented spectrum). This stand alone CRRM can carry out the “central controller” presented in section 1.4 (clause 2).

There are to possibilities for the resources control:

- The CRRM node gives only general directives to the RRM entities based on the reports from this RRM like traffic load, interference, etc. The RRM take the final decision of for example intersystem handover (RRM is the master).
- The CRRM receives the reports of the RRM and take all the decisions of handover, admission of calls, etc. (CRRM is the master).
  With this approach the resources are controlled very efficiently but a lot of information must be interchanged between CRRM and RRM. Also some delay is added in every action like admission calls or handovers.

From the DSA point of view, the CRRM entity (and not every RRM), have to be responsible for controlling the spectrum use among the RATs, as it implies two or more RRM and this decision can not be taken by a single RRM. So the CRRM will take a decision based on historical predictions, traffic load of each RRM, and neighbouring information of other CRRMs. It will order to prepare for the change (advise MTs and reallocate traffic) in advance and give the new spectrum allocation and exact time for this. Also it will inform to the neighbour CRRMs. The signalling information interchanged is not necessarily much because the spectrum re-assignation is not performed very often (several minutes).

As the CRRM must have also knowledge about the spectrum status of neighbouring CRRM, an interface must be established between them.

**Centralized vs. distributed**
For the spectrum management, this CRRM entity will control one or several DSA regions (presented in section 4.1.2.2). For border coordination it must be in contact with the adjacent CRRMs. Decisions of adjacent CRRM have influence in its own decision (for guard bands arrangement). Let’s assume that the CRRM controls only one DSA region. Then, this DSA region is managed in a centralized way. But the control among different DSA regions is made in a distributed way among the CRRM entities. So, centralized and distributed control of spectrum are not competing approaches. In this document we call distributed control when the DSA region is very small (e.g. the cells of one RNC/BSS).

#### 6.2.2.2 Joint RRM

The architecture of JRRM is quite similar to the one of CRRM, except that JRRM is not restricted to UMTS and GSM only. Moreover, JRRM complements the CRRM approach by several modifications and additional features. This architecture correspond to a very tight coupling, where the traffic is splitted among the RATs. Optimal QoS can be achieved with traffic splitting supported by adaptive radio multihoming, which provides multiple radio access for a single terminal in order to allow the terminal to maintain simultaneous links over RATs. The incoming traffic is split over two or more substreams. The important information goes through a reliable RAT, the rest through other RATs.
Load balance and vertical handovers can be made easily because the terminal are using several RATs at the same time. But the deployment of this approach is difficult as it implied changing the current core network.

### 6.2.3 Concurrent RRM (Distributed)

Whereas in the Common RRM approach the control over resources can be implemented either centralised or distributed way, in the concurrent RRM approach the control and management is organized only in a distributed manner. In Concurrent RRM, resources are allocated within each RAN by a local entity. These entities have to cooperate in a distributed manner to come up with efficient resource utilization. The efficient cooperation of different networks requires an inter-working between heterogeneous systems. From the description it becomes obvious that the Concurrent RRM fits quite well to the loose-coupling architecture as defined by ETSI, 3GPP [36] and BRAIN project. One advantage of loose coupling is that it allows flexibility and rapid deployment, but also a loss in efficiency.

### 6.2.4 Layered RRM

In the layered architecture propose by IST-MIND, the management or radio resources is made across the layers 2 and 3. It is a generic architecture for the cooperation of several technologies and/or operators. It is assumed that L3 will be based on IP. Fig. 46 shows the generic layered RRM architecture as an example between H2 and UMTS, with the division of RRM functions between L2 and L3.

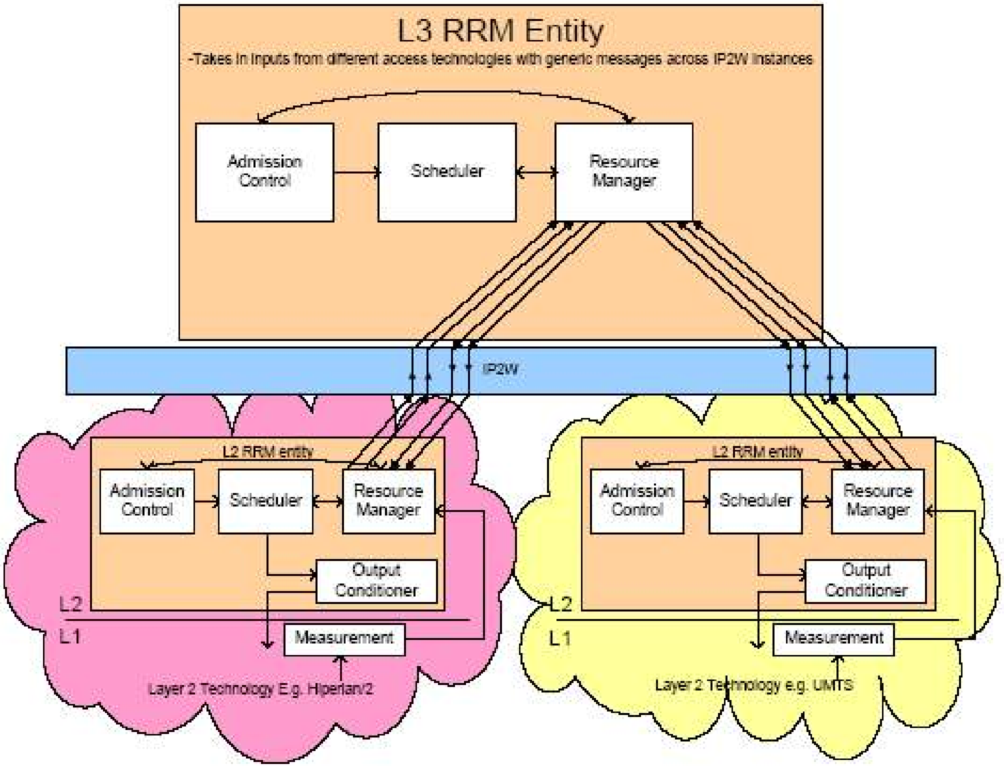


Fig. 46 The layered RRM Architecture [54].

The entities that take part in the management of resources are:

- Measurement entity. It is located only in L1 and measures the signal reception strength.
- Output Conditioner Entity. It contains the power control and link adaptation functions (like selecting the more suitable modulation and coding scheme). This is done depending on the current interference situation, fading and noise. This entity must be optimised to a particular link layer technology and should remain in L2.
- Admission Control (AC) Entity. It is implemented in L2 and L3 layers. It contains the AC algorithm for admitting or rejecting new connection calls or handover calls based on the current system state, the traffic and QoS requirements of the service that has to be supported. The L2 part support horizontal handovers (the same RAT). The L3 part is implied in the vertical handovers. At L3 the AC algorithm needs information from L2 about allocated and total available capacity, etc.
- Scheduler and queue entity. This guarantees that all flows receive the desired service. The scheduler and it's queue in L3 should be aware of the link layer conditions and receive the information about the current state of the L2 scheduler from the RM entity, such as the condition of L2 buffers/queues. The L3 queues and scheduler send their current state to the L3 RM entity. The L2 queues and scheduler send their state to L2 RM entity such as the current PHY Mode allocation, PER (CIR), load of the system as well as error correction/checking mechanisms. This information is used in order to decide when the channels can be used.
- Resource manager (RM) entity. This is used to control and manage more efficiently all other functions in the RRM architecture, as well as acting as a "gateway" to upper layer functions outside of the RRM function, such as routing or handover. The RM entity is present in both L2 and L3 and the entities in each layer cooperate very tight.

### 6.2.5 Implementation of FSU and DSA

In section 4.1 DSA was introduced, and in sections 4.1.2 and 4.1.3 FSU between two modes and several operators was presented. For optimal spectrum use, it is envisaged that spectrum will have to be reallocated among operators (see Fig. 34). This spectrum reallocation implies that:

- Most of the WB frequency channels of every operator must be changed (centre frequency and bandwidth) and some NB channels must be moved in frequency. Additionally some traffic must be moved from one channel to another (for example to clear up a NB channel in order to make room for increasing WB channel bandwidth).

This change must be individually informed and granted to all mobiles in advance. The signalling to all mobiles in connected mode is inefficient, and can be enhanced if this new spectrum arrangement is broadcast: when it will be happened, how the new configuration is, how it is the default arrangement of the ongoing channel, etc. Only those MTs that must change the channel to other different from the default one will have to be signalled individually.

Broadcasting the new spectrum arrangement can reduce the signalling but implies that all MTs must listen periodically the broadcast channels, in one of the following way:

  - The MT is capable of receiving simultaneously two channels, the traffic channel and the cell-broadcast one, even though they can be in different frequencies. This is not very efficient for the final cost of the MT.
  - The "new spectrum arrangement" is broadcast in all the frequency channels currently allocated for traffic. It is easier to receive several channels if they are in the same frequency.
  - The MT receives the broadcast channel in the spare time it has for making measurements of neighbouring cells. This is the most efficient but it is not sure that all MTs will get all the information in time. The spectrum new configuration must be broadcast much time before the change.

- The spectrum "change" must be perfectly synchronized among operators. It implies a time synchronization at bit level among operators of the same country/zone. This is difficult to obtain even among cells of the same operator. Nevertheless, for TDD scheme this time synchronization inside an operator is mandatory for avoiding the DL-UL interferences, and also very convenient among operators.

  Getting/maintain the time synchronization among adjacent cells/operators, can be done with the help of a positioning system (e.g. Galileo or GPS) and MT measurements (needed for indoors). They can measure the time difference between its own cell and the others. Of course propagation delay must be taken into account with the MT location knowledge, or can be mitigated with the mean of several measurements over the space.

  These delay measurements can be reported for example to the CRRM entity (in case of Common RRM), that will decide what changes are needed to each cell. It can order individual "time movement" to each RRM if synchronization is needed (for example for a TDD scheme), or only take in account the time differences when commanding a new "spectrum change" in order to get it at the same time in all the cells.
- There will be a time of completely inactivity. RF transmitters and filters need a time of some ms to change it frequency of operation. For this reason mainly and for the signalling load, the times of change must not be very frequent. For example not less than 15 minutes.
- It is desirable that the DSA regions must be equal for all the operators. Border effects are very difficult to control if DSA regions for each operator are not equal. This is a great drawback because each operator normally have its own deployment of cells, antennas places, etc.

The period for collecting information, taking a decision (proposing and making an agreement if distributed control) and broadcast the final decision, must be fixed and know in advance.

## 6.3 Re-configurability – Impact of Software Defined Radio on Flexible Spectrum Use

### 6.3.1 Definition of Software Defined Radio (SDR)

It is foreseeable that new radio equipments (mobile and base station) are going to used Software Defined Radio technologies, (reconfigurable or in a less feasible, cognitive radio), due to the many advantages it offers.

**Software Defined Radio** is a radio in which the operating parameters including frequency range, modulation type or maximum output power can be altered post-manufacturing by making a change in software without making any changes to hardware components that affect the radio frequency emissions. Software defined radio is merely a new technological implementation of classical radio functions. [94]

The "change" can be ordered externally by e.g. the base station controller, or the user. This is called "**reconfigurable radio**". But the radio can have some kind of intelligence that allows it to determine when and how to reconfigure itself. This is called adaptive intelligent software defined radios or "**cognitive radio**". A cognitive radio is a radio that can sense its environment and dynamically and intelligently alters its operating parameters as a function of its operating environment [94].

Software defined radios use adaptable software and flexible hardware platforms to address the problems that arise from constant evolution and technical innovation in the wireless industry, particularly as waveforms, modulation techniques, protocols, services, and standards changes. This definition also address the implementation of radios that facilitate satisfying the increasing need for users to communicate as they move between different wireless network environments [93].

The SDR Forum has published a software radio reference model with several sets of revisions. Fig. 47 shows a version oriented toward commercial applications that is useful in considering base station architectures. It separates information and control channels (**I,C**), and shows the separation of individual channels and the transition from analog to digital processing. It also shows a number of network connections for information and control in different formats [96].

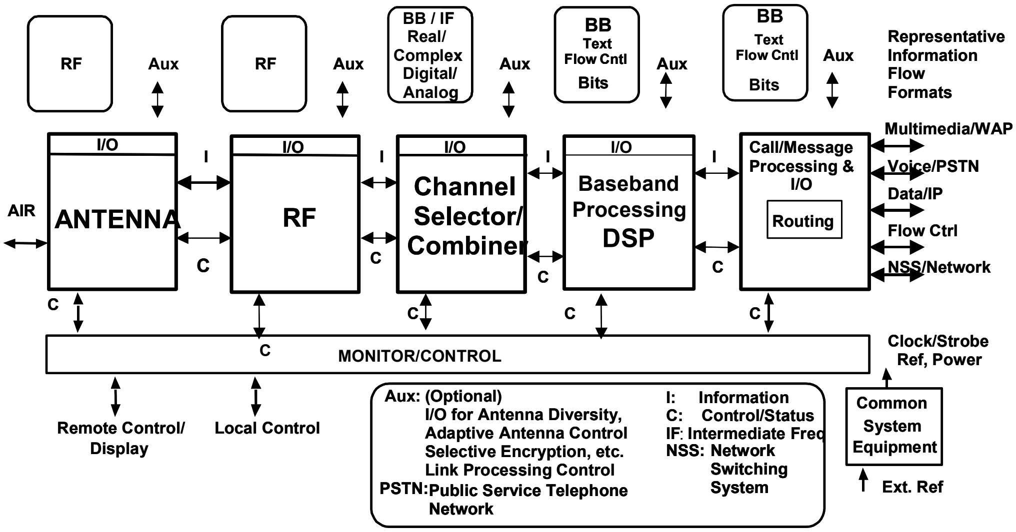


Fig. 47 Software Defined Radio block diagram[96].

### 6.3.2 Performances that will offer on going research activities on SDR

Many organizations and IST projects (SDR Forum, TRUST, SCOUT) aim to analyse and develop this novel techniques. Two important improvements are being aimed:

- The technological

  Major advantages have been done, but faster and higher resolution ADC converters are needed, faster and more power efficient microprocessors, and smaller radio-frequency antennas, filters and amplifiers.

- The standardization and study of the scenarios.

  TRUST project, and now the SCOUT (also SRG Forum) are studying the scenarios and the standardization of the SDR. It is needed to develop rules for security in software downloads, in order to avoid non-allowed power spectrum transmissions.

### 6.3.3 Requirements of SDR for FSU in WINNER

In many applications (such as software reconfiguration, multi-mode home networking devices or single-band (e.g. 1900 MHz) mobile terminals), operation within a limited range of frequencies are acceptable, and conventional RF chipsets and antennas may be employed together with SDR equipment (mobile and base station), which will allow updates in e.g. new modulation schemes without the need of change the hardware equipment. This is very interesting for operators from a economical point of view.

But in future systems **multi-band** operation over a wide frequency range of probably several Gigahertz is required. It is foreseeable that mobile terminals have to work in the 3-5 GHz band and also in 900 MHz or less taking in account the re-farming of e.g. 2G or sharing the spectrum with other systems. An international multi-band, multi-mode 2G/3G/WINNER mobile terminal will be required to operate in several bands. For these multi-band, multi-mode (MB/MM), novel RF chipsets, power amplifiers and antennas are required [92].

Several technologies are arisen in order to fulfil these requirements, like for example [92]:

- The RF micro-electrical mechanic systems (RF MEMS). These tiny devices will permit practical multi-decade antennas and small, low-power RF receivers and synthesizers.
- Cryogenically cooled multi-band RF receivers and transmitters.
- Wideband and ultra-wideband (UWB) antenna elements. Novel antenna element technologies Examples include ultra-wideband "resistive" antennas, as well as the "meander line" antennas (MLA).

Before SDR radios can be fielded for cellular systems, two simultaneous and often conflicting requirements must be met: wide instantaneous bandwidth and high dynamic range in both the digital and analog domains. For a variable bandwidth operation, a SAW IF filter for the desired channel can not be used. Instead a large bandwidth must be filter by analog components and sampled. The necessary selectivity on the target channel has to be achieved in the digital domain with digital and programmable filters. So a fast ADC is needed, the wider band, the faster. But also the wider band, the more power of unwanted signals enter to the ADC and the higher dynamic range is needed. The worst case occurs when several channels are present in the entire band that sample the ADC, and the target one has low power compared with the adjacent channels. Then a very high-resolution ADC is needed to get this channel in the digital domain. Fast and high-resolution ADCs are competing requirements. With the current sample technologies of, for example 16 bit ADC at 80 Msamples per second, are not enough. But the ADC technologies are progressing continuously. On average 1bit of resolution increase is achieved every 8 years.

Another promising technique used more and more is the direct-downconversion instead of the traditional IF detector, as can be seen in Fig. 48. The desired bandwidth is downconverted directly without any IF. The advantage is that it is easier to implement a multiband receiver, and the ADC can be slower. On the other hand, higher performance is needed for the local oscillator (noise phase) and the 90º sifter. Anyway, higher resolution ADCs than the current ones are still needed.

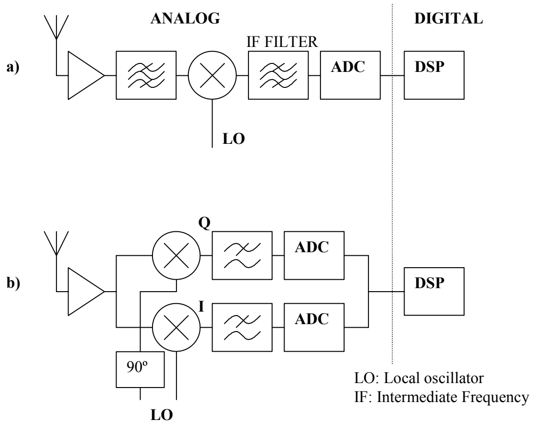


Fig. 48 Possible SDR receptor block diagram.

For the transmitter chain the direct upconversion needs a final analog filter to avoid spurious emissions, so a bank of filters will be needed for multiband transmitters. Although progress has been made in the area of reconfigurable devices to support high-resolution, high-data-rate digital processing, only recently technology has evolved to meet the same requirements for the analog side of the processing chain. [24]

One desirable characteristic of reconfigurable network equipment, that could further increase the cost savings associated to SDR technology, is the existence of standardized interfaces that will allow the development of software by third parties.

The technological evolution to SDR will take an important role on spectrum efficiency, utilization, and allocation. SDR will allow an equipment to work in different frequency bands, what is suitable for FSU and for re-farming. Also it will be useful for roamers between countries where the same system can have different bands assigned.

The opportunity of modifying the operation of base stations and terminals allows network operators to make a more efficient use of their network resources:

- For load balancing described in section 3.3.2: For instance, in a situation with more than one RAT, network resources could be assigned dynamically to each technology according to the number of users in each network and their needs, in order to avoid congestion. Then a solution to avoid network congestion would be to ask user terminals to switch to a less congested RAT. This terminal may need a new software download for working in the new RAT. In case the software can be downloaded autonomously by the network and terminal the reconfiguration could be performed transparently to the user.

- For spectrum reallocation: SDR terminals and base station will allow changing dynamically the centre and bandwidth of the radio frequency channel needed for an optimum spectrum use between WINNER modes as described in section 4.1.2.2.

It also must be considered that SDR technology will allow base stations and terminals to operate in a larger frequency range, and to modify its operating frequency (or frequencies) within this range as well as the multiple access technology, the transmission power or the modulation scheme. This may enable a modification in the current scenario and allow operators to achieve higher spectral efficiency.

### 6.3.4 Impact on base station and user equipment

**Base station reconfiguration** [94]
Base station reconfiguration includes both the complete change of functionality, for instance the move from one RAT to another, as well as the update to a new version or an optional capability of a certain RAT.

For operators, this capability may enable more flexibility and scalability in network deployment and operation, and, although equipment incorporating SDR technology may be more costly initially than non-reconfigurable equipment, it seems reasonable to expect that in the long term infrastructure investments will become cost effective. For optimum FSU in WINNER, SDR will allow the needed flexible bandwidth and modulation..

**Terminal reconfiguration** [94]
Terminal reconfiguration favors world-wide roaming and interoperability, because, ideally, one single terminal could be reconfigured to employ any RAT. Likewise, it enables the separation of services offered to the user, and the technology used to provide them. And it also makes bug corrections easier and more economical. The economic impact of software radios will occur in three areas:

- Bug fixes: Software errors, or 'bugs,' can be corrected with new software downloads.
- Upgrades: Rather than make large equipment changes to implement new features, modulation techniques, or protocols, software downloads can be used to implement generational changes in equipment thereby reducing capital expenses.
- Reduced handset inventory: Manufacturers can take advantage of having a core system that can adapt to local conditions rather than have a specific radio design and implementation in all regions.

## 6.4 Gradual re-farming of frequencies used by "legacy technologies" for new technologies

Re-farming in the traditional sense means the recovery of spectrum from its existing users for the purpose of re-assignment, either for new uses, or for the introduction of new spectrally efficient technologies. One of the way to get more spectrum when a cellular system expand is to re-use the frequency used by old systems, if this become underused.

When new radio communication services are introduced or new spectrally efficient technologies replace older technologies this often occurs as a natural migration that does not cause noticeable problems to spectrum management authorities and hence does not require the use of specific re-farming instruments. However, when re-farming involves a forced withdrawal of existing frequency assignments and licensees, that is not in the interest of the incumbent user, then re-farming may require application of a set of various instruments, such as: [19]

- re-farming funds, compensation to incumbent spectrum operators.
- pricing incentives, creating cost incentives for spectrum licensees
- secondary trading, allowing a trading of the spectrum for new technologies.
- license expiry

From the current experience of CEPT countries, up to now the voluntary withdrawal of incumbent operators was the most commonly used re-farming option, with the re-farming processes being still sufficiently quick in this case (2-3 years on average). However this voluntary withdrawal may no longer be suitable in the future, because of different reasons, such as high sums that have been paid for the access to the frequencies, and more and quicker frequency harmonization processes that could be expected to be triggered by the new EU Frequency Decision [19].

Another way to re-farming in a non-force way is allowing the operator to use the new technologies (WINNER) in spectrum they have already licensed for other technologies. The operator can use part of its spectrum for the old technologies an the other one for WINNER. It is expected that the operator wants to change to the new technologies if this one offers new and more valuable services that meet users' demand. Also it is expected that more and more users will change from one technology to the other when changing their mobile terminals. The new mobile terminals will operate in both technologies, so it is foreseeable that in few years the majority of users will have dual mobile terminals.

For this gradual re-farming it is necessary that the operator has enough frequency in the old technologies in order to re-use the assigned spectrum for two technologies, or it will have to share its spectrum between both technologies. Of course this is not the case if an operator has also license to operate in new WINNER frequencies. But in any case, it is desirable that the minimum WINNER bandwidth would not be very wide, for better allocation possibilities.

The majority of operators in Europe have licensed more than 10 MHz in GSM900 or GSM1800 [33] (apart from Albania, Bulgaria, Russia, Liechtenstein Ukrania and Portugal). Many countries have licensed no contiguous bandwidth because part of the band is used for other services, but this services are going to expire before 2010. A big bandwidth can be get if the operators joined its licensed spectrum for refarming, but this is very complicated and improbable in a technology already deployed, so it is desired a narrow bandwidth mode inside WINNER that can operate in this bandwidth.

For re-farming the UMTS technology, 10 MHz bandwidth is also a good number since it corresponds to 2 channels and most of the operators have at least 2 contiguous channels in FDD mode.

# 7. Conclusion

The purpose of this document is basically two-fold. Firstly, it aims at giving a review on the spectrum sharing and compatibility issues as well as on flexible spectrum use (FSU) methods that are relevant to WINNER. The second goal of the document is to discuss how these issues could be taken into account in the development of WINNER system concept, and what kind of requirements they may set to the system concept. In order to reach this goal, several scenarios where spectrum was shared or dynamically allocated between different RANs using the same frequency band were considered. The main spectrum sharing and flexible spectrum use opportunities are summarized in the following paragraphs, and the main recommendations to be considered in the WINNER system concept development are highlighted.

## Spectrum sharing between WINNER system and another radio service

Since the involved RATs are quite different in nature, one has to assume that no coordination or only a very limited one can be established between the implicated RANs. ***If the WINNER system is the secondary service***, it must guarantee that the primary service is not affected by harmful interference. This requirement and limited coordination have several consequences in practice:

- The primary service should have unused ‘white spaces’ in the spectrum that are spatially sufficiently large and do not exhibit rapid variations over time. A promising candidate is the fixed services in the WINNER target frequency band. Broadcasting service not using SFN may also be also a promising candidate, although this requires multi-band capabilities from the equipment.
- It will be difficult to achieve guaranteed ubiquitous service with shared spectrum alone. *Operation in shared spectrum is more suitable for a WINNER mode providing capacity enhancements* than for a mode providing the baseline set of WINNER services.
- The WINNER system needs to know the locations of primary service receivers or, in some cases, transmitters and their ranges. This is a straight forward requirement for network planning if the primary service is based on permanent receiver or transmitter installations. If the primary service uses also portable equipment, as fixed service may use, the *WINNER system must be able to detect and track the appearance and movement of the active portable equipment*. This capability could be achieved by introducing sensor network characteristics to the WINNER system concept. In other words, either access points or mobile terminals should have capabilities to measure primary service signals, the frame structure should allow periodic measurements and reporting and the network should have control functionality for processing and acting upon measurements. *Measurements can be also used to estimate interference towards primary service*.
- If the primary service uses portable equipment, *WINNER networks must have sophisticated functionalities for controlling the spectrum sharing*. The WINNER system must also support a fast release of shared spectrum, e.g., with efficient frequency hand-over procedures. These can be included to advanced RRM like CRRM or JRRM.
- The *WINNER system should be able to* use the ‘white spaces’ in the spectrum efficiently and to *minimize the guard bands towards primary service*. This can be achieved if the WINNER system concept supports suitable carrier rasters and multiple bandwidths. Most of the dynamic spectrum allocation (DSA) functionalities are required for dynamic control of the guard bands.
- The *guard areas towards primary service should be also minimized* (with reasonable safety margins). This promotes the use of shared spectrum for short range and peer-to-peer communications with low transmit powers. Guard area reductions can be achieved also with suitable modification and *efficient utilization of transmit power control*. In the case of narrowband primary service, further reductions in guard areas may be achieved if the WINNER *signal structure allows for decreasing its transmission to very low levels in certain subbands within its signal band*.
- This sharing scenario needs also some coordination between WINNER operators, either based on fixed allocations or more flexible methods.

***In the case that WINNER system is the primary service*** on the band, it can promote secondary use of spectrum on its band by actively creating ‘white spaces’ in the spectrum when possible. In other words, *WINNER system would release a portion of its spectrum in areas and at times of low traffic*. This requires that a WINNER network uses either multiple carriers or bandwidths. It also requires procedures to release and retrieve spectrum, as well as well-defined coordination or etiquettes on the spectrum use with the secondary service.

## Gradual re-farming of spectrum used by legacy communication systems

In the case that legacy system operator(s) agree with re-farming, the WINNER system concept would need to *include a mode operating on separate bands than other modes with relatively narrow bandwidth*, as already indicated in [71].

## Flexible spectrum use between WINNER modes

Dynamic spectrum allocation between WINNER modes may become beneficial if the modes are optimized to different services/scenarios, and the traffic demands for the services/scenarios are distinct and vary in time and/or space. Employment of DSA requires implementation of DSA control functionalities, including spectrally efficient control of DSA region borders, as a part of advanced RRM, joint optimization with load balancing, an air interface with multiple bandwidth capabilities to obtain sufficient spectrum granularity, and support for periodic (with long intervals) carrier and bandwidth changes. In some cases, efficient use of DSA between WINNER modes of one operator may require some cooperation between operators. Carrier/bandwidth changes may need to be time-aligned with quite high accuracy, operators may need to change the carrier frequency upon request of other operator, and it may be desirable that operators employ the same DSA regions.

## Sharing and flexible spectrum use between multiple WINNER operators

In extreme, this scenario allows for fully obtaining the benefits of the previous FSU scenario. Several levels of sharing can be envisaged, imposing different requirements for control and signalling. Several interesting sharing opportunities appear with the employment of relaying [67]. One of them is the use of shared spectrum for the connection between access point and relay station. This requires highly directive links and coordination between operators in the network planning. It may also set some restrictions on the used relaying method.

**Recommendations**

It is recommended that the feasibility of following items is considered in the WINNER system concept development:

- use of shared spectrum for a WINNER mode providing capacity enhancements, possibly in short range,
- support for few multiple bands and bandwidths as well as for a carrier raster between which equipment can switch dynamically ,
- measurement capabilities to detect and track the equipment of primary services, and to estimate interference towards primary service,
- sophisticated functionalities controlling the spectrum sharing and providing, e.g., fast release of spectrum, minimization of guard bands with DSA functionalities, minimization of guard areas via interference estimation and transmit power control, and required level of coordination between WINNER operators and primary service,
- signal structure that allows for decreasing its transmission to very low levels in certain subbands within its signal band,
- control functionalities for releasing a portion of possible dedicated spectrum in areas and at times of low traffic and retrieving it back,
- inclusion of narrow bandwidth WINNER mode designed for re-farming the spectrum of legacy communication systems,
- functionalities for dynamic spectrum allocation between WINNER modes, and possibly between WINNER operators,
- spectrum sharing between operators on the link between access point and relay station.

It should also be noted that ***further information is needed*** from operators on ***the temporal and spatial traffic load variation of existing and future radio access technologies.*** Unless this information is available and operators believe in the prospects of temporal and spatially DSA, any further research in this area will have difficulty delivering meaningful and agreeable results.

This document presented a variety of opportunities for spectrum sharing and flexible spectrum use in WINNER. The main implications to the system concept design were also indicated. However, the assessment of achievable gains and required increase in system complexity was not performed. This remains one of the main goals of future work.

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# 9. Annex

## 9.1 Spectral Efficiency

A fundamental parameter, which describes the spectrum utilization of an air interface, is *spectral efficiency*. This measure describes the relationship between the bit rate in bit/s and the necessary bandwidth in Hz. Due to its importance to spectrum utilization and also due to misconceptions that exist in even technical literature, it seems adequate to review the basic concepts related to spectral efficiency. Different measures exist:

**Link spectral efficiency**, or simply spectral efficiency, considers a point-to-point transmission from one transmitter to one receiver over a given channel. The information-theoretic limits with regard to white Gaussian noise of this measure are well understood.

**Area spectral efficiency** considers the bit rate per bandwidth and area in wireless systems and is measured in bit/(s·Hz·m$^2$). It is related to the

**Cell or sector spectral efficiency**, which gives the bit rate per bandwidth and cell or sector.

In contrast to the cell spectral efficiency, the area spectral efficiency increases with decreasing cell size.

### 9.1.1 Link Spectral Efficiency

The link spectral efficiency is upper-bounded by Shannon's channel capacity and can be calculated easily for the following canonic channel models.

**AWGN Channel**

The simplest channel model is the AWGN channel, which is depicted in Fig. 49 and given by

$$y_k = x_k + n_k$$

where $x_k, n_k \in \mathrm{X}$. The signal and noise power are given by $E_S = \mathrm{E}\left[\| x_k |^2\right]$and $N_0 = \mathrm{E}\left[\| n_k |^2\right]$. The capacity of this channel is given by

$$C_{\mathrm{awgn}} = \mathrm{ld}\left(1 + \frac{E_S}{N_0}\right) \tag{9.1}$$

*C* is given in bits per channel use, which is equivalent to the spectral efficiency in the corresponding continuous channel, provided the effect of the pulse shaping filter can be neglected.

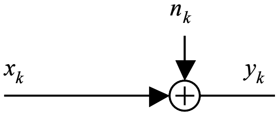

Fig. 49 Discrete AWGN channel.

To achieve the channel capacity, the transmitted signal $x_k$ must have Gaussian statistics which would require an infinite peak-to-average ratio. In practical transmission systems, the transmitted symbols are taken out of a discrete alphabet. If the input signal $x_k$ is restricted to the discrete alphabet $\Theta = \{a_1, \ldots, a_M\}$ the channel capacity is given by the maximum mutual information

$$C_{\mathrm{qam,awgn}} = \max_{P(a_m)} \{I(X;Y)\}$$

In the literature, for the channel capacity often the expression for the mutual information is used without maximizing with respect to the probabilities of the symbols in the input constellation. Using this convention, we can simply write

$$\begin{aligned} C_{\mathrm{qam,awgn}} &= I(X;Y) = \frac{1}{M}\sum_{m=1}^{M}\int_{\mathrm{X}} p(y \mid x = a_m)\,\mathrm{ld}\frac{p(y \mid x = a_m)}{p(y)}dy \\ &= h(Y) - h(Y \mid X) \end{aligned} \tag{9.2}$$

For the AWGN channel, the differential entropies are given by

$$h(Y \mid X) = h(N) = \mathrm{ld}(\pi e N_0)$$

$$h(Y) = -\mathrm{E}[\mathrm{ld}\, p(y)] = -\mathrm{E}\left[\mathrm{ld}\left(\frac{1}{M\pi N_0}\sum_{m=1}^{M}\exp\left(-\frac{|y-a_m|^2}{N_0}\right)\right)\right] \tag{9.3}$$

In general, closed form solutions for this expression do not exist. However, they can be calculated easily with a Monte-Carlo method by generating samples of $y$ corresponding to the channel model and taking the mean as indicated in (9.3).

For M-QAM, the spectral efficiency is obviously upper-bounded by the number of bits per QAM symbol. Fig. 50 shows the channel capacities for various various QAM constellations and the Shannon capacity for continuous-valued $x_k$. as a function of the SNR $E_S/N_0$ .

The capacity curves approximate the Shannon capacity for low SNR values and saturate for higher SNR. Note that these capacity curves are valid for infinite block length and do not consider decoding complexity. Advanced adaptive modulation and coding schemes are capable of operating at several operating points close to the theoretical limits.

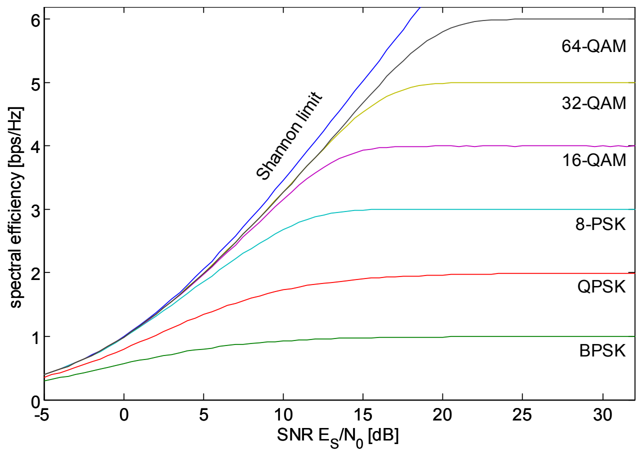

Fig. 50 Channel capacity for discrete AWGN channel for continous input (Shannon limit) and discrete input (from BPSK to 64-QAM).

### Rayleigh Fading Channel

While the AWGN channel is the best understood, the Rayleigh fading channel, depicted in Fig. 51, is much more relevant for wireless communication systems. The fading is modelled by a random attenuation $h_k$, whose magnitude is Rayleigh distributed.

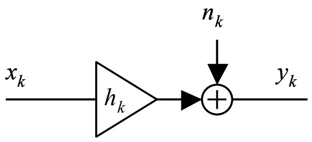

Fig. 51 Discrete Rayleigh fading channel.

The (perfectly interleaved) Rayleigh channel is defined as

$$y_k = h_k \cdot x_k + n_k$$

where $h = h' + jh'' = a \cdot e^{j\varphi}$ and $h', h''$ are independently Gaussian distributed with variance $\sigma_a^2 = 1/2$. The absolute value $a$ is thus Rayleigh distributed. Under the assumption that the fading coefficient $h_k$ is known at the receiver side, the channel capacity can be calculated, as detailled in the following.

The channel capacity for continuous inputs is

$$\begin{aligned} C_{\text{rayleigh}} &= \mathrm{E}\left[\mathrm{ld}\left(1+|h|^2\frac{E_S}{N_0}\right)\right] = \int_0^\infty p_a(a)\,\mathrm{ld}\left(1+a^2\frac{E_S}{N_0}\right)da \\ &= \frac{1}{\ln(2)}\exp\left(\frac{N_0}{E_S}\right)\cdot\Gamma\left(0,\frac{N_0}{E_S}\right) = \frac{1}{\ln(2)}\exp\left(\frac{N_0}{E_S}\right)\mathrm{E}_1\left(\frac{N_0}{E_S}\right) \end{aligned} \tag{9.4}$$

where $\Gamma(a,z)=\int_z^\infty t^{a-1}e^{-t}dt$ is the incomplete Gamma function, and $\mathrm{E}_1(x)=-\mathrm{Ei}(-x)=\int_x^\infty e^{-t}t^{-1}dt$ is the exponential integral [45].
For M-QAM, the channel capacity for the Rayleigh fading channel is given by

$$C_{\text{qam,rayleigh}} = h(Y)-h(Y\,|\,X)$$

with

$$\begin{aligned} h(Y\,|\,X) &= \mathrm{ld}(\pi e N_0) \\ h(Y) &= -\mathrm{E}\left[\mathrm{ld}\left(\frac{1}{M\pi N_0}\sum_{m=1}^{M}\exp\left(-\frac{|y-a_m|^2}{N_0}\right)\right)\right] \end{aligned} \tag{9.5}$$

where the expectation is now taken over *y* and *h*. For BPSK and QPSK, there exist analytical expressions [16][103]:

$$\begin{aligned} C_{\text{bpsk}} &= \frac{1}{\ln 2\cdot\sqrt{1+N_0}}\,\beta\left(\frac{1+\sqrt{1+N_0}}{2}\right) \\ C_{\text{qpsk}} &= 2\cdot C_{\text{bpsk}} \end{aligned} \tag{9.6}$$

where the β-function can be expanded as

$$\beta(x)=\sum_{k=0}^{\infty}\frac{(-1)^k}{x+k}=\sum_{k=0}^{\infty}\frac{1}{(x+2k)(x+2k+1)}$$

The capacity of the Rayleigh channel, depicted in Fig. 52, is naturally smaller than that of the AWGN channel, but the differences are not significant. This is in strong contrast to the performance of uncoded QAM on both channels, where the BER degrades strongly for Rayleigh fading. A simple conclusion that can be drawn from this situation is that for wireless communications significant improvement is obtained by employing channel coding.

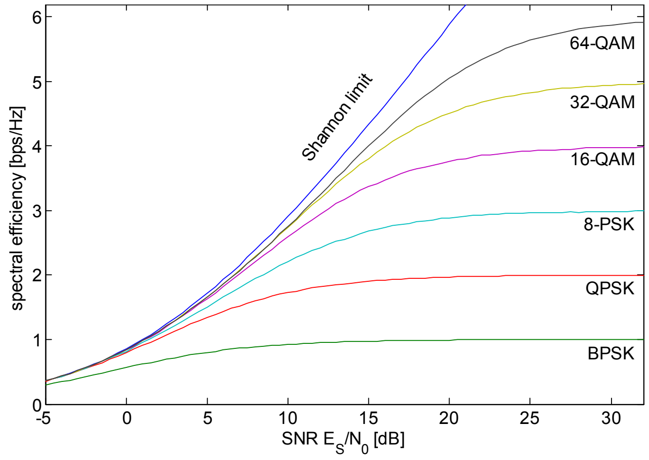

Fig. 52 Channel capacity for Rayleigh fading channel for continuous input (Shannon limit) and QAM input signals.

**Gap Approximation**

The gap approximation is motivated by the expression that is obtained when calculating the spectral efficiency in QAM for a given symbol error probability: For M-QAM with quadratic constellation, the symbol error probability is approximated by

$$P_S \approx \underbrace{4\left(1-\frac{1}{\sqrt{M}}\right)}_{K_m} \cdot Q\left(\frac{d}{2\sigma_n}\right) \tag{9.7}$$

where $d$ is the minimum distance between two symbols. The average symbol energy for square constellations is $E_S = \frac{1}{6} d^2 (M-1)$, thus the SNR can be written as

$$\frac{E_S}{N_0} = \frac{M-1}{3}\left[Q^{-1}\left(\frac{P_S}{K_m}\right)\right]^2$$

The SNR gap is defined as

$$\Gamma = \frac{1}{3}\left(\frac{d}{2\sigma_n}\right)^2 = \frac{1}{3}\left[Q^{-1}\left(\frac{P_S}{K_m}\right)\right]^2$$

which leads to

$$M = 1 + \frac{E_S}{\Gamma N_0}$$

The spectral efficiency for QAM, neglecting the pulse-shaping filter, is simply

$$\varepsilon = \mathrm{ld}\, M = \mathrm{ld}\left(1 + \frac{E_S}{\Gamma N_0}\right)$$

which for $\Gamma = 1$ corresponds to the Shannon capacity. The factor $\Gamma$ is thus the “gap” between the spectral efficiency that is achievable with M-QAM for a given symbol error probability $P_S$ and the Shannon capacity.

**Effects of Interference**

The effect of interference on a point-to-point radio link can be explained directly with the curves in Fig. 52. Interference that stems from an unknown source or, what is more realistic, from several unknown sources appears to the receiver like noise. As interference is normally neither Gaussian nor white, its effect is possibly more severe than AWGN. For a coarse estimation, we may regard interference as AWGN, which adds to the noise power $N_0$. The SNR in Fig. 52 is thus reduced by interference, decreasing thus the possible spectral efficiency according to the capacity curves. For a non-adaptive transmission system, which operates at a fixed link spectral efficiency, this simply means that transmission brakes down at a certain interference level. Adaptive coding and modulation schemes can react to increased interference by lowering their data rate, i.e. by selecting an operating point with less spectral efficiency.

The only way to make a system immune against interference is to provide sufficient SNR margins, i.e. increasing the transmit power. However, this leads to higher power consumption and possibly unnessary high transmit powers and thus cannot be considered as a viable countermeasure to interference.

### 9.1.2 Area Spectral Efficiency

In a cellular system, a more suitable figure of merit is the *area spectral efficiency* (ASE) [15][47]. It is defined as the sum bitrate per cell over the total allocated bandwidth and the cell area. We define $C_k$ as the maximum bit rate of user $k$, the number of users in a cell is $K$; $d$ is the reuse distance, i.e. the distance between two base stations using the same frequency band, $r$ is the cell radius and $f_B$ is the total allocated bandwidth. Then the ASE for omnidirectional cells is approximated by

$$\varepsilon_A = \frac{2\sum_{k=1}^{K} C_k}{3\sqrt{3}r^2 f_\mathrm{B}} \tag{9.8}$$

The *link* spectral efficiency, which determines $C_k$, is increased by increasing the reuse distance $d$, since this lowers the cochannel interference. On the other hand, increasing $d$ decreases the ASE $\varepsilon_\mathrm{A}$ by increasing the total bandwidth $f_\mathrm{B}$. Thus there is clearly an optimum for the reuse distance which maximizes $\varepsilon_\mathrm{A}$, depending on $C_k$ as a function of $d$.

Unfortunately, for the ASE it seems not possible to derive a universal bound like the Shannon limit or the mutual information. For the derivation of (9.8), many assumptions about the user distribution, the radio propagation model, etc. have to be made.

### 9.1.3 Further related metric

In the context of cooperative ad-hoc networks without central access point, some further metrics, which measure the ability of the network to transmit information, are in use [46][82]. The network is said to transport one *bit-meter* if one bit has been transported successfully over a distance of one meter towards its destination. The *transport capacity* of the network is the sum of the bit-meters of all nodes per second. The *feasible throughput* is the average bitrate at which each user can transmit information to its chosen destination. Under a specific set of assumptions, [46] arrives at the conclusion, that the transport capacity increases with the number of nodes in the network whereas the feasible throughput decreases.

## 9.2 Radio Propagation Models

The following propagation models are used in the preliminary coexistence investigation of fixed services with the WINNER system, because these models have been used in [28].

**Basic Propagation Model: Free Space Loss and Spherical Diffraction**

The basic propagation model for the 3.5 GHz band includes the free space loss and the spherical diffraction attenuation, which depends on the antenna heights [28]. The link budget, with all parameters defined in dB, is given by:

$$P_\mathrm{r} = P_\mathrm{t} + G_\mathrm{t} + G_\mathrm{r} - A_\mathrm{fsl} - A_\mathrm{sp} - A_\mathrm{fm} \tag{9.9}$$

where $P_\mathrm{t}$, $P_\mathrm{r}$ are the transmitted and received power, respectively. $G_\mathrm{t}$ and $G_\mathrm{r}$ are the antenna gains of the transmitting and receiving antenna. The free space loss is given by

$$A_\mathrm{fsl} = 20\cdot\lg\left(\frac{4\pi}{\lambda_\mathrm{c}}d\right) = 92.4 + 20\cdot\lg\left(\frac{d}{\mathrm{km}}\right) + 20\cdot\lg\left(\frac{f_\mathrm{c}}{\mathrm{GHz}}\right) \tag{9.10}$$

where $\lambda_\mathrm{c}$ is the wavelength, $f_\mathrm{c}$ the carrier frequency and $d$ the distance between transmitter and receiver. The spherical diffraction attenuation can be approximated linearly and depends heavily on the antenna heights. In the following we assume a height of $h_\mathrm{c} = 30\mathrm{m}$ for the CS and $h_t = 10\mathrm{m}$ for the TS, which is described as a typical case in ERC 33 [28]. With these antenna heights, we get $d_0 = 20$ km, $K_2 = 1.3$ dB/km,

$$A_\mathrm{sp} = \begin{cases} 0 & \text{for } d < d_0 \\ K_2(d - d_0) & \text{for } d \geq d_0 \end{cases}$$

That is, for distances less than 20 km, spherical diffraction can be neglected. A detailed description of spherical diffraction can be found in ITU-R P.530-8, and exacter values can be calculated with the program GRWAVE (ground wave propagation), which is available from ITU.

The fade margin $A_\mathrm{fm}$ accounts for deep fades. This margin is necessary in fixed radio links to meet the high yearly availability objectives which are typically in the range 99.99% to 99.999%. It can be calculated according to ITU-R P.530. In ERC 33 [28], the following approximation was used:

$$A_\mathrm{fm} = \max\left\{10, -48.44 + 36\cdot\lg\left(\frac{d}{\mathrm{km}}\right) - 10\cdot\lg\left(\mathrm{un}_\mathrm{year}\%\right)\right\}$$

where $\mathrm{un}_\mathrm{year}\%$ is the yearly unavailability.

### Extrapolated Okumura-Hata Model

In [28], a tentative extrapolation of the Okumura-Hata propagation model has been defined. The median path attenuation, defined in the original Okumura model is given by

$$A_{50} = A_{\mathrm{fsl}} + A_{\mathrm{bm}} - G_{\mathrm{c}} - G_{\mathrm{t}}$$

where $A_{\mathrm{fsl}}$ is the free space loss as defined in (9.10), $A_{\mathrm{bm}}$ is the "basic median path loss", for which Okumura provides extensive experimental data for frequencies up to 3 GHz, as a function of the antenna heights. $G_{\mathrm{c}}$ and $G_{\mathrm{t}}$ are the central and terminal station height factors, which are also based on experimental data. In [28], these parameters have been extrapolated to the 3.5 GHz band, based on curve-fitting:

$$A_{\mathrm{bm}} = 20.41 + 9.83 \cdot \lg\left(\frac{d}{\mathrm{km}}\right) + 7.894 \cdot \lg\left(\frac{f_c}{\mathrm{GHz}}\right) + 9.56 \cdot \lg^2\left(\frac{f_c}{\mathrm{GHz}}\right)$$

$$G_{\mathrm{c}} = \lg\left(\frac{h_{\mathrm{c}}}{200\mathrm{m}}\right)\left(13.958 + 5.8 \cdot \lg^2\left(\frac{d}{\mathrm{km}}\right)\right)$$

$$G_{\mathrm{t}} = \begin{cases} \left(42.57 + 13.7 \cdot \lg\left(\frac{f_{\mathrm{c}}}{\mathrm{GHz}}\right)\right)\left(\lg\left(\frac{h_t}{\mathrm{m}}\right) - 0.585\right) & \text{medium city} \\ 0.795\frac{h_t}{\mathrm{m}} - 1.862 & \text{large city} \end{cases}$$

For European suburban areas, the "medium city" model is considered to be more adequate. With the antenna heights $h_{\mathrm{c}} = 30$ m, $h_{\mathrm{t}} = 10$ m and the carrier frequency $f_{\mathrm{c}} = 3.5$ GHz, the median path loss is

$$A_{50} = 121.5564 + 29.83 \cdot \lg\left(\frac{d}{\mathrm{km}}\right) + 4.7787 \cdot \lg^2\left(\frac{d}{\mathrm{km}}\right) \tag{9.11}$$

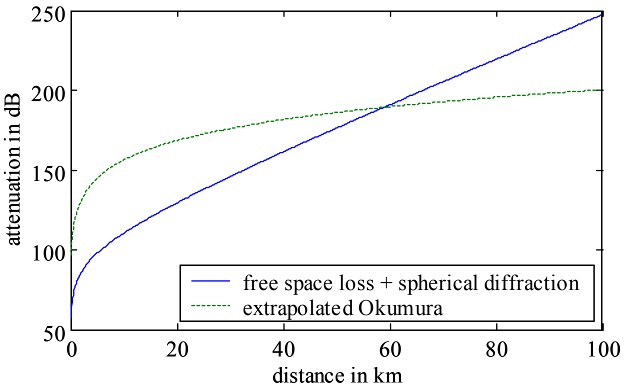

Fig. 53 Attenuation due to free space loss plus spherical diffraction in comparison to the extrapolated Okumura model.