Spectrum Scenarios in Composite Radio Environments

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***Abstract*— Although providing a number of very powerful concepts, it has been a challenge to find sufficient economical reason for the research and development of SDR technology. Applying the SDR concepts in the end-to-end reconfigurability context, and in particular with view on the possibilities reconfigurability offers to more efficient use of radio spectrum, the technology offers the means to facilitate concepts like flexible spectrum management (FSM) as well as joint radio resource management (JRRM). The paper outlines and describes four basic application scenarios that are being investigated in the E^{2}R project to evaluate the efficiency gain of both JRRM as well as FSM.**

***Index Terms*—Spectrum Efficiency, Flexible Spectrum Management, Joint Radio Resource Management, Spectrum Efficiency Gains.**

Introduction

THE E^{2}R work on efficient spectrum usage considers four basic scenarios to describe the different possibilities about how spectrum can be used more efficiently. The scenarios consider two basic mechanisms (flexible spectrum management and joint radio resource management) and can be implemented in either a centralised structure (domain spectrum manager) or in a distributed manner (cognitive radio technologies).

Scenario # 1 and # 2 deal both with flexible spectrum management (FSM) but from two different perspectives. For these both scenarios, there is no joint radio resource management (JRRM), i.e. the inter-system handover is not allowed. The differences and commonalities between scenario #1 and #2 rely on criteria including the coverage range, the QoS guarantee level, the rate of spectrum variation exploitation, entity centricity (operator or user), and the nature of the primary and secondary systems. Both scenarios include spectrum brokerage. Scenario #3 considers joint radio resources management (i.e. inter-system handover is enabled) but without FSM. Scenario #4 includes both JRRM and FSM capabilities. This scenario is the combination of Scenario #1 and #3.The radio access technologies considered for each these scenarios are depicted in Table 1.

Aforementioned scenarios are discussed in detail in this paper; they will be used to highlight the technical requirements for reconfigurable technology and will show possibilities how the scenarios can be applied to and can influence reconfigurability based business models.

	Cellular	Broadcast	WLAN
Scenario 1	GSM/GPRS UMTS FDD	DVB-T	
Scenario 2	GSM/GPRS UMTS TDD		IEEE 802.11 a/e
Scenario 3	GSM/GPRS UMTS FDD/TDD		IEEE 802.11 a/b, HiperLan2
Scenario 4	GSM/GPRS UMTS FDD/TDD	DVB-T	IEEE 802.11 a/b, HiperLan2

Table 1: Scenarios vs. radio access technologies

Approach

The four scenarios have been designed independently, whereby some minor parts have been considered in some previous FP5 Projects ([1]-[9]). E^{2}R brings together all these scenarios and captures them in a single scenario framework. This enables a comprehensive view on the requirements and facilitates the design of appropriate analysis mechanisms.

The design of the mechanisms is closely connected with the underlying business models for each scenario; motivated by the recent and ongoing changes in the regulations ([10]-[16]). The approach proposed, aims at showing (by concepts and numerical results) how each of these scenarios can be profitable to all players (users, operators): (1) benefit the operators in terms of savings in CAPEX or/and OPEX, (2) benefits the users with a larger range of QoS at the time when they need it, but also with lower priced services thanks to the savings of the operators; and (3) the benefits in terms of spectral efficiency thanks to a temporally and spatially efficient resource management.

Commonalities between spectrum scenarios

The efficiency of frequency resources does not only depend on the usage in time and frequency plane, but also on the spatial arrangements. An increase in communication activities caused by special or periodic events has impacts on the demand profile of certain wireless applications. Conferences, concerts, sport events, end of season sales, vacations, high seasons, etc, can create temporary peaks in demand of communication resources within a regionally limited area.

Over time such hot spot traffic areas can move and service demands can change. For example, during the day time the traffic may be concentrated on business areas, with services related to business requirements, while in the evening the residential or entertainment areas (restaurant, cinemas, etc.) will be more loaded with non work related communication services. The different RANs involved must be able to adapt to these load and service variations during a day to optimally make use of the available radio spectrum. Moreover in case of unusual events (sport event, accident, natural disaster…) the different RANs must also be able to reconfigured (e.g. availability of sufficient radio channels is ensured) to cope with unforeseen traffic patterns and demands.

Flexible Spectrum Management (FSM) in mixed Cellular and Broadcast Systems

Scenario

The first scenario (Spectrum sharing between heterogeneous systems), see Figure 1, exploits the space time spectrum varying use (up to the hour unit) from the different coexisting licensed radio access technologies. According to the characteristics of this scenario, the spectrum can be exchanged between different parties on a market based mechanisms basis. In this scenario, the QoS of the delivered services is high (guaranteed) for large scale coverage areas. The approach proposed is to enable spectrum sharing on a cell by cell basis between different radio access technologies. In addition to this, this scenario also allows the reconfigurable radio equipment sharing, i.e. the base stations are multi-modes/bands and multi-operators enabling evolved radio engineering capabilities. Also, the concept of Opportunistic and Dynamic Spectrum Management (ODSM) is introduced in support of this scenario.

Technical Requirements

The system technical requirements of Scenario #1 are driven by following conditions: (1) the spectrum is leased/hired by the primary system (spectrum leaser/hirer) to one or several secondary systems (spectrum tenant). The primary system is the spectrum owner. Each system can be either a primary (spectrum leaser/hirer) or secondary (spectrum tenant) system.). The primary and secondary systems are spectrum licensed systems. (2) the coverage range capability of varies from several hundred of meters (pico/micro cells) to several kilometers (rural areas); (3) the QoS guarantee is high since the minimum QoS (i.e. the one provided without spectrum sharing capability) has to be guaranteed; (4) the spectrum sharing is based on the temporal spectrum need variations varying down to the minute unit (e.g. communication session level), and up to the hour unit (several sequential communication sessions).

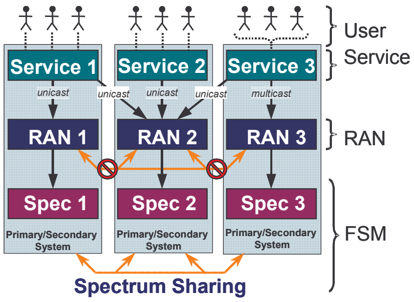

Figure 1: : Scenario #1 description

With respect to the associated frequency bands and radio access systems, the physical technical requirements for the radio equipments capabilities (end user terminal or radio access network) are: (1) the end user terminal and radio access network are both multi bands and single mode, or (2) the end user terminal is multi bands/single mode, and the radio access network is multi-modes and multi-bands.

FSM in mixed Cellular and WLAN Systems

Scenario

Scenario #2 will help to investigate short term spectrum exploitation (in contrast to the scenario #1). Short-term refers to seconds or even milliseconds. This means that spectrum rearrangement and allocation occur very often in order to optimize spectrum efficiency. Both, among the systems and among users the spectrum will be allocated, but there is no Joint Resource Management (JRRM) entity which assigns the resource to optimize spectrum efficiency. Nevertheless services can be offered over more than one RAN, for example data download is possible over both UMTS and WLAN IEEE 802.11x. However, the services cannot be handed over among radio networks. Once a user started a service over RAT #1, they may change to RAT #2, the service will then be interrupted because of the failed intersystem handover (Figure 2).

Based on the short term functionalities resulting in a highly dynamical process the systems possess the possibilities of Dynamical Network Management and Planning (DNMP). Each system can react on changes on demands, traffic load and common spectrum usage by monitoring the spectrum. The systems will be able to access not only a constant bandwidth or multiples of it, but also continuous bandwidth parts which not nee to be contiguous.

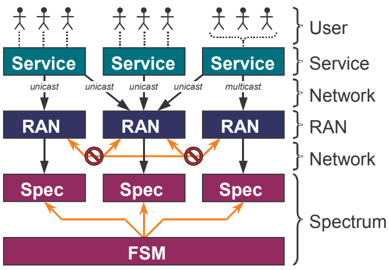

Figure 2: Scenario #2

There are two more detailed approaches for spectrum pooling:

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1 "OFDM based Spectrum Pooling in FDMA/TDMA systems"

In this sub-scenario the Spectrum Pool is an accumulation of disjoint Spectrum Fragments (SF). The Spectrum Fragments belong to different licensees. The resources can be leased by users who temporarily need bandwidth for data transmission. The constraint for the renter is that he has to leave the bandwidth as soon as the licensee of the spectrum fragment needs it. In this case the renter may switch to a free Spectrum Fragment. The licensee and the renter access the Spectrum Fragment using a combination of FDMA and TDMA access schemes.

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In this case the rental system needs to be coordinated by a Spectrum Fragment Access Coordinator (SC), which can be placed in the Access Point (AP). The SC needs information about the allocation of the SFs. There are two possibilities to get the SF allocation information. In the first method it is assumed that the SC can communicate with the licensee. In this case the licensee will signal to the SC that it needs his spectrum. In the case that the spectrum is occupied by a renter the SFCA disposes the renter to free the SF. In the other method it is assumed that the AP initiates Spectrum Monitoring (SM) which can be done by Spectrum Monitoring Agents (SMA). SMAs may be temporarily registered users which measure SFs specified by the AP or stations which are placed at several points in the network. The measurement information is used to decide weather a spectrum is occupied by a licensee or not. It is clear that the first method is much safer but needs interaction by the licensee. In the first method the AP and the Base Station (BS) of the licensee should have capabilities to communicate. This can be done over predefined signalling channels or the licensee send prior to transmission a Unique Word (UW) over the SF. In this case the renter interrupts all communications over this channel. In the second method the SMAs should have the capability to monitor the SFs.

In Figure 3 the access of the SFs by the licensee and the renters is shown. Without loss of generality it is assumed that all SFs have the same width. The second presented method clearly needs more sophisticated requirements. The SMA should detect free spectrum under a heavy time constraint and furthermore the detection method should guarantee a very high detection probability. Several rental user can participate in detection in order to increase detection probability according to a special boosting protocol [18].

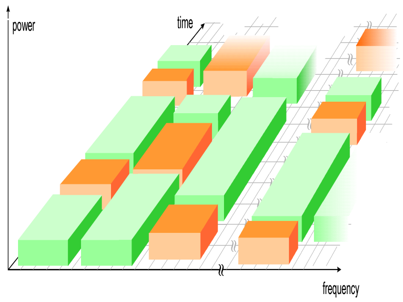

Figure 3: Access of the spectrum fragments by the licensees (green) and renters (red)

Concerning flexible and highly dynamical spectrum allocation in the physical layer the entity configuration should be able to access precisely and contemporarily to separate bandwidth. The Medium Access Control (MAC) should coordinate and react on sudden bandwidth changes in order to keep QoS requirements or at least minimize QoS losses.

A quite different, yet more special scenario, is presented in the following, this scenario illustrates the wide range of allocation applications.

2 "Brokerage based Spectrum pooling inl OFDMA/TDD"

OFDMA/TDD is a resource allocation in which the communication system is based on OFDM. Spectrum Brokerage (SB) assigns a proper bandwidth to each user. This involves implementations, like detection of free subbands within a certain frequency band. To integrate SB into a communications system new and optimized processes have to be investigated.

The system consists of users, Instances Supervising Channels (ISC) and backbone (Figure 4). The ISC controls the cells. All cells build up a system. In one cell at least one ISC has to be located. The cells have to be connected to the backbone over an instance which can also be an ISC. The backbone is connected to external networks.

In a cell there are users who have different priorities concerning cost, time and bandwidth. In a periodically repeated auction all users will bid for bandwidth and time for using the services. This auction sequence is highly dynamical in time and in the amount of bidder. These issues are investigated by different approaches of auction theory in combination with evolutionary game theory.

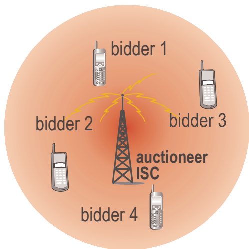

Figure 4: Auctioning as spectrum allocation and billing

At first glace applying fast repeated auctions in communication systems leads to high signalling effort. Thanks to a special auction family, the multi-unit seal-bid auction, the signalling effort is highly reduced in comparison to other standard auction types like multi-unit open or sequential auction.

Another important point is the technical implementation. If several users compete for the same bandwidth and they want to allocate parts of the spectrum dynamically, several questions arise concerning allocation handling.

Considering a special case, each user gets an amount of sub-carriers in a system based on OFDMA, these sub-carriers can be assigned as blocks, in periodic distances or in a more sophisticated way based on special algorithms. Furthermore the dynamics of allocation and assignment in time involve mutual collision and distortion. In addition all users have to be synchronized in order to keep advantages of OFDM. Therefore coordination, signalling and synchronization of users have to be considered.

OFDMA in combination with SB is a highly interesting approach to create a new flexible communication system handling spectrum in a highly efficient way. All topics mentioned above need are investigated in order to realize such a system in future.

Joint Radio Resource Management (JRRM) in mixed Cellular and WLAN Systems

The prevalence of heterogeneous networks is the new paradigm for B3G systems. Then in such scenarios appears as natural consequence the Joint Radio Resource Management (JRRM) of all the Radio access Technologies (RATs) involved. This is an advanced RRM able to overview all the covering RATs in the same area and hence to select the more appropriate RAT for a given specific user terminal or even share, as multihoming strategy, some of them. In that respect the availability of multimode terminals is an enabler for JRRM.

The JRRM in heterogeneous networks is believed to play a significant role in the world of communications. In particular, when a RAT cannot offer the required QoS, users will be directed to a different RAT that has to cope with less demand at that specific instant. This has as a consequence an increase in the operators wins, as more users will be able to be provided with the desired QoS. For the operator point of view, JRRM will allow to optimise the use of the radio resources. The users can be attended at each moment for the proper RAT, in terms of load balance, costs criteria, etc. At the same time, competition among RATs that can deal with the demand will reduce the prices and will, consequently benefit the users. In addition, the quality of communication will rise, as the use will be distributed effectively between the different RATs.

This scenario builds on these joint radio resource management aspects. JRRM concepts and algorithms have to meet requirements from the viewpoint of overall network performance, the individual user's point of view and the operator's point of view. JRRM solutions should integrate all these aspects.

The proposed scenario intends to be the basis for the assessment of the JRRM benefits to the different parties involved. The following considerations apply to this scenario: 1) No spectrum sharing is taken here in the sense of no FSM. The association of several RATs will however be implemented, taking into account the sharing conditions in the sense of not creating additional interferences, in comparison to a non JRRM situation, 2) One user can be handed over from one RAN to another, and 3) Full flexible services delivery: the services can be offered over more than one RAN (downlink complementarities), and may also move to a different radio access network during a call.

The main system requirements associated to this scenario are: 1) Systems are operated in their originated allocated spectrum band (i.e. with a fixed amount of spectrum). Spectrum regulation changes are not required. However, regarding convergence aspects, adaptations may be required, 2) Systems under consideration are cellular 2G (GSM/GPRS), cellular 3G (UMTS FDD/TDD) and WLAN at 2.5 GHZ and 5 GHz (IEEE 802.11 a/b, HiperLan2) and 3) Tight coupling between networks

In turn, two sets of requirements on the radio equipments capabilities (end user terminal or radio access network) are considered: 1) The end user terminal is multi modes/single band and the radio access network is single mode/single band, or 2) The end user terminal and radio access network are both multi-modes and single band allowing integration/coupling with other radio entities

The main driver in the study of this scenario is motivated by the fact that the user’s activity along a day implies changes at different levels: 1) Changing environment, the user being at home, at office, in a meeting, on the move from one place to another, etc. Movements from outdoor to indoor environment (e.g. from outside to company building) or vice versa may also occur. In a given environment (i.e. in a same geographical region), several layers are present. These layers can potentially consist of different technologies (e.g. GSM, GPRS and UMTS). In a given scenario, user is also characterized by a given mobility behavior (e.g. static in indoor office). 2) Changing traffic. During daytime, hot spot traffic areas can move, and services required by users are also evolving. For example, during the day the traffic may be concentrated on business areas, with services related to business requirements, while during the evening the residential or entertainment areas (restaurant, cinemas, etc.) will be more loaded, with different required services.

In this changing environment and changing traffic scenario, the different RANs must adapt to these load and services variations during daytime. In addition to this, when unusual events (sporting event, accident, natural disaster…) occurs, it is needed that the different RANs are to be momentarily reconfigured (e.g. different cooperation strategies may be used) in order to overcome the unusual traffic profile while providing fast and cheap hot spot coverage. In case the user moves from outdoor to indoor environment (e.g. from outside to company building) or vice versa, outdoor coverage could be ensured by a 2G and 3G systems, indoor coverage could also be ensured by WLAN. The user needs to change RAT to access new services or to ensure service continuity when a RAT is no more available.

In case that some layers are overloaded whereas another one offers still availability, and in order to maximize systems capacity and optimize user QoS, load balancing between layers would be performed. Some users would be redirected to the third layer according to certain criteria and mechanisms.

JRRM mechanisms must be defined to allow an operator with different RANs to move some users from the most loaded RAN to the less loaded RAN. The main requirement is to optimise the use of radio resources while offering the best QoS to users. This transfer must be seamless, transparent for the users, the users' terminal must be reconfigured while operating, the operator needs to know which terminals are multi-mode and the load status of the RANs.

The scenario is very relevant in the context of heterogeneous networks, not only because of the diversity on RANs availability but also because of service diversity and mixture with QoS demands.

The scenario is envisaged to help devising a JRRM algorithm development framework to cope with the multi-RAT management problem. The individual JRRM solutions are then expected to improve the networks performance by optimizing the networks capacity and QoS delivery.

JRRM and FSM in a Broadcast/Cellular/WLAN environment

Scenario

The fourth scenario (Figure 5) constitutes the flagship of the work undertaken in E^{2}R. It is the combination of the previous scenarios #1, #2 and #3. FSM and Joint Radio Resource Management (JRRM) will act as cooperating components within a heterogeneous infrastructure. This scenario illustrates an intelligent future network which is capable of being self-tuning with the support of FSM and JRRM.

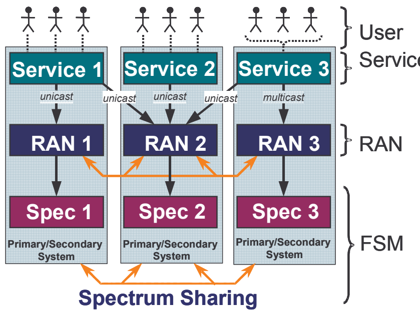

Figure 5: Scenario #4 description

The intelligence of the radio network relies not only on the level of user QoS reorganization and service provisioning through a dedicated radio access technology over a dedicated frequency band, but also on optimal network reconfiguration including the implementation parameters of the radio elements, the selection of inter-RAT coupling structure, the setting of spectrum usage shared or allocated to different RATs from the same or even different operators and the setting of proper JRRM mechanisms.

Technical Requirements

The system technical requirements of Scenario #4 are driven by: (1) RRM and FSM mechanisms must be defined to allow an operator owning different RANs to move some users from the most loaded RAN to the less loaded RAN or to allocate more radio channels where and when needed to the RANs; (2) optimise the use of radio resources while offering the best QoS to users. This transfer must be seamless, transparent for the users, the users' terminal must be reconfigured while operating, and the operator needs to know which terminals are multi-mode and the load status of the RANs; (3) The observations of the radio performance are required as input to the network management domain in order to execute resource efficient network reconfiguration. The changes of network parameters must be carefully planned to guarantee a stable radio network.

Conclusions

The four scenarios presented contain the most promising application scenarios for reconfigurability based flexible spectrum and joint radio resource management schemes. The scenarios presented cover the most prominent cases where and how cross system and cross band load balancing can be applied and used in different situations, they outline the need for a range of new technologies and the introduction of new concepts (such as spectrum pooling and auctioning) into the wireless communications area.

The investigations ongoing in IST-E^{2}R are based on these scenarios and the expected outcomes of this research include: FSM & JRRM concepts, technological guidelines, algorithms and simulation based results will give indications about quantitative spectrum savings are expected

ACKNOWLEDGMENT

This work has been performed in the framework of the EU funded project E^{2}R. The authors would like to acknowledge the contributions of their colleagues from E^{2}R consortium.

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