Urban planning for Radio Communications

SP 2

Measurements of propagation and cohabitation in Île-de-France

Task D2.1.3

Dynamic Spectrum Allocation algorithms

Edition 19, 23/04/2008

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Table of Contents

Table of Figures

Abstract

In future systems, the challenge is to optimize available radio resource in composite networks comprising several radio access technologies. To achieve this goal, it is essential to adapt the spectrum allocation so that it matches with the actual traffic needs, and finally improves the user's experience. Dynamic Spectrum Allocation (DSA) algorithms enable spectrum exchange between technologies, following increases and decreases of spectrum needs, while avoiding harmful interference situations.

1 Introduction

In the future, the radio environment would not be limited to a single Radio Access Technology (RATs) but would be composed by a multi-systems platform: 2G, 3G, Wifi, Wimax, Digital Video Broadcasting (DVB), etc. Each RAT has its own interests and applications. RATs performances vary depending on the needs for mobility, rate, coverage or service type. Future systems would be built of heterogeneous networks, taking benefit of each RAT advantages and balancing their weaknesses. RATs have different performance capabilities, and may not necessarily be competing, but should cooperate to satisfy a large panel of traffic needs. By making the RATs cooperation efficient, the composite network improves its adaptation capabilities. In particular, such a collaborative approach leads to improve the overall spectrum usage efficiency and consequently to improve customers' experience. Thus the composite networks are able to provide the best connection experience to the user, whichever the location or the time.

In this heterogeneous networks context, Dynamic Spectrum Allocation (DSA) is a powerful technique that allows better adaptation of the spectrum allocation to the current needs, to improve the overall spectrum efficiency. The main challenge is to reach the best matching between spectrum bands allocated to RATs and their traffic variations, while avoiding harmful interferences. The spectrum allocation has to follow the Regulation rules, this is why the DSA must also be considered from a regulatory point of view. Many regulation bodies have started to consider this new type of spectrum management as well.

In this document, we propose technical approach and algorithm building for spectrum allocation adaptation in composite networks.

2 Towards DSA

2.1 Rationale

Spectrum needs vary over time and space, following the networks traffic evolution. Moreover, networks may have uncorrelated spectrum needs, and within a particular network, base stations have different loads and may require non-uniform spectrum distribution. If a spectrum portion is unused for a while, a RAT may want to free it, and then it can be used by another RAT. The amount of spectrum required by a RAT may vary, depending on current need in a given location. This means that if the RAT needs decrease, it can release some unused spectrum, and thus create a potential spectrum offer. Released spectrum can be used by another RAT belonging to the same operator, or by another operator. On the contrary, a RAT with increasing needs will raise a spectrum demand.

Hence, Dynamic Spectrum Allocation is a key feature for enhancing cooperation between heterogeneous networks towards an efficient use of the spectrum resource. Moreover, this technique offers new economic opportunities of spectrum trading between networks owners.

The technical improvement and economic interest are necessary but not wholly sufficient conditions to implement DSA. A preliminary requirement for DSA in a multi-operator and multi-RAT scenario is to ensure communication and collaboration between them, so that spectrum bands can be exchanged between the involved parts. Different business models can be envisaged in order to enable spectrum reallocation between separate economic entities.

In such a context of collaborative networks, a consortium of operators could jointly manage and share the spectrum, based on agreements between operators and provided spectrum regulation is respected. Consequently the architecture in which the DSA algorithm described in this document would be processed would be at a meta-operator level, as shown in Figure 1.

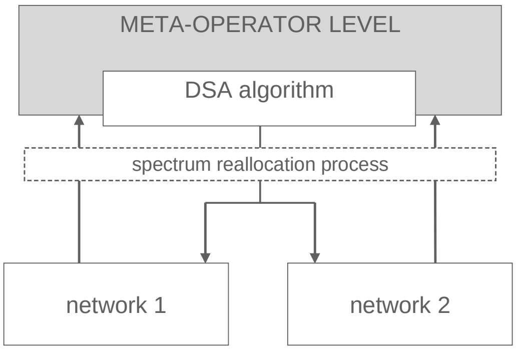

Figure 1 : DSA functional architecture.

To summarize, DSA can be operated if it brings better overall spectrum efficiency in the multi-RATs networks. Inter-operator DSA requires a shared interest between Operators. However, the technical interest leads us to consider the associated constraints presented in **Figure 2**.

2.2 Technical approach

This section presents the technical aspects that must be considered when building a generic solution for DSA between RATs.

Dynamic spectrum sharing raises the problem of compatibility between the considered RATs. Harmful interference must be avoided when sharing dynamically spectrum between them.

DSA means that spectrum allocation may not be uniform over time and space; then some interference may appear, for example between two adjacent areas with different spectrum allocations as shown in Figure 2.

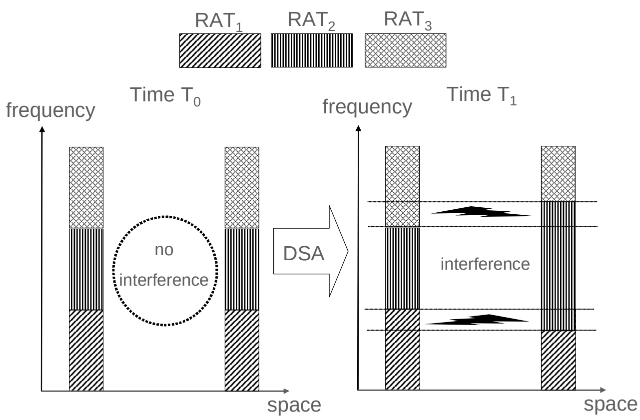

Figure 2: Interference due to harmonization rupture

3 Use Cases for DSA

Deliverable 1.3.1 of URC [URC131] has provided a technical classification of existing spectrum management schemes. Four main classes have been identified: Command and Control (not in the scope of URC), Operator Sharing, Primary and Secondary Usage (a primary user is the owner of the spectrum and have strict priority on the use of it; secondary users can access the spectrum in an opportunistic manner – overlay, or with very low output powers – underlay), Commons.

The class Operator Sharing is of primary importance in URC. In this class, there are a limited number of entities (meta-operators, operators, possibly MVNO), which are licensees of their own band or can share a common band. As the number of players is small and well controlled by the regulator, spectrum access rules can be relatively strict and precise. Operator Sharing has been further divided into two sub-classes:

Long Term Operator Sharing and Dynamic Operator Sharing. The first sub-class describes more or less the situation as it is today: license owners have fixed spectrum bands and these bands are often dedicated to a service and/or a radio access technology (RAT).

In this section, we focus on the second sub-class, namely Dynamic Operator Sharing. Reference [URC131] has given some hints (non exhaustive) of the possible use cases in this sub-class. Technology agnostic licensing: the license is not any more dedicated to a service or a RAT but can be used by the operator for any technology. Secondary markets: an operator can sell part of his spectrum to another operator. Spectrum pooling: part of the spectrum (sometimes called Coordinated Access Band – CAB [Bud05]) can be shared by several operators or RATs in an opportunistic manner.

In this context, the P1900.4 group of the IEEE is currently defining a standard describing an architecture enabling network-device distributed decision making for optimized radio resource usage in heterogeneous networks [P1900.4draft]. Latter reference is only a draft and nothing has so far been defined precisely. It is however clear from E2R works (see e.g. [E2RWWRF]), available presentations on P1900.4 and meeting minutes [SCC41] that P1900.4 is definitely building blocks for the sub-class Dynamic Operator Sharing. According to [SCC41], the field of application of P1900.4 is indeed is radio systems with composite radio network environment (multi-RAT, multi-RAN); terminals with cognitive, multimode and optionally multi-link capabilities; multi-operator, meta-operator environments. In this section, we detail the three use cases envisioned by P1900.4 for this context:

- Dynamic spectrum assignment,
- Dynamic spectrum pool,
- Hybrid dynamic spectrum assignment.

3.1 Involved entities

We first recall in this sub-section the involved entities (see [URC132] for more details).

Radio Access Technology (RAT): it is a single standard technology accessible via radio. Examples are GSM (and the evolutions, GPRS, EDGE), UMTS (WCDMA, HSPA, HSPA+, LTE), IS95, CDMA2000, IEEE 802.11, IEEE 802.16, etc. A RAT is not necessarily dedicated to a single service (e.g. voice).

Cellular network: it is an operated network using one or several RATs.

Operator: In a cellular network, an operator is in charge of the “good use” of frequencies, i.e., there is no or negligible interference towards other systems and an efficient use of the spectrum. An operator is today owner of one or several licenses for spectrum usage. It is able to perform JRRM (joint radio resource management – if RAT spectrum bands are fixed) or DSA (if spectrum bands can be exchanged) between its RATs.

Meta-operator/RAN manager: This is unique entity above operators in charge of performing resource management between several operators (auctions, spectrum allocation/assignment, spectrum usage optimization, etc). In [Bud05], this meta-operator is called “spectrum broker”. This broker is permanently owns the CAB spectrum and only grants timebound lease to the operators. Today, there is no such entity but we can imagine that this function could be endorsed by the regulator or a common structure created by several operators.

There are three scenarios in which the following use cases can be applied:

- Single operator, multiple RATs: an operator has several spectrum bands, several RATs and tries to optimized the use of its resources.
- Multiple operators, no meta-operator: operators have their own spectrum bands and can lease part of their bands on a market.
- Multiple operators and a meta-operator: operators have their own spectrum bands, there can be a spectrum pool; spectrum exchanges or spectrum accesses are coordinated by the meta-operator which is trying to optimize the use of the spectrum.

3.2 Dynamic spectrum assignment

The use case “dynamic spectrum assignment” is illustrated on Figure 3. There are two entities with their own spectrum bands. These entities are allowed to exchange spectrum blocks. Spectrum blocks include guard bands in order to prevent neighbor bands from interference. They can be of fixed of variable size. In the latter case, the issue arise of avoiding spectrum holes due to an inefficient packing of the allocated blocks.

In case of TDD RATs, spectrum blocks exchanges can be performed provided that a FDMA dimension is available is each RAT. In order to take advantage of several disjointed blocks, terminals and infrastructure should indeed be able to switch from one carrier frequency to another.

In case of FDD RATs, spectrum exchanges have to be done both in uplink and downlink in order to keep the duplexing symmetry.

In case of mixed TDD/FDD, the FDD RAT can provide to the TDD RAT only a downlink or an uplink band. The TDD RAT should be able to give however two blocks, one for the uplink, one for the downlink.

Single operator, multiple RATs interpretation – an operator has obtained two spectrum allocations for two different RATs, e.g. WiMAX and UMTS (black parts for RAT1 and RAT2 on the figure), which potentially offer different kind of service or quality of service, have different capacities and/or coverage and generate different revenues. Each RAT has a “natural” , i.e., priority, access its allocated band. According to the capacity, coverage and the revenue generated by each RAT, terminal capabilities, load balancing decisions, etc, the operator performs dynamic spectrum access between its RATs. Note that, under the supervision of the operator, there is in this case a full cooperation between RATs.

Multiple operators, no meta-operator – The technical problem is similar except that the economical aspect is different. On the figure, the two RATs belongs to two competing operators, so that the economical game is modified. An operator may not accept to exchange or sell spectrum blocks for the same service he is providing. He may however sell spectrum for a different service or in a region where he has no RAT deployed.

Multiple operators, meta-operator – this context is very similar to the latter one in the sense that there are multiple competing operators and to the former one because there is a meta-operator with optimization objectives. The meta-operator can for example organize auctions if more than two operators are involved in exchanges. He is however also responsible for an efficient use of the spectrum.

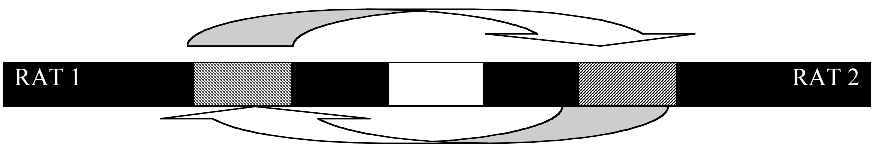

Figure 3 Use case “dynamic spectrum assignment” illustration.

3.3 Dynamic spectrum pool

The dynamic spectrum pool use case is illustrated in Figure 4. There are two entities that don’t have their own spectrum band. They have however the possibility to access a pool of block frequencies. These blocks can be of fixed or variable size. An entity has no priority on the spectrum pool, i.e., entities have equal access to the pool.

Single operator, multiple RATs interpretation – an operator has mutualized all the bands he obtained a license for, and uses this pool for all its RATs. In this case, considered entities are two different RATs accessing the common pool. As in the previous use case, it is logical to assume in this case a full cooperation between RATs, allowing load balancing, JRRM, geographical DSA, etc. The operator is here a central intelligence organizing this cooperation.

Multiple operators, no meta-operator – In this case, there are multiple operators without exclusive band that access to the spectrum pool. There is no meta-operator, this means that there is full competition between operators and the situation can be analyzed e.g. using non-cooperative games.

Multiple operators, meta-operator – In contrast to the latter case, there is a meta-operator or regulator that is able to regulate the access to the spectrum. In particular, the pricing can be organized by the meta-operator.

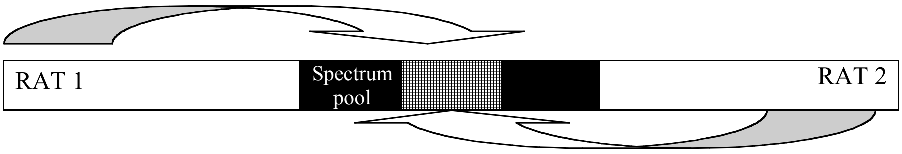

Figure 4 Use case "dynamic spectrum pool" illustration.

3.4 Hybrid dynamic spectrum assignment

The hybrid dynamic spectrum assignment is illustrated in Figure 5. This is a combination of the two last use cases. There are two entities that have dedicated frequency bands on which they have an exclusive access (as in the dynamic spectrum assignment use case). In addition to these two bands, there is a spectrum pool that entities can access on a equal basis (as in the dynamic spectrum pool use case).

Single operator, multiple RATs interpretation – An operator has several RATs and decided to mutualize part of its spectrum between its RATs. On their dedicated bands, RATs have still an exclusive access, but there is in addition to this, a spectrum pool that RATs can access on demand. This is a way of better utilizing the operator spectrum.

Multiple operators, no meta-operator – Entities are here operators and there is no meta-operator. Each operator has its own bands on which it has an exclusive access. There is however a full competition between operator for the access to the spectrum.

Multiple operators, meta-operator – In contrast to the latter case, a meta-operator is able to regulate a little bit the competition in order to have a good spectrum utilization. Pricing is a means for the meta-operator to encourage leaving a spectrum block when traffic is low and demanding more blocks when traffic is high.

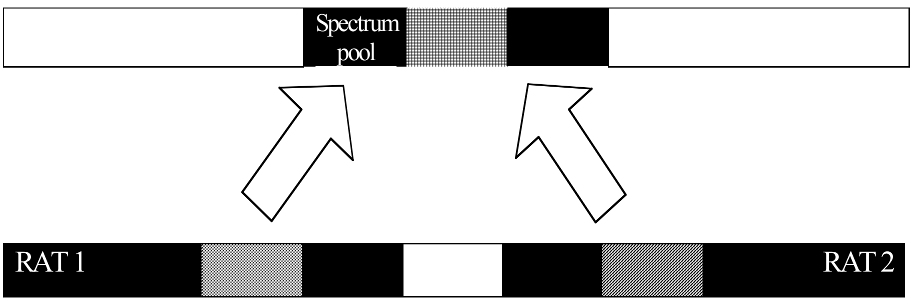

Figure 5 Use case "Hybrid dynamic spectrum assignement" illustration.

3.5 DSA Use Cases in URC Scenarios

The following table gives the mapping, when meaningful, between the DSA use cases presented above and URC scenarios [URC121]. If several use cases are applicable, the most probable one, or the more realistic is given. On the contrary, if none of them is applicable, it is notified as N/A.

URC Scenario or Theme	DSA Use Case
SC1: Unlicensed Networks	Dynamic Spectrum Pool
SC2: Wireless Local Loop	Dynamic Spectrum Assignment
SC3: Analog to Digital TV	Dynamic Spectrum Pool or Hybrid Dynamic Spectrum assignment
SC4: Exceptional Events	Hybrid Dynamic Spectrum Assignment
SC5: Major Crisis	Dynamic Spectrum Assignment
SC6: Metropolis	N/A
TH1: UWB	N/A
TH2: Geographical coexistence	Dynamic Spectrum Assignment
TH3: Frequency management and local authorities	N/A

Notes :

- In SC1, RATs have no dedicated licensed band, so only the spectrum pool is applicable.
- In SC2, WLL operators operate in regions and can thus possibly exchange bands from one region to another or at region borders.
- In SC3, in case of multiple frequency networks (there is a frequency reuse in digital TV), the frequency used in a region can be reused for secondary usage in another region. RAT1 is a broadcast system, and so not subject to DSA. RAT2 is an opportunistic system, using geographical spectrum holes as a spectrum pool, maybe in addition to a dedicated frequency band. Without this dedicated frequency band, the relevant case is Dynamic Spectrum Pool, with the dedicated frequency band, the relevant case is Hybdrid Dynamic Spectrum Assignment, from the point of view of RAT2.
- SC4 is described in more details below.
- In SC5, several use cases are applicable, but dynamic spectrum assignment seems to be the most probable. In this case indeed, congested RATs (security, firemen, etc) have dedicated spectrum bands but can also borrow some spectrum from RATs with less priority.
- In TH2, two RAT that are sufficiently far away can share the same spectrum band. Even if DSA use cases are not really applicable in this case, the dynamic spectrum assignment one seems to be the closest one.
- SC6 and TH3 are related to the role local authorities could play in spectrum management and so are not applicable in the context of this deliverable.

The scenario “exceptional event” is a clear application of the above concepts [URC121]. There are two operators, one with only a GSM network, the other with both GSM and UMTS. GSM is deployed in 900 and 1800 MHz bands and UMTS in 2 GHz. According to [URC121], there is a possibility of frequency reallocation between two RATs of a single operator in this scenario.

An operator managing in a city two bands for GSM/GPRS/EDGE on the one hand, UMTS on the other hand, can either use dynamic spectrum assignment or hybrid dynamic spectrum assignment in order to better utilize its spectrum. For example, if there is a sudden increase of data traffic load because of the downloading of a video, GSM network can lend part of its bands to UMTS network.

In the scenario “exceptional event”, it is explained that supporters can use WLAN hot spots. If hot-spots in the stadium belong to two operators, WLAN access in the 2.4GHz band is done according to the dynamic spectrum pool use case without meta-operator. If the city or stadium administration want to regulate the 2.4GHz band in the stadium, the same use case applies but there is a meta-operator.

Suppose now that Operator 2 has UMTS bands in city 1 but has not yet deployed UMTS network. It is able to lease part of its spectrum to Operator 1 during the exceptional event. This example is an illustration of dynamic spectrum assignment between operators without meta-operator.

4 Cognitive features for DSA

4.1 Cognitive-inspired algorithm model

In Figure 6, J. Mitola introduced the Cognitive Cycle, where the main cognitive tasks are: *observe the outside world, orient, plan, learn and act.* The *outside world* corresponds to the radio environment, and the different cognitive tasks correspond to the different technical aspects and constraints of a DSA procedure.

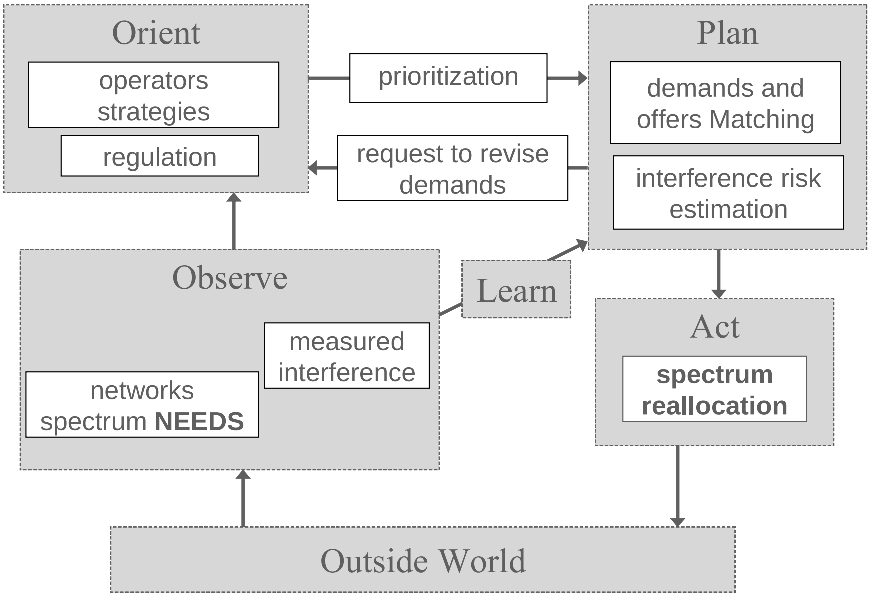

Figure 6: Cognitive-inspired DSA algorithm

Some adapted regulation policy should be respected when operating DSA. Policies may depend on the local time or on the geographical location; therefore radio communications rules respected by cognitive networks would be a dynamic input understandable by the DSA algorithm. This step of DSA is illustrated by the block *Orient* in Figure 6.

With this information, the algorithm is able to plan and target a new spectrum allocation, as represented in the blocks *Plan* and *Act*.

Nevertheless, the operation of DSA algorithm and the resulting spectrum reallocation may cause unexpected interference. Therefore, some measurements can be performed in order to check if the results satisfy the expectations in terms of accepted interference in all the impacted networks. By comparing the effective results with the expectations, the algorithm can *learn* and eventually correct the way of planning for future reallocations (e.g. estimate guard bands).

4.2 A Cognitive Radio enabler

DSA mechanisms are defined assuming the availability of suitable radio cognitive equipments in the context of coexisting and cooperating multiple access technologies. In this context of multiple access techniques and changing spectrum allocation, a dedicated radio enabler transmitting relevant information on radio environment could be a technical support to facilitate DSA mechanisms.

Indeed, when a mobile is switched on, it has no information about the available systems in its area nor on the current spectrum allocation to these systems. In order to avoid the scanning of all the spectrum range and to facilitate the initial connection to the network, the mobile could listen first to a broadcast radio channel containing the necessary information to initiate its connection. This radio channel could be the enabler for helping the network selection.

Actually, the "classical" (3GPP standard [1]) initial selection of network is not efficient. Indeed, the mobile has no information about the location of the RATs within the DSA frequency range (e.g. from 500 MHz to 6 GHz). It is then necessary to scan the whole band to get the spectrum constellation. Thus, the idea is to have a "radio enabler" in a harmonized frequency band to initiate the connection with the available network. This radio enabler will be available anywhere and anytime, and would allow to efficiently managing a large number of standards.

Naturally, the content of this broadcast channel would need to be specified before any technical implementation. However, the technical specifications are out of scope of this deliverable but should be defined in a more relevant URC deliverable [D2.1.2].

5 DSA generic algorithm

The global architecture of the main algorithm is described in the present section and illustrated in the following figure.

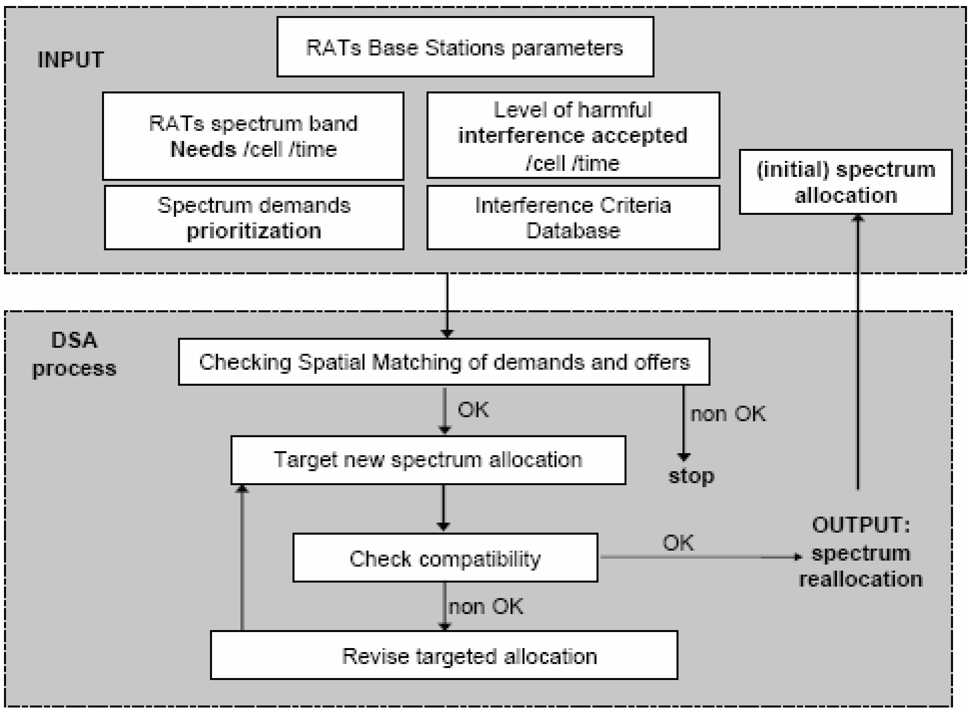

Figure 7: global architecture of DSA process

5.1 Input parameters

5.1.1 Spectrum needs, offers and demands definition

Spectrum needs are one of the main inputs to the DSA algorithm and should be expressed with their associated interference tolerance levels. Networks manage their radio resources, and calculate their spectrum needs depending on the time and space. In a more concrete way, these needs could be expressed for example by a number of carriers needed by a base station for a given period.

From the spectrum needs, the algorithm will deduce spectrum offers and spectrum demands. Indeed, if the need is superior to the current amount of spectrum available, it means that the RAT is demanding spectrum. On the contrary, a base station that would be allocated a spare amount of spectrum may release this spectrum for the usage of a demanding RAT.

In a reconfigurable context, the amount of spectrum required by a RAT may vary, depending on current need in a given location. The evolution of spectrum needs automatically produces spectrum offers and demands. Indeed, if a network need is greater than the spectrum currently allocated to it, this means that this network is raising a spectrum demand. On the contrary, if the need is smaller than the allocated band, this may produce a spectrum offer if the network owner wishes to make the spare spectrum available.

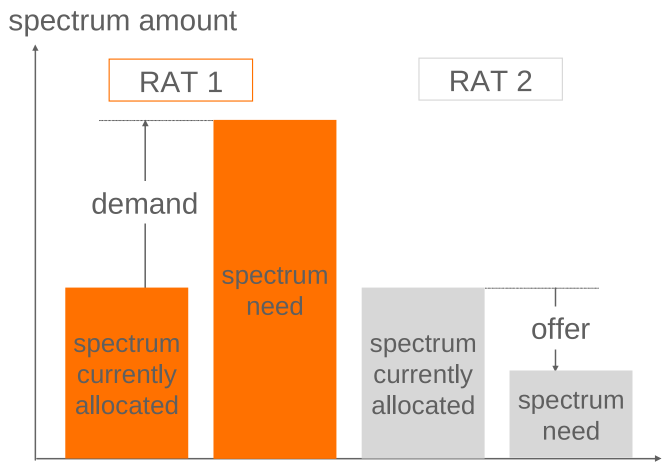

FIGURE 8: Spectrum offers and demands

It may occur that several networks have competing spectrum demands. In this case, a prioritization of the demands is required in order to process DSA algorithm.

Operators' strategies determine the way of prioritizing RATs spectrum demands, and may depend on their traffic and load balancing strategy and on trading mechanisms between operators.

5.1.2 Stations characteristics

The main inputs include parameters of the RATs base stations as well as their locations, the initial spectrum allocation, the band plan and the initial frequency assignment of each base station. The RF parameters of the Base stations are important for the calculation of the co-existence conditions. These conditions could be a minimum guard band required between operating bands and separation distance between heterogeneous stations coexisting in the same band.

Several coexisting RATs may accept different levels of interference, depending on technology sensitivity. Moreover, the accepted interference level can vary, following the overall required quality of service. For example, a network may require a large amount of spectrum, even if there is a fair amount of interference in it, whereas in other circumstances, it may need a small amount of additional spectrum but requiring a very low level of interference. The box "level of harmful interference accepted" in Figure 7 aims to take into account this parameter as an input of DSA algorithm.

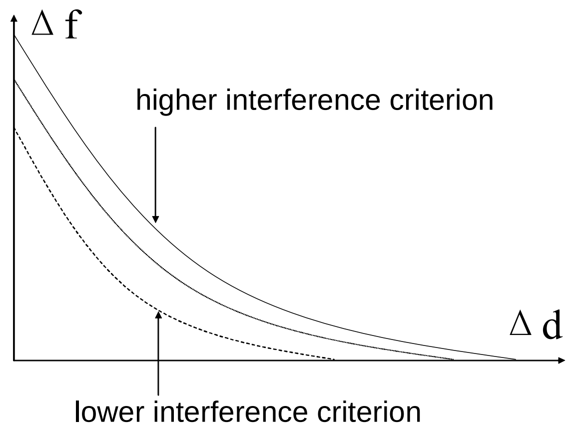

Figure 9: Interference criteria

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Before targeting a new spectrum allocation, the level of interference after reallocation has to be estimated as accurately as possible. If the forecast interference is lower than the specified accepted level, then the reallocation is triggered. For this reason, the DSA algorithm has to know the interference criteria to be fulfilled before checking the compatibility. As mentioned above, interference between two systems can be avoided if sufficient guard band and/or separation distance are used. The Figure 9 shows three different curves, representing 3 interference criteria, corresponding to 3 tolerance levels. Compatibility is ensured between two networks if the couple of points (Δf, Δd) is above the curve associated to the desired tolerance level, whichever the terminals location in their coverage area. The higher the interference criterion is, the greater Δf is required, for a given Δd.

The interference criterion is related to the allowed QoS degradation and is to be defined for each RAT and service profile (voice, data rate, chip rate Eb/No). Depending on the RAT, it is usually given in terms of (C/I)dB, (I/N)dB or capacity Loss.

5.1.3 Interference criteria database

The interference criteria database is derived from coexistence conditions calculations that are performed within a spectrum management engineering tool.

The example depicted in Figure 10 shows DSA issue considering spectrum reallocation between 2 RATs, limited by interference from/to a third RAT. We observe that there is an area where some spectrum is offered by a RAT, named offer area, and another area where some spare spectrum is needed by another RAT, named demand area. Although we could target a spectrum reallocation between offer and demand in their overlapping zone, it is not possible everywhere due another RAT interfering.

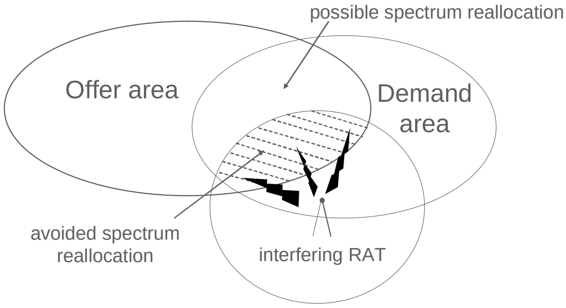


Figure 10: interference constraint in DSA.

In a real case, the interference issue may be much more complicated as we will have to consider several RATs whose spectrum needs vary, and study coexistence with all RATs in the adjacent bands/ adjacent areas.

This means that for each reallocated portion of spectrum, we need to estimate the interference risk between this RAT and RATs of the frequency neighbourhood and/or geographic neighbourhood.

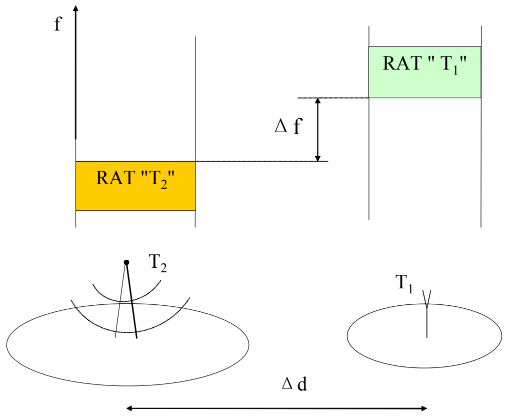


Figure 11 : Frequency and distance separation between two RATs

There are three basic ways to avoid interference between two RATs:

- frequency bands separation : "guard band" between their operating bands (Δf)
- separation distance between zones of usage to avoid co-channel interference (Δd)
- a combination of the two above (Figure 11).

RAT T_2 is protected from interference from RAT T_1 if

$$\Delta f \leq \Phi_{1/2}(\Delta d, H(T_2))$$

Where Φ is a function which gives the minimum frequency separation Δf to be kept, depending on the separation distance Δd and on the maximum level H of interference (H for *harmful*) accepted by T_2. An example of function Φ is shown in **Figure 12**

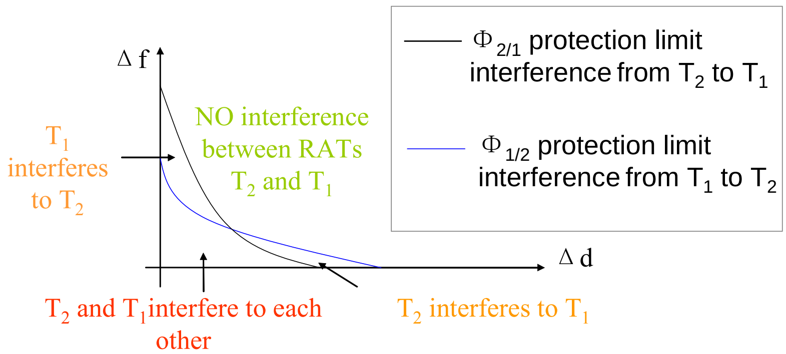


Figure 12 : interference zones between two RAT

5.1.4 Monte-Carlo method for interference risk estimation

The Spectrum Engineering Advanced Monte Carlo Analysis (SEAMCAT) tool is a software product based on the Monte Carlo simulation method, which permits statistical modelling of different radio interference situations. This simulation model was developed by the group of CEPT Administrations (Communauté Européenne des Postes et Télécommunications), ETSI (European Telecommunication Standard Institute) members and international scientific bodies. Now this model is widely introduced and used within CEPT and ITU-R (International Telecommunication Union- Radiocommunication). Furthermore, it is public domain software distributed by the European Radiocommunications Office (ERO).

SEAMCAT let us infer different important results, as well as, the necessary separation distance between the antennas and the suitable bandwidths between the frequency allocations, in order to meet the desired level of interference between systems in the simulated scenario.

The most important part in a SEAMCAT simulation is the specification of the systems that will appear in the scenario. The position of the interferer transmitter in relation to the victim receiver, the noise level, the minimum signal/noise ratio, the frequencies of the victim and of the interferers are, amongst others, important inputs of the SEAMCAT scenario specification. Moreover, in order to quantify the level of interferences that could cause one system to another, we need a specific characterization of the interfering transmitters. Characteristics such as the height and the tilt of the antennas, the coverage, the reception mask, the emission mask, the power level, etc. All the interfering transmitters will be distributed in the scenario following the user's distribution configuration. It is also possible to configure the receivers' characteristics and the propagation model.

The effect of each interfering transmitter on the victim is given by using the formulas and the parameters of the victim and the interfering transmitter. Several mechanisms of interference are taken into account, such as the emissions out of band, the non ideal reception filters, as well as the products of inter modulation. In order to obtain the total level of interference we have to sum up the effects of all the interfering transmitters. The level of useful signal that arrives at the receiver will be calculated with the comparison between the interference and the transmitted useful signal.

Calculation is reiterated a number of times equal to the number of samples chosen by the user, and for each calculation, the position of the victim compared to its wanted transmitter and compared to the various interference transmitters will change. In each loop the level of the useful signal (C) and the level of the interference (I) are compared: we could consider that we have an inadmissible interference when the calculated C/I is lower than the C/I defined by the user. If that happens we will try to modify different characteristics of the scenario such as the separation distances or the bandwidths until we achieve an acceptable percentage of probability of interference.

The Figure 13 shows the different signal levels that we could find in two different situations, with interferences (right side) or without interferences (left side). On the right side the difference between the level of the useful signal and the interference measured in dB is the C/I which must be higher than a certain threshold (Protection Ratio) if one wants to avoid the interference.

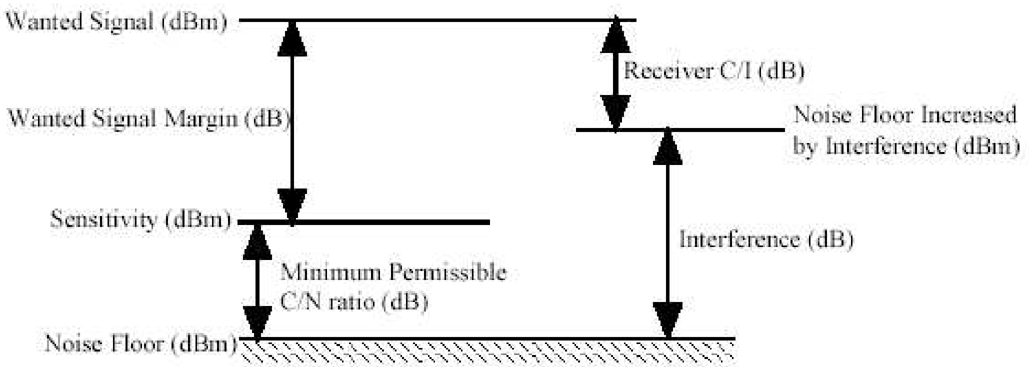


Figure 13 : Noise, Sensitivity, C/I in a SEAMCAT framework

In the Figure 14, we can observe a typical scenario where we can find all the components that take part in a SEAMCAT simulation. In that scenario we can observe how one fix system (Interfering transmitter – It) introduces interferences into the mobile receiver, the victim receiver (Vr). Clearly, the victim link is the mobile link and the Interfering link belongs to the fix communication. The wanted receiver (Wr) is, for example, one antenna placed at the top of a building and the wanted transmitter (Wt) is the antenna of the mobile phone.

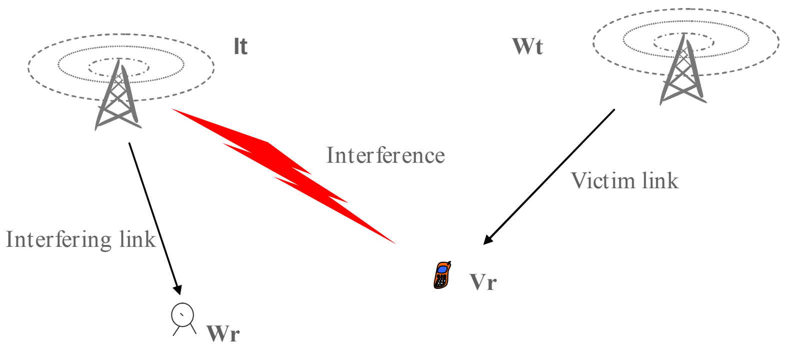


Figure 14 : Example of a typical scenario studied in SEAMCAT

The RATs need zones representative of spatial and time capacity demand and the spectrum demands prioritization. These need zones are considered per cell, per antenna and therefore for each RAT and calculated according to the capacity and coverage requirements.

5.1.4.1The case of broadcasting systems

The figure below illustrates the different interference situations involving a broadcast system.

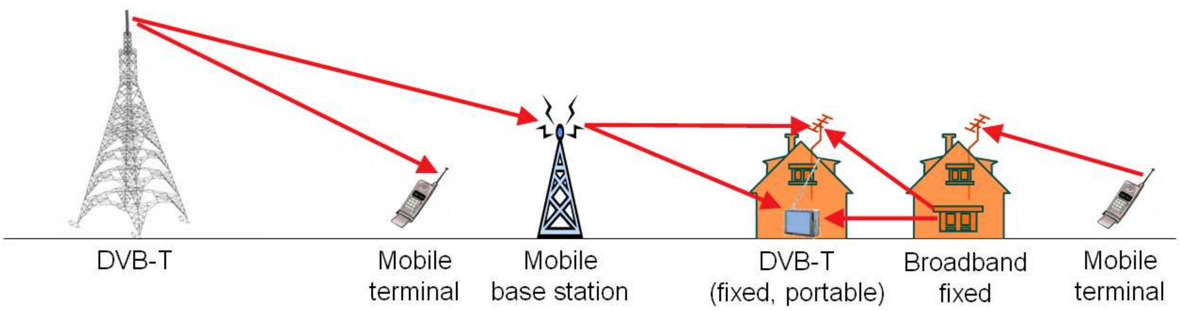


Figure 15 : Interference scenarios for sharing between broadcast and fixed/mobile services (from [13])

Since broadcast systems are unidirectional, the possible interference situations are as follows:

- Co or adjacent channel interference from broadcast system to fixed/mobile services downlink: such interference occurs at the fixed/mobile base station.
- Co or adjacent channel interference from broadcast system to fixed/mobile services uplink: RF interference occurring at the fixed/mobile terminal.
- Co or adjacent channel interference from fixed/mobile services downlink or uplink to broadcast system receiver: when fixed DVB-T reception is considered, interference is caused through the (potentially high gain/high directivity) antenna system (this antenna system can be considerably complicated or constrained in the case of collective reception, as is the case when considering large cities/areas such as Paris and its suburbs); when portable DVB-T/DVB-H reception is considered, the receiving antenna system can be considered as one of the same kind as those used on mobile terminals (that is omnidirectional and low gain antenna are assumed).

Note: in case the broadcast system receiver is subject to interference, adjacent channel interference is not restricted just to the first adjacent channels, but can extend far away from the received useful channel. In particular, due to the super-heterodyne technology and intermediate frequency used in the receivers, interference from channel N+9 can be a real concern (see §5.1.4.4 for details on current protection ratios, see [14]for a rough explanation of why this is a concern in receivers: this information is still applicable to the majority of DVB-T receivers since the same technology is still at use).

In the first case, the location of the interferer and the victim are fixed while in the last two cases, either the interferer or the victim are subject to location variation or at least to a spatial distribution; as a consequence for those two cases, effective interference heavily depends on interferer/victim location and distribution.

At first sight, the broadcast transmitter never suffers from fixed/mobile services interference:

- This is true for the main transmitting sites (high power/high antenna height) because the signal on those sites is generally fed by a satellite or a dedicated RF link
- Nevertheless, secondary transmitting sites can suffer from this kind of interference when they are fed directly by a broadcast channel. This is the case when a main transmitter is piloting a secondary transmitter: the secondary transmitter is equipped with a dedicated receiver; the received signal (sometimes demodulated/decoded and recoded/re-modulated) is then transmitted by the secondary transmitter. Any interference caused on the reception side of the secondary transmitter can have a huge impact since the whole coverage area of this transmitter will suffer from the interference. This case of interference is critical when the secondary transmitting site is located in urban zones (this can happen either to compensate for lack of coverage or to densify the field strength, e.g. for increased availability of portable reception) since interference is more probable due to the potentially increased number of customers of fixed/mobile systems.

As can be seen above, at least 3 interference situations have to be considered when evaluating the interference risks between broadcast and non broadcast systems, with the eventuality of an additional one (fixed/mobile system interference into broadcast station pilot reception). In addition, for broadcast reception, at least two reception conditions have to be considered (fixed and portable receptions) according to the intended audience, which can have considerable different sensitivity to interference due to real different antenna system.

5.1.4.2Monte-Carlo methods applied to broadcasting systems

When considering the various interference situations described above, two approaches can be taken in evaluating the potential interferences:

- Interference situations where broadcast station and base station are involved can be solved by means of static analysis: since both types of stations are bound to a specific location, useful and interfering signals can be predicted/measured on a large set of reception points (or a regular grid) to determine on which set of reception points interference may occur and to find mitigation techniques.
- Interference situations where fixed/mobile terminal is involved, the use of statistical methods is compulsory to take into account the random location and operation of those terminals throughout the day. This randomness is solely used for the fixed/mobile terminals as broadcasters seek protection for the whole are covered by their broadcast stations. In addition broadcast receivers can have a varying location from one broadcast reception zone to another, but their location is fixed (at least for fixed reception!) and they can operate on a continuous basis.

The use of Monte-Carlo methods usually happens in the last situation, to simulate the time and location variation of the fixed/mobile terminals. When Monte-Carlo methods are used, the outcome of such methods is an interference probability, which is usually a time probability. Location probabilities can be defined as well, see for example [15]

Interference probability depends on the location of the reception points as well as of the random location and operation of the fixed/mobile terminal:

- When the fixed/mobile terminal is a potential victim of interference from a broadcast station, the reception points are clearly defined by the location of these fixed/reception terminals.

- When the broadcast system is a potential victim of interference, the potential interference is usually investigated at the edge/boundary of the broadcast coverage, where relatively low useful field strength increase sensitivity to interference. But potential interference can also occur within the coverage area, for example near the interfering transmitter (when this one lies within the coverage) where high field strength values can be found (provoking an overload of the broadcast receiver frontend and/or interference due to a degraded C/I ratio)

Considering the previous description of interference tolerance, and due to the non-static nature of the fixed/mobile interference, at least two criterions must be taken into account in defining interference probability:

- Spatial interference probability over a small area, at a local point of view: for example, the mobile service uplink service may have a local interference probability of 1% near the broadcast coverage edge, but only .001% near the broadcast transmitter. The average global interference probability, over the entire broadcast coverage area, may however be only 0.1%, the global interference probability might seem to be acceptable, but the local interference probability at the coverage edge might be considered highly unacceptable.
- Time interference probability: the fixed/mobile service has time-varying characteristics, such as communication time length, rate of communication …Those characteristics have a direct impact on the interference tolerance: for example, a short interruption of 1 second once a week might be considered acceptable, while it would not be the case for the same short interruption once an hour, and a long interruption of 30 seconds/1 minute would not be acceptable at all.

A detailed description of broadcast coverage calculation, broadcast coverage loss calculation and the relationship between interference probability and coverage loss are given in annex (see §**11.2**)

5.1.4.3Sample Monte-Carlo simulation model

This sample simulation model is directly extracted from [20]. The simulation model is taken “as-is” as it is really representative of what has to be done to assess the broadcast coverage loss.

Such a simulation model can be used for other cases of interference, for example for mobile DVB-T reception interfered with by a mobile service uplink (eg. [21]). If it were to be applied to situations where specific interference has to be evaluated within the broadcast coverage area, the location of the area of interest would have to be adjusted accordingly. In the same way, the scenario presented in [20] is used to evaluate the urban UMTS-uplink interference into a DVB-T fixed receiver. The interferers (UMTS UE) are located outdoors, within a typical UMTS cell and power controlled as part of a UMTS network. The DVB-T (victim) receiver antennas are located at 10 m height on the roof tops of typical domestic buildings.

Each UMTS cell forms part of a hexagonal ring-formed cluster, as in Figure 16, and a number of clusters form a network. A uniform number of interferers are distributed randomly across the UMTS cluster. A large number of victim DVB-T receivers are randomly distributed throughout a small area of investigation (the 'area of interest'), usually located at or near the broadcast coverage boundary, fixed within the 'cell of interest' (usually the central cell of the cluster) as in Figure 17. The impact of the total interference from the UMTS UE cluster is aggregated (power summed) at each victim DTT receiver within the 'area of interest'. The 'cell of interest' is arranged to be coincident with, or near, the perimeter of the broadcast coverage area, see Figure 2. The victim DVB-T receivers are thus located in, or near, a marginal coverage area at the extreme of broadcast coverage where they are most susceptible to interference. The positioning of the broadcast coverage area, the 'area of interest', and the 'cell of interest' are displayed in Figure 3.

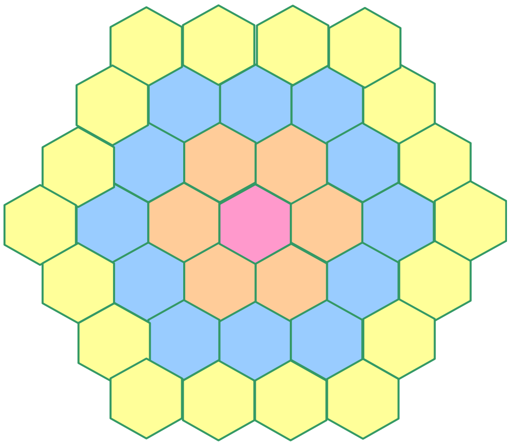


Figure 16 : The basic network unit used, a Cluster of 37 Cells, in 3 rings around the central cell

The Monte Carlo statistics are generated using the following parameters (see Figure 18):

- For a given Monte Carlo simulation, a thin (10 m depth) 'area of interest' is chosen at, or near, the broadcast coverage (BC) boundary; it extends across the 'cell of interest' at the given distance from the broadcast transmitter
- A new set of 1000 test points (TP/victim receivers) are chosen randomly within the 'area of interest' for each 'snapshot'
- A new set of 2109 (= 111 x 19 cells) active interferers are chosen randomly within the 2-ring cluster of 19 cells for each 'snapshot'
- A simulation consists of 1000 'snapshots'

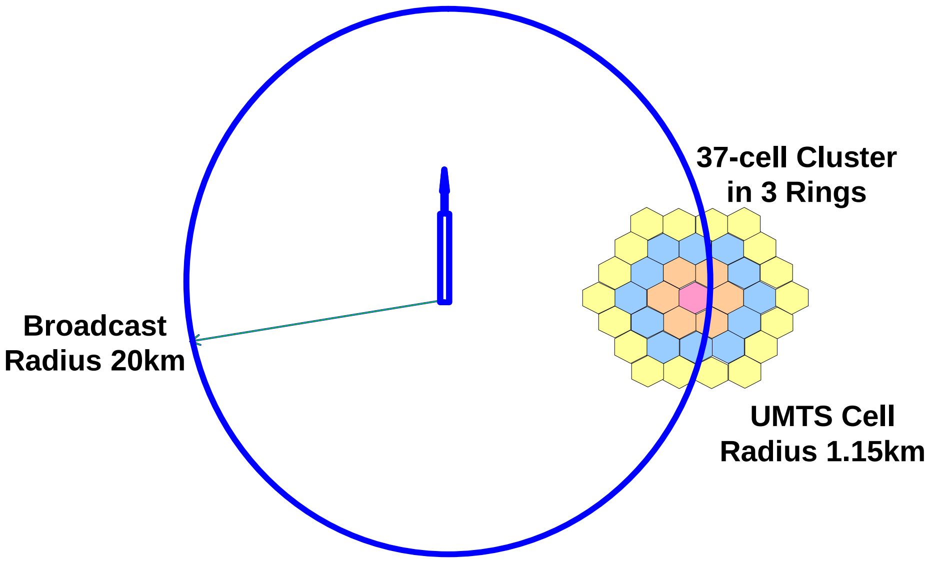


Figure 17 : The Urban Marginal Case

Using this simulation model, interference probability Pi, within the 'area of interest' is calculated as follows:

Pi = (total # of interfered victim sites)/(# of snapshots x # of victim sites per snapshot).

Because the Monte Carlo simulation is carried out over a small area, the interference probability and the coverage on the area of interest can be related:

Probability of coverage = 1 - Pi.

If this probability of coverage is larger than 95%, then the area of interest is considered 'covered'. Otherwise this area of interest pertains to the collection of areas interfered with. In this simulation model, the area of interest coverage is considered as a small area coverage (i.e; Level 2, referring to the definitions given in §**11.2.1**)

The computation of this probability of coverage over a large number of areas of interest permit to evaluate either the broadcast coverage loss induced by the interferers or the necessary boost in ERP to maintain the original coverage area. Determining both can be rather straight forward for simple simulations situations, for example the one shown in **Figure 42** where everything is symmetrical and thus doesn't require the computation of the probability anywhere apart the broadcast coverage limit. The situation becomes rapidly more complicated when terrain effect, real network modelling, more refined propagation models … are introduced.

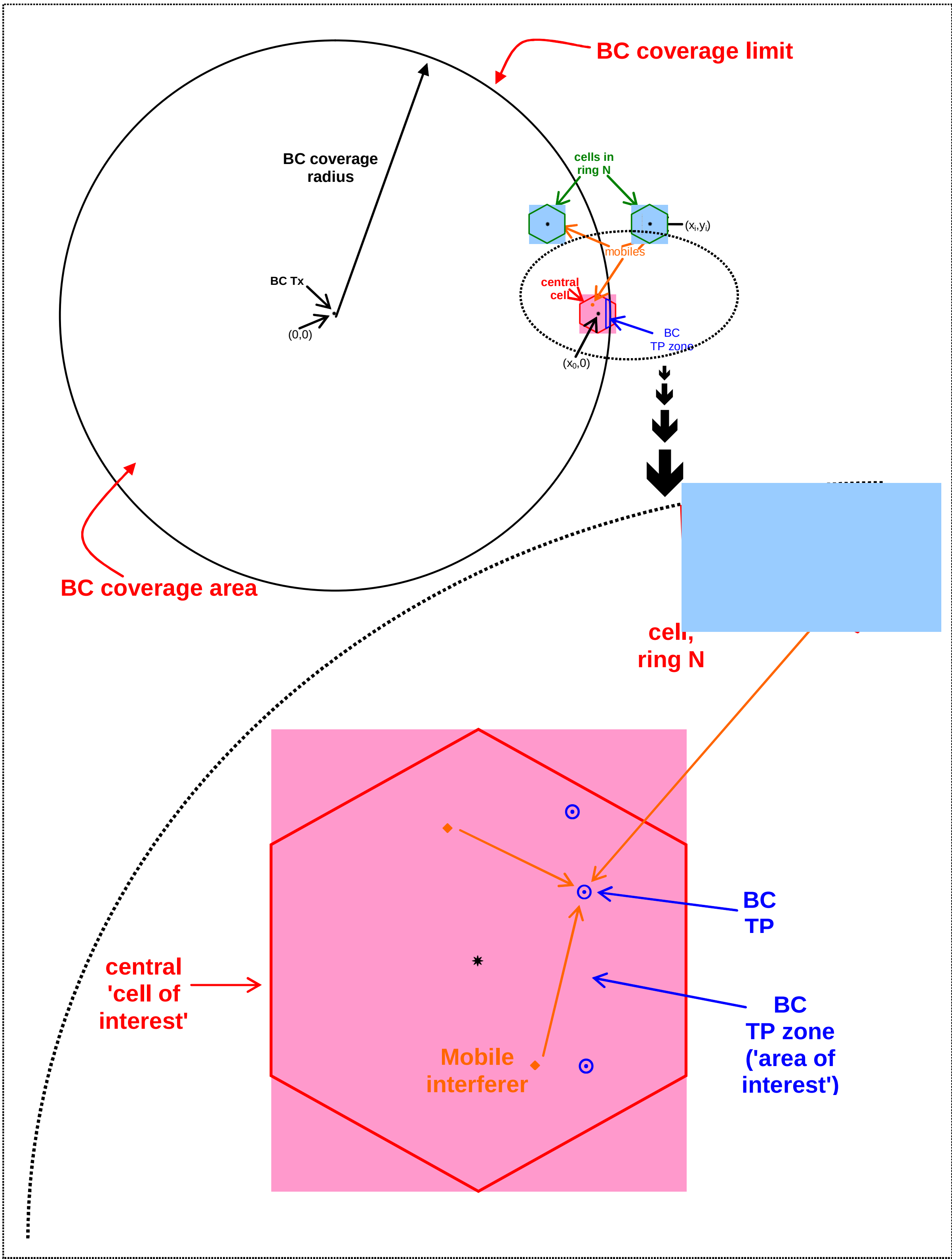


Figure 18 : Monte Carlo simulation in action

5.1.4.4Broadcasting interference criteria

Interference criteria data involving broadcast systems can be found in various sources, among which:

- [22]this recommendation provides useful values of protection ratios for protection of broadcast services towards other broadcast services, as well as towards other existing services in the same frequency bands (VHF/UHF). The data provided by this document is to be taken as a **Reference**.
- Several contributions to international study groups focusing on sharing with broadcast services; currently, the most relevant study group is TG4 (CEPT study group dealing with the digital dividend and coexistence between broadcast/multimedia/telecommunication services in the same frequency bands or adjacent ones), which provides several pieces of information regarding interference criteria data (The data provided in these documents are to be taken as **Informative**):
    - See [25] for data on sensitivity to front-end overloading,
    - See [24], [25] and [27] and for data on protection ratios
    - See [23], [26] and [28] for data on separation distances).

The previous contributions give informative data on interference criteria in the sense that the various tests were performed in lab conditions using very pure signals (either useful or interferer signals were very pure, specifically regarding out of bands emissions which can be harmful for systems cohabitating in the same frequency bands on adjacent channels).

Considering broadcast receivers, in addition to their inherent behaviour when facing interference (reflected in the previous documents through the C/I ratios) they are sensitive to front-end overloading as well (i.e. high field strength level at the input of the receiver, caused by the proximity of the interferer). Front-end overloading causes desensitisation of the receiver and degrades the protection ratios as compared to normal operation. This degradation can be very high as shown in [24] and [25].

As a consequence, and due to the fact that DVB-T receivers only have to comply with EMC standard IEC 62216-1, the protection ratios defined in this standard should be used (see table below), whatever the interfering system is (in case the interfering signals have a “sufficient” bandwidth, i.e. above 1 MHz, which is the case for UMTS, WiMax …).

Channel position	N-10	N-9	N-6	N-4	N-1	N	N+1	N+3	N+4	N+6	N+8	N+9	N+10
C/I (dB)	-40	-40	-40	-40	-25	(*)	-25	-40	-40	-40	-40	-30	-40

Table 1 : Protection ratios for DVB-T as a useful signal (interpolating between these values is necessary for adjacent channels not mentioned here)

(*) : C/N value of the DVB-T system, depending on the system variant and reception type (see [16] for the list of applicable values).

5.2 DSA process

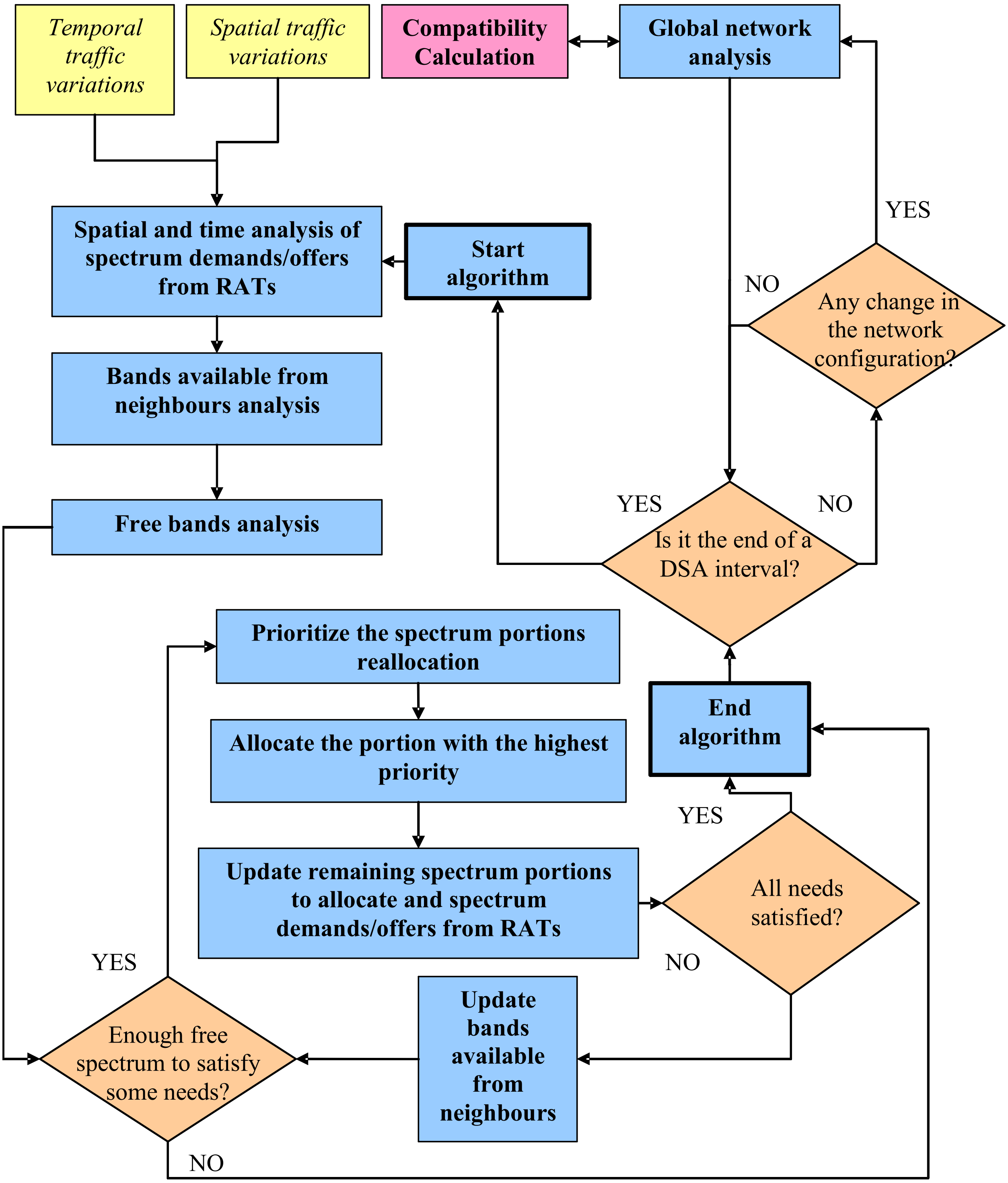
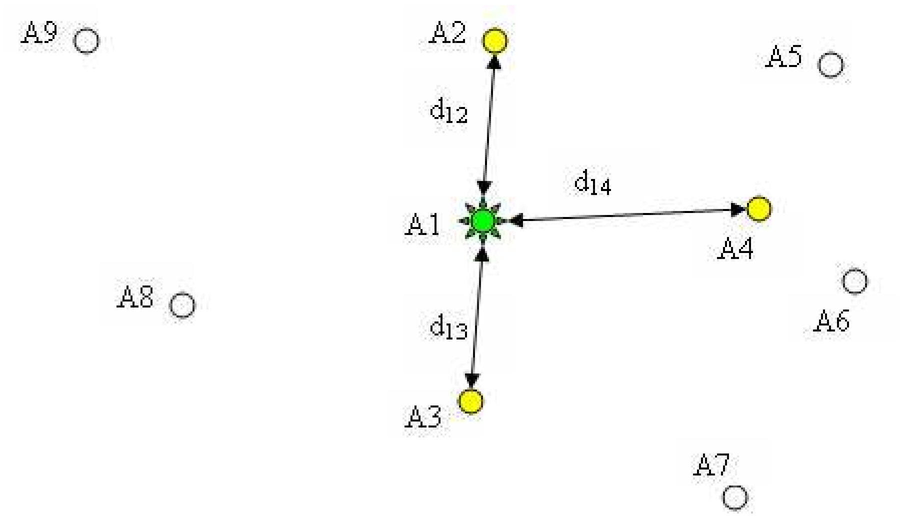


Figure 19: Functional DSA algorithm

5.2.1 Demands and offers matching

First, DSA process starts from a global network analysis in order to define spatial mapping of neibourhood stations/antennas. For every station, the neighbourhood area is considered as a network of the closest linked stations as illustrated in the following figure:



In order to satisfy spectrum demands, DSA algorithm has to check whether spectrum has been made available, potentially by other networks.

DSA interest is to allow the allocation process to better fit with demands, but another important gain is the spectrum efficiency. The efficiency is higher if spectrum released by underloaded networks can be allocated to networks that have increasing demands. Of course, demand and offer should match in the same time and place: a free spectrum band may be available in a given area but unavailable in another adjacent area. We define the zone where RAT_o can offer a spectrum band *b* to RAT_d, as the zone where the band *b* cannot be used by RAT_d due to interference caused by RAT_o. Therefore, a spectrum portion can be offered not only in the coverage area of the offering RAT, but also in the area of interference range previously produced. In the example described in Figure 20, the RAT_d demand matches with the offer, although demand and offer coverage zones don't overlap.

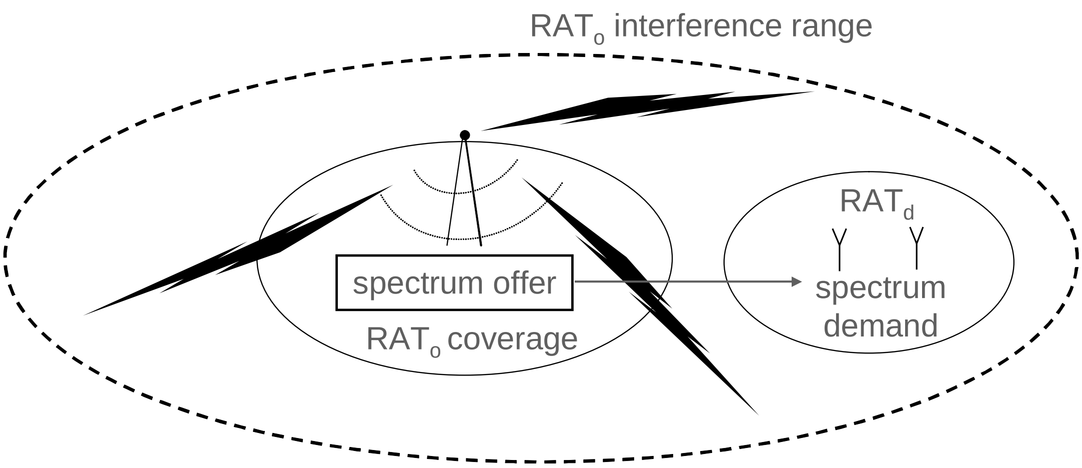


Figure 20: Spectrum demand and offer matching.

Therefore, the RAT_d demand for antenna A_d matches with RAT_o offer from antenna A_o if the distance between A_o and A_d is such that

$$\Delta\left(A_d - A_o\right) \leq D_{\text{int max}}\left(RAT_d, RAT_o\right)$$

D_{intmax} *(RAT_d, RAT_o)* is the distance above which RAT_o and RAT_d cannot interfere with each other, even using the same frequency band.

After having checked the spatial matching of demands and offers, the step forward consists on targeting a new spectrum allocation. The simplest case would be reallocating a given band from a RAT to another RAT in the same place. However, it may occur that several possibilities can be envisaged. For instance, if two frequency bands are offered, but only one is required by the demand. Then the algorithm will consider the two possibilities, and will chose according to compatibility criteria that will be checked by the following functional block.

5.2.2 Spatial and time analysis of demands and offers

In this subsection, the goal behind traffic study is twofold: Traffic prediction and spatiotemporal traffic generation. Traffic prediction concerns the DSA algorithm operations where the DSA areas (cells or bigger zones) would have to make future traffic predictions as an input for DSA, while the characterization spatiotemporal distribution of the demand is essentially related to the simulations of traffic and aims at furnishing some traffic generation models in order to have more realistic simulation scenarios**.** Figure 21 summarizes the interaction between traffic modules and the DSA simulator.

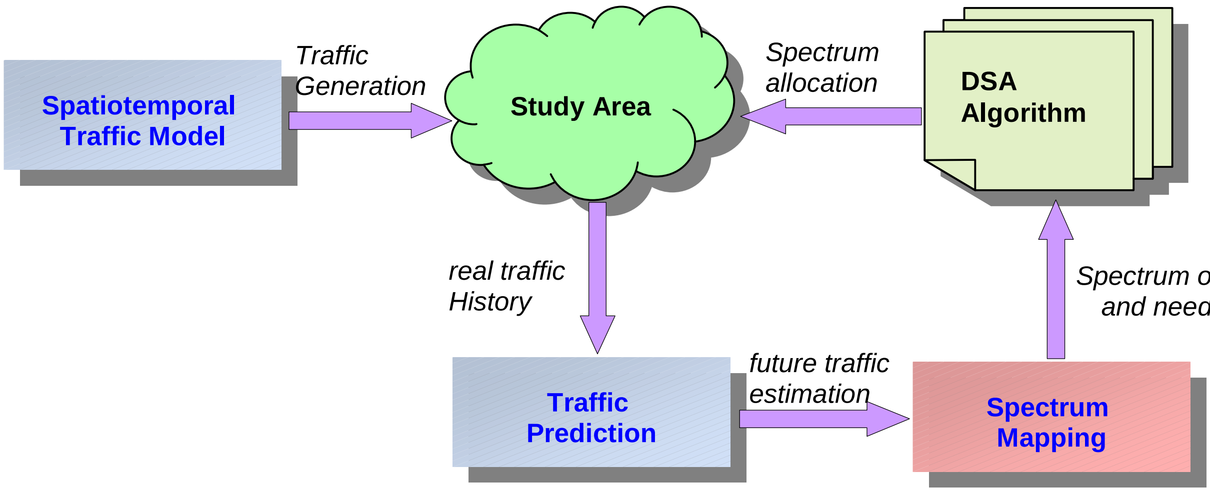


Figure 21: Traffic study in the simulation model

The main input of a DSA algorithm is the spectrum need/offer of the different DSA regions (cells in our case) for the next DSA interval. In the DSA simulator implementation, these offers and needs are known for each DSA interval and for each cell. However, in a more realistic scenario, the future demand or load of a cell is not well known; the role of the traffic prediction block is to provide a prediction of what the traffic demand would be in a given cell at the next DSA interval based on previous traffic measurement history. This history is constructed from the traffic run over the study area and being generated according the spatiotemporal traffic modeling block.

5.2.2.1Traffic prediction modelling

The Study Area (SA) is a geographical area where DSA will operate over *R* RATS that are present in the given SA. A point in the SA is covered by at least one RAT and each terminal in the SA is connected to one RAT. Each RAT has its own cell topology, *C(j,r)* being the j^{th} cell of the r^{th} RAT. Figure 22 shows a study area with 2 RATs operating inside.

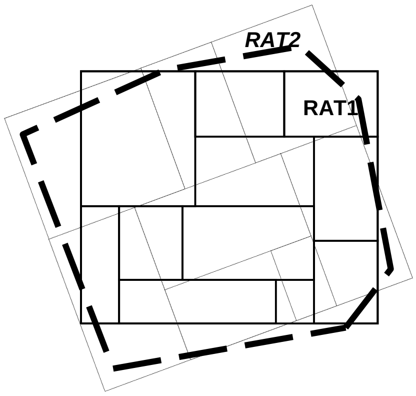


Figure 22: DSA Study Area with 2 RATs

5.2.2.1.1 Traffic Assumptions

The traffic in the study area is a process varying in time and space. We make the following general assumptions that catch the main spatiotemporal properties of the traffic, and in the same time, simplifying its modeling and prediction:

1- The time and space dimensions are uncorrelated; the traffic evolution in a cell is independent from what is happening in other cells.

   a. For the traffic prediction, this assumption implies that each cell would independently predict its traffic based only on its own traffic measurements.

   b. Concerning the traffic modeling and generation, each cell will have its own traffic temporal process. Practically, in a study area, we will use the same temporal process which parameters will be tuned for each cell.

2- The traffic temporal process presents daily-based periodicity, which mean that in a given DSA interval within a day d, the traffic values (or variations) will be similar to those measured in the same DSA interval of the same day d of previous weeks.

3- The traffic at time t depends also partially on the previous values. This dependence is assumed to be linear or exponential so that linear or exponential regression can be applied.

4- We assume that for each cell, traffic measurements are available. These measurements could be:

   a. The mean arrival rate of sessions of each traffic class in a given time interval t.

   b. The mean load of the cell in a given time t.

5.2.2.1.2 Measurement Process

Let *T(i,d) i=1..N, d=1...* be the instants at which DSA operated in the day *d*. The day d=1 is the first day of DSA operation. Therefore, at *T(i,d)*, each cell *C(j,r)* must make some predictions concerning its future demand for the coming interval *T(i+1,d)-T(i,d)*. These predictions are based on traffic measurements that are done at instants *t(k,d)*, *k=1..M, M>N*. Recall that each RAT has its own measurements database and makes prediction independently from other RATS. Moreover, measurements sampling interval can be adapted, increased/decreased, according to the observed traffic variability.

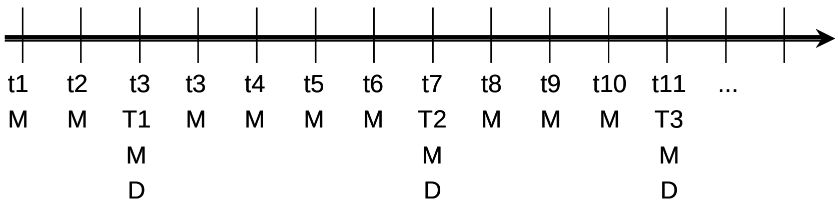


Figure 23: DSA and measurements chronology

DSA and measurements are assumed to operate periodically, which means that *T(i,d)=T(i,d')* and *t(k,d)=t(k,d')* ∀ d and d'. For each *T(i,d)*, a statistical measure *S(i,d)* is derived from the set of measurements done in *T(i+1,d)-T(i,d)* (average, peak value, etc.). In the current day D, *H(i)={S(i,d), d={d-7,d-14...}}* is the history of the interval *T(i+1,d)-T(i,d)*. In other words, the history of a DSA interval is the set of past measurements done in the same day at the same interval.

Given the notations and the assumptions above, the problem can be stated as follows:

How would a cell *C(j,r)* calculate a prediction *S*(i,d)* of the traffic on the future interval *T(i+1,d)-T(i,d).* We note that predictions are done on both downlink and uplink.

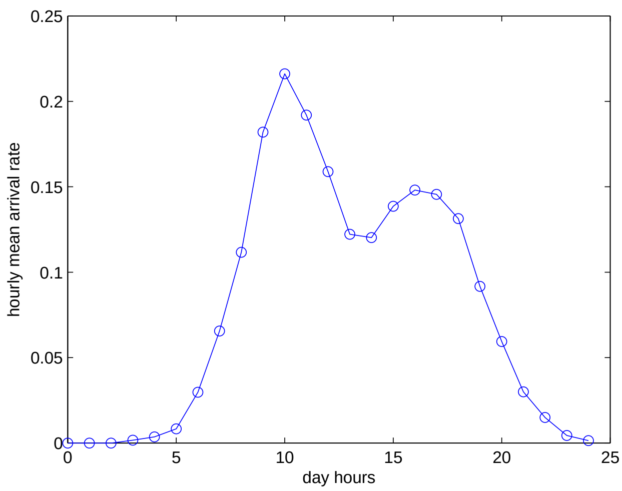


Figure 24: example of one day history

5.2.2.1.3 "far past" and "near past" prediction approaches

Using the traffic assumption above, this approach, presented in the Drive project, consists in using either history based prediction ("far past") when measurements are close to history, or previous measurements ("near past") when there is some unexpected traffic variations.

The history based prediction ("far past") utilizes aa function *FP* of the history *H(i)* for calculating *S*(i,d)*: *S*(i,d) = FP(H(i))*. This exploits the fact that in general, the traffic is globally the same in a given day at a given interval. Two options can be adopted for *FP*:

S(i,d)=E[H(i)]* meaning that the history is averaged

or more pessimistically

S(i,d)=max[H(i)]*

When the measured traffic diverges from the history, a linear or exponential regression with the near past measurements in order to predict the next load of the cell. *S*(i+1)=NP(H(i)).*

<u>Linear regression example:</u>

S(i+1)=a*T(i+1) + b*

where a and b are calculated according the a regression model assuming that :

*S(k)= a*Tk + b, k*=i-n+1..i for the n past measurements at the current day d.

a and b are derived by a least square analysis:

$$b = \frac{\sum_{k=i-n+1}^{i} (T(k)-\overline{T})(S(k)-\overline{S})}{\sum_{k=i-n+1}^{i} (T(k)-\overline{T})^2}$$

and

$$a = \overline{S} - b\overline{T}$$

where $\overline{S}$ and $\overline{T}$ are the emprical means of S(k) and T(k) respectively.

5.2.2.1.4 Combined “far past”-“near past” prediction approaches

We propose a compromise approach that use a combination of the far past and near past measurements. The proposed solution is given below with 2 defined thresholds, x and y.

If |*H(i-1)-S(i-1,d)*| < *x.H(i-1)*

Use far past estimation: *S*(i,d) = FP(H(i))*

If |*H(i-1)-S(i-1,d)*| > y.*H(i-1)*

Use near past estimation *S*(i,d) = NP(H(i))*

If x.*H(i-1)* < |*H(i-1)-S(i-1,d)*| < y.*H(i-1)*

Use a compromise value:

(|*H(i-1)-S(i-1,d)*| - x.*H(i-1))* FP(H(i))* + (y.*H(i-1)* - |*H(i-1)-S(i-1,d)*|)* *NP(H(i)) / (*y.*H(i-1)*- x.*H(i-1))*

5.2.2.1.5 Variation based prediction approach

Another approach is to use an alternative history of variations HV defined as followed:

HV(i) = {(S(i,d)-S(i-1,d))/S(i-1,d), d={d-7,d-14...}}

In this case, the predicted value would be:

S*(i,d) = S(i-1, d) + VP(HV(i)) . S(i-1, d)

where VP could be the mean or the max function.

We may also combine this estimation based on derivative with those calculated based on the classical history.

Below, an example of the history measurements for load values and variations that should be available for predictions, this for each DSA area.

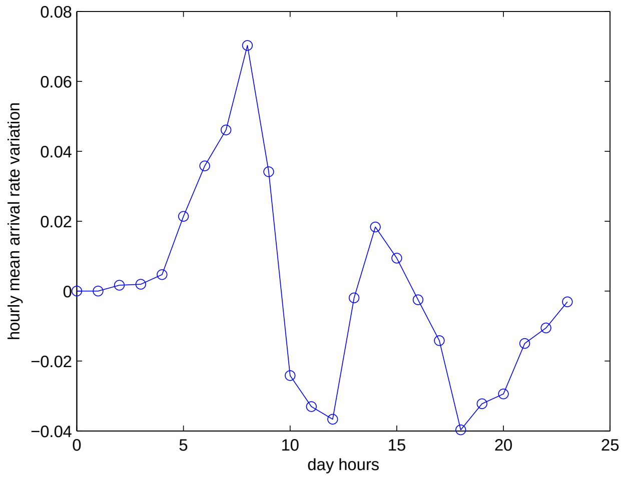


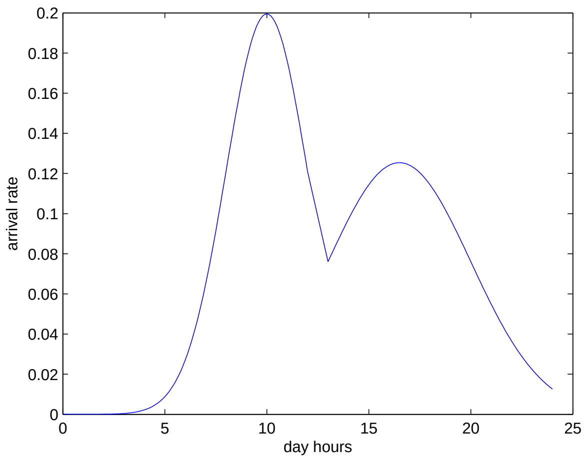
Figure 25: Example of variations history.

5.2.2.2 Spatiotemporal traffic generation

The traffic modeling consists in obtaining models that generates spatiotemporal realistic traffic. This kind of models must be tuned using real operator measurements. However, existing models can be used to approximate the reality.

5.2.2.2.1 Simple approach - Use of average traffic graphs

In this approach, we use a simple function that describes the average traffic load as a function of the day time. An example would be the double Gaussian function that were found to approximate the daily traffic load A(t) in Lisbon city (see [12]).



$$DG(t) = \begin{cases} p_1 . \exp\left(\dfrac{t - t_1}{2d_1^2}\right), & t < t_1 \\ p_2 . \exp\left(\dfrac{t - t_2}{2d_2^2}\right), & t > t_1 \end{cases}$$

Figure 26: double Gaussian function

We propose the following methodology for using a function f(t) for traffic generation:

1- Tune the parameters of the function to meet the reality of each cell for every day.

2- For all instants t, the real traffic value is supposed to follow a given random distribution TD(m), e.g. normal or Poisson distribution, of mean m=f(t).

3- At each measurement time t(i,d), the measured traffic, is simply a sampled from TD(f(t(i,d))).

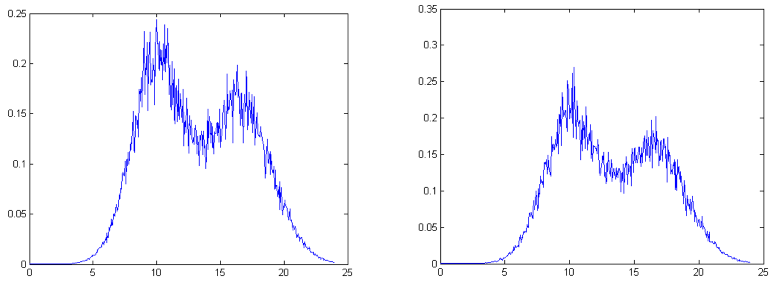


Figure 27: Example of random generated traffic for 2 different days

5.2.2.2.2 Discrete event simulation

We propose to run a discrete event simulation beside the DSA simulator: This will give a traffic distribution based on individual session properties and mobility models

- We model traffic at session level. For each region, we define an arrival call rate at a mobile and the duration of the call.
- We distribute mobiles over the region with certain profile.
- The events are :
  - Session arrival
  - Session end
  - Mobility steps
- The simulation is run between Ti and Ti+1,
- If a mobile leaves a cell, it connects the one it reaches and may loose the call if no available resources.
- The simulation outputs the mean load or traffic in each cell. This will be the measurements done by cell.
- The carrier distribution for the next interval is provided by the DSA algorithm
- Possibility of having handover failure rates.

5.2.3 Spectrum Mapping

The spectrum mapping bloc translates a traffic demand into a quantity of spectrum needed to serve this future traffic under some QoS constraints.

We consider C traffic classes where each class i is characterized by 8 parameters: ($\lambda(i, d)$, $\mu(i, d)$, $T_{on}(i, d)$, $T_{off}(i, d)$) for the downlink, and ($\lambda(i, u)$, $\mu(i, u)$, $T_{on}(i, u)$, $T_{off}(i, u)$) for the uplink. These parameters define the traffic model on uplink and downlink as follows:

1- Sessions of class i arrive according to a Poisson process of intensity $\lambda(i, d)$ (resp. $\lambda(i, u)$) on the downlink (resp. uplink). The mean of inter-session time is thus 1/ $\lambda(i, d)$ (resp. .uplink)

2- A class i session length is exponentially distributed with parameter $\mu(i, d)$ (mean length = 1/ $\mu(i, d)$).

3- A session of class i generates ON/OFF traffic as shown in Figure 28. The ON/OFF parameters are:

   a. $T_{on}(i, d)$: the mean duration of the exponentially distributed ON periods .

   b. $T_{off}(i, d)$: The mean duration of the exponentially distributed OFF periods.

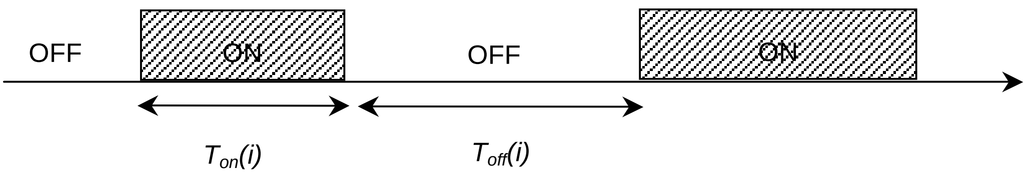


Figure 28: ON/OFF model of a session traffic

5.2.3.1GSM/GPRS case

In the GSM/GPRS case, we consider two traffic classes. Class 1 corresponds to GSM voice calls and class 2 corresponds to GPRS data sessions. We consider the case of complete partitioning where a fixed number of slots is allocated for each traffic class. Let us define the following parameters

1- N_1: the number of time slots dedicated to GSM calls.

2- N_2: the number of time slots dedicated to GPRS.

3- N: the maximum number of active GPRS mobiles.

4- D, U: the reception capability of a GPRS mobile. D (resp. U) is the maximum number of time-slots that can be used simultaneously for the downlink (resp. uplink) traffic.

The complete partitioning assumption allows us to calculate the GSM and GPRS spectrum separately.

5.2.3.1.1 GSM slots calculation

In GSM technology, the traffic is circuit switched and dimensionning is done using Erlang-B formula. The voice traffic is assumed to be symmetrical, and therefore, the uplink and downlink models have the same parameters. The QoS constraint on GSM calls is the blocking probability which is derived from the Erlang-B formula. The Erlang-B formula gives the blocking probability knowing: (1) the amount of traffic to be handled in Erlang and (2) the number of available channels (TCH time slots in the case of GSM).

$$Pb = \frac{\dfrac{\left(\dfrac{\lambda_1}{\mu_1}\right)^{N_1}}{N_1!}}{\displaystyle\sum_{i=0}^{N_1} \dfrac{\left(\dfrac{\lambda_1}{\mu_1}\right)^{i}}{i!}}$$

The cell capacity depends on:

1-The available number of physical channels (frequency time slots or, in short, slots)

2-The blocking probability value the system is designed to support.

Using Erlang-B formula, the number of traffic channels is calculated and then converted into number of carriers. In GSM one pair of frequencies (or –duplex– carrier, managed by a transceiver or TRX) can handle 8 time slots. The time slots for the control and signalling channels, i.e. broadcast control channels, common control channels (CCCH), SDCCH (Stand-alone Dedicated Control Channel), and associated SACCH, has to be considered also during capacity calculation.

The number of slots for signalling is not fixed per GSM carrier (or GSM transceiver). For a rural BS, with one duplex carrier frequency (one DL and one UP) the number of SDCCH is 4 (corresponding to 0.5 physical channel).

Giving a target blocking, N_l can be obtained by solving the Erlang-B equation or by using numerical tables. The total needed slot number will be $N_l + N_s$ where N_s is the number of signaling slots.

Example:

For a blocking probability value equals to 2%, the number of time slots needed is given in table (1) for different traffic values (in Erlang).

Traffic	2 Erlang	4 Erlang	10 Erlang	14 Erlang
Number of TCH (#TCH) N_1	3.3	5.1	10.2	13.7

Table 2: Number of traffic channels (TCH) needed for 2% blocking probability

The number of needed GSM frequencies = 2x(#TCH + #Signaling_slot)/8 = $2(N_1+N_S)/8$. We can adopt the simple rule that 1 signalling slot is needed every 7 traffic slots: $N_S=N_1/7$

Taking the 14 Erlang case example: the number of needed GSM frequencies equals to 2x(14+2)/8 = 2x2. Considering that 14 TCH would need 2 slots for signalling.

As radio channel spacing in GSM is 200 KHz. The required bandwidth is then 2x2x200 KHz BW.

5.2.3.1.2 GPRS downlink slots calculation

Based on discrete-time Markov chain, an Erlang-like law have been proposed in [Baynat05] for packet services. The formula is as simple as Erlang-B and C laws. However it could be applied for packet services GPRS/EDGE. We estimate the number of needed slots on the downlink, as it is assumed to be the limiting link.

Fixed number of mobiles N (in active session) is assumed to share the total bandwidth of the cell. Every mobile generates an ON/OFF traffic. (See Fig. 1). Note that for elastic traffic T_{on} is replaced by X_{on}, which is an amount of data.

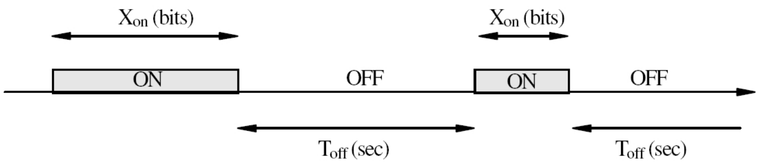


Figure 29: On/Off traffic [Baynat05]

The GPRS/EDGE system is characterized by the following parameters:

1- tb: the system elementary time step that equals to the radio block duration.
2- xb: number of data bytes that are transferred during tb over one time-slot.

3- T_{rr}: the number of radio resources slots (PDCCH) dedicated to GPRS users.
4- Xon: the amount of data (bytes) to be downloaded by each user.
5- d: the maximum number of slots that can be used simultaneously by the mobile in DL (depends on the mobile class).
6- Toff: the mean time of the OFF period (reading time), which is typically > 1s.

The state of the Markovian model is to be described at the end of each radio block by the number n of mobiles in active transfer (in ON period). The state space is given by the set $\{0,n_{max}\}$, where n_{max} is the physical limitation on n.

n_{max} is the maximum number of mobiles that can simultaneously have an active downlink TBF (Temporary Block Flow). It is given in [Baynat05] as;

$n_{max} = \min(N,32,7T_{rr},mT_{rr})$, where m is a configurable parameters by the GPRS network (takes values less than 7) describes the minimum throughput per mobile if admission control is used. The m parameter is negligible in our analysis.

Example:

Taking the following assumptions for a GPRS system:

- The number (N) of mobiles in session period = 50 mobiles.
- tb = 20ms
- xb = 20 bytes
- T varies between 1 and 50 slots
- Xon = 1 Kbytes
- d = 4
- Toff = 7s

The average throughput obtained by each mobile is then illustrated in "Fig 2" as a function of the number of slots (T_{rr}).

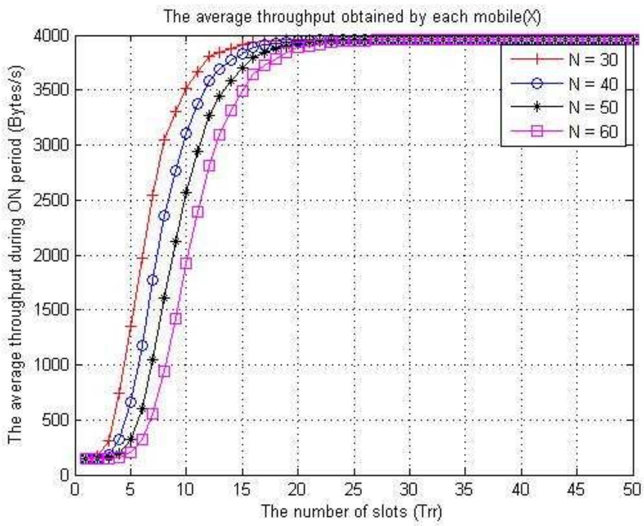


Figure 30: The average throughput obtained by each GPRS mobile for different number of mobiles (N) in active period

Table 2 gives the number of needed slots (T_{rr}) for different number of users in session (N), when an average achievable bit rate of Rmin=2KB/s is granted for each user.

Number of mobiles (N)	10	20	30	40	50	60	70	80	90	100	110
Number of needed slots (T_{rr})	3.16	4.59	6.04	7.38	8.77	10.1	11.5	12.8	14.2	15.5	16.8

Table 3: The number of needed slots (T_{rr}) for (N) GPRS mobiles in session, each gets an average rate of 2KBps.

"Fig 3" gives the relation between the number of mobiles (N) and the number of needed slots (T_{rr}). we can notice that the relation is quite linear.

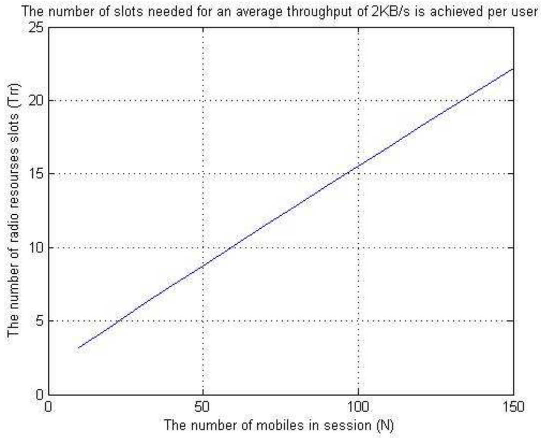


Figure 31: The number of needed slots (T_{rr}) as a function of the number of mobiles (N) in session

We see that on this special case, the number of needed slots is in fact proportional to the maximum number of active sessions. This suggests that a computation in average is also possible. Let Rc=xb/tb the maximum data rate, n_{mean} the mean number of active users. Then, we have three relations:

[1] $T_{ON}=X_{ON}/Rmin$

[2] $n_{mean}=T_{on}N/(T_{off}+T_{on})$

[3] $Trr=n_{mean}Rmin/Rc$

From these relations, we deduce that $Trr=Rmin/Rc*X_{ON}N/(RminT_{off}+X_{ON})$. An example of result is now shown for Rmin=2KB/s. The average calculation provides a good approximation as soon as the number of mobiles is high.

Number of mobiles (N)	10	20	30	40	50	60	70	80	90	100	110
Number of needed slots (T_{rr})	1.33	2.66	4.00	5.33	6.66	8.00	9.33	10.66	12.00	13.33	14.66

Table 3: The number of needed slots (T_{rr}) for (N) GPRS mobiles in session, each gets an average rate of 2KBps (average computation).

Note that for EDGE, xb, the average MCS payload, has to be chosen higher but the computation is the same.

5.2.3.2UMTS case

While the capacity in GSM is limited by the reuse factor (1/*K*) the frequency time slots and hardware equipments (number of transceivers TRX), which makes the Erlang capacity obtainable from the Erlang B model [Lee&MillerCDMAHandB98], the capacity in UMTS is limited by the amount of interference in the air interface, it is by definition a soft capacity [Holma&Toskala.04]. The Erlang B formula is then not valid.

Here we will consider the capacity calculation in UL for one UMTS carrier (2x5 GHz). The noise rise generated by the UL users at the node-B level typically limits the system. The number of simultaneous users connecting to the node-B is then limited by the maximum value of noise rise the node-B can support. Usually this noise rise value is considered to be 6dB (equivalent to 75% of the pole system capacity).

It has been shown in [Holma&Toskala.04] (relation 8.12) that the uplink load factor in the WCDMA system depends on the service the connection is establishing. The UL load factor, η_{ul}, is then given by,

$$\eta_{ul} = (1+i_f).\sum_j \frac{1}{1+\frac{W}{(EbNo_j).R_j.v_j}}$$

where *W* is the chip rate, *R* is the bit rate of the service *j*, i_f is the other cell interference to the own cell interference ,typically 0.65, (see [Kelif.08] for more details on i_f). ($EbNo_j$) is the required energy per bit over the noise power spectral density (E_b/N_0 threshold) to establish a connection with a service *j* of bit rate R_j, and activity factor v_j. The relation between the noise rise and the load factor is,

$$NoiseRise = 1/(1-\eta_{ul}).$$

For a 6dB noise rise (i.e. *NoiseRise* =4) and using the previous formulas, the maximum simultaneous number of users can be calculated for a certain/mono service. Table (2) gives the UL capacity for three different services based on their target EbN0 values [typical values considered in the industry]

	AMR 12.2 kbps	PS 64 kbps	PS 384 kbps
EbN0 threshold	5.3 dB	3.8 dB	2 dB
Capacity	42 users	7 users	2 users

Table 4: UL capacity for mono-service in UMTS

In order to make similar calculations for mixed types of services, an iterative method is used.

In table (3) we show three possible capacity examples for mixed (12.2 kbps users, along with others establishing PS 64 kbps service, and users establishing PS 384 kbps) users the system could handle.

	AMR 12.2 kbps	PS 64 kbps	PS 384 kbps
EbN0 threshold	5.3 dB	3.8 dB	2 dB

Capacity1	1 user	4 users	1 user
Capacity2	12 users	2 users	1 user
Capacity3	5 users	1 user	2 users

Table 5: examples for mixed service capacities

5.2.3.3 WiMAX/OFDMA case

In the following, we define all WiMAX parameters involved in spectrum calculations, then, we present a WiMAX downlink capacity model essentially inspired from **Erreur ! Source du renvoi introuvable.** as a general model for studying the capacity of a WiMAX cell and show how this model could be used for spectrum mapping purposes.

5.2.3.3.1 General Downlink Model

5.2.3.3.1.1 Parameters definition

We consider a OFDMA-based WiMAX cell within a cellular WiMAX network and using Adaptive Modulation and Coding (AMC) scheme. The traffic is divided into two classes: CBR (Constant Bit Rate) class and elastic data class. The parameters of the model are defined below:

OFDMA parameters (**Erreur ! Source du renvoi introuvable.**, **Erreur ! Source du renvoi introuvable.**, and **Erreur ! Source du renvoi introuvable.**)

1- W: channel bandwidth. Typically multiple of 1.75 MHz.

2- W_T: total bandwidth allocated to the cell including all sectors.

3- n: sampling factor. Typical value of 8/7.

4- N_s: total number of subcarriers in a channel. It corresponds to the size of the Fast Fourier Transform (FFT) used in OFDM processing. N_s must be a power of 2 for DSP reasons.

5- Δf: Subcarrier spacing. $\Delta f = \lfloor n.\ W / 8000 \rfloor\ .\ 8000 / N_s$

6- N_u: number of used subcarriers. $N_u = N_s - N_{nu}$

7- N_{nu}: number of unused subcarriers. $N_{nu} = N_p + N_{gr} + N_{gl} + 1$ where :

   I. N_p is the number of pilot subcarriers used for synchronizing the receiver to the transmitter.

   II. N_{gr} and N_{gl} are respectively the number of rigth and left guard subcarriers.

   III. The DC subcarrier is an additional unsused subcarrier. It corresponds d

8- T_s: overall OFDM symbol time. $T_s = T_b + T_g$ where:

   I. T_b: useful symbol time. $T_b = 1 / \Delta f$

   II. T_g: Cyclic Prefix(CP) time. This is an extra time added to the symbol duration in order to collect multipath information. $T_g = G.T_b$. G is a given ratio.

9- L: number of subchannels. A subchannel is a subset of subcarriers assigned to one user at a time. Note that a given user can utilize more than one subchannel at a given time.

10- K: number of subcarriers in a subchannel. $K = N_u / L$.

11- S_c: sector coefficient.

Radio parameters

We assume that radio conditions are identical for all users in the cell.

12- SNR: Signal to Noise Ratio. SNR is the same for all users.

13- $BLER$: Block Error Rate. The $BLER$ can be deduced from SNR using link level curves of a given modulation.

Modulation parameters

14- M: modulation order. All clients use the same modulation

15- C: coding rate of the M-ary modulation.

16- E: modulation efficiency in bits/symbol.

17- B: baud rate in symbols/second

18- R: instantaneous bit rate of a session using instantaneously l subchannels.

$$R = \frac{l \times K \times C \times \log_2(M) \times (1 - BLER)}{T_s \times S_c} = l \times K \times E \times B \times (1 - BLER)$$

Traffic parameters

The arrival of traffic sessions of each class is modeled by a Poisson process. For CBR session, the service time is exponentially distributed, while for data sessions, this is the session size that is exponentially distributed. Each CBR session is assigned a fixed number of subchannels. The remaining subchannels are used for servicing the data sessions in a Processor Sharing (PS) manner.

19- λ_c: arrival rate of CBR sessions.

20- μ_c: departure rate of CBR sessions.

21- R_c: the required instantaneous bit rate for CBR session

22- λ_d: arrival rate of elastic data sessions.

23- $E[Z]$: mean session length.

24- μ_d: departure rate of elastic data sessions. μ_d is not constant and depends on the system state.

25- n_c: number of CBR sessions in the cell.

26- n_d: number of data session in the cell.

27- l_c: a fixed number of subchannels allocated for each CBR session in order to meet R_c.

$$l_c = \frac{R_c}{K \times E \times B \times (1 - BLER)}$$

28- $n_{c,max}$: maximum number of CBR sessions that can be admitted. The maximum value of $n_{c,max}$ is $\lfloor L / l_c \rfloor$

29- l_d: the average number of subchannels per data session. $l_d = (L - n_c.l_c) / n_d$.

30- $n_{d,max}$: maximum number of data session. The number of data sessions will be limited by an admission control. In our case, we consider that $n_{d,max} = L$.

31- R_d: the instantaneous bit rate of a data session.

$$R_d = l_d \times K \times E \times B \times (1 - BLER)$$

5.2.3.3.1.2 System modeling

For the capacity calculations, we use the Markovian approach introduced in **Erreur ! Source du renvoi introuvable.**. The system is then modeled by Markov process whose state space is:

$$S = \{(n_c, n_d) \in \mathrm{N} \times \mathrm{N} / n_c \le n_{c,\max}, n_d \le n_{d,\max}\}$$

A state is characterized by the number off sessions of both classes. The steady-state probabilities can then be analytically obtained as follows:

$$\pi(n_c, n_d) = \Pr(n_c = j, n_d = k) = \Pr(n_c = j).\Pr(n_d = k | n_c = j)$$
$$= \frac{\dfrac{\left(\dfrac{\lambda_c}{\mu_c}\right)^j}{j!}}{\displaystyle\sum_{i=0}^{n_{c,\max}} \dfrac{\left(\dfrac{\lambda_c}{\mu_c}\right)^i}{i!}} \times \frac{\displaystyle\prod_{i=0}^{k}\left(\dfrac{\lambda_d}{\mu_d(j,i)}\right)}{\displaystyle\sum_{k=0}^{n_{d,\max}}\prod_{i=1}^{k}\left(\dfrac{\lambda_d}{\mu_d(j,i)}\right)}$$

where $\mu_d(i, j)$, the state-dependent departure rate of a data session is calculated by:

$$\mu_d(j,i) = \frac{i.R_d}{E[Z]} = \frac{(L - j.l_c) \times K \times E \times B \times (1 - BLER)}{E[Z]}$$

<u>Blocking probabilities:</u>

The blocking probability of CBR sessions is given by:

$$B_c = \sum_{k=0}^{n_{d,\max}} \pi(n_{c,\max}, k)$$

Note that the CBR blocking probabilty is identical to that obtained by Erlang-B model.

The blocking probability of data sessions is given by:

$$B_d = \sum_{j=0}^{n_{c,\max}} \pi(j, n_{d,\max})$$

<u>Throughput:</u>

The mean throughput of a data session is:

$$th = \frac{\lambda_d (1 - B_d) E[Z]}{\displaystyle\sum_{k=0}^{n_{d,\max}} k \sum_{j=0}^{n_{c,\max}} \pi(j,k)}$$

5.2.3.3.2 *Spectrum calculation procedures*

The spectrum mapping calculation consists in finding the number of subchannels required to meet some given QoS constraints. We propose the following procedure based upon the previous Markov model, in order to determine the needed subchannels number:

<u>Inputs:</u>

1- Get the demand parameters : (λ_c, μ_c, λ_d, $E[Z]$)

2- Calculate the average SNR in the cell.

3- Choose the modulation to use.

4- Use the modulation curves to obtain the $BLER$.

5- Calculate l_c using 27-)

6- Define the QoS constraints

a. CBR blocking probability B_c

b. Data blocking probability B_d

c. Mean data session throughput th

<u>Calculations:</u>

7- Given the CBR load λ_c / μ_c and B_c, use the Erlang-B formula to determine $n_{c,max}$. ($n_{c,max}$. l_c) is the minimum number of subchannels needed to have a CBR blocking probability of B_c.

8- We assume that $n_{d,max} = L$. We must now find the value L^* of L that guaranties B_d and th. It can be done by iterating the calculation of both B_d and th for L starting from $n_{c,max} + 1$.

9- If we assume that the spectrum unity is the channel of bandwidth WandThe number of FFT subcarriers N_s is constant within a channel, and so the intercarrier spacing, the requested spectrum will be $W^* = \lceil L^* / L \rceil .W$

5.2.4 Main policies

With regards to the operator technical, financial and quality constraints, some priorities could be implemented in DSA policies in order to match operational requirement to the user satisfaction.

These policies could be related to the operator preference that could be taken into account as a balance factor in the decision rule. These decision factors are both contained in for example:

<u>Spectrum allocation rules are much dependant on demand factors:</u>

- RAT requirement: an integrated operator or a regulator may prioritize the RAT satisfying spectrum needs for a certain RAT with regards to the license mode, pricing and auction for a cost-effectiveness purpose. It is a RAT prioritization.
- Service requirement: a certain service could be satisfied in priority due to the operator business strategy and market demand.
- Link direction requirement: in the case of paired systems, a link could be prioritized based on demand amount. The priority could be put on the higher requirements, for example the Down Link, demanding larger bandwidth to meet higher data rate.
- Throughput requirement: is related to the capacity demand, data rate, chip rate… Generally, we would try to satisfy high capacity demand in priority.

<u>Available spectrum selection:</u>

- Available frequency: depending on the frequency, the propagation conditions will be different and enable certain coverage. When the traffic and capacity variation result to an additional spectrum demand, the preferred candidate band would be in the frequencies reaching a certain coverage requirement. Noting that lower frequencies are scarce resource and should be selected in the case of high necessity.
- Minimising fragmentation: in order to optimise channel utilization and to avoid unused bandwidth, narrow band will be selected in priority as well as possible so that wide bandwidth are kept for broadband technologies when necessary.

5.2.5 Compatibility checking

If the demand of RAT_d for base station antenna A_d matches with the offer of spectrum portion F_d, the algorithm has to check whether the reallocation of F_d to A_d will not cause compatibility issue.

The algorithm is described hereafter:

Whichever j,k

Check for each RAT_j base station antenna #k $A_{j,k}$, using frequency band $F_{j,k}$ such that

$$\Delta d\left(A_d - A_{j,k}\right) \leq D_{\text{int max}}\left(RAT_d, RAT_j\right)$$

whether

$$\Delta f\left(F_d - F_{j,k}\right) \leq \Phi_{j/k}\left(\Delta d\left(A_d - A_{j,k}\right), H\left(RAT_j\right)\right)$$

$$\Delta f\left(F_d - F_{j,k}\right) \leq \Phi_{k/j}\left(\Delta d\left(A_d - A_{j,k}\right), H\left(RAT_k\right)\right)$$

6 DSA operation and evaluation

6.1 Spectrum allocation evaluation

In order to evaluate the DSA (Dynamic Spectrum Access) algorithms performance, evaluation criterions have to be defined. As one of the most interesting targets of developing DSA techniques is to overcome the actual situation of spectrum crowd, the DSA gain in terms of spectrum usage efficiency, compared to the fixed spectrum access method, would be interesting to observe.

Spectrum usage efficiency might be defined as average (over the time) used spectrum band using DSA compared to the band used using fixed spectrum access method given that it provides the same QoS to the end-users.

Spectrum usage efficiency = (average used band with DSA)/(average used band with FSA)

In DSA mode, as the different operators/RATs are sharing dynamically the spectrum, this mode is supposed to reduce the interference level (noise rise level) at a certain geographical point and at a certain time instant. Then the interference level/noise rise level in the areas where DSA is deployed becomes one of the interesting DSA algorithms' evaluation metrics when compared to other areas where fixed allocation methods are used.

Interference level per RAT per MHz = sum of all interference powers at a given point per RAT and per MHz. (à retravailler/clarifier) DSA géographique, par antenne ? uplink et downlink ?

In case the DSA algorithms are applied to cellular networks, the classical performance indicators of cellular networks are also applicable for DSA algorithms performance's evaluation. Classical metrics related to capacity and coverage such as: blocking rates, dropping rates, and handover failure rates can be used. However DSA in ad-hoc context requires other performance indicators.

Blocking rate = probability that a new call requiring a minimum QoS is blocked (related to CAC).

Dropping rate = probability that an on going call is dropped.

Hand-over failure rate = probability that a hand-over is not successful.

Coverage probability = probability that a point is covered by common channels or for a specific service.

Average throughput during packet call = mean throughput during packet transfer.

Average packet call delay = delay taking into account buffer delay, downloading and hand-over delays.

Note on the last performance parameter: a DSA algorithm performing hand-overs and spectrum changes very often will cause higher delays. If the resulting throughput is higher, a trade-off has to be found. So the number of hand-overs per packet call and the number of reconfigurations are critical parameters.

In case of inter-RAT DSA within the same operator, **end users satisfaction** evaluation is essential from the operator side. As an example, reference [EL03] provides a definition of the user satisfaction K_u as a function of the throughout D (compared to a so called “comfort throughput” D_c):

$$K_u (D) = 1 – \exp(–D/D_c).$$

However, other similar definitions including other performance parameters impact can also be designed.

In case of inter-Operator DSA, in addition to the end user satisfaction, operator satisfaction evaluation is essential either in a decentralized game between operators, or from the regulator/meta-operator side.

Operator satisfaction = probability that the operator gets the demanded bandwidth.

In the context of competing operators, where spectrum leasing, spectrum exchanges and auctions are possible, the average net benefit per time unit is defined as the total revenue generated by end users minus the price paid to other operators or to the meta-operator for spectrum usage. Revenue generated by end user can be deduced e.g. from the end user satisfaction defined above, from downloaded volume, assuming flat rate (depending e.g. on the technology). The price paid for spectrum usage can be fixed per MHz or can depend on demand or on the size of the free spectrum in the CAB.

Un paragraphe pour commenter l’histoire de free CAB.

Net benefit per time unit for the operator = end user revenue – spectrum price.

End user revenue = $K_u (1 – \exp(–D/D_c))$, where the revenue factor K_u is in euros/satisfaction.

Spectrum price (fixed per MHz) = K_s x BW, where K_s is in euros/MHz and BW in MHz.

Spectrum price (in case of CAB) = K_s x BW x exp(–free CAB size/α), where α is in MHz.

The following figure shows an example of spectrum price per MHz function (without K_s x BW factor and with α=4) in case of WiMAX networks using blocks of 1.25 or 5 MHz and a CAB size of 10 MHz.

Figure 32 Example of spectrum price per MHz function in case of CAB (α=4).

In case the DSA is applied to situations where broadcast systems are involved, the situation is twofold:

- For broadcast systems (not subject to DSA according to the scenarios defined in [1] and [2] :
  - As defined in [2], compliance with the interference criterion defined in ITU-R BT1786 must be ensured by the potentially interfering systems, that is to say interference on broadcasting systems has to be limited to 1% of the total receiving noise system power (for a 8 MHz channelling as used in DVB-T/DVB-H, the receiving noise power is -98.2 dBm, hence limiting the interference to 1% of this noise power results in an interfering power less than -118.2 dBm).
  - In addition, the broadcast coverage area **must not suffer** a reduction in its size (see § **11.2** for the evaluation of the reduction) due to the potentially interfering DSA enabled cohabitating systems.
  - As a consequence, two key parameters can be defined :
    - **Interference criterion**: the elementary interfering level generated by the DSA enabled cohabitating systems respect the maximum interference level (as defined above) in every place where the broadcast system is received.
    - **Service area criterion**: the coverage area of each broadcast system potentially interfered with is not reduced by the interfering systems. This

aspect is complementary in the sense that it takes into account multiple interfering sources (from DSA enabled cohabitating systems).

- For DSA enabled cohabitating systems, the relevant parameters applicable to these systems (e.g. those defined previously) can be used.

We now provide some possible methods for performance evaluation:

- Monte Carlo simulations (see simulations in this document).

- Game theory has also been used for performance evaluation in cellular network field [FC07]. Also for the evaluation of spectrum access schemes performance, The comparison between cooperative and non-cooperative approaches has been presented in [NC05] through game theoretical analysis.

- Optimization methods can also be used for DSA algorithms performance evaluation (e.g. Markov Decision Process).

6.2 DSA algorithm gain evaluation

After having defined the DSA algorithm, we have to quantify the gain of DSA compared to fixed spectrum allocation. In order to assess the spectrum efficiency improvement, we can consider that we have to minimize the difference between the amount of spectrum actually allocated and the needed spectrum amount. This difference has to be minimized over the time.

Let's consider that *N(t)* is the spectrum amount needed by a base station, depending on time t, and *A(t)* is the spectrum actually allocated. In a non-ideal case, *A(t)* is different from *N(t)*, as shown by the curves in Figure 33.

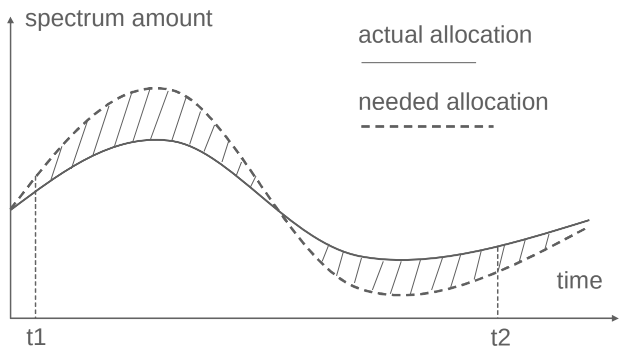


Figure 33: Difference between needed allocation and actual allocation.

Therefore, in order for *A(t)* to better match with *N(t)*, *A(t)* should be such that the following integral is minimized:

$$\sigma = \int_{t1}^{t2} \left| N(t) - A(t) \right| .dt$$

σ decreases as the surface of hachured zone in Figure 33 is reduced. The adaptation of *A(t)* to the need *N(t)* can be measured by the following ratio :

$$q = \frac{\int_{t1}^{t2} \left| N(t) - A(t) \right| .dt}{\int_{t1}^{t2} N(t).dt}$$

In a real case, the spectrum allocation would be constant over periods of time and spectrum evolution would be discrete. *q* will actually be calculated as a sum. Moreover, we have to estimate whether the spectrum allocation fits with the needs for all the RATs that are included in the DSA process.

$N_{R,Ti}$ denotes the spectrum amount need for the radio access technology R in the time period T_i.

$A_{R,c,Ti}$ is the spectrum band actually allocated to R in the time period T_i around the central frequency f_c. Indeed, the spectrum allocated for one RAT is not necessarily a single spectrum band, but can be various spectrum bands with different centre frequencies.

However, all spectrum bands are not equivalent. For instance, the VHF/UHF band has very good propagation properties, whereas propagation is more critical in higher parts of the spectrum. Then it may be useful to introduce weights corresponding to the preferences for some parts of the spectrum. Figure 34 gives an example of an operator using four carriers for the same RAT, with different degrees of preference.

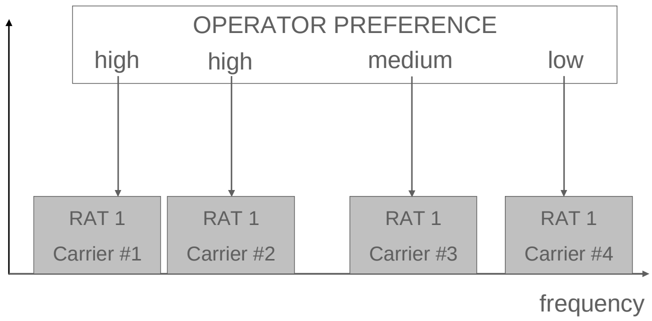


Figure 34: Weighting bands according to operator's preferences.

For a given band, the associated coefficient could reflect the operator's preferences, as well as economic considerations, regulatory considerations, etc. The spectrum band occupancy duration and the moment at which it is used should also affect the coefficient. Thus, a large bandwidth spectrum portion with good propagation properties in a peak traffic period will be estimated with heavier coefficient than a band with smaller bandwidth in a non-busy time.

For the RAT R, the preference coefficient depends on the centre frequency f_c, on the bandwidth $A_{R,c,Ti}$, and on the time T_i; we note it p_R ($A_{R,c,Ti}$, f_c, T_i). Then, from time T_1 to time T_n, the allocation to RAT R is all the more adapted that the following quotient is minimized:

$$Q_R = \frac{\sum_{i=1}^{n} \left| N_{R,T_i} - \sum_c A_{R,c,T_i} . p_R\left(A_{R,c,T_i}, f_c, T_i\right) \right| . T_i}{\sum_{i=1}^{n} N_{R,T_i} . T_i}$$

It has to be noted that the above expression estimates the allocation for a local need, e.g. for a base station; following the same principles we could extend the sum to a wide area including several base stations.

From the operator's point of view, the spectrum allocation adaptation has to be estimated not only for one RAT, but for all RATs involved in the DSA process. However, some RATs may have heavier priorities than others, due for instance to operator's strategy. It is convenient to weight Q_R by a coefficient W_R that takes into account RAT 'R' priority or weight. Then, the adaptation of spectrum allocation to the network need is given by:

$$Q = \frac{\sum_R Q_R . W_R}{\sum_R W_R}$$

In order to estimate the spectrum efficiency improvement allowed by DSA, we compare the value of Q when $A_{R,c,Ti}$ is fixed to the Q value obtained for $A_{R,c,Ti}$ depending on time.

7 Theoretical limits of DSA performance

In this section, we provide description of the joint resource allocation and DSA problem in heterogeneous network. The problem is formulated as convex optimization problem with respect to minimum user data rate, maximum available power and maximum available bandwidth. An algorithm issued from the optimization is presented and results are depicted. The described algorithm assumes centralized implementation of DSA.

The remainder of this section is organized as follows. The state of the art on joint resource allocation and DSA is given in subsection 7.1. The state of the art is focused on theoretical solutions using information theory (capacity region) and graph theory. Subsection 7.2 provides description of the optimization conducted and results are depicted in Figure 35.

Theoretical modelling of DSA allocation

Centralized dynamic spectrum allocation was first investigated as a part of the IST-drive project [35] that investigates spectrum allocation procedure for UMTS and DVB-T systems. The goal of DSA in this context is to allocate, i.e. adapt, only the amount of spectrum to a radio access network (RAN) that is required to satisfy the *short term* traffic load within a given geographic area and a given grade of service (GoS) [35] thus making spectrum currently unused by one RAN available to other RAN. In the context of the Drive project, different dynamic spectrum access schemes was investigated, i.e. contiguous dynamic spectrum allocation, fragmented dynamic spectrum allocation and cell by cell dynamic spectrum allocation. Figure 35 Illustrates these dynamic spectrum allocation schemes for UMTS and DVB-T systems when compared with fixed spectrum allocation.

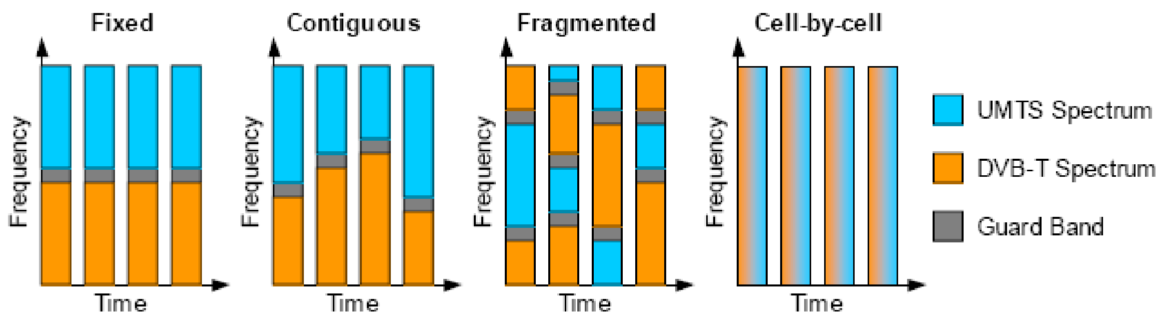


Figure 35: Drive's dynamic spectrum allocation schemes (from [33])

The main idea behind contiguous dynamic spectrum allocation is to maintain the same frequency allocation as in the FSA while allocating spectrum in contiguous frequency blocks to different RAN's. The width of the spectrum blocks allocated to each RAN is allowed to vary with the demand of each RAN.

In fragmented dynamic spectrum allocation, the spectrum to be dynamically allocated is treated as a single pool and any RAN may be assigned an arbitrary piece of the available spectrum anywhere in the pool. However the main disadvantage of this scheme is that it is quite different to control from the interference of each RAN on another, thus requiring tradeoffs between guard band lengths and interference constraints [35].

The cell by cell dynamic spectrum allocation [40] is a fully dynamic cell by cell spectrum assignment where the individual base station of each RAN could be allocated any part of the spectrum. Each individual base station of a particular RAN can be operating on different frequencies and cells of another RAN may be allocated the same frequency and cell in another location. This technique is very similar to an open access (i.e. unlicensed access) and would be subject to the constraints such as incentives to stop RAN's wasting spectrum at the expense of competitors sharing the band, although dynamic spectrum allocation should be subject to greater coordination between RAN's than the open access [36] and [38].

As shown in Figure 35, each of the aforementioned algorithms is working on periodic basis, i.e. the spectrum is allocated/reallocated to each RAN every dynamic spectrum allocation period T_D . The spectrum allocation is based on measurements and *prediction* of the network load and the demand from previously recorded load history [33]. The load/demand prediction is performed using different regression models and the performance of the different DSA schemes are compared in terms of user satisfaction ratio and the mean grade of service for each DSA area [33].

The approach of the Drive/Overdrive projects was quite promising (i.e. 33% gain over FSA for the worst case demand modelling and only temporal evolution of the demand). However, the approach is quite restrictive by considering only two RAN's settings and ideal traffic/demand models.

7.1.1 Dynamic Spectrum allocation using Graph Theory

A pragmatic centralized dynamic spectrum allocation scheme is introduced that relies on RAN's access to a coordinated Access Band (CAB) through regional spectrum brokers [41, 42, 43]. The reference architecture for the spectrum allocation problem through a centralized spectrum broker is depicted in Figure 36.

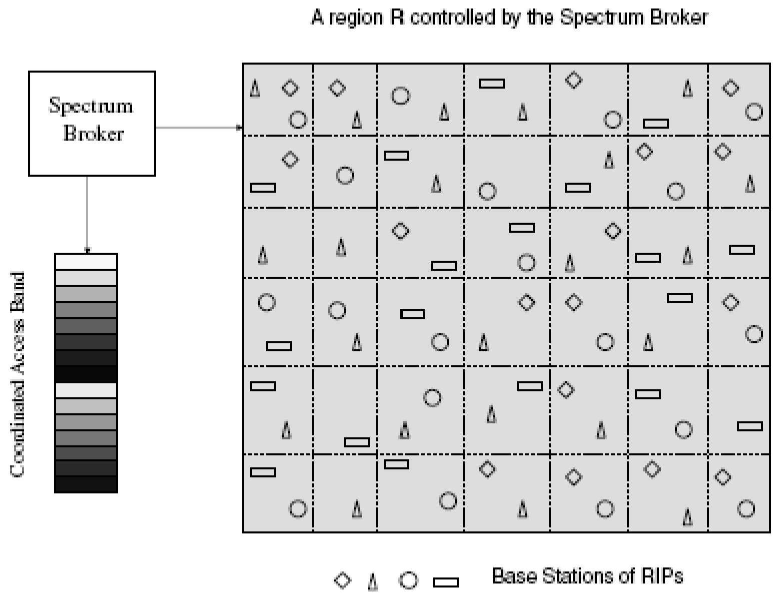


Figure 36 : Architecture of the dynamic spectrum allocation controlled by spectrum broker

The dynamic spectrum allocation problem for this coordinated access may be well described by the *interference graph* concept, well known in the GSM frequency planning literature [44]. In this approach the network of various Radio Infrastructure Providers (RIP) in a given region *R,* controlled by a spectrum broker is modelled as a weighted undirected graph $G(V,E)$, called the interference graph. Each base station in the region is represented by a node in the graph, V is the set of the graph nodes and E is the set of the graph edges.

There is an edge (i,j) between the nodes i and j, if the base stations they represent belongs to different RIP's and interfere with each other when they are allocated the same channel. Thus the edges of the interference graph captures the interference constraints DSA algorithms must satisfy. Let us define the following notations for the interference graph: The number of the nodes is $N=|V|$, the available bandwidth is split into *K* channels and the set of the available channels indices is defined as $\kappa=\{1,2,...,K\}$. For each node *i* of the graph, the spectrum demand is supposed to be bounded with minimum value $d_{\min}(i)$ and maximum value $d_{\max}(i)$. The spectrum allocation function is defined as the mapping between the node set V and the power set of κ, given that the number of channels allocated for the node *i* is compliant with the demand constraints, i.e. $d_{\min}(i)\le|F(i)|\le d_{\max}(i)$, and $p_{i,j}$ is the power penalty when the nodes *i* and *j* are assigned the same channel, i.e. interference constraint.

With this graph theoretic setting it is possible to introduce various formulations for the coordinated dynamic spectrum allocation problem [42, 43].

In this report we will briefly review two formulation from [43], namely, the maximization of the satisfied demand for each node of the graph and the minimization of the overall interference in the graph.

7.1.2 Max-Demand DSA problem formulation

The aim of the max-demand setting is to maximize the overall demand, serviced among the different base stations such that no two base stations belonging to different RIP's, that interfere, are assigned the same channel. These constraints are known as collocated cross- providers constraints (CCPC). The formal problem definition is given in the following. Given the notations of the interference graph described previously the Max- demand DSA is defined by the two step procedure:

1) Find $F(.)$, $\forall i\in V, |F(i)|=d_{\min}(i), \quad \forall(i,j)\in E, F(i)\cap F(j)=\phi$
2) If yes $\arg\max_{F(.)}\sum_{i\in V}\left(|F(i)|-d_{\min}(i)\right)$ with the constraints

   $\forall i\in V, d_{\min}(i)\le|F(i)|\le d_{\max}(i)$ and $\forall(i,j)\in E, F(i)\cap F(j)=\phi$

Where $|F(i)|$ is the number of channels allocated to the node *i*, from the index set κ. As pointed out in [42, 43], the max demand DSA problem is cloesly connected to the maximum K-colorability problem (max K-CIS) of the related interference graph, i.e. the problem of finding the subgraph with maximum number of vertices and colorable in such a way that two adjacent nodes dont share the same color. The max K-

CIS problem is known to be NP-complete for general graph structure [43, 45, 46. For a particular case of unit disk graphs[1], it is possible to approximate the solution of the max K-CIS problem whithin a factor of 1.582 [45,46], though [43] have proposed a *greedy* flovored to solve the max demand DSA problem that is closely linked to game theoretic Nash equilibrium of the spectrum allocation game [45]. In [45,46] the autors have pointed out another distributed algorithms, based on *network connectivity graph* [46] chromatic number and a game theoretic formulation of the spectrum allocation problem [45]. These algorithms will be presented in more detail in the next section.

7.1.3 Minimum interference DSA

The objective of minimum interference DSA approach is to minimize the overall interference in the network while the maximum spectrum demand $d_{\max}(i)$ of the base stations are serviced, i.e. the idea is to finf an assigement policy for $d_{\max}(i)$ for each node of the interference graph such that the power penality of assigning a commone channel to the node *i* is minimized. The formal description of the minimum interference DSA problem may be formulated as follows. If $F(.)$ is a spectrum allocation function such that $|F(i)| = d_{\max}(i), \forall i \in V$, then the interference in the network may be defined as

$$I(F) = \sum_{(i,j)\in E} p_{ij} \left| F(i) \bigcap F(j) \right|$$

The min interference DSA problem may be formulated as the minimization of the interference in the network under the constraint of satisfied maximum demand for each node, i.e.

$$F^* = \arg\min_F I(F)$$
$$|F(i)| = d_{\max}(i), \forall i \in V$$

As for the max demand DSA, the min interference DSA is related to well known graph theoretic problems namely the *Max-K-Cut* graph colouring problem [43, 44]. The max K-Cut problem on the interference graph may be formulated as finding a K- partitioning of the vertices set *V* such that the number of edges which have their end points in different partitions that are part from the cut is maximized.

The *weighted Max-K-Cut* problem is to partition the vertex set such that the sum of the weights associated with edges that have their endpoints in the different partitions is maximized. When the maximum demand for each node is normalized to $d_{\max} = 1$, the min interference DSA problem may be viewed as the problem of assigning one of the *K* colors, i.e. channels, to each node of the graph such that the sum of the weights, i.e. $\{p_{ij}\}$, of the *monochromatic edges* is minimized. This turns to be equivalent to the problem of the maximization of the weights for *non-monochromatic edges* [42, 48] which is exactly the objective of the Max-K-Cut problem. When the demand of each node *i* is more than one channel, it is possible to define a multi- color Max K-Cut problem in which we assign to each node of the graph

[1] The unit disk graph is defined as a graph with vertices that can put in one to one correspondance with equisized circles in a plane in such a way that two vertices are joined by an edge if the two circles intersect.

multiple partitions equals to the node demand such that the sum of the edges crossing the partitions is maximized.

The multi- color K- Cut problem may be formulated as the assignment of $d_{\max}$ different colors to each node of the weighted interference graph[2] such that the sum of the weights of the non- mono- chromatic edges is maximized, i.e.

$$F^* = \arg\max_F \sum_{(i,j)\in E} p_{i,j} \left(d_{\max}(i)\, d_{\max}(j) - \left| F(i) \bigcap F(j) \right| \right)$$

One feasible solution to this problem is the random coloring methodology [47, 48], i.e. pick up for each node *i*, $d_{\max}(i)$ different colors from the available *K* colors at random. This methodology achieves $\left(1-\frac{1}{K}\right)$ approximation ratio to the optimal solution and may be an input to a more refined search algorithms, as the *Tabu search* heuristics [48].

Simulation results from [42, 44, 47, 48] have shown an overall improvement of 41% in terms of interference level in the network when compared to fixed spectrum allocation and random frequency assignment. In [47] various traffic models was considered for the particular setting of 802.11 WIFI networks, showing that the centralized approaches introduced previously has good performance.

7.1.4 Information theoretic view of dynamic resource allocation

Next, the problem of centralized spectrum and resources allocation is examined from the point of view of information theory. Two main items will be investigated, the first one, related to the cognitive radio formulation of the problem [50, 51] and the second is related to the power and rate allocations formulation for general multiple access fading channels [49].

7.1.5 Fundamental limits on cognitive radio channels

In this section is dedicated mainly to spectrum overlay approach and some of its improvements when we are concerned with the fundamental limits of the cognitive radio. In [50, 51 , 52, 53] the authors have proposed different models for characterizing capacity region of a network of cognitive terminals, i.e. the best rates at which these terminals may communicates.

In [52, 53], dynamical spectral activity model was considered for cognitive terminals signaling through spectrum overlay approach. This model is given by the following two switches channel model

[2] The weighted interference graph is the graph $G(V,E)$ associated with the penalties $p_{i,j}$

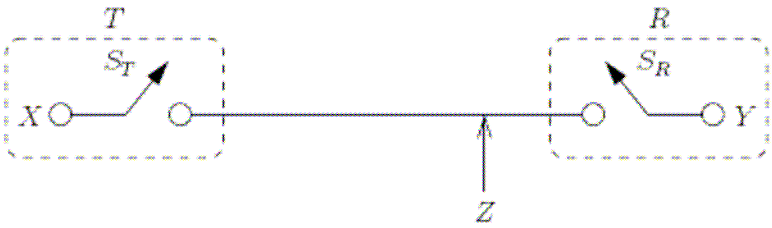


Figure 37 : Two switches equivalent channel model for cognitive terminal

Where *T* denotes the transmitter, *R* the receiver, *X* and *Y* are respectively the transmitted and received waveforms. The switches S_T and S_R capture the dynamical nature of the spectral activity of the primary users in the network. A key observation is that the switch state S_T is known only to the transmitter while the switch state S_R is known only to the receiver. The received signal may be expressed as the following

$$Y = (XS_T + Z)S_R$$

The random variables S_T, S_R are associated with the two switches of the model are related to detected primary users at the transmitter/receiver, i.e. $S_T = 0, S_R = 0$ or the detection of spectrum opportunity at the transmitter/receiver, i.e. $S_T = 1, S_R = 1$. The usual power constraints are imposed by the following average and peak power constraints.

$$E\left\{|X|^2 S_T\right\} \leq P$$
$$|X|^2 \leq P_{\text{peak}}$$

Where P is the average power constraint and P_{peak} is the peak power constraint of the transmitter. Different capacity bounds were investigated in [52,53] showing that the capacity of the system is highly dependent from the correlation of the spectral activities at the vicinities of the transmitter and the receiver, i.e. S_T, S_R switches of the model in Figure 37, and that the benefit of having non- causal information about the spectral activities of primary users at the transmitter over causal side information is insignificant. Another important result from [52][53] is that the feedforward rather than the feedback overhead is more beneficial for the underpopulated primary users environment, the opposite holds true for the overpopulated case.

In [50, 51], another approach was investigated the fundamental limits of the cognitive radio channels where a new idea of cognitive radio communications was introduced. In this new paradigm, the cognitive terminal is not restricted to transmit in the primary users spectral voids but may decide to proceed with simultaneous transmissions with other users of the channel where one sender have side information about the message transmitted by the other. This idea is depicted in the Figure 38 from [51] and will be detailed next.

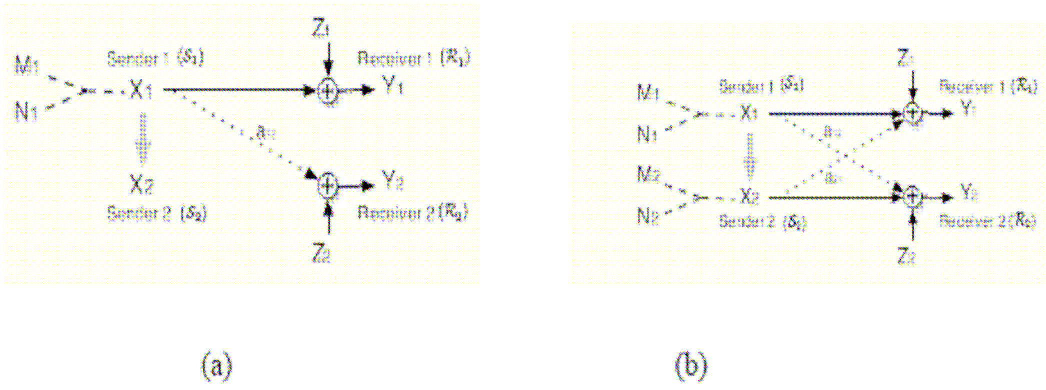


Figure 38: Opportunistic communications under the cognitive channel model of [SUP23]

Let us denote $\left(\mathrm{S}_1,\mathrm{R}_1\right)$ and $\left(\mathrm{S}_2,\mathrm{R}_2\right)$ the sender/receiver pairs of the users 1 and 2 respectively. In phase (a) of the communication protocol depicted in Figure 38, user 2 is listening to the user 1 communication and user 1 is in broadcast mode to the receivers $\left(\mathrm{R}_1,\mathrm{R}_2\right)$. In this phase user 2 is having side information about the message to be transmitted by user 2 [50,51]. In the second phase of the communication, i.e. phase (b), both users communicate through the interference channel, defined by the interference coefficients $\left(a_{12},a_{21}\right)$, where $a_{i,j}$ is the interference coefficient of the user *i*, over the user *j* transmission.

Two coding techniques for the cognitive radio channel defined in Figure 38 phase (b) . The first coding technique is to treat the message issued from the sender S_1 as interference and use the side information collected in the phase (a) of the communication to perform Gel'fand Pinsker coding [54] for the discrete case, or dirty paper coding [55] in the continuous case with Gaussian distributions at the input.

The second coding technique is to use the sender S_2 as a relay for the information of S_1. In this case multiple input single output (MISO) channel between $\left(\mathrm{S}_1,\mathrm{S}_2\right)\longrightarrow\mathrm{R}_1$ is obtained. The main result of [50, 51] argues that the time sharing technique introduced in [56] and represented in Figure 38 by the public message parameters $\left(M_1,M_2\right)$ and the private message parameters $\left(N_1,N_2\right)$, achieve the convex hull obtained by using the two coding techniques described previously. Simulation results are showing that the capacity region delimited by the results of Han and Kobayashi [56] and the MIMO Gaussian 2x2 broadcast channel [57] is achievable under the settings of Figure 38 in information theoretic sense. The authors of [50, 51] has also suggested and partially studied in [58] successive dirty paper coding for the case of network of cognitive users employing the communication protocol of Figure 38, and compared the capacity obtained for the cognitive channel with competitive as well as cooperative achievable regions. The results reported in [58] are similar to the 2x2 terminals case of [50, 51] showing that the cognitive achievable region is better than the competitive communication case and worse than the capacity region obtained with complete cooperation.

7.1.6 Information theoretic view of resource allocation

In this section some results about the information theoretic formulation of the resources allocation problem are introduced. The developments reported here are mainly related to [49,]. In [47] the authors consider an uplink communication scenario where *M* users communicate to a single receiver. This setting introduce the following discrete- time multiple access Gaussian model

$$y(n)=\sum_{i=1}^{M}\sqrt{H_i(n)}x_i(n)+z(n)$$

Where *M* is the number of active users in the cell, $x_i(n), H_i(n)$ are respectively the transmitted waveform and the fading channel for the user *i,* and $z(n)$ is the AWGN noise with variance σ^2 and *n* is the time index. We assume that the fading processes for all the users are jointly stationary and ergodic and that the stationary distributions are continuous and bounded. The user *i* is subject to an average power constraint $\overline{P}_i$.

The characterization of the capacity region of a memoryless multiple access channel with probability transition $p(y|x_1,...,x_M)$ is well known; it is given by the set of all rate vectors $\mathbf{R}$ satisfying the relation [47,50]

$$\sum_{i\in S}\mathbf{R}(i)\le I\left[y;(x_i)_{i\in S}\middle|(x_i)_{i\notin S}\right]\quad \forall S\subset\{1,2,...M\}$$

For some independent input distribution $p(x_1)p(x_2)...p(x_M)$. Here $I\left[y;x|z\right]$ is the mutual information between the variables *y*, *x,* conditioned on the random variable *z*, *S* is any users subset taken from $E=\{1,2,...,M\}$.

In the case of Gaussian multiple access channel the capacity region defined previously is given by the following relation

$$C_g(\mathbf{h},\mathbf{P})=\left\{\mathbf{R}\middle|\sum_{i\in S}\mathbf{R}(i)\le\frac{1}{2}\log\left(1+\frac{\sum_{i\in S}h_iP_i}{\sigma^2}\right)\text{with } S\subset\{1,2,...M\}\right\}$$

Where $\mathbf{h}=(h_1,...,h_M)$ is a vector of realizations of the channels $\{h_i\}_{i=1}^{M}$ and $\mathbf{P}=(P_1,...,P_M)$ is the vector of the transmission powers of the users. Let us define the power control policy P associated with the Gaussian multiple access channel as the mapping from the joint channel fading states

$\mathbf{h} = (h_1,...,h_M)$ to R_+^M. Where each element of the power control policy $\mathrm{P}_i(\mathbf{h})$ can be interpreted as the power allocated to the user *i* given the fading state of the *multiple access channel*.

For a given power control policy let us define the following set of rates

$$C_f(\mathrm{P}) = \left\{ \mathbf{R} \left| \sum_{i\in S} \mathbf{R}(i) \le E_{\mathbf{H}} \left\{ \frac{1}{2}\log\left(1+\frac{\sum_{i\in S} h_i P_i}{\sigma^2}\right) \right\} \text{with } S \subset \{1,2,...M\} \right. \right\}$$

¨Where the operator $E_{\mathbf{H}}\{.\}$ is the averaging operator over the joint fading process that may be expressed using the usual ergodicity and stationarity argument as

$$E_{\mathbf{H}} \left\{ \frac{1}{2}\log\left(1+\frac{\sum_{i\in S} h_i P_i}{\sigma^2}\right) \right\} = \lim_{T\to\infty} \frac{1}{T} \sum_{n=1}^{T} \frac{1}{2}\log\left(1+\frac{\sum_{i\in S} h_i(n) P_i}{\sigma^2}\right)$$

Finally, the throughput capacity region for the Gaussian multiple access channel where the receivers as well as the transmitters have side information of the channel state may be defined as the union of all the sets of rates over feasible power control policies, i.e.

$$C(\overline{\mathbf{P}}) = \bigcup_{\mathrm{P}\in\mathrm{F}} C_f(\mathrm{P}) \quad \mathrm{F} = \left\{ \mathrm{P} : E_{\mathbf{H}}\left[\mathrm{P}_i(\mathbf{H})\right] \le \overline{P_i} \right\}$$

The authors of [SUP21] have used a special combinatorial structure of the capacity regions $C_g(.)$, $C_f(.)$ to solve various optimization problems related to power and rate allocation for Gaussian multiple access channels, i.e. *polymatroids*. This combinatorial structure will be defined next.

7.1.7 Polymatroid structure

In this section some definitions and relevant properties of polymatroid structure are introduced. As previously we will use boldface letters for vectors and matrices, we will use the power notation 2^E to denote the set of all the subsets from *E*.

Definition : Let $E = \{1, 2, ..., M\}$ an index set and $f : 2^E \longrightarrow \mathrm{R}_+$, a set function with the following properties

1- $f(\varnothing) = 0$, i.e. the function is normalized.
2- $f(S) \le f(T)$ if $S \subset T$, i.e. the function is nondecreasing.
3- $f(S) + f(T) \ge f\left(S \bigcup T\right) + f\left(S \bigcap T\right)$, i.e. the function is submodular.

The polyhedron defined as

$$\mathrm{B}(f) = \left\{ (x_1, x_2, ..., x_M) : \sum_{i \in S} x_i \le f(S), \forall S \subset E, x_i \ge 0, \forall i \right\}$$

is a *polymatroid*.

If the function f satisfy the relation $f(S) + f(T) \le f\left(S \bigcup T\right) + f\left(S \bigcap T\right)$ rather than the property (3) bellow, we call the polyhedron

$$\mathrm{G}(f) = \left\{ (x_1, x_2, ..., x_M) : \sum_{i \in S} x_i \ge f(S), \forall S \subset E, x_i \ge 0, \forall i \right\}$$

A *contra- polymatroid.*

The key properties related to the polymatroid structures are summarized in the following. [56] have proven that every vector $\mathbf{v}(\pi) \in \mathrm{R}^M$, defined by the following relation

$$\begin{aligned}
&v_{\pi(1)}(\pi) = f(\pi(1)) \\
&v_{\pi(2)}(\pi) = f(\{\pi(1), \pi(2)\}) - f(\pi(1)) \\
&\ldots \\
&v_{\pi(i)}(\pi) = f(\{\pi(1), ..., \pi(i)\}) - f(\{\pi(1), ..., \pi(i-1)\}), i = 2, ..., M
\end{aligned}$$

for a given permutation π over the set E is a vertex of the polymatroid $\mathrm{B}(f)$, moreover, if $\boldsymbol{\lambda}$ is a given vector in R_+^M, the solution to the linear programming problem

$$\mathbf{x}^* = \arg\max \sum_{i=1}^{M} \lambda_i x_i \quad \text{subject to} \quad \mathbf{x} \in \mathrm{B}(f)$$

is achieved for $\mathbf{x}^* = \mathbf{v}\left(\pi^*\right)$, where π^* is any permutation such that $\lambda_{\pi^*(1)} \geq \lambda_{\pi^*(2)} ... \geq \lambda_{\pi^*(M)}$. One way to solve this optimization problem may be obtained following a greedy algorithm that increases for each iteration, the value of $x_{\pi^*(k)}$ until the constraint become tight and do not revisit the same component of the solution twice [49].

7.1.8 Lagrangian characterization of the capacity regions

In this section we will discuss the Lagrangian characterization of the capacity regions $C_g(.)$, $C_f(.)$. First, it is clear from the definitions of the capacity region and the power control policy that these regions have polymatroidal structure. Hence while restricting our attention to the border of the throughput capacity region $C\left(\overline{\mathbf{P}}\right)$ we may reformulate the rate allocation problem defined by the linear programming formulation

$$\mathbf{R}^* = \arg\max \sum_{i=1}^{M} \mu_i R_i \quad \text{subject to} \quad \mathbf{R} \in C\left(\overline{\mathbf{P}}\right)$$

as a solution to a lagrangian optimization that gives us for each joint fading state $\mathbf{h}$, the rate and power allocation policies $\left(\mathrm{P}\left(\mathbf{h}\right), \mathrm{R}\left(\mathbf{h}\right)\right)$ that are solution to

$$\begin{aligned}&\max_{(\mathbf{r},\mathbf{p})} \sum_{i=1}^{M} \mu_i r_i - \sum_{i=1}^{M} \lambda_i p_i \text{ subject to } \mathbf{r} \in C_g\left(\mathbf{h},\mathbf{p}\right)\\&E_{\mathbf{H}}\left[\mathrm{R}_i\left(\mathbf{H}\right)\right] = R_i^*, \quad E_{\mathbf{H}}\left[\mathrm{P}_i\left(\mathbf{H}\right)\right] = \overline{P_i}\end{aligned}$$

7.2 Joint resource allocation and DSA optimal Algorithm

In this section, we present the algorithm developed in order to ensure joint resource allocation and DSA in heterogeneous network. The conducted study assumes multiple access gaussian channel between base stations and users. The problem is formulated as a convex optimization and relaxed then by introduction of lagrangian parameters. Due to the convex nature of the problem, KKT (Karush-Khun-Tucker) conditions ensure the convergence of the proposed algorithm to the global stable optimum of the system. In other words, the algorithm described hereinafter allows optimal joint resource allocation and DSA.

Let us first describe our system. We consider a heterogeneous network composed of *N different systems serving K* users and sharing a common bandwidth B. These systems have different maximal power budgets denoted by $P_{\max} = \left[P_{\max}\left(1\right), P_{\max}\left(2\right), ..., P_{\max}\left(N\right)\right]$.

Users have also different minimum bit rates constraints to achieve denoted by $R_{\min} = \left[R_{\min}\left(1\right), R_{\min}\left(2\right), ..., R_{\min}\left(K\right)\right]$. Let $p(k,n)$ be the power of k-th user connected to n-th system on bandwidth $b(k,n)$. The corresponding bit rate is given the Shannon formula of the channel capacity as follows: $r(k,n)=b(k,n)\log\left(1+\frac{p(k,n)}{b(k,n)\sigma^2}\right)$.

The problem consists in optimizing the bandwidth allocation while minimizing the total allocated power and achieving the minimum bit rates of the users. The minimization of the total power is of interest since it allows reducing the inter cell interference within each system. The problem can then be formulated as follows :

$$
\begin{aligned}
&\arg\min \sum_{n=1}^{N}\sum_{k=1}^{K} p(k,n) \\
&sc \quad R_{\min}(k)-\sum_{n=1}^{N} r(k,n)\leq 0 \ \forall k\in\{1,...,K\} \\
&\qquad \sum_{k=1}^{K} p(k,n)\leq P_{\max}(n) \quad \forall n\in\{1,...N\} \\
&\qquad \sum_{n=1}^{N}\sum_{k=1}^{K} b(k,n)\leq B \\
&\qquad p(k,n)\geq 0 \qquad \forall k,n \\
&\qquad b(k,n)\geq 0 \qquad \forall k,n
\end{aligned}
$$

One can easily prove the convexity nature of the problem by determining the Hessian Matrix. The problem is then relaxed by introducing lagrangian parameters, the associated lagrangian of the problem is then given by:

$$
\begin{aligned}
&\mathrm{L}\left(p,b,\boldsymbol{\lambda}_1,\boldsymbol{\lambda}_2,\boldsymbol{\lambda}_3,\boldsymbol{\lambda}_4,\boldsymbol{\lambda}_5\right)=\sum_{k=1}^{K}\sum_{n=1}^{N} p(k,n)+\sum_{k=1}^{K}\lambda_1(k)\left(R_{\min}(k)-\sum_{n=1}^{N} r(k,n)\right) \\
&+\sum_{n=1}^{N}\lambda_2(n)\left(\sum_{k=1}^{K} p(k,n)-P_{\max}(n)\right)+\lambda_3\left(\sum_{k=1}^{K}\sum_{n=1}^{N} b(k,n)-B\right)-\sum_{k=1}^{K}\sum_{n=1}^{N}\lambda_4(k,n)p(k,n)-\sum_{k=1}^{K}\sum_{n=1}^{N}\lambda_5(k,n)b(k,n)
\end{aligned}
$$

Karush-Kuhn- Tucker (KKT) [SUP33] can then be expressed as follows:

$$
\begin{aligned}
&\frac{\partial \mathrm{L}}{\partial p(k,n)}=1-\lambda_1(k)\frac{b(k,n)}{\sigma^2 b(k,n)+p(k,n)}+\lambda_2(n)-\lambda_4(k,n)=0 \qquad \forall k,n \\
&\frac{\partial \mathrm{L}}{\partial b(k,n)}=-\lambda_1(k)\left(\log\left(1+\frac{p(k,n)}{\sigma^2 b(k,n)}\right)-\frac{p(k,n)}{\sigma^2 b(k,n)+p(k,n)}\right)+\lambda_3-\lambda_5(k,n)=0 \quad \forall k,n \\
&\{\boldsymbol{\lambda}_i\}_{i=1}^{5}\succ\mathbf{0},\quad \lambda_1(k)\left(R_{\min}(k)-\sum_{n=1}^{N} r(k,n)\right)=0,\forall k,\quad \lambda_2(n)\left(\sum_{k=1}^{K} p(k,n)-P_{\max}(n)\right)=0\forall n \\
&\lambda_3\left(\sum_{n=1}^{N}\sum_{k=1}^{K} b(k,n)-B\right)=0,\quad \lambda_5(k,n)b(k,n)=0,\quad \lambda_5(k,n)p(k,n)=0
\end{aligned}
$$

The optimal power is then given by :

$$p(k,n)^* = \begin{cases} b(k,n)\left(\dfrac{\lambda_1(k)}{1+\lambda_2(n)} - \sigma^2\right)^+ \text{si } \dfrac{\lambda_1(k)}{1+\lambda_2(n)} > \sigma^2 \\ 0 \quad \text{sinon} \end{cases}$$

The solution is not explicit but can be achieved using waterfilling algorithm by adjusting the level of λ_3 in order to achieve the bandwidth constraint while verifying the following constraint:

$$\lambda_3 \geq \lambda_1(k)\left(\log\left(1+\frac{p(k,n)}{\sigma^2 b(k,n)}\right) - \frac{p(k,n)}{\sigma^2 b(k,n)+p(k,n)}\right)$$

The constraints of power and bandwidth are coupled through the multipliers $\lambda_1(k)$.

In Figure 39 we depict the evolution of the user attributed power in each system vs the Signal to Noise Ratio SNR. Two different systems and two different users are considered. The total bandwidth is 250 bandwidth unities. The comparison between fixed and dynamic bandwidth allocation is depicted in Figure 40.

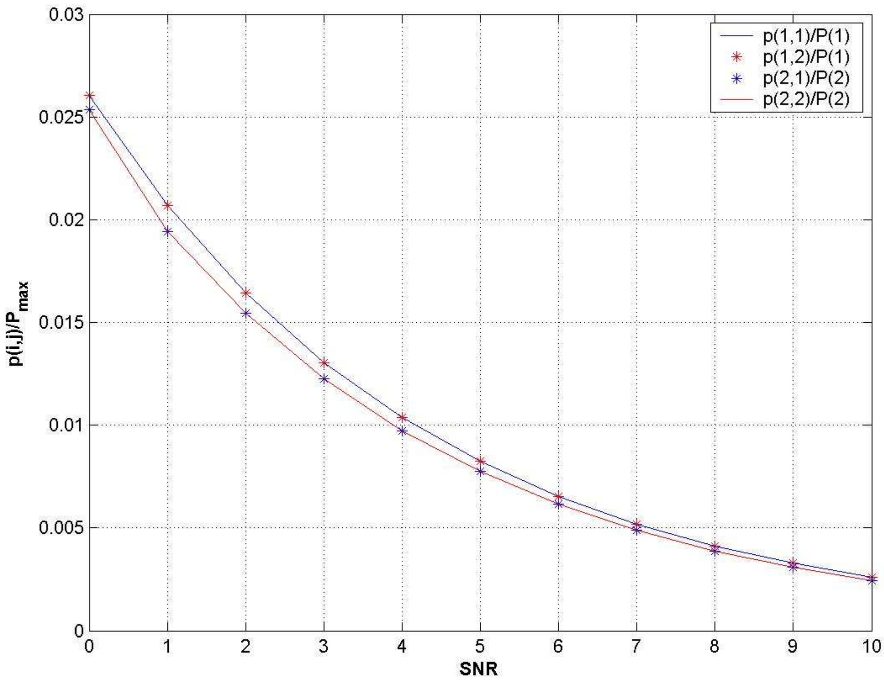


Figure 39 Performance of waterfilling vs SNR

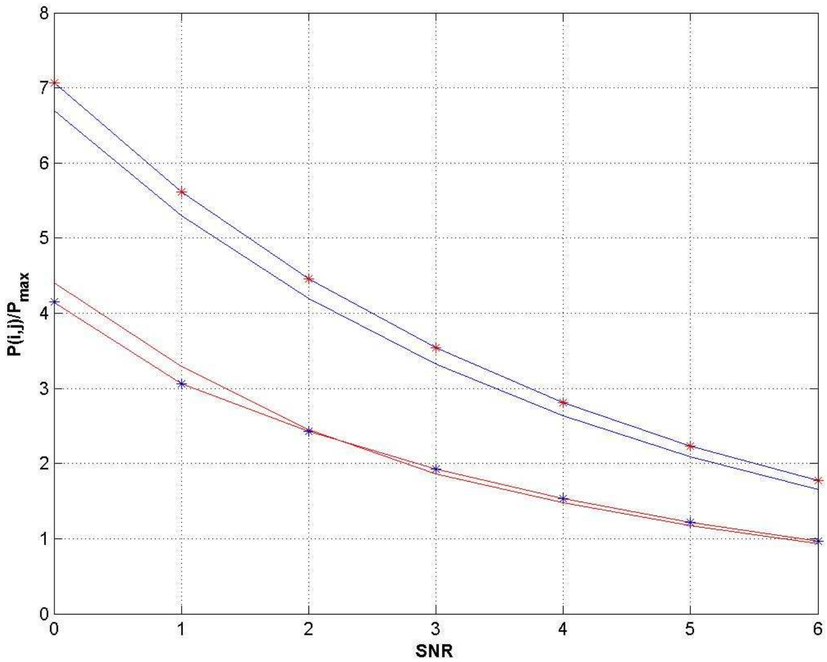


Figure 40 Power allocation with fixed and dynamic bandwidth allocation

8 Conclusion

This deliverable has introduced a DSA algorithm proposal and developed a solution based on frequency assignment rules on base stations. This solution enables spectrum sharing in a multi-operator and multi-technology context. The algorithm is generic enough to take into account flexible needs and varying interference tolerance in order to fit with spectrum acting strategies and radio regulation. The DSA approach presented in this deliverable studied some possibilities to adapt spectrum allocation in composite networks, based on capacity demand, politics that could be further defined, and on interference constraints. It also studied the methodologies to derive spectrum requirements according to the capacity and traffic needs, the limitations of DSA algorithms based on "polymatroïd" approach. A method for DSA gain estimation has also been detailed.

The next step is to enhance the cognitive aspects in the algorithm by introducing a learning procedure. On the one hand, the observation of the environment behaviour after the spectrum reallocation, and the comparison of the effective results with the expectations will allow the algorithm to *learn* and correct the planning of the future reallocations, for instance by improving the guard bands calculation. On the other hand, a learning procedure will be used to accelerate the reallocation algorithm processing, by reducing the number of interference risk evaluations. Then it will be possible to reach the optimal spectrum allocation in a network and to adapt the scarce spectrum resource to the actual needs.

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10 Acronyms

CAB : Coordinated Access Band

CAC : Call Admission Control

DSA : Dynamic Spectrum Allocation/Access

ERP : Effective Radiated Power

FSA : Fixed Spectrum Access

JRRM : Joint Radio Resource Management

MVNO : Mobile Virtual Network Operator

QoS : Quality of Service

RAN : Radio Access Network

RAT : Radio Access Technology

RRM : Radio Resource Management

URC : Urbanisme des Radiocommunications

11 Annexes

11.1 DSA algorithm high level/generic description

11.1.1 Pseudo code description

FOR each station (i)

FOR each station (j)

Calculate distance between stations i and j

Determine if stations i and j are neighbours

IF stations are neighbours

Calculate necessary guard bands between adjacent channels for the four combinations station i, link - station j, link

END IF

END FOR

IF the use case is Dynamic Spectrum Assignment

Station i owned bands is its corresponding RAT's owned bands

Station i neighbours bands is the sum of the neighbours' owned bands

ELSE IF the use case is Dynamic Spectrum Pool

Station i owned bands is the spectrum pool

Station i neighbours bands is the spectrum pool

ELSE IF the use case is Hybrid Dynamic Spectrum Assignment

Station i owned bands is its corresponding RAT's owned bands

Station i neighbours bands is the spectrum pool

END IF

END FOR

Compute the adjacency matrix of the network

FOR each state

Needs calculation:

FOR each station

Determine the state's needs in carriers in function of the need zones

END FOR

Demands and offers calculation:

FOR each station

IF downlink needs are superior to the already allocated downlink carriers

Station is demanding for more spectrum in downlink

ELSE IF downlink needs are less than the already allocated downlink carriers

Station is offering some spectrum in downlink

END IF

IF uplink needs are higher than the already allocated uplink carriers

Station is demanding for more spectrum in uplink

ELSE IF uplink needs are lower than the already allocated uplink carriers

Station is offering some spectrum in uplink

END IF

END FOR

Release unused carriers:

FOR each station

IF station is offering some spectrum in downlink

Release downlink carriers, giving priority to carriers with higher centre frequency in neighbours bands

END IF

IF station is offering some spectrum in uplink

Release uplink carriers, giving priority to carriers with higher centre frequency in neighbours bands

END IF

END FOR

Demand satisfaction in owned bands:

FOR each station

IF station is demanding for more spectrum in downlink

Determine available bands in station's owned bands ensuring that a downlink reallocation would not cause harmful interference with neighbours' allocated channels

WHILE there is remaining downlink spectrum demand **AND** available bands contain bands large enough to reallocate at least one downlink carrier

Allocate the available band minimizing fragmentation with the station's already allocated carriers

Update downlink spectrum demand

END WHILE

END IF

END FOR

FOR each station

IF station is demanding for more spectrum in uplink

Determine available bands in station's owned bands ensuring that an uplink reallocation would not cause harmful interference with neighbours' allocated channels

WHILE there is remaining uplink spectrum demand **AND** available bands contain bands large enough to reallocate at least one uplink carrier

Allocate the available band minimizing fragmentation with the station's already allocated carriers

Update uplink spectrum demand

END WHILE

END IF

END FOR

Demand satisfaction in neighbours bands:

Add remaining downlink demand and remaining uplink demand

IF there is remaining spectrum demand

Determine available bands for all demanding stations

WHILE there is remaining spectrum demand **AND** there is at least one station which available bands contain bands large enough to reallocate at least one carrier

Find the band available for the most important set of non interfering stations

Allocate the band to the stations belonging to the most important set of non interfering stations

```
                Update remaining spectrum demand
            END WHILE
        END IF
END FOR
```

11.1.2 DSA efficiency

Using $A_{dw}(s,i)$ for the number of allocated carriers in downlink at station *s* for state *i*

W_{dw} for the downlink carrier bandwidth

$N_{dw}(s,i)$ for the number of needed carriers in downlink at station *s* for state *i*

$A_{up}(s,i)$ for the number of allocated carriers in uplink at station *s* for state *i*

W_{up} for the uplink carrier bandwidth

$N_{up}(s,i)$ for the number of needed carriers in uplink at station *s* for state *i*

This can be computed for

- the whole scenario

$$\varepsilon_{DSA} = \frac{\sum_{i=1}^{n_i} \sum_{s=1}^{n_s} (A_{dw}(s,i) x W_{dw} + A_{up}(s,i) x W_{up})}{\sum_{i=1}^{n_i} \sum_{s=1}^{n_s} (N_{dw}(s,i) x W_{dw} + N_{up}(s,i) x W_{up})}$$

- a specific state

$$\varepsilon_{DSA}(i) = \frac{\sum_{s=1}^{n_s} (A_{dw}(s,i) x W_{dw} + A_{up}(s,i) x W_{up})}{\sum_{s=1}^{n_s} (N_{dw}(s,i) x W_{dw} + N_{up}(s,i) x W_{up})}$$

- a specific station

$$\varepsilon_{DSA}(s) = \frac{\sum_{i=1}^{n_i} (A_{dw}(s,i) x W_{dw} + A_{up}(s,i) x W_{up})}{\sum_{i=1}^{n_i} (N_{dw}(s,i) x W_{dw} + N_{up}(s,i) x W_{up})}$$

- a specific station and link direction

$$\varepsilon_{DSA}(s,dw)=\frac{\sum_{i=1}^{n_i}(A_{dw}(s,i)xW_{dw})}{\sum_{i=1}^{n_i}(N_{dw}(s,i)xW_{dw})}$$

$$\varepsilon_{DSA}(s,up)=\frac{\sum_{i=1}^{n_i}(A_{up}(s,i)xW_{up})}{\sum_{i=1}^{n_i}(N_{up}(s,i)xW_{up})}$$

- a specific station, state and link direction

$$\varepsilon_{DSA}(s,i,dw)=\frac{(A_{dw}(s,i)xW_{dw})}{(A_{dw}(s,i)xW_{dw})}$$

$$\varepsilon_{DSA}(s,i,up)=\frac{(A_{up}(s,i)xW_{up})}{(A_{up}(s,i)xW_{up})}$$

11.2 Broadcast coverage area and interference evaluation

11.2.1 Coverage area and location probability

The broadcast coverage area concept is defined in the final acts of the RRC-06 as follows (see [16]):

“The coverage area of a broadcasting station, or a group of broadcasting stations, in the case of a single-frequency network (…), is the area within which the wanted field strength is equal to or exceeds the usable field strength defined for specified reception conditions and for an envisaged percentage of covered receiving locations.

In defining the coverage area for each reception condition, a three-level approach is taken:

– *Level 1: Receiving location*

The smallest unit is a receiving location; optimal receiving conditions will be found by moving the antenna up to 0.5 m in any direction.

A receiving location is regarded as being covered if the level of the wanted signal is high enough to overcome noise and interference for a given percentage of the time.

– *Level 2: Small area coverage*

The second level is a “small area” (typically 100 m by 100 m).

In this small area the percentage of covered receiving locations is indicated.

– *Level 3: Coverage area*

The coverage area of a broadcasting station, or a group of broadcasting stations, is made up of the sum of the individual small areas in which a given percentage (e.g. 70% to 99%) of coverage is achieved.”

The percentage of covered receiving locations defined above is also called “Location Probability”, its value depends on the type of system and reception considered: for DVB-T, a location probability of 95% shall be used for fixed, portable (indoor/outdoor) and mobile reception. This concept of location variability is also addressed in [17].

11.2.2 Practical computation of 'broadcast coverage area' and 'broadcast coverage area loss'

In this paragraph, we intend to illustrate the notions of broadcast coverage area as defined above, and to define the notion of broadcast coverage area loss, based on a simplified example.

Figure 41 shows a broadcast transmitter. The transmitter has a given ERP, heff (effective antenna height), and non-directional antenna. Using a statistical propagation model such as [18], and not taking into account terrain effect on reception and due to the assumed symmetry of the situation, the coverage area will be circular. The green surface in Figure 41 represents the coverage area; the red circle is the boundary of the coverage area.

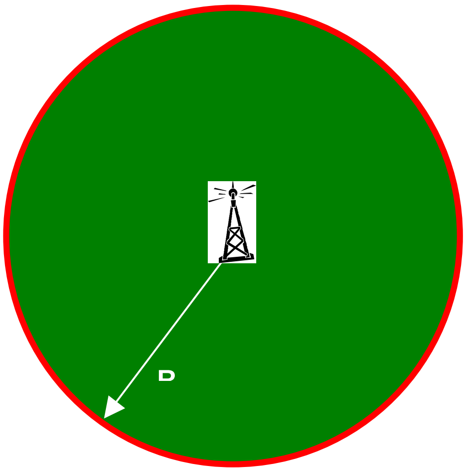

Figure 41 : Circular coverage area (noise limited or "uniform" interference limited)

- **Point coverage** (Level 1 – Receiving location)

  A reception point/site is 'covered' (i.e., has an acceptable service quality) if the received field strength, E, at that point/site is larger than the 'minimum field strength', Emin.

  E > Emin

  The value of Emin is equal to the noise, N, plus the required carrier-to-noise ratio, C/N:

  Emin = N + C/N

  In this idealised case the coverage at the point/site is noise limited.

- **Pixel coverage** (Level 2 – Small area coverage)

  A 'small' area, sometimes called a 'pixel', is covered if a given percentage of the reception points inside that area is 'covered'. The 'given percentage' (called the 'location probability') is, say, 95%, a typical value to ensure good broadcast reception. This means that (at least) 95% of the reception points in the 'small' area are covered, in which case

  E > Emin

  for (at least) 95% of the locations in the small area.

  Because the field strength is assumed to follow a log-normal distribution, this means that the reference median field strength, Emed_ref, in the small area (pixel) must be larger than Emin by a specific amount:

  Emed_ref = Emin + $\mu(P)\sigma$.

$\mu(P)$ is a statistical factor depending on the location probability desired (P), and σ is the standard deviation of the field strength variation. For example, for σ = 5.5 dB and P = 95%, $\mu(95)$ = 1.28, and $\mu\sigma$ = 7.7 dB.

For DVB-T, the various values for Emed_ref applicable to the different reception conditions are given in the table below:

Type of broadcast reception	Fixed reception	Portable outdoor reception or lower coverage quality portable indoor reception or mobile reception	Higher coverage quality for portable indoor reception
Reference location probability	95%	95%	95%
Reference C/N (dB)	21	19	17
Reference Emed_ref (dB(µV/m)) at fr = 650 MHz	56	78	88

For other frequencies, the reference field-strength values in the table above shall be adjusted by adding the correction factor defined according to the following rule:

- Emed_ref(f) = Emed_ref(fr) + Corr;
- Corr = 30 log10 (f/fr) where f is the actual frequency and fr the reference frequency of the relevant band quoted in the table above.

- **Area coverage** (Level 3 – Area Coverage)

The coverage area consists of all pixels which are covered, that is 100% of the pixels have each at least 95% of the reception sites covered.

Using the ITU-R 1546 propagation model (see [18]), and not taking into account terrain effect, the distance, R, from the transmitter at which the median field strength, Emed(R), equals the reference median field strength, Emed_ref, is determined from [18] propagation prediction curves, E1546(R):

Emed(R) = E1546(R) + erp = Emed_ref

If the distance, D, from the transmitter is larger than R, the median field strength reached at that distance, Emed(D), is less than the reference median field strength

Emed(D) < Emed_ref

and coverage (with a 95% location probability) is no longer possible. The (circular) coverage area is defined by the radius R; the area outside the area defined by R is not part of the coverage area, even though poorer reception with a location probability less than 95% would still be possible.

- **Reduction of coverage / Coverage area loss**

If the distance at which Emed_ref is reached (see Figure A.1.1) is reduced for some reason (for example, as the result of a reduction in erp) from R to R', say, the area covered is also reduced, as shown in Figure 42: the original coverage area, the red solid circle, is reduced to the white dashed circle. Areas well within the original coverage area could also have the pixel coverage percentage reduced from 95% (e.g. due to the introduction of local interference), with a consequent reduction of the total coverage area.

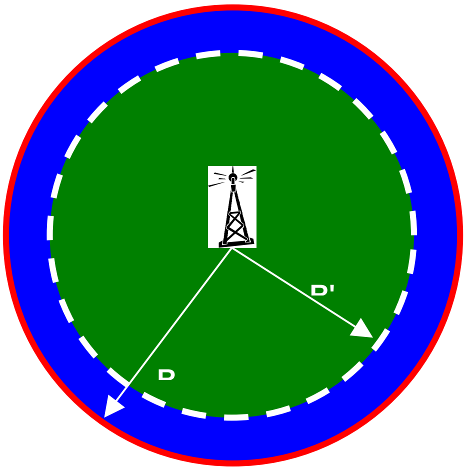

Figure 42 : Reduced coverage area (green)
Noise limited with ERP reduction or noise limited with added uniform interference

The blue area between the solid and dashed circles in Figure 42 represents the 'coverage area loss' and this loss can be expressed as a percentage of the original area

% coverage area loss = 100•(coverage area lost)/(original coverage area) % or

% coverage area loss = 100•blue area/(green area + blue area)%

- **<u>Effects of the introduction of interference (i.e. interference tolerance)</u>**

Another way of thinking of noise-limited reception is in terms of a noise 'nuisance field', defined by

- Nnuis = N + C/N, and

- E > Nnuis, or equivalently, E - Nnuis > 0

for (at least) 95% of the locations in a small area means that the 'small' area (pixel) is covered.

If interference is introduced (and noise is ignored for the moment), coverage within a 'small' area will be achieved if the wanted field strength is larger than the interference nuisance field, EInuis, for the required location probability:

E > EInuis, or equivalently, E - EInuis > 0

for (at least) 95% of the locations (receiving locations) in a small area means that the 'small' area (pixel) is covered.

For a single interferer case, EInuis is defined by

EInuis = EI + PR

where EI is the interfering field strength and PR is the required protection ratio for a satisfactory reception quality in the presence of interference.

When multiple interference sources have to be taken into account, the individual EInuis values corresponding to each source have to be summed up.

Additional notes:

- <u>For digital systems, PR = C/N for co-channel interference, usually. Other protection ratio values can be used for adjacent channel interference cases (several cases of adjacency are possible: either near adjacent or far adjacent, as can be seen in §5.1.4.4).</u>

- To offer a good protection of the coverage area, the E > Elnuis criteria must be met in 99% of the time. In order to meet this requirement, E is usually determined for 50% of the time (there is no great difference in field strength statistics between 99% and 50% of the time), while EI is determined for 1% of the time (contrary to the 99% case, the difference between 50% and 1% of the time is significant).

If the interference were uniform everywhere, then the coverage area for the wanted broadcast service would look like that shown in Figure 41, where the red boundary line denotes the coverage edge at which E - Elnuis > 0 for (at least) 95% of the locations. Figure 42 illustrates the reduction in size when the original noise limited coverage is degraded by uniform interference.

Because the broadcast service is generally the most sensitive at the coverage edge (wanted field strength is at or near the lower limit for good reception) the acceptable interference criterion should be especially suitable at that edge. A small average interference probability over the whole coverage area may imply a high interference probability near the coverage edge. A high interference probability near the edge may imply an even higher loss of coverage area.

11.2.3 Relationship between interference probability and coverage loss

In order to understand fully the relationship between 'interference probability' and 'coverage loss', the following simple example is taken from broadcast planning methodology:

- At the top of Figure 43, a situation is shown where a wanted transmitter achieves a semicircular coverage in the presence of noise only. That is, the boundary of the wanted coverage area is defined by the limit where a 95% location probability of reception is achieved in the presence of noise only (or, more generally, in the presence of noise and existing interference)[3].
- A new, interfering broadcast transmitter, "X", is introduced at the right. Its erp, distance, etc are chosen such that an interference probability of 1% is introduced at the closest point on the wanted coverage boundary in the absence of noise (and other existing interference)[4]. As the wanted coverage edge (and interior to the coverage edge) curves away from the interferer the interference probability will diminish because of decreasing interference field strength (and increasing wanted field strength).

[3] That is $E_w > E_{min} \oplus N [\oplus I]$ at least at 95% of the locations on the coverage edge. ("⊕" indicates a power sum.)
[4] A 1% interference probability means that $E_w > E_X + PR$ at least at 99% of the locations on the coverage edge.

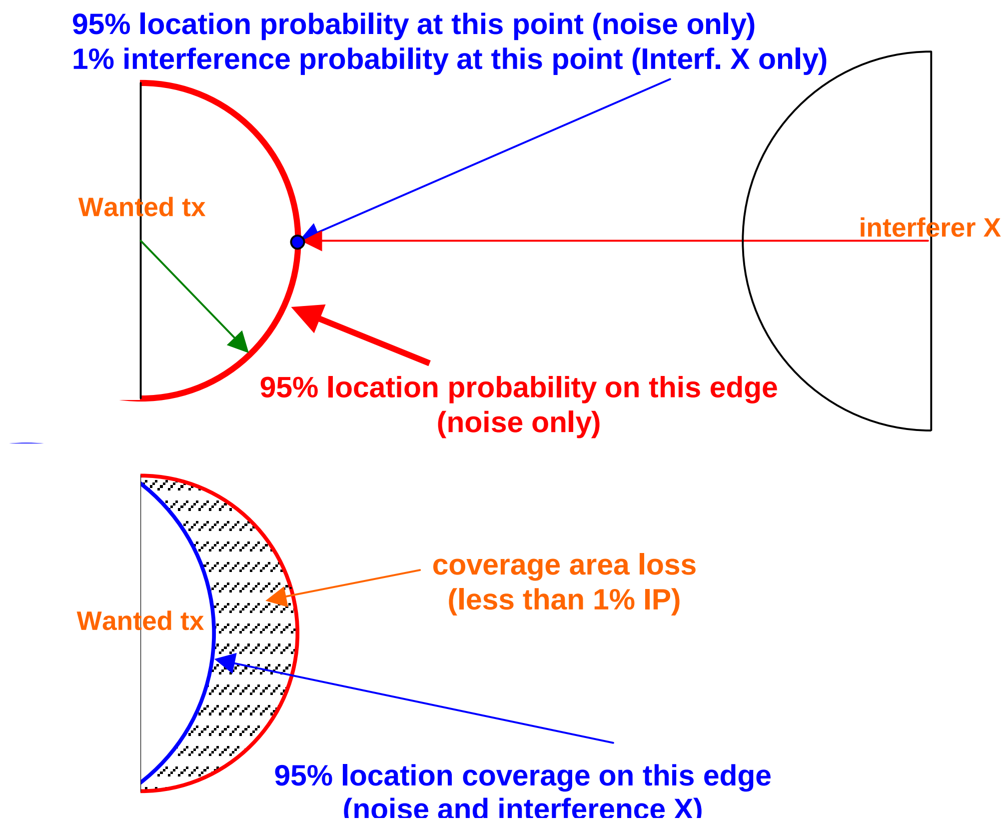

Figure 43 : Interference probability and coverage loss

- In the bottom half of Figure 43 is shown (marked in blue) the new, reduced coverage edge in the presence of the additional interference, that is, the edge where a location probability of 95% is re-established in the presence of the additional interference.
- In the shaded area in between the original, red coverage edge and the new, blue coverage edge, the interference probability is less than 1%, and the location probability is less than 95%; this is area which is no longer covered - it is coverage area loss. The shaded area can represent a large percentage of the original coverage area, and may be more than the 1% interference probability existing in that area. **Thus, a coverage loss may be much more than the percentage of interference probability introduced by a new interferer**.

Determination of interference probability and relationship with coverage loss for broadcasting has been investigated in [15] and [19] for example.