Hybrid Cellular-Broadcasting Infrastructure Systems

Radio Resource Management Issues

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Licentiate Thesis in
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Abstract

This thesis addresses the problem of low-cost multicast delivery of multimedia content in future mobile networks. The trend towards reuse of existing infrastructure for cellular and broadcasting for building new systems is challenged, with respect to the opportunities for low cost service provision and scalable deployment of networks. The studies outline significant potential of hybrid cellular-broadcasting infrastructure to deliver lower-cost mobile multimedia, compared to conventional telecom or broadcasting systems. Even with simple interworking techniques the achievable cost savings can be large, at least under some specific settings.

The work starts with a foresight study shaped around four scenarios of the future. New face of the wireless mobile industry is envisioned around of the merging of telecommunication, data communication, and media. The role of the scenarios is mainly to set the working assumptions about future user behavior and media consumption pattern. The focus is set on a special class of interactive multimedia applications, which is expected to generate a large amount of data traffic in future wireless networks. They consist of recreational and educational content, and are mainly characterized by highly asymmetric traffic pattern (i.e. the user terminals request massive amounts of information, while transmitting only short burst of data themselves) and multicast type of delivery, as most of the content is popular among customers.

Multicasting can be implemented through point-to-point transmissions in a cellular system or through physical layer broadcasting in a broadcasting system. As we target multicasting to a fairly large number of users, the broadcasting system is believed to be the major contributor. However, only reusing existing digital broadcasting infrastructure for radio and TV is demonstrated to not be enough for a cost efficient deployment of a broadband broadcasting system for mobile and portable terminals. For this reason, reuse of the existing cellular sites as a complement is proposed and evaluated.

Two approaches on the hybrid system architecture are considered. The first one assumes different degrees of interworking between conventional cellular and broadcasting systems, in single and multi-operator environments. Second, is a broadcast only system where cellular sites are used for synchronized, complementary transmitters for the broadcasting site.

In the first approach, the key issue is the multi-radio resource management, which is strongly affected by the degree of integration between the two networks. An ambient networking framework is first developed and then two case studies are analyzed in the specific case of cellular-broadcasting systems. Both of them deal with the problem of delivering, for lowest cost, a data item to a certain number of recipient users. An interesting result is the fact that real-time monitoring of the user reception conditions is not needed, at least when multicast group is large. This indicates a high degree of integration between cellular and broadcasting networks may not by generally justified by significant cost savings. A flexible broadcasting air interface, which offers several transmission data rates that can be dynamically changed, is demonstrated to significantly increase cost efficiency under certain conditions.

Scalability of the hybrid infrastructure is the main topic in the second approach. For a network designed with one of the state of the art technologies (DVB-H) the results show that achieving economies of scale through higher modulation and coding rate or by installing new transmission sites is difficult, if high capacity and area coverage are targeted. Therefore, it is suggested to avoid dimensioning the network for full coverage, and instead employ a cellular system for gap filling and packet error correction. The use of Raptor coding (an application-layer forward error correction technique) in the broadcasting system is suggested for enabling a simple interworking with a traditional cellular system.

Acknowledgements

Thanks to the existence of this thesis section I enjoyed a few moments of remembering all my close friends and colleagues. In particular, there are several people who I am grateful for inspiring me during the past years. The most important person of all is my advisor, prof. Jens Zander, who guided and encouraged me all the time, and being a bit more than a research advisor through his way of performing at work, family duties and ... innebandy. Special thanks go also to prof. Gerald Q. McGuire for interesting discussions, and especially for his visionary and outside-the-box type of thinking.

My studies started within the graduate school in Personal Computing and Communication, from which I received financial support and where I found a bunch of great people working on related areas. Thanks PCC, especially for the great time spent during the Summer Schools and Workshops. To my colleagues from PCC-4GW project, in particular Matthias Unbehaun and Olav Queseth for interesting and stimulating discussions.

My thesis is also result of my involvement in two projects which I want to mention here. The studies about the future were mainly performed within Wireless Foresight project, supported by Wireless@KTH center. The work I did together with the other team members: Bo Karlson, Peter Lönnqvist, Cristian Norlin and Jonas Lind has been of great importance for me. The multi-radio resource management framework was developed within the EU-IST Ambient Networks, where I enjoyed working together with my colleagues Jan Markendahl, Miguel Berg, Johan Hultell and Fedrik Berggren, but also with many other partners across Europe.

The digital broadcasting studies were performed together with my friend David Gomez-Barquero, Ph.D. Student in Valencia (Spain). Thank you David for your dedication to our common objectives, and I apologize for recently disturbing your siesta time.

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Finally, I express my gratitude to my family, which supported me as much as they could. Dear Ovidiu, my son, you gave me wings by being the way you are. Thanks for sleeping well over the last period. Lili, my dear wife, I am grateful to you for being so supportive, patient and understanding during all these years. Many thanks to all of you at home, in Romania, our grandparents, parents and my brother Alex, for being a great family all these years.

Contents

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List of Abbreviations

2G/3G/4G	Generations of Wireless Systems
AL-FEC	Application Layer - Forward Error Correction
AN	Ambient Networks
CNR	Carrier-to-Noise Ratio
DAB	Digital Audio Broadcasting
DSA	Dynamic Spectrum Allocation
DVB-H	Digital Video Broadcasting - Handheld
DVB-RCT	Digital Video Broadcasting - Return Channel Terrestrial
DVB-T	Digital Video Broadcasting - terrestrial
GLL	Generic Link Layer
GSM	Global System for Mobile Communications
HSDPA	High-Speed Downlink Packet Access
M/B	Multicast/Broadcast
MBMS	Multimedia Multicast/Broadcast Service
MCR	Modulation/Coding Rate
MPE-FEC	Multi-Protocol Encapsulation - Forward Error Correction
MRA	Multi-Radio Architecture
MRRM	Multi-RRM
PCC	Personal Computing and Communications Program
QoS	Quality of Service
RA	Radio Access
RAT	Radio Access Technology
RRM	Radio Resource Management
SIR	Signal-to-Interference Ratio
SFN	Single Frequency Networks
UMTS	Universal Mobile Telecommunication System
WCDMA	Wide-band CDMA

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Part I

Chapter 1

Introduction

1.1 Background

The wireless telecommunications industry has gone through an amazing development during the last decade. The global number of mobile telephone users is now well over one billion. It is a truly global business with markets spanning the world, large multinationals as well as small companies competing fiercely. At the same time, the telecommunications industry is facing severe difficulties. Blinded by the hype in the late 1990s and early 2000, operators have spent enormous amounts on licenses for third generation (3G) cellular systems. With the introduction of packet switched 2.5G and 3G systems, a whole new range of mobile data services are now possible. New types of systems, providing advanced services in specific locations will complement the traditional wide area cellular systems. This will no doubt lead to the emergence of new players on the wireless scene and probably a restructuring of the whole industry. The merging of telecommunication, data communication, and media into an integrated industry, will offer new business opportunities for existing and new companies. It seems the wireless industry is at a crossroads. The coming few years will indeed be exciting! [1]

This research work has started as a part of the Personal Computing and Communication (PCC) program in Sweden, aiming towards future provision of *mobile multimedia communication to all at the same price as today's fixed telephony*. In particular, the PCC-4GW (4-th Generation Wireless) project, where the author was particularly involved, aimed at designing the wireless infrastructure that will be deployed as a complement/replacement of 3G, around 2010-2015. Studying alternative technologies and architectures for such wireless access infrastructures was the aim of this project. Key limiting factors have been identified as spectrum shortage, power consumption and infrastructure costs. [2]

The evolution of the most popular multimedia[1] based services, such as Internet radio and TV, and recently Podcast, was driven by the fast development of broadband wired Internet connectivity at offices, homes and public spaces. Offering the same applications in a wireless mobile mobile environment is not straightforward. The main reason is the significantly large amount of bits they require to be transmitted to and from the mobile terminal. Implementation of true *mobile Internet*, especially in cellular networks, has caused many troubles in the recent years. Cellular operators tried to implement data access as a simple extension to their voice based networks, but they face an important limitation: the value of the bits is not perceived in the same way as the voice calls are. User satisfaction does not necessary scale with the amount of bits received or transmitted. Scaling up the capacity of the cellular systems, while maintaining anytime/anywhere availability encounters a big problem: cost per transmitted bit is virtually constant and higher user bandwidth translates directly into higher cost per supported user, due to higher investments needed in infrastructure. In general, the infrastructure cost of a cellular system grows linearly with the number of users and the user bandwidth. Accordingly, the cost of a service grows linearly with its bandwidth for any wireless system providing full coverage [3, 4]. This is most probably unacceptable, the tariff structure cannot be proportional to the data-rate, since the perceived value is not.

In order to enable the use of truly new and innovative multimedia services, higher bandwidths need to be provided at a lower cost that are provided by 2G and 3G systems. The main trends in the evolution of wireless networks are two. One is to design a new integrated system, 4G, of cellular type, following a similar design as 2G and 3G. This would perform similar to a *Swiss army knife*, being able to provide all kinds of services by means of a novel and very flexible air interface. However, the main challenge for such a system it will be to replace already existing systems. This may happen, for example, if the new system offers an order of magnitude lower cost. Following the same design and scaling up the 3G to 4G would definitely not achieve this. Already 3G has proven very expensive, and the experience shows that if broadband mobile multimedia is to be affordable, either some QoS parameters (e.g availability, delay) have to be sacrificed or new system architectures with radically lower cost factors must be developed (e.g. architecture based on sharing infrastructure or spectrum)[5]. Another success story can be to deliver new services which 2G or 3G will only dream about, a *killer application*, which is able to generate money proportional with the necessary investments both in the new system infrastructure but also in tearing down the existing systems. Nowadays, the killer applications seem to be voice calls and text/picture messaging, but these two are already successfully implemented in 2G and 3G. Not only the demand is the problem, but also the spectrum allocation. The new 4G system needs large

[1] According to Encyclopedia Britannica the term *multimedia* refers to a computer-delivered electronic system that allows the user to control, combine, and manipulate different types of media, such as text, sound, video, computer graphics, and animation

amounts of spectrum, which we cannot say that are unconditionally available on request. Unfortunately, the spectrum allocation for the next 10-15 years does not seem to suffer disruptive changes.

The second trend is to enable cooperation between existing technologies and infrastructures for cellular, hot-spot and broadcasting networks. As parts of a new heterogeneous system, the operators of these networks can share the same core network, infrastructure, billing mechanism, transport network, etc. The problem is that all these systems belong to different industries, each of them developed in a different business environment, under very different value chains and revenue models (see Appendix A). For example, broadcast operators base their revenues mostly on commercials and flat fee subscriptions. Revenues do not depend as much on the system throughput as on the number of subscribers. Transmitted bits are shared by all customers and spectrum is perceived as free. Cellular operators live in a separated world based on expensive licensed spectrum, very strict control of their customer base, and payments can be as low as few cents for a call or data session. Hot-spot systems based on wireless local area networks (WLAN) are part of the datacom industry dominated by computer manufacturers and Internet developers. The hot-spots provide local coverage with high data rates, the spectrum is unlicensed and most of the time customers pay a flat fee for access. The cooperation among these can be enabled through integration under the same administrative entity, a third party entity (e.g. a broker) and/or smart terminals supporting a variety of air-interfaces and protocols. An Ambient Networking framework following these directions is already proposed and investigated [6].

This heterogeneous infrastructure vision is sustained by the downward evolution of cellular industry in the last few years, together with new regulatory framework, which leads the mobile operators to change their business models and strategies for expansion. The new European regulations on communications [7, 8, 9] intend to change the *vertical* integrated business into a fragmented or *horizontal* one. In other words, we expect the commission to encourage the shift from vertically integrated operators positioned in the whole value chain (e.g. providing handsets, content, service and network operation) towards separate providers for service (bit pipe providers), network operation, content, handsets, etc. Different actors will compete/cooperate at different layers (e.g backbone network, radio access network, network management, service provisioning, etc.). Already today, if we take a look at the value chain in the broadcasting business there are different actors for content provision (program editor), commercial distribution, delivery (multiplex operator) and access (infrastructure provider). A similar situation exists already in the cellular business market when a number of virtual operators (e.g. Tele2) share the same infrastructure with other operators. On the other hand, the modularization of the business certainly trade performance and complexity for flexibility and reduced cost. Therefore, some operators, especially multi-nationals, fight hard to keep alive their integrated business. In this way they try to secure the bridge between revenues generated by selling the services and content, and costs from operations and necessary investments.

1.2 Hybrid cellular-broadcasting systems

Existing infrastructure and the significant chunk of allocated spectrum for broadcasting represent extremely valuable resources. The broadcasting industry, both satellite and terrestrial, is now shifting gradually to digital transmissions of TV and radio programs. Several European countries have already fully functional terrestrial systems based on digital video broadcasting (e.g. DVB-T in Sweden, Finland, Germany, Italy, etc.). The present trend in this business is to define broadcasting as being an *interactive* service, so broadcasting operators are in a continuous search for a feedback channel from their users. Solutions based on return channel through PSTN or cellular networks already exists in consumer products. E-mail, web browsing, movies on demand, software updates are already possible in DVB systems (terrestrial, cable and satellite). A new standard for a return channel was proposed and adopted recently for the terrestrial broadcasting. The system is called DVB-RCT (Return Channel Terrestrial) [10] and the transmissions from user terminal take place in the spectrum allocated for TV broadcasting. In order to cope with portable terminals limited to small power consumption the broadcasting industry together with some equipment manufacturers introduced several adaptations of the broadcasting standard DVB-T in order to cope with handheld devices. The new standard is called DVB-H (Handheld) and it is supposed to be able to provide broadcast/multicast services for low power and small screen handheld devices [11].

The integration of existing cellular and broadcasting system into a unified platform is not new topic, and it started with the introduction of radio digital broadcasting technologies back in early 90's. The benefits and drawbacks of different architectures were widely exposed in the literature, for example in [12, 13, 14, 15, 16, 17]. The most important aspects are summarized in two contributions of the thesis author, together with a personal view about future design of cellular-broadcasting architectures [18, 19]. Among the most important opportunities that arise from cellular-broadcasting integration we mention:

- Compared to dense cellular architecture, large broadcasting cells posses very good multicasting capabilities to mobile, especially high-speed, users. The advantages are: (1)frequent hand-offs are avoided, (2)the same transmission is shared by all receiving terminals.
- Cellular systems can provide the return channel necessary for enabling interactive broadcast/multicast services.
- Digital broadcasting systems can be used as well for personal services, to complement the capacity in the cellular downlink for fixed, mobile or even portable terminals.

- Reuse of cellular sites for complementary broadcasting transmitters or gap-fillers is one way to utilize existing infrastructure and reduce deployment time and cost.

- The spectrum presently allocated to analogues and digital TV broadcasting may partly become available for personal communication when the digital switch-over takes place.

regarding the particular case of multicasting services, the limitations of present cellular and broadcasting systems are quite clear. Cellulars do multicasting through individual transmissions to each recipient user, so the cost of such service is directly proportional with the number of users and the necessary bandwidth per user. Recently, cell broadcasting technologies are developed for 3G (e.g. MBMS), but their potential for broadband multicasting is very low if they have to share the same cell resources with other services. The highest potential for implementing cost efficient broadcast/multicast necessary for mobile multimedia is presented by the newly deployed digital broadcasting systems, but they miss the return channel which can be provided securely by a cellular system.

1.2.1 Efforts on Concept Demonstration

First proposals on the integration of cellular and broadcasting systems appeared in ACTS-MEMO project [20] back in 1996. In this first proposal the targeted service was asymmetric Internet access (similar to a wireless version of ADSL). The broadcasting system (DAB/DVB-T) was supposed to provide high data rate downlink (2-10 Mb/s) while the uplink was implemented on circuit switched GSM at 9.6 kb/s.

A following EU funded IST project MCP - Multimedia Car Platform [21] demonstrated the feasibility of in-car provisioning of multimedia services by combining GSM/UMTS and DAB/DVB-T. A demonstrator was presented at IFA2001 Congress in Berlin.

Another project dealing with similar issues was COMCAR - Communication and Mobility by Cellular Advanced Radio [22]. This project focused on integration of broadcasting technologies as an additional downlink of UMTS cellular systems. A concept demonstrator was built.

The IST-DRIVE (Dynamic Radio for IP-Services in Vehicular Environments) [23] project proposed a strategy to share the spectrum resources of both systems in a dynamic manner. The technique, called DSA (Dynamic Spectrum Allocation), was later perfected in the OverDRIVE (Spectrum Efficient Uni- and Multicast Services over Dynamic multi-Radio Networks in Vehicular Environments) project [24]. The main interest was the delivery of high quality vehicular multimedia services in a multi-operator environment. The projects addressed the interworking of cellular and broadcasting systems in a common frequency range, employing DSA.

The IST-MONASIDRE (Management Of Networks And Services In a Diversified Radio Environment) project [25] developed a platform for multi-radio resource management in heterogeneous systems (cellular, broadcasting and hotspot). The goal was to design a joint access selection and resource allocation strategy that is able to assign in realtime the users to the best suited radio access for the service they require. The investigations were focused on the real-time and streaming services and how to allocate them to one of the managed radio accesses.

These projects proved through simulations, measurements and prototypes that higher spectrum efficiency is achieved by combining cellular and broadcasting resources. The targeted services were mostly audio/video streaming or real-time voice/video calls, under the assumption that there is one entity which control the resource management process. Unfortunately, there is no much attention payed on the performance evaluation when cooperation and dynamic agreements between separated network operators exist. Leaving aside the dynamic spectrum allocation, which is not encouraged by the existing regulatory framework in EU, it will be interesting to see how much the operators can benefit if they cooperate for enabling new ways of delivering the multimedia services, with more efficient use of existing infrastructure.

1.3 Problem and Thesis Scope

As the technical feasibility was proven by different prototypes, the key question is not if hybrid cellular broadcasting systems are possible, but if they can actually provide a long-term economically viable solution, when networks have to cope with larger user population and higher demand for services. A complete answer requires many aspects related to technology and business to be considered, and it consists of a full scale comparison, in terms of network cost and complexity, with conventional *telecom*-style infrastructures (e.g. UMTS) for various user populations and infrastructure densities.

The most challenging technical problems with hybrid infrastructure systems involve efficient resource management and deployment strategies. The new challenges are related to the design and implementation of the interworking platform between cellular and broadcasting systems, especially the definition of the necessary interfaces.

From a resource management perspective the goal is to reduce the cost of service through as efficient as possible use of existing radio resources. However, definition of cost is not obvious and careful modelling and business assumptions setting must be performed. The main questions lie around how existing radio resources can be shared efficiently, and how flexible combinations of multicast and point-to-point delivery should be used to provide the same service. Design and implementation of algorithms for dynamic spectrum assignment, radio access selection and resource allocation in heterogeneous networks is one important research area. Error control strategies for the data flows transmitted through broadcasting radio access are also of great interest. From a system deployment perspective, scalability of network infrastructure with increasing demand for services is the main concern. Achievement of scale economies (e.g. decreased cost per user if number of users increases) through novel system architectures is key.

Even if it looks very promising from the technical side, the successful deployment of new systems on hybrid infrastructure is also conditioned by several business related aspects. Besides lower investment in infrastructure and lower operational costs due to resource sharing in a cooperative manner, there is still a question mark regarding the viability of the new business models. How the hybrid systems will be able to make money out of reduced cost and introduction of new services is not yet clear. Competition and trust relationships between cellular and broadcasting operators will likely affect the cost of the service and the degree of integration/interworking among the systems, since operators may not agree to share certain sensitive information about their network performance, user data, etc. These aspects must be accounted for in the resource management design, and their direct implications should be reflected in terms of cost figures.

Out of this vast domain of possible problems the thesis has its main objective to identify and evaluate the basic opportunities, but also the bottlenecks, arising from infrastructure sharing and cooperative resource management among cellular and broadcasting systems. The presented contributions target the following areas:

- Identification of relevant working assumptions necessary for investigation of future wireless networks, with special focus on the media consumption patterns and user behavior.
- Framework for multi-radio resource management in future heterogeneous infrastructure systems, with multicasting capabilities.
- Evaluation of operational cost savings in a system that provides multicast services by employing joint resource management between a cellular point-to-point network and a digital broadcasting network.
- Evaluation of deployment cost when existing wireless infrastructure (GSM, 3G and DVB-T) is reused for building a mobile broadband broadcasting system (DVB-H).

1.4 Methodology

Due to the nature of the services and system architectures we are looking at, the time targeted for deployment of the envisioned systems is probably several years from today. In such case, *setting the working assumptions* at the beginning of the work is one of the important, but also difficult, part of any research attempt. The fundamental problem with assumptions is that they are based on conditions external to the study (e.g. user preferences, social development, economic growth, etc.) and most probably these external determinants will not remain stable over the course of the study. Future is uncertain and the experience of last years shows that long term predictions of the wireless market development failed in many cases. Because of this a substantial effort was spent in identifying trends, user expectations and technology drivers before engaging in system design issues, infrastructure deployment and system performance evaluation. Setting up the right assumptions is crucial for understanding how to evaluate the true potential of the proposed system design choices. The method employed to set up the working assumptions was the *scenario method* [26].

Through the scenario process few assumptions about future multimedia services, user behavior, market and business environment, are formulated. These assumptions helped in the identification of several relevant hybrid system performance measures coming from the business domain (e.g. cost of service, economies of scale, etc.).

Case studies and Monte Carlo simulations are utilized for getting an insight into the performance achieved by the proposed system architectures and resource management techniques.

1.5 Definitions

The term *infrastructure* refers to the masts, antennas, sites, cables for data and power, etc. The term *network* is utilized for the the core network and the associated infrastructure(s). A *system* consists of one or more networks operated by a *network operator*, and end user terminals.

The term *broadcasting* is utilized for referring to transmissions, through the radio channel, dedicated to all receivers in the service area. The transmitter does not have any information about existing receivers or if they receive the transmitted data correctly. Moreover, the receivers are not able to ask for retransmissions. We define *multicasting* as a particular case of broadcasting when the transmission is addressed to a specific group of terminals, called the multicast group. Every single terminal in the multicast group has to correctly receive the transmitted packets, otherwise communicate the failure back to the transmitter (e.g. using an uplink channel provided by the cellular system).

1.6 Summary of Contributions

Papers attached to the thesis as appendix:

1. Berggren F.; **Bria, A.**; Badia, L.; Karla, I.; Litjens, R.; Magnusson, P.; Meago, F.; Tang, H. and Veronesi, R.: Multi-Radio Resource Management for Ambient Networks, *in IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, 2005, Berlin, Germany.

[The introduced concepts are the result of teamwork within AN-WP2-T3 working group and no-one can claim exclusive rights. My major contributions are mostly in the last sections of the paper, where multi-operator aspects are discussed. I further contributed with evaluation studies on this topic, providing figure 3. I was also the second editor of the paper and I presented it at the conference]

2. Meago, F.; **Bria, A.**; Karla, I.; Magnusson, P.; Litjens, R. and Tang, H. Multicast/Broadcast Opportunities in Beyond-3G, *in International Workshop on Convergent Technologies (IWCT)*, 2005, Oulu, Finland.

   [The introduced concepts are the result of teamwork within AN-WP2-T3 working group. My personal contributions are: (1) partial input on all chapters, and iteratively reviewing and editing parts of the paper, (2) writing the conclusions section]

3. **Bria, A.**, Cost-Based Resource Management in Hybrid Cellular-Broadcasting Systems, *in Proceeding of Vehicular Technology Conference - Spring*, 2005 pp. 3183–3187 Vol. 5., Stockholm, Sweden

4. **Bria, A.**, Performance of Cost-Based Resource Management in Cellular-Broadcasting Systems with Multicast Push Traffic, *in International Conference on Telecommunications*, 2006, Madeira, Portugal.

5. **Bria, A.**, Gomez-Barquero, D., Scalability of DVB-H Deployment on Existing Wireless Infrastructure, *in IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, 2005, Berlin Germany

   [The scalability study was designed by myself, together with the cost model. My partner provided very good input and comments, as well as the necessary Matlab code and simulation results.]

6. Gomez-Barquero, D.; **Bria, A.**, Evaluation of Application Layer FEC for Streaming Services in DVB-H Networks for Mobile Terminals, submitted to *Vehicular Technology Conference - Fall*, 2006.

   [I came up with the idea of using application layer FEC in the form of Raptor coding for achieving a flexible trade-off between perceived data rate and coverage. The reason is to start creating a framework for integrating the DVB-H technology into the cost-based resource management framework described in papers 3 and 4. However, my partner was the main editor, and he provided the necessary simulation code.]

The following contributions are related to the topic:

Books and reports:

1. Book: Karlson B.; Bria A.; Lönnqvist P.; Norlin C.; and Lind J., *Wireless Foresight: Scenarios of the Mobile World in 2015.* Wiley, September 2003.

2. Technical Report: Karlson B.; Bria A.; Lönnqvist P.; Norlin C.; and Lind J., *Wireless Foresight: Scenarios of the mobile world in 2015.* Technical Report, TRITA-S3-WS-0201, Royal Institute of Technology (KTH), Wireless@KTH, June 2002.

Journal articles:

1. Bria A.; Gessler F.; Queseth O.; Stridh R.; Unbehaun M.; Wu J.; Zander J.; and Flament M., *4th-Generation Wireless Infrastructures: Scenarios and Research Challenges.* Personal Communications, IEEE, 8(6):2531, 2001.

Conference papers:

1. Bria A., Digital Broadcasting and Mobile Cellular Networks to Provide Asymmetric Data Services - a Survey, *in Proceedings of RadioVetenskap och Kommunikation (RVK) Conference*, June 2002, Sweden.

2. Gomez-Barquero D.; Bria A. *Feasibility of DVB-H Deployment on Existing Wireless Infrastructure.* In International Workshop on Convergent Technologies (IWCT), Oulu, Finland, June 2005.

3. Bria A. *Joint Resource Management of Cellular and Broadcasting Systems - Research Challenges.* In RadioVetenskap och Kommunikation (RVK), June 2005.

4. Cedervall, C.; Karlsson, P.; Prytz, M.; Hultell, J.; Markendahl, J.; Bria, A.; Rietkerk, O. and Ingo Karla. Initial Findings on Business Roles, Relations and Cost Savings Enabled by Multi-Radio Access Architecture in Ambient Networks, *in Proceedings Wireless World Research Forum Meeting*, July 2005.

5. Kouduridis, G.P.; Aguero, R.; Alexandri, E.; Berg, M.; Bria, A.; Gerbert, J.; Jorguseski, L.; Karimi, H.R.; Karla, I.; Karlsson, P.; Lundsjo, J.; Magnusson, P.; Meago,¨F.; Prytz, M. and Sachs, J., Feasibility Studies and Architecture for Multi-Radio Access in Ambient Networks, i*n Proceedings Wireless World Research Forum Meeting*, Paris, France, December 2005.

6. Kouduridis, G.P.; Karlsson, P.; Lundsjo, J.; Bria, A.; Berg, M.; Jorguseski, L.; Meago, F.; Aguero, R.; Sachs, J. and Karimi, R., Multi-Radio Access in Ambient Networks. In IST Workshop, *in IST - Everest Workshop*, Barcelona, Spain, November 2005.

7. Aktaş, B.; Bria, A., Evaluation of User Perceived Performance in Sparse Infrastructure Wireless Systems, *in Proceedings of the Affordable Wireless Services and Infrastructure Workshop*, Stockholm, Sweden, June 2004.

Chapter 2

Future of Wireless Media Consumption

This chapter outlines the main working assumptions about long-term specific aspects of social and market domain, which will have an important impact on the development of the wireless systems and services. This step is absolutely necessary in any research attempt, it is also maybe the most difficult one, especially when targeting system deployment in, let's say, ten years time. In our specific context, it will be of little value to investigate hybrid cellular-broadcasting systems delivering today-like services, as voice calls, wap browsing or TV streaming, by simply assuming present consumption patterns, user behavior and system architectures. That is because even five years of wireless technology development is an enormous time period, which involves significant changes. Most probably, IT and wireless technologies will be soon regarded as commodities, they will be taken for granted by anybody on this planet. The paradox might be that the more efficiently they manage to fulfill their promises, the less people will notice them. Then what can we assume about the future users of wireless services? What services will they like to consume? How much are they going to pay? To whom is he or she going to pay? How will the wireless services market look like? etc.

2.1 Scenario Work

The author started the foresight work in late 90's, together with PCC-4GW project. The chosen approach was to develop scenarios of the future, painted to show possible future developments. Please note that *scenarios are not predictions*, but visions. They point in different directions, and can be seen as tool for ordering our perceptions. The goal is to use the scenarios for making strategic decisions that will be sound for all probable futures. No matter what future takes place, you are much more likely to be ready for it and influential in it if you have already thought about it thoroughly. The main focus in our scenarios is on challenges and development of the wireless industry, i.e. operators, infrastructure and terminal vendors, service providers, and service developers [1].

Even a very limited literature search shows that there is an incredible amount of scenarios reported in the literature. Given the specific aims of our effort, we have of course been more inspired by some scenarios than others, the most important being: *the Book of Visions* by the Wireless World Research Forum [28], *The Swedish Technology Foresight* by the Royal Swedish Academy of Engineering Sciences (IVA), and *Beyond Mobile*, a study carried out by people at the consultancy Kairo. In the scenario making process we have been mostly inspired by Peter Schwartz' book on this topic [26].

The standard method for scenario development is a very structured process. It is derived from a hypothesis driven working method and is built on quickly identifying what is most relevant, on cutting the ambiguities. Complexity is reduced in an iterative process where less important scenario dimensions are dropped. Ideally, you end up with identifying the two most important dimensions. If these are assumed to be independent, you can illustrate the scenario space in a two-by-two matrix. Finally, four scenarios are formulated, each in one corner of the matrix.

The Wireless Foresight project partly followed this approach. The main difference is that we have been striving to keep method and format for the scenarios open. When formulating the four final scenarios, we chose to explore what we believe are important topics for the future of the industry. We did not have the ambition of reducing the complexity to two independent variables illustrated in a two-by-two matrix. We have instead developed the scenarios by combining 14 trends in different ways (see Appendix B), giving us more freedom in the creation. These trends are in turn derived from a set of fundamental drivers of development, assumed to be true in all scenarios.

Nevertheless, this approach is traditional in the sense that it takes off from the world as it looks today and by identifying driving forces and trends, attempts to say something about the future. The starting point is the present. As a complementary approach, we tried to start from the other end as well, trying to put ourselves in 2015 looking back. This has been done by posing provocative questions and looking for weak signals. This approach has been fruitful in removing the thinking from the bonds of the present. Examples of provocative questions are: How would the wireless world look if base stations can be bought and installed by any user at a very low cost and the user can earn money from providing wireless access to others? What if radiation from mobile terminals proves to be harmful to humans after lengthy exposure? What will happen if

[1] The first set of scenarios were created in the 4GW project of the Personal Computing and Communications program [2], the thesis author being involved in the last part of the process. However, in the Wireless Foresight project [27, 1] he was an active member from the beginning to the end

one or several of the world's large service providers for wireless access goes out of business due to large debts? What if government, due to security issues, decides not to release more of the spectrum?

The work was conducted in an iterative manner. On numerous instances we went back and did alterations and changes to work in progress. Preliminary ideas, drafts etc. have been presented and discussed at several occasions in different environments and with experts from various fields, both from industry and academia. These external experts aided in identifying important trends, research issues etc. They also provided a sanity check of our thinking and gave us feed-back in various ways.

2.2 Working Assumptions

Through scenario rehearsal process we were able to determine a set of assumptions about the future. The following compilation is used as the set of working assumptions in this thesis:

- *Packet switching technology will dominate in the future systems, both in wired and wireless domains.*
- *Broadcast media for public and local information services will remain a strong business.* This implies that *multicast* will be one of the major type of information and entertainment delivery in future systems.
- *Cost of network planning and infrastructure deployment will significantly exceed the cost of electronic equipment.* From and economical perspective the deployment of new broadband wireless infrastructure will be too expensive to afford it, so *reusing already existing systems* becomes a must. *Competition* between many operators and service providers will be encouraged by regulators, but it is likely that several operators would like to *share* the same radio resources in order to save costs. Launching of wireless broadband multimedia services will be initially enabled by *coexistence and cooperation* among all kind of existing wireless networks.
- *Wireless services will become a commodity.* Competition and lower profit margins will characterize the future market for wireless services, requiring operators to be very careful when investing in new infrastructure. *Over-dimensioning* of network capacity will be avoided and a *scalable* system infrastructure will be preferred. This must offer a deployment cost that scale nicely with number of customers and bandwidth provided to them. One of the most important goals of the system design will be the achievement of *economies of scale* (i.e. lower cost per customer when more customers are joining the network).
- The terminals will exhibit a wide range of capabilities, handling several air-interfaces, high data rate or different user interfaces. However, short

battery time due to large *power consumption* will remain a problem especially for advanced multi-mode terminals.

- One essential condition for the mass market success of mobile multimedia services is that they have to be *affordable* for the consumers. Future users are definitely not prepared to spend more for wireless services compared to today. For these reason, the future wireless networks must be able to deliver, for *low cost*, significant quantities of bits to the user terminals. The cost of retrieving the content through the radio interface should be much lower than the cost of the content itself.

- The end user would appreciate the feeling of being *always best connected*. The implication of this fact is that users may have the opportunity to choose not only between different radio accesses available, but also between providers.

- Users are already today accustomed to be connected *anytime and anywhere*, so coverage (as perceived by the user) can hardly be compromised in the future. It is not expected that future users are willing to sacrifice functionality for the added value of mobility - mainly because he will hardly be using any other stationary telecommunication devices. However, providing wide-area availability of mobile multimedia services is a challenging task, if the service cost must be kept low.

2.3 Implications on sub-problem definitions and methodology

The trend towards heterogeneous systems is challenged in this thesis, with particular focus on the hybrid cellular-broadcasting infrastructures.

The main reason to look at such hybrid systems is the early identification of a special class of interactive multimedia applications, consisting of recreational and educational content[2], which is expected to generate a large amount of data traffic in future wireless networks [2]. These services are characterized especially by highly asymmetric traffic pattern (i.e. the user terminals request massive amounts of information, while transmitting only short burst of data themselves) and multicast type of delivery, as most of the content is popular among customers. Most of this content is not delay sensitive, in the sense that it can be consumed at a later point in time after its delivery in the terminal. As examples of such service we mention time-shifted TV, video-clip download, cache memory synchronization (e.g. AvantGo type of application), Itunes, etc. The mentioned service characteristics (asymmetry, content popularity and time shifted consumption) fit perfectly with a hybrid cellular-broadcasting system architecture.

[2]also found in literature as infotaiment and edutainment

From the foresight studies a few approaches towards system design for low-cost provisioning of future mobile multimedia services can be identified:

- Avoid over-dimensioning of network capacity and coverage, through sharing the under-utilized resources of alternative available systems.
- Try to reuse existing infrastructure instead of deploying new one. Share existing infrastructure among different systems.
- Share bits among many users through physical layer broadcasting, when this is possible and economically justified.
- Maximize *user perception of coverage* through utilizing clever techniques for off-line data delivery and data caching and management in user terminals.

These guidelines are reflected in the identification of the key problem addressed in the thesis: resource management for efficiently sharing existing infrastructure and radio resources among several operators and services. Ambient networking and its specific multi-radio resource management is therefore developed as a larger concept, which can be particularized for cellular-broadcasting systems (papers 1 and 2).

The cost based resource management techniques proposed for evaluation in the attached publications 3 and 4 has its roots in the assumptions that a resource management for a hybrid system must offer (1) cheapest service cost (2) competition for resources among services and operators. Introducing service cost in the resource management and making an objective out of minimizing it is justified by the assumption of mature markets, where revenues cannot increase any more so the only way to increase profit would be to decrease costs. The fact that different operators or service providers will compete for delivering their services through shared cellular and broadcasting radio accesses is accounted for in the chosen cost model. More detailed reasoning for system modelling is provided in section 3.2.2.

The foresight studies tell that the performance measure we should look at is scalability of the infrastructure deployment with demand for services. In paper 5 we therefore investigate if economies of scale are achievable. Maximizing user perceived coverage, on the expense of additional delay and reduced system capacity is the approach taken in paper 6.

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Chapter 3

Radio Resource Management in Cellular-Broadcasting Systems

One of the main issues in hybrid cellular-broadcasting systems is the radio resource management (RRM). This involves decisions on how to utilize available radio resources (e.g. power, sites, spectrum) in the most cost-efficient manner, while delivering the promised quality of service. This chapter investigates issues related to the radio resource management specific to multicast services delivered through wireless systems built on hybrid cellular-broadcasting infrastructure. The main questions are: (1) How much do we gain or loose if existing systems and their radio resources are integrated into a larger system or by letting them cooperate and share their resources in a dynamic manner? (2) How much cooperation is needed and how much gain is achievable compared to traditional cellular or broadcasting design?

First, a high level framework for radio resource management in heterogeneous networks is introduced and descriptions of functionalities needed for multicast/broadcast services in ambient networks are formulated. These contributions are part of a larger project dealing with *ambient networking* [29]. The aim is to provide concepts and a general framework for the design of future heterogeneous networks, including hybrid cellular-broadcasting infrastructure systems. Second, a cost-based radio resource management technique is proposed and evaluated, in an effort to quantify the potential gains compared to traditional systems, under some specific settings.

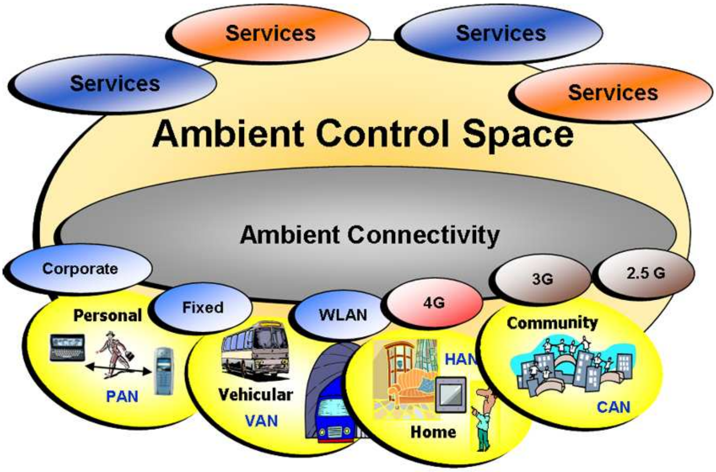

Figure 3.1: Ambient Networking

3.1 Ambient Networking

The work presented in this section was performed as a part of the Ambient Networks Project, an European effort towards an innovative, industrially exploitable new network vision based on dynamic coordination and integration between networks to avoid adding to the growing patchwork of extensions to existing architectures. Networks target forthcoming dynamic communication environments where a multitude of different wireless devices, radio access technologies and network operators can cooperate as well as compete by means of instantaneous inter-network agreements.

Ambient Networks aim to establish this inter-operation through a *common control plane* distributed across the individual, heterogeneous networks. This new control plane functionality can be deployed both as an integral component of future network architectures that have better intrinsic support for network heterogeneity or as an add-on to existing, legacy networks that allows them to inter-operate with future networks [30].

3.1.1 Multi-Radio Access Architecture

In order to facilitate such a dynamic composition of access networks, a Multi-Radio Access (MRA) architecture has been devised consisting of Multi-Radio Resource Management (MRRM) and Generic Link Layer (GLL) functionality. In Figure 3.2 the solid lines represent user plane data flow while the dashed lines show the MRA (MRRM and GLL) signalling through the layers. Arrows indicate control interfaces between different functional blocks, carrying information exchange and control commands e.g. for configuration or for measurement data

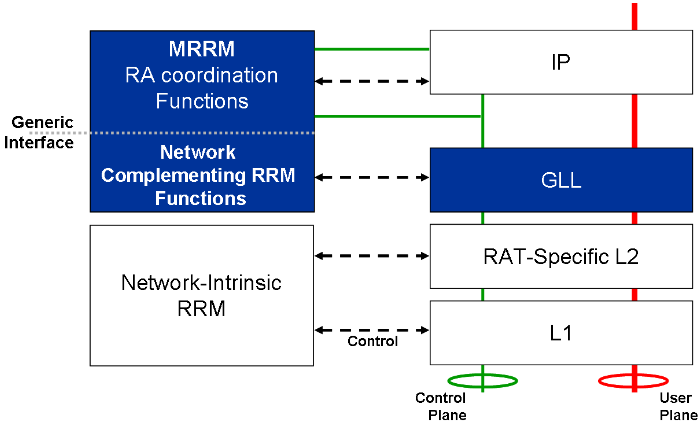

Figure 3.2: Multi-Radio Access Architecture

retrieval [31].

One of the key objectives of the MRA architecture is the efficient utilization of the multi-radio resources by means of effective radio access selection mechanisms. This is of interest to end users, providers, and regulators. Users and providers benefit from flexible use of different types of radio accesses (RA), including selection of a *best* type of access, both from a user point of view, e.g., low cost versus high performance, and from a provider point of view, e.g., load sharing. Users will further benefit from getting access to *any* network, requiring support for rapid establishment of roaming agreements (dynamic roaming) and efficient announcing strategies (of both user needs and provider offers). This calls for the capability of overall management of network resources of multiple network providers and operators. MRA is the part of the ambient control space that is closest to the radio interface.

The MRA architecture consists of two main components: *Multi Radio Resource Management (MRRM)*, for joint management of radio resources and load sharing between the different RAs; and *Generic Link Layer (GLL)*, which provides a toolbox for unified link layer processing, offering a unified interface towards higher layers and an adaptation to the underlying radio access technologies. MRRM is purely a control-plane function in charge of access selection in AN, GLL represents the AN Layer 2 interface for user-plane data. MRRM maps higher level requests on services provided by GLL. A main feature of the MRA architecture is resource sharing and dynamic agreements between ANs, including different access providers, through composition. Other features are efficient advertising, discovery and selection of RAs, including the possibility for a user to simultaneously communicate over multiple RAs, in parallel or sequentially, and efficient link layer context transfers. Further, the MRA architecture supports multi-radio multi-hop communication using both moving and fixed relays.

3.1.2 Multi-Radio Resource Management (Paper 1)

A general framework for multi-radio resource management (MRRM) in multi-operator and multi-RAT environments is defined in the first attached paper to this thesis [32]. Due to the limited space available in the paper, the reader might find difficult to understand several issues which would require more reading of Ambient Networks project contributions. In the following subsection complementing material is introduced, together with a better description and motivation of several related issues. Since the paper was presented additional work has been performed by the project partners, and published in two other papers: [31, 33].

Located in the control plane, the MRRM consists of RA coordination and network-complementing RRM functions (see Figure 3.2). The former are generic and include the principal coordination abilities, such as load/congestion control and RA selection. In contrast, the latter are RAT-specific functions, and provide missing (or enhance inadequate) RRM functions to legacy or future networks, or act as translation layer between the RA coordination functions and RA intrinsic RRM functions. The MRRM RA coordination functions are generic and can coordinate the RAs at system, session and flow level.

The MRRM functions are built upon, or mapped onto the network intrinsic RRM functions, which belong to the underlying radio access. Signalling among MRRM communicating entities is conveyed either over IP or directly mapped onto the GLL. The MRRM handles the access to radio resources, over both single- and multi-hop links, provided by the available radio accesses, where each radio access corresponds to distinct or possibly identical RATs and administrative entities.

MRRM aims at providing flexibility in the implementation of service delivery over different spectrum and business regimes for both legacy and future technologies. Basically, RA coordination consists of the following functions:

- **RA Advertising**: informs about the presence of a network, the ability to communicate and cooperate with other networks and/or its capabilities to provide a given service possibly in a business oriented fashion (with associated costs). For example, proxy advertisements could be sent on behalf of other access providers or network nodes.

- **RA Discovery**: uses the RA Advertisements to identify and monitor candidate RAs and routes for specific flows.

- **RA Selection**: selects the appropriate RAs for a given flow. The RA Selection process completes in two steps: The first step is the RA Evaluation wherein several parameters may be considered, including signal quality and strength, end-user QoS needs, end-user cost-capacity performance, multi-operator network capacity, RA capabilities, RA status, RA availability, user and provider preferences and policies, and operator revenues in single/multi-operator scenarios. The evaluation is then followed by an RA Admission decision, ensuring that already established QoS agreements are protected. The RA Selection function also involves negotiation of MRRM roles during composition, and exchange of relevant information during MRRM operation, through various forms of information exchange.

- **RA Monitoring**: provides measurements data (e.g., different network load measures) as input to other MRRM functions.

- **Overall Resource Management**: keeps an overall control of network resources and protects established QoS agreements proactively within an AN and in coordination with other ANs. Means for this include load sharing, excess QoS elimination, QoS downgrading, flow/session dropping and dynamic spectrum control within or between RAs.

MRRM functions can be distributed in a centralized or decentralized way, between MRRM entities of different ANs depending on network composition agreements (e.g., master-slave relation), among the constituent RAs. Additionally, MRRM functions should support single-hop or multi-hop networking (including ad-hoc networks without fixed infrastructure) as well as multicast/broadcast services.

Access Selection

As the fundamental MRRM function, Access Selection[1] uses knowledge about available access flows for a particular terminal to assign one or more of them to each active AN bearer [33][2].

Access selection function decides which (radio) access flows(s) (among the available ones) that should be used for the end-to-end bearer in a multi-radio access scenario. An access flow can contain a single access link, in case of single-hop communication or multiple access links in case of multi-hop or multicast/broadcast communication. The radio access flows are the elements managed by MRA functionality. Managing the access flows is achieved by means of Access Sets that are established and maintained by the RA coordination functions:

- Detected Set (DS): is the set of all access flows that have been detected by MRRM for an AN through e.g. scanning or reception of RA advertisements.

- Candidate Set (CS): is the set of access flows that are candidates to be assigned by MRRM access discovery function to a given active bearer; it is always a bearer-specific subset of the DS.

[1]Through the first phase of AN project the author worked mainly on Access Selection functionality

[2]The author has contributed in this paper in section Multi-Radio Access Selection Concepts and provided figure 5

- Active Set (AS) is the set of access flows, assigned by the Access selection MRRM function, to an active bearer at a given time; it is always a subset of the CS. It should be noted here that in special situations when a GLL entity controls two or more tightly integrated radio accesses we have an additional access set:

- GLL Active Set (GLL AS) is the set of access flows assigned to a given GLL entity by MRRM to serve a given data flow at a given time; it is always a subset of the AS. The GLL AS is used for fast access selection when multiple single access nodes are connected via GLL to a common multi-access anchor node or for access flow forwarding in multi-hop situations.

Access selection algorithms may consider many parameters when determining the best bearer-to-flow mapping. They also need to continuously react to any changes in conditions, e.g., deteriorations in radio signal quality, and reallocate resources accordingly. For the purpose of RA selection [3] MRRM interacts with other functional areas which corresponds to other AN control functions such as handover control, context management, security control etc.

In general, the objective of the Access Selection algorithm can be implemented via optimization of a utility function. The utility function can be derived from one performance metric or a weighted combination of several performance metrics such as achievable user throughput, blocking or dropping probability, communication costs (in terms of resource consumption and/or price), resource utilization (load balancing), etc. Examples of objectives for the Access Selection algorithm can be to select the available radio access with the highest radio link quality (e.g. highest SINR), the lowest congestion level, combinations of the previous mentioned, etc.

A special objective is the so-called *fast radio access flow selection* i.e. fast switching between the radio accesses done at GLL level and independently from the MRRM functions. The objective is to increase the spectral efficiency (i.e. Mbits/Hz) of the transmission and also user throughput. This fast selection requires tightly integrated radio accesses and instantaneous radio link characteristics as input (e.g. instantaneous SINR) to the GLL functions, and could be seen as the enabler of highest possible gains. Fast access selection is unlikely to exist in multi-operator network due to the physical separation of the different access points (from different operators), which introduces longer signalling delays.

Multi-Radio Access Selection Input Parameters

For any decision process there is information necessary upon which the decision should be derived. The Access Selection algorithm uses as input one or more parameters that characterize the candidate access flows, user's terminal, and the

[3] The term *Radio Access (RA) selection* is used interchangeably with *access selection.*

desired service [33]. These parameters can be divided in the following two broad categories:

1. *Static parameters*: The values of these parameters are changed on a time-scale that is much longer than the usual life-time of a flow (or session) and is not dependent on current radio and load conditions. These parameters are: Access Point (AP) capacity, service QoS requirement, RAT preference, financial costs (Euros/min or Euros/MByte), terminal capabilities, level of integration among RAs.

2. *Dynamic parameters*: In this category the parameters are dynamic because their values vary on a time-scale (e.g. hours, minutes, seconds or even milliseconds) that is comparable to the usual session life-time and depend on the current load conditions, user's speed and location, etc. These parameters are: AP load and congestion level, instantaneous or averaged radio link characteristics (signal strength, interference level, SINR, etc.), amount of resources needed for satisfactory communication quality, financial costs, terminal velocity. Note here that these parameters could be also used by the Access Discovery algorithm in defining the candidate set.

The input information for the Access Selection algorithm will be signalled between the MRRM entities either via backhaul fixed network (on the network side) or transmitted by the network or the terminals over the air. For signalling over the radio interface the network and/or terminals could use either broadcast or dedicated type of radio channel. This is necessary in order to make this information available to the MRRM entities throughout the MRA system for their Access Selection decisions.

Multi-Radio Access Selection Deployment

The Access Selection algorithm in case of Multi-operator networks is strongly influenced by the level of cooperation and/or competition between the network operators. In order to present the effects on the Access Selection we can define the following three categories [4]:

1. Fully cooperative operators.

   In this case the different RAs from different operators fully share the control over their respective resources. This level has been agreed upon during the composition process and also configured in the MRRM functions. *Effectively, this situation is merging into a single operator case.* All relevant information that is required for the Access Selection decision is available e.g. operator-sensitive information such as current congestion level; resource consumption per user; pricing information etc. is freely shared

[4] Note here that in reality any degree of cooperation is possible i.e. the cooperation level could be interpolated between these three categories

between the MRRM entities and could be used in the Access Selection decisions.

2. Partially cooperative operators

   In this case the different operators only partially share the control over their respective resources. The information available to the MRRM entities for the Access Selection decision is limited because some of the operator-sensitive information is filtered out (i.e. not exposed to the other operators). This information could be the congestion level, pricing, resource consumption etc. However, a certain amount of trust can be established and also some compensation schemes are agreed upon. For example, if a user is transferred from operator A to operator B then operator B shifts other user(s) back to operator A in order to have fair sharing of traffic and revenues.

3. Non-cooperative (fully competing) operators

   In this case there is no shared control of the operators' resources but rather fierce competition to serve as many users as possible. The Access Selection algorithm here has rather restricted information available to make the access selection. Unless in the previous cases, where access selection was mainly the job of the network, the physical location of the Access Selection algorithm in this non-cooperative case is expected to be either at an MRA anchor node (e.g. Access Broker) or in the terminal. The Access Broker is an external entity which has trust relationship with all operators that are involved in the communication (as they don't have trust relationships between each-other). Obviously this broker can facilitate a certain amount of information flow among operators. If brokers do not exist and Access Selection happens only in the terminal then operators can compete by sending offers (e.g. broadcast or personalized pricing information) to the user terminals, helping them in selecting the desired RA. However, an important consideration at this kind of access selection is the system stability i.e. the risk of having a (large) group of terminals frequently change between the operators due to rather variable pricing information.

3.1.3 Multicast/Broadcast Services in Ambient Networks (Paper 2)

The main contribution of this paper [34] is a description of multicast/broadcast services that are expected to arise in the future networks, along with the service provisioning methods and radio resource management functions needed for their support in ambient networks. This step is necessary in order to understand the particular impact of multicast/broadcast to the overall service transmission scheme and necessary MRRM functionalities that could arise in a multi-access environment.

Service Classification

Future wireless multimedia services can be described by several important characteristics which determine the requirements on the radio access performance.

One of them is the *popularity of the content* among the users. We may experience anything from very high popularity (e.g. videoclips or live transmissions from the Olympic Games) to very low popularity (e.g. an obsolete movie series targeting a limited class of customers).

Another is the *tolerance to delay* in the sense that the actual consumption of the content may happen some time after the delivery time or the time of the content creation. For services as live streaming from a sport event users are not likely to tolerate excessive delay. In contrast, video clips from the same event may be downloaded and stored in the terminal over night and consumed next day in the morning.

Tolerance to errors is another property that stress the service provisioning. For video and music content the user does not visually perceive existing bit errors as long as the quality of image and sound is acceptable. This is not the case for games or other interactive applications where errors may not be tolerated at all.

Last but not least, the manner the service is initiated is important. When the content is ordered separately by each user we have a *pull-service*, while when the content is supplied by the provider, without a specific request at a certain moment in time from the user, we have a *push-service*.

MRRM functions for multicast/broadcast support

Having devised different service provisioning methods for different M/B service classes, we summarize here the main characteristics of beyond-3G RRM functions for M/B support, from both distribution side and receiver side.

With distribution side we mean the M/B source as well as any potential AN node or receiver functioning as a relay towards further receivers. The distribution side RRM should be able to:

- Operate on a service area defined such that it accounts for multiple RATs and hops, as well as multiple domains and moving networks.

- Use resource reservation strategies (Fixed or Dynamic)

- Use the reserved resource for other services (even non-M/B) with non-guaranteed QoS.

- Identify spare resources in sub-parts of the service area for transmission of M/B service content in those areas.

- Advertise the M/B service through possibly different RATs and hops, with potential user interaction.

- Poll the involved users over possibly different RATs and hops, either just before transmission (polling) or in advance, keeping memory of the status over time (tracking).
- Poll the users in the whole or part of the service area in order to know whether M/B transmissions of the whole or specific parts of the M/B service content are still required. This may also be initiated by the user.
- Transfer ongoing sessions to available RATs in order to free up resources to support a pending M/B service.

The receiver side includes the intended destinations of content delivery (e.g. users, sensors, etc.), plus any potential AN functioning as a relay towards further receivers . The receiver side RRM should be able to:

- Join the service through possibly different RATs and hops, independently from the side where this is initiated.
- Require transmission of the whole or specific parts of the M/B service content (e.g. some packets or frames).
- Combine different transmissions over possibly different RATs to improve the quality of the received content.

3.2 Case Study: Cost-Based RRM in Cellular-Broadcasting Systems

With respect to the Ambient Networking concepts, this section constitutes an evaluation study of the achievable gains through composition of cellular point-to-point communication system and a wide area broadcasting system. Emerging examples of systems with such capabilities can be the evolution of WCDMA towards MBMS (most probably tight integration), but also hybrid WCDMA/DVB-H systems (may assume different degrees of integration).

Multicasting at physical layer is seen as the key element in radio resource saving when providing mass multimedia services. Radio resource management concepts (both short and long term) that aim at *multicasting at minimum cost* of service are then proposed. The key is to show how flexible combinations of physical layer multicast and point-to-point (unicast) should be used to minimize the delivery cost of popular multimedia content. A simple cost model, based on the time of radio channel usage, is assumed. By means of simulations, the potential of the technique to reduce the transmission costs up to several times is demonstrated, for some particular cases [5].

3.2.1 Related literature

The issue of radio resource management in hybrid cellular broadcasting systems was previously treated in the literature, with respect to the opportunities to offer better radio resources utilization. In [35] and [36] assigning the data traffic to the broadcasting or cellular access, depending on a utility value, is investigated. Their results show significant gain in spectrum efficiency compared to traditional systems. However, the investigation did not considered combinations of unicast and multicast for reducing the cost even further. Moreover, the radio channel characteristics and user mobility are not taken into account, the analysis being more or less a queuing theory issue. The main contribution of these papers is the suggested framework for resource management, based on adaptive service scheduling policy and dynamic access network selection.

In IST-DRIVE [23] and IST-OverDrive[24] projects the investigations targeted mostly the dynamic spectrum allocation between cellular and broadcasting systems. They have proven increased spectrum efficiency if this mechanism is allowed in a WCDMA/DVB-T hybrid network. A good summary of these projects, from a resource management perspective, can be found in [37].

The MONASIDRE project [25] managed to mathematically formulate a resource management problem, in the form of joint radio access selection and resource allocation, for a generic heterogeneous environment composed by cellular, hot-spot and broadcasting systems. A detailed description can be found in [38]. Unfortunately, most of the systems evaluations performed by the project are

[5]Cost reductions are in comparison with the case when broadcasting provides a single data rate over the service area

related to combinations of cellular and hot-spot systems and very little appears regarding cellular-broadcasting combinations. However, the problem formulation and the general conclusions of this project constituted an important source of inspiration.

3.2.2 System modelling

Service and Traffic Model

Future wireless multimedia will be delivered mostly in a push fashion, and this is true even for interactive services (users are individually requesting the items they want). After batching and ranking of these requests, as suggested in [35, 36] we end up with a push-type of multicast, as perceived by the operator [6]. The service provider initiate the transmission according to its own cost preferences, QoS constraints, etc. This is the reason why in Papers 3 and 4, the service model consists of pushing multimedia items to different sets of recipients through multicast. Each multimedia item i is characterized by a length L_i (bits) and its set of recipients N_i, of size n_i.

RRM objective

One of the assumptions about the future is that wireless services become a commodity and industries mature. The implication of such assumption is that market is saturated and the average revenue per user is expected to remain almost constant over time, so minimizing the cost of service delivery becomes one essential way to maximize the profit. Therefore, *minimization of the service cost* was chosen and the overall objective of the radio resource management.

RRM design

Competition, but also cooperation, among operators and service providers are two important aspects of the future wireless marketplace. We believe that future will show us an open wireless access market, where the resources are distributed in almost real-time according to the demand and supply paradigm. As a result, pricing the access becomes of great importance for any network operator. For this reason, the radio resource management in a heterogeneous infrastructure environment and especially the access selection functionality should be designed so that it supports *competition* in order to maximize the benefits from sharing available resources among different services, but also *cooperation* among operators (e.g. sharing and co-farming infrastructure and spectrum) for saving resources through a more efficient utilization. Micro-economics suggest *congestion pricing* as a very efficient manner of resource utilization in communication

[6] if the service is delay tolerant and allows batching of the requests for a certain period of time, the operator/service provider must transmit each requested item to a certain set of terminals, referred as the multicast group, or set of recipients

networks [39]. Prices may vary according to the congestion level experienced by the each system or radio access (congestion pricing is a known method for maximizing producer revenues). Following this guideline, the author proposes a cost model based on the time of usage of the radio resource, here the broadcasting and cellular radio accesses. The cost is experienced by the service provider which access the cellular and broadcasting resources for a certain price set by the respective operators. For the broadcasting radio access this will be a cost per second of transmission, while in cellular radio access the cost is defined per second per user. The motivation behind this model is given by the assumption that adaptive modulation and coding can be utilized in both radio accesses and each time slot can be utilized according to the service QoS demands (e.g. data rate, time and space availability, packet delay, bit error rate, etc).

The cost per time unit of using broadcasting is c_c, while the cost per time unit per user in cellular is c_b. The cost experienced by the operator when delivering the item (file) i using broadcasting rate R_l is C_{il}. This cost is the sum of the cost for multicasting the item to the set K_l using the broadcasting infrastructure and the cost of serving the remaining users (the set $N_i - K_l$) through point-to-point connections provided by the cellular infrastructure.

The sets of available data rates in broadcasting and cellular air interfaces are R_B, and R_C. For each available broadcasting rate $R_l \in R_B$ there is a set of users K_l, of size k_l that is able to receive the item with this rate (e.g. if they meet a certain carrier-to-noise ratio required by R_l). Obviously, K_l is a subset of N_i. The cost per item, C_{il} can be written as:

$$C_{il} = c_b \frac{L_i}{R_l} + c_c \sum_{j=1}^{n_i - k_l} \frac{L_i}{r_j} \tag{3.1}$$

where $r_j \in R_C$ is the cellular data rate for each user j in the set $N_i - K_l$. This expression is valid if $0 < k_l < n_i$. For $k_l = n_i$ we have only broadcasting with the lowest rate available. For $k_l = 0$ only the cellular system is employed.

The goal of the resource management is to minimize the transmission cost per item, C_{il}, by deciding the broadcasting data rate, ideally the one that minimizes this transmission cost. Intuitively, the decision on the broadcasting rate will determine the percentage of recipients served by broadcasting radio access, while the remaining ones will request the content from the cellular network. The make an *optimal decision* perfect knowledge must exists about achievable data rates in both radio accesses for each terminal in the multicast group.

The proposed scheme for cost minimization can be applied in the case when cellular and broadcasting systems belong to a single operator, but also in the case when they are operated separately. c_b and c_c can be seen as both costs and prices: they are costs when a single operator manages both cellular and broadcasting and its goal is to minimize the total delivery cost, but they are prices to be paid by a service provider which buys access capacity from two different cellular and broadcasting operators on a time-usage basis. These costs/prices can be defined according to different economic strategies. One alternative is to continuously change them according to the predicted congestion level (resource utilization) in each radio access.

3.2.3 Initial evaluations (Paper 3)

The paper introduces the framework for cost-based resource management in a hybrid cellular-broadcasting system, assumed to be operated by a single operator. The motivation for this assumption is the wish to aim for highest achievable cost savings. The comparison is performed with a reference case defined as simply choosing the cheapest alternative, either cellular or broadcasting.

Minimization of the transmission cost, as defined by 3.1 is performed with a simple method, basically exhaustive search through all possible broadcasting rates until the one providing minimum cost is found. Design and implementation of any algorithm does not present special interest here, if number of available broadcasting rates is small enough. The costs c_b and c_c are taken as parameters and the achievable gains are studies over a large span of their values. The reason of this investigation is to see how the cost savings will be affected by variations of the individual costs (e.g. due to increased demand, congestion, etc).

The main contributions of the paper are: (1) to show that adaptive rate broadcasting may bring significant cost savings in some specific cases, (2) to outline potential bottlenecks for practical implementation of such systems (at least with the existing technologies).

Note that the cost curves for the hybrid system involve utilization of both radio resources (e.g. spectrum) from cellular and broadcasting systems, and it may look suspicious to compare them with *only cellular* and *only broadcasting* curves which assume only the resources allocated to the respective system. As the dynamic spectrum sharing between the system is not assumed to be possible in the proposed framework, this comparison is correct.

3.2.4 Implementation issues (Paper 4)

This paper mainly addresses two implementation bottlenecks raised by the previous study:

- How are the cost savings affected by the number of available broadcasting rates?
- How are the cost savings affected by the correctness of the data rate estimations for the recipient users?

Numerical evaluations are performed on a test-bed with air-interfaces similar to WCDMA-HSDPA and DVB-H. The outcomes show that three broadcasting rates offer close performance to 100 rates. This is illustrated in Figure 3.3, where it can be noted that the relative cost savings of having 100 broadcasting

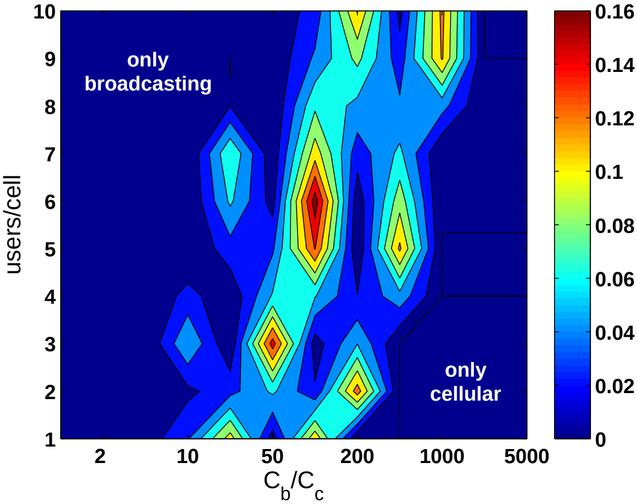

Figure 3.3: The relative cost savings obtained with 100 versus 3 broadcasting rates.

rates compared with only 3 rates is marginal (The values on the scale represent $\frac{G_{100}-G_3}{G_3}$. G is the cost saving compared to the reference strategy).

Regarding the correctness of estimated data rate values it is proved that it may not have a tragical impact on the cost savings (does not decrease them), at least when number of recipients is large. Moreover, the issue of estimating directly the optimum broadcasting rate by means of statistical analysis is also addressed. As this performs well, it means that real-time tracking of the achievable rates for each recipient may not be necessary. The paper discusses the conditions when this can happen. To better clarify how statistical analysis is used for finding the optimum broadcasting rate (out of the available set), hereafter a better explanation than the one in the paper is provided. When running simulations for the system with ideal monitoring and individual instantaneous data rates are assumed to be known by the resource manager, for each item the cost minimization problem will lead to a management solution consisting of a decision on which data rate to be used. If the statistics of the possible management solution are recorded for different sizes of the multicast group, a matrix-type of database (structure) can be generated.

For example, when a certain number of recipients n is considered the decision of the resource management over a number of realizations may be a histogram, as shown in the figure. Due to different positions of the users in the system in each realization the chosen broadcasting rate may be different, such that over a large number of realizations the decision may be, for example R_k in 10% of the realizations, R_{k+1} in 20%, etc (see Figure 3.4). Such a database, can be

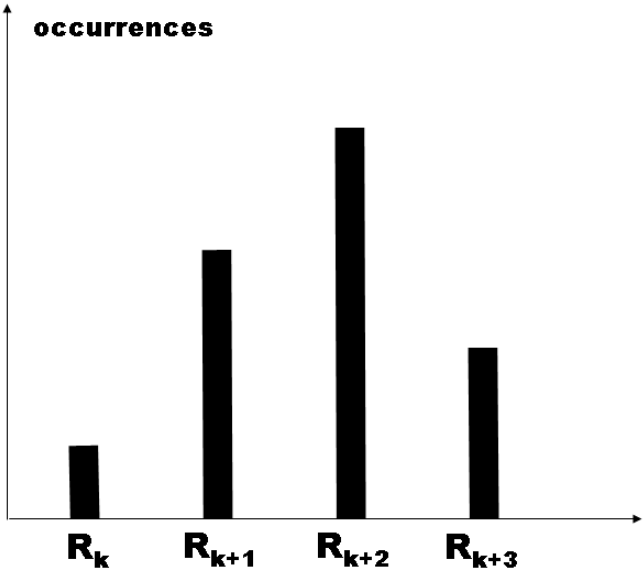

Figure 3.4: Example of histogram obtained from simulating an ideal system

generated from simulations or even collected from the real system over a period of time, and can be utilized for taking the resource management decision. In this way, polling and tracking the recipient users are avoided. The relevance of the values for a specific realization is very much depending on n, being problematic for low values. In the paper, the broadcasting rate which has the highest probability is chosen. Obviously, this simplified approach can be discussed and better algorithms may be further developed, but the obtained results are promising and showing that the achievable cost savings are almost close to the maximum.

As an example, the cost values for the particular case when c_b/c_c=200, are compared in Figure 3.5.

3.3 Chapter's conclusions

The MRRM functionality in ambient networks was defined and consists of RA coordination and network-complementing RRM functions. Out of all identified coordination functions, Access Selection is found to be the most important and challenging. The Access Selection algorithm in case of Multi-operator networks is strongly influenced by the level of cooperation and/or competition between the network operators. With respect to multicast/broadcast services the key issues for MRRM were identified to be advertising, joining, polling and tracking. It should be noted how the difference between multicast and broadcast tends

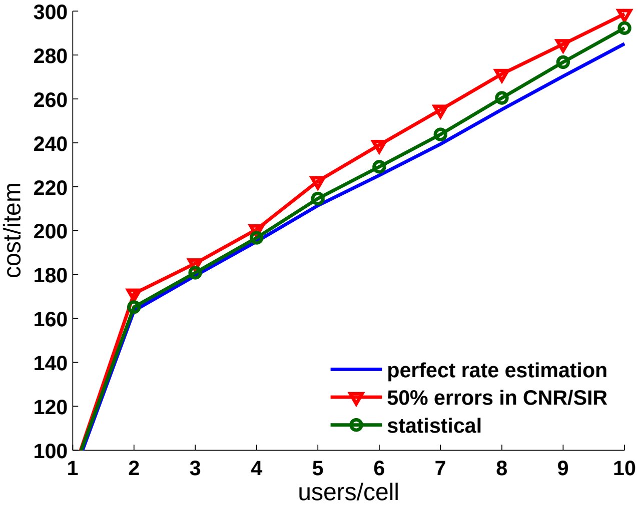

Figure 3.5: Cost comparison between optimal (perfect rate estimation) resource management, the case when errors in CNR/SIR measurement are accounted for, and the case when resource management takes the decision from statistically collected data.

to vanish, as the heterogeneous multi-hop and multi-RAT environment forces to reconsider whether a broadcast could be done in more efficient ways through coordination of all the available resources.

The evaluation case of a cost-based resource management scheme for a hybrid cellular-broadcasting system outlined few important conclusions. First, it proved that it is possible to obtain operational cost savings (2 to 4 times) if broadcasting radio access offers several data rates to choose from. In our case, having three data rates were shown to be an acceptable situation, which is a bit surprising (the expectation was to get cost savings proportional with the number of available data rate larger), but also encouraging. An interesting result is also the fact that real-time monitoring of the user reception conditions is not needed, at least when multicast group is large. This opens up the possibility to take the resource management decisions only from a statistical analysis of previous transmissions or simulations. In the case analyzed in Paper 4 this technique seems to work quite well.

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Chapter 4

Digital Broadcasting Systems for Mobile Users

This chapter addresses issues related to infrastructure design and dimensioning for future mobile broadband broadcasting systems. The aim is to verify the potential of state-of-the art broadcasting technologies (hereafter DVB-H) for integration in the hybrid systems. The enabling factor for a smooth integration with cellular systems is the utilization of Application Layer - Forward Error Correction (AL-FEC), based on *digital fountain codes*. Their advantage over the other FEC techniques are obvious in the context of cellular-broadcasting integration. With a digital fountain, a client obtains encoded packets from one or more servers, and once enough packets are obtained, the client can reconstruct the original file. Which packets are obtained should not matter [40]. Obviously, AL-FEC with digital fountain coding is the best option in the case of file downloading and it was already included, in the form of Raptor coding, in the 3G-MBMS and DVB-H standards [41, 42].

Integration of DVB-H in the previously introduced cost-based resource management framework is hindered by one bottleneck, the fact that modulation and coding rate (MCR) cannot be dynamically changed. Due to this reason we are looking at the manipulation of Forward Error Correction (FEC), either at link layer or application layer. A technique based on AL-FEC is proposed for implementing rate adaptivity in a DVB-H system serving mobile terminals. Taking advantage by the spatial diversity introduced by terminal mobility, we make possible to trade system capacity and delay for enhanced perceived coverage at mobile terminals, in an almost similar manner as would have been offered by changing modulation and coding rate (MCR). The difference consist on the facts that it works only for moving terminals (not stationary), introduces some delay (e.g. higher zapping time), but allows for a lower average power consumption of the terminals.

4.1 Short introduction to DVB-H

DVB-H (Digital Video Broadcasting - Handheld) [11], is a recent extension of DVB-T to reach mobile and handheld terminals. DVB-H is backwards compatible with DVB-T, and the main features introduced are: a) time slicing - reduces the average power consumption of the terminal and enable smooth and seamless handovers b) the 4K mode - improves Single Frequency Network (SFN) planning flexibility, and c) MPE-FEC (Multi Protocol Encapsulation - Forward Error Correction) - an optional coding scheme at the data link layer to improve the robustness. A detailed description of these features can be found in [43, 44, 45].

Planning of the DVB-H transmission mode is based on the choice of four parameters: FFT size, relative Guard Interval (GI), modulation and Coding Rate (CR). The FFT size (8K, 4K, or 2K) is related to the number of OFDM sub-carriers, their inter-carrier distance and the useful symbol period. The choice of the FFT size has no impact on the capacity, but on the trade-off between mobile reception (maximum speed) and SFN cell sizes. The 2K is the most suitable for mobile reception, whereas the 8K gives the largest SFN cell size. The relative guard interval can have a duration of 1/4, 1/8, 1/16, or 1/32 of the useful symbol duration and together with the FFT sizes gives the absolute guard interval value. The choice of the relative guard interval represents a trade-off between capacity and SFN cell size. Modulation and coding rate determines the minimum required Carrier-to-Noise Ratio (CNR) and, together with the relative guard interval, the channel capacity.

With time slicing, terminals synchronize to the bursts of the desired service and switch their receivers (front-end) off when bursts of other services are being transmitted. Between bursts, data is not transmitted, and for streaming services terminals play the information received in the last burst in such a way that users do not notice a discontinuous transmission. If one burst is lost, the service is interrupted until the next burst is received. To indicate to the receiver when to expect the next burst, each burst indicates the starting time of the next one.

4.2 Design and Dimensioning of Future Mobile Digital Broadcasting Systems

Due to the lack of information in present literature (DVB-H is a still a new technology), evaluation of the deployment feasibility of broadband broadcasting, together with scalability figures of such systems with coverage and bandwidth, are performed first. The main question is how affordable are the systems if they are designed for wide area coverage. Obviously, avoiding the deployment of new sites if of crucial importance, but is it enough to reuse existing infrastructure (e.g. masts) for analogue radio and TV broadcasting? If not, then would it be useful to reuse the infrastructure for cellular systems for installing repeaters or synchronized transmitters for DVB-H?

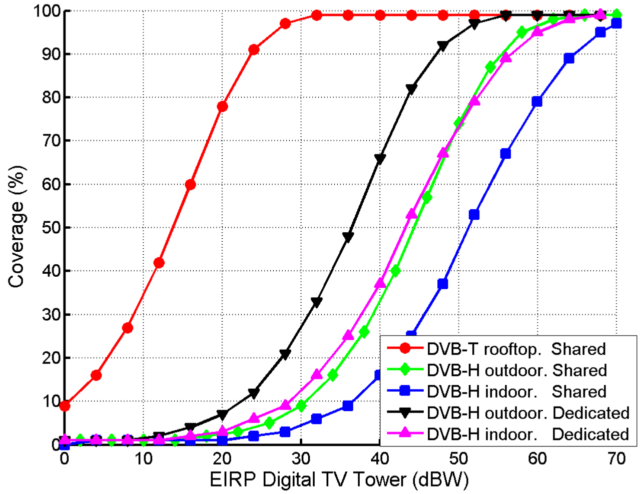

Figure 4.1: Area coverage vs. EIRP for a 150m height TV tower. Service area radius is 25 km.

First, the feasibility of deploying a DVB-H broadcasting system on existing cellular and broadcasting infrastructure was investigated [46]. We show, by simulations on 25km radius test area with a TV tower in the middle of it, what capacity and coverage for portable reception can be achieved for different transmission power and density of the reused cellular transmitting sites. The results show that only reusing the existing broadcasting infrastructure for DVB-T leads to very poor coverage and capacity, especially for a shared deployment of DVB-T and DVB-H (Figure 4.1). If cellular sites are used for complementary transmitters to the broadcasting system the required power level at broadcasting site can be significantly reduced, but on the expense of a large number of cellular sites (Figure 4.2). A capacity value of 10 Mb/s for indoor handheld terminals, is therefore hard to achieve over a wide area without very high transmission power, and a proper planning of the transmitting sites.

In Figure 4.2 we can see that even with a 50 dBW broadcasting tower (150m) almost all cellular sites have to be utilized if they contribute with transmission powers up to 22 dBW, which is not good news if the plan is to deploy simple RF repeaters on the sites. If we assume up to 30 dBW for the cellular sites, about 30 sites are needed, which is still quite a significant number. On the other hand, if no broadcasting tower would exist, 60 cellular sites of 30 dBW can do the job. From this example, where 95% indoor coverage is targeted, we can draw some conclusions: (1) A 50 dBW transmitter placed on a traditional broadcasting tower can replace about half of the necessary cellular sites, (2) Half of the cellular sites can substitute for 50 dBW to 60 dBW EIRP increase

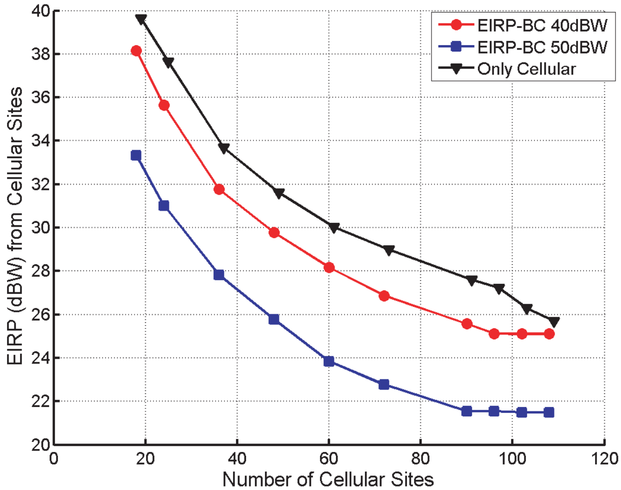

Figure 4.2: Required EIRP at a cellular site as a function of the number of sites employed. Cell radius is 2.5 km. Service area radius is 25 km (around broadcasting tower). Target coverage is 95% for indoor handheld devices.

at broadcasting tower. It is very difficult to generally estimate which of the implementations will be cheaper: a broadcasting tower with 60 dBW EIRP, 60 cellular sites of 30 dBW EIRP or a hybrid infrastructure. The actual investment size and operational costs depend on the specific business environment, relationships between infrastructure owners, competition from other systems, etc. Most probably, a hybrid infrastructure solution will be preferred if cellular and broadcasting operators cooperate for sharing their infrastructure.

4.3 Scalability of DVB-H Infrastructure Deployment (Paper 5)

This is a continuation of the previous study and it investigates the scalability of the DVB-H deployment [47]. The same test bed was employed for analyzing how much infrastructure is required for enhancing capacity by switching to a higher modulation and coding rate (MCR). As a performance measure the *number of additional cellular sites per Mb/s* is used. The underlying assumption is that the cost of deployment, for a given EIRP setting for broadcasting tower, is proportional with the number of the additional cellular sites required to meet the target area coverage.

The results plotted in Figure 4.3 and Table 4.1 show good scalability for outdoor scenarios, even little economies of scale (i.e. cost per Mb/s decreases

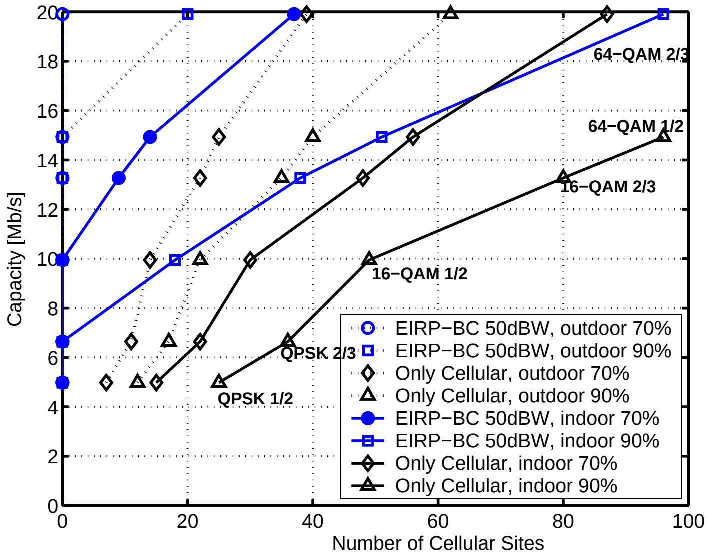

Figure 4.3: DVB-H service capacity vs. number of employed cellular sites, for different area coverage targets and EIRP values for the broadcasting tower. Service area radius is 25 km.

if more Mb/s are provided) if the capacity is up to 10 Mb/s. If using only one broadcasting tower and no additional transmitters on the cellular sites the scalability figures are very bad (Required dBm per Mb/s increases when MCR increases, mostly because of the non-linearity of the upper part of the Shannon curve).

4.4 Adaptive Data Rate in DVB-H (Paper 6)

From previous investigations we have seen that one condition for achieving significant cost reductions when jointly managing broadcasting and cellular radio accesses is the availability of a number of data rates over the broadcasting air interface, each of them characterized by a different area coverage. If MCR is fixed (as in current DVB-H implementations), the only way to vary the user data rate is by FEC manipulation. In DVB-H this can be done at two levels: a) at the link level by means of standardized Multi Protocol Encapsulation FEC (MPE-FEC), b) at the application layer by means of Raptor codes. Dynamic adjustment of FEC provide a mechanism which is able to map certain average SINR value experience by the mobile users to an achievable data rate.

A new technique based on spreading variable size parity data (generated by Raptor coding) among two or more bursts is proposed and its goal is twofold: first to provide a mechanism for trading data rate for improved robustness, and

Table 4.1: Number of cellular sites per Mb/s under different settings for EIRP of the broadcasting tower, coverage target, and MCR

P_b (dBW)	Cov. (%)	i/o	QPSK		16-QAM		64-QAM	
			1/2	2/3	1/2	2/3	1/2	2/3
0	70	i	3.0	3.3	3.0	3.6	3.8	4.4
		o	1.4	1.7	1.4	1.7	1.7	2.0
	90	i	5.0	5.4	4.9	6.0	6.4	-
		o	2.4	2.6	2.2	2.6	2.7	3.1
	95	i	6.4	6.9	6.1	7.7	-	-
		o	3.0	3.0	2.8	3.2	3.3	4.0
40	70	i	1.2	1.5	1.7	2.5	2.7	3.4
		o	0	0	0	0.7	0.7	1.1
	90	i	2.8	3.6	3.6	5.0	5.3	-
		o	0	0.9	1.1	1.6	1.9	2.4
	95	i	4.0	4.8	4.8	6.4	6.8	-
		o	1.2	1.5	1.6	2.3	2.4	3.1
50	70	i	0	0	0	0.7	0.9	1.9
		o	0	0	0	0	0	0
	90	i	0	0	1.8	2.9	3.4	4.8
		o	0	0	0	0	0	1.0
	95	i	1.6	2.6	3.0	4.5	5.1	-
		o	0	0	0	0.8	0.9	1.8

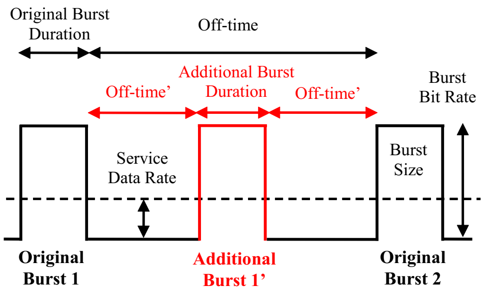

Figure 4.4: Introducing extra bursts with Raptor generated parity information in the DVB-H transmission

second to hide the coverage discontinuities for the vehicular users at the expense of higher packet delay. In the proposed implementation we choose to introduce additional bursts, between the original bursts. Introducing additional bursts containing redundant information for one service determines a reduction in the capacity available for other services.

The principle is simple. Mobile terminals unable to successfully decode a burst will synchronize to the extra burst, having an extra chance to receive the content correctly before the next burst arrives. Note that this extra bursts are intended for mobile users in bad coverage locations, since users in good coverage locations will neglect all extra bursts. Terminal velocity, fading correlation distance and time between retransmissions determine the statistical correlation between reception of the original burst and the extra one. The probability that a terminal in a bad reception position will get out of there by the time the extra burst is transmitted will be very low if the terminal moves very slow, if the fading correlation distance is very high, or if the the time between transmissions is very short.

The simulations are performed on a 25 km radius service area, urban environment, vehicular users (e.g. people travelling by the public transportation), and a service of 10 minute video stream at 200 kb/s. Comparative evaluation of using extra Raptor generated bursts, switching to lower MCR or employing stronger MPE-FEC were performed. The results in Figure 4.5 show that AL-FEC with Raptor coding provides a larger span of available data rates. Almost the same performance (e.g. percentage of satisfied users) as for QPSK 1/2 MPE-FEC 3/4 can be achieved with 16-QAM 1/2 with AL-FEC and one full additional burst delayed with 3 bursts time interval.

It is therefore possible to offer streaming services to in-car users with a handheld device, in a network originally dimensioned for pedestrians. This happens on the expense of additional delay (time-shift) of the streaming and twice as much radio resources (bursts) utilized by the service.

Additional results in the paper outline a significantly lower average terminal

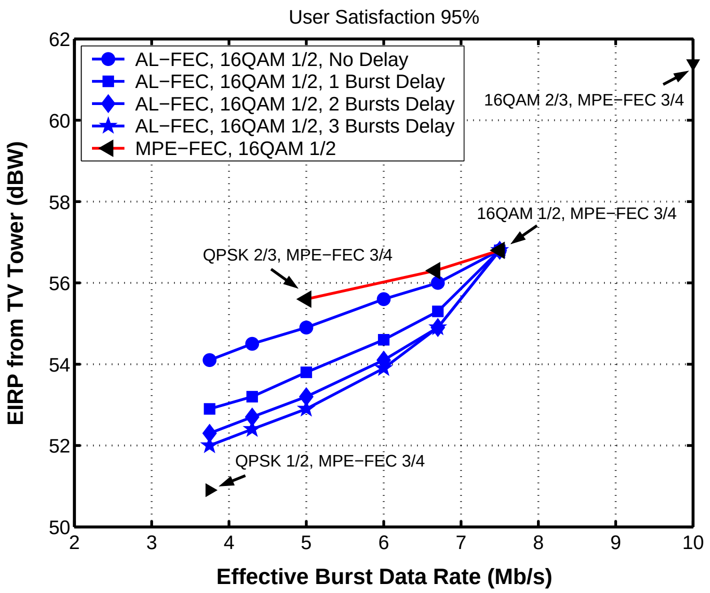

Figure 4.5: EIRP power vs. effective burst capacity

power consumption if AL-FEC is used.

4.5 Chapter's conclusions

The main conclusion from the first two papers [46, 47] is that deployment of DVB-H systems with high area coverage (i.e over 90%) is very costly, especially when target over-the-air data rates is around the envisaged commercial requirement of 10 Mb/s (as suggested by [44]). For this reason, it is suggested that network operators follow a different direction than the traditional one (e.g. dimension their infrastructure so that this rate is available anytime and anywhere). Instead, the operators must try to take advantage of the service characteristics and QoS requirements, user mobility patterns, etc. in order to provide high rate maybe sometime/somewhere. Packet losses generated by time intervals when mobile terminals experience poor or even no coverage can be mitigated by smart interworking with a cellular system and/or clever media content management in terminals (e.g. caching). This approach may lead to lower infrastructure cost and less over-provisioning in the network, while at the same time delivering satisfactory services to the end users.

Several service providers will probably share the available capacity of the DVB-H air interface in a competitive manner. As the services may have different QoS requirements (e.g. area coverage, packet delay and jitter, packet error rate, data rate, etc.) the network operator needs a mechanism which offers flexibility in choosing the transmission parameters so that each service is acceptably delivered with the minimum amount of radio resources. A good example of such situation is the traffic model assumed in the evaluations of cost-based resource management, section 3.2. Each multimedia file, is supposed to be delivered to a certain number of customers, under a certain time. For example, if the file is small, number of customers is large and acceptable delay is small a low rate and robust transmission must be available. If the file is large, the tolerable delay is large, customers are few and happens to experience high signal-to-noise ratio, a high rate transmission may be the best choice.

Obtaining the wanted combination of QoS parameters in a broadcasting system as DVB-H can be achieved either by introducing adaptive modulation and coding techniques (as in WCDMA, GPRS, WLAN, etc.) or by maneuvering the forward error correction (FEC). The first alternative is not possible in present DVB-H standardization and there is no sign yet of any intention in this direction, so the only solution remains to use FEC for this purpose. AL-FEC with Raptor coding was investigated and proved to be suited for easy implementation of rate adaptivity in broadcasting for mobile users. Moreover, the use of AL-FEC with Raptor coding provides a good support for integration of DVB-H networks with cellular systems.

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Chapter 5

Concluding Remarks

The studies outline significant potential for hybrid cellular-broadcasting infrastructure systems to offer, for lower cost compared to conventional telecom systems, interactive mobile multimedia services which require multicast type of delivery.

The main enabler of low cost features is a better utilization of existing radio resources for cellular and digital broadcasting systems through novel system architectures and resource management.

Two case study evaluations have shown that service cost can be reduced several times under certain settings and assumptions, which may reflect real implementation cases. The interesting part is represented by the fact that achievable cost savings are not strongly influenced by the integration level of the hybrid system. More precisely, the results prove that resource management can perform close to optimal even if real-time tracking of user reception conditions is not present [1]. A good news is also the indication that close to optimal performance can be obtained with a fairly low number of available broadcasting rates. This makes possible the implementation of such resource management scheme in a hybrid system containing existing technologies for digital broadcasting, if we assume that two or three DVB-H data rates can be made available with the same infrastructure.

Dimensioning of future digital broadcasting infrastructure for mobile users leads to expensive deployment process, if only the existing broadcasting infrastructure (e.g. for DAB and DVB-T) is utilized. To avoid the deployment of new sites for the only purpose of mobile broadcasting, we have investigated the reuse of cellular sites for complementary broadcasting transmitters. By using hybrid infrastructure, the deployment becomes more cost efficient and scalable with demand, but only if data rates up to 10 Mb/s (in DVB-H) are targeted. Dimensioning the broadcasting network infrastructure for full area coverage proved to

[1]More work is needed for validating this affirmation under more general assumptions than the ones in the case study

be very expensive and not cost efficient. Therefore, the evaluation results may suggest that cellular systems of 3G type should complement the broadcasting infrastructure in order to avoid planning for full coverage, by temporary taking care of the users which strongly suffer from shadowing, or fast fading.

In conclusion, future hybrid cellular-broadcasting systems should be a serious option for the future of multimedia multicasting services. The obtained results from study cases show that even with basic interworking techniques, the performance is already close of what can be achieved with a specialized integrated network. This should encourage any service provider or virtual operator to rent access capacity in existing cellular and broadcasting systems, and start offering its services to the customers in a competitive and cost efficient manner.

5.1 Future Work

The studies presented in this thesis provide only partial answers to the big question on how to design and manage hybrid cellular-broadcasting infrastructure systems, such that they provide a long-term cost efficient solution for mobile multimedia multicast. Few other investigations are therefore needed.

Maybe the most important criticism to the cost-based resource management framework introduced in section 3.2 can be the assumption about the rate adaptivity of broadcasting air-interface. Present DVB-H systems, for example, do not offer this feature, at least for now. To fix this, AL-FEC has been used in DVB-H and it was shown in [48] that is possible to obtain a variable perceived data rate at the expense of reduced system capacity. A revision of the cost-based RMM in the sense of estimating the amount of AL-FEC redundancy instead of broadcasting rate must be performed. It will be interesting to find out how much cost-savings are possible under this new settings. Examples of interesting studies include the capacity evaluation in a 3G cellular network, both HSDPA and MBMS, in order to support the DVB-H network which is not dimensioned for full area coverage.

In order to understand how hybrid infrastructure systems should be expanded in case of increasing demand for multicasting capacity, a few investigations are also necessary. For example, it is not clear when the expansion of the network should be performed with a cellular point-to-point technology (e.g. MBMS), cell-broadcasting technology (e.g. MBMS) or simply adding synchronized DVB-H transmitters (in SFN formation). Most likely, the choice will depend on the amount of demand increase and the cost related parameters.

Last, but not least, the integration of broadcasting systems in the ambient networking framework is an interesting subject and hopefully the author will be involved in the work around it. It is important to identify what kind of information flow and interfaces are necessary between a cellular and a broadcasting operator for achieving a significant resource saving when they are willing to cooperate. Up to now, most of the efforts were put into designing ambient networking support for cellular and WLAN type of systems [2]. The type of interfaces and resource management needed for patching existing broadcasting systems are significantly different from what we need for cellular or WLAN systems. From a business point of view, is not obvious how to use technology for creating cooperation and trust among actors coming from two extremely different industries. The big difference between the broadcasting and telecom stays in almost all aspects from the network architecture to the business model. The industry investment, revenue models and security issues are maybe the most important bottlenecks in the path towards convergence of the two industries [49].

[2] We refer to efforts of partners in Ambient Networks project

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Appendix A

Existing System Architectures and Value Chains

This appendix consists of a a short description of system architecture and value chains for cellular (UMTS) and broadcasting (DVB-T/H) systems.

A.0.1 Cellular Systems

Today's cellular networks are based on the concept of cells. Each cell is characterized by a coverage area and the offered capacity is expressed as a number of supported users or maximum data throughput. The main components are the Core Network (CN) and Radio Access Network (RAN). The CN includes network management, customer management, billing, interconnection with other networks, etc. RAN provides the connection between the CN and mobile terminals. All elements of RAN are connected together and to the CN by means of a Transport Network (TN). A simple schematic of a UMTS cellular network is depicted in the Figure A.1.

A GSM Base Station (BS) or a WCDMA NodeB provides the radio coverage in its corresponding cell. The Base Station Controller (BSC) and Radio Network Controller (RNC) are responsible for handling radio resource management features such as power control, handover, admission, and load control. Core network contains global resource management functions, user databases, billing center, gateway to other networks, etc.

The value chain specific to an UMTS cellular system is represented in Figure A.2

- *Content providers* generate and aggregate content and usually have direct billing relationships with the customers. A portal, as a content aggregator,

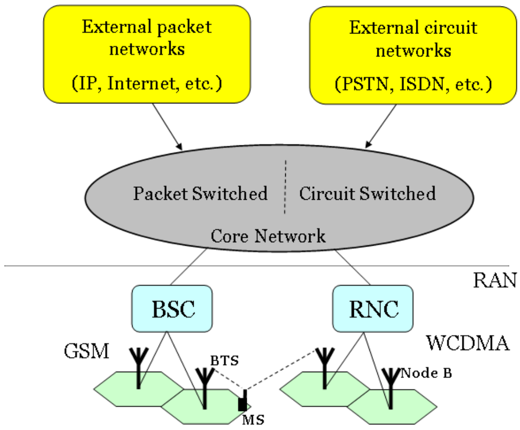

Figure A.1: UMTS access network

Figure A.2: UMTS Value Chain

is part of this category.

- *Network Operator* hold licenses for spectrum, supply the radio access infrastructure and functionalities as billing, roaming, interconnection, etc.

- *Service provider* sell network services on behalf of a network operator. They can also provide value added services (e.g. news, headlines, stock quotes) and may have a direct billing relationship with the customers.

- *Handset provider* manufactures the handsets used by the customers.

Traditionally, cellular operators tend to get positioned everywhere in this value chain, providing everything from handset to content. Few examples from Sweden are Vodafone and its *Vodafone Live* service package or Telia with *Telia Go*.

A.0.2 Terrestrial Broadcasting Systems

Digital Audio Broadcasting (DAB) and Digital Video Broadcasting - Terrestrial/Handheld (DVB-T/H) are the ETSI standards for digital audio, respective video broadcasting in VHF-UHF bands. DVB-T transmissions can transport MPEG video, audio and IP with data rates from 5 to 32 Mb/s. DVB-T networks are designed for large coverage areas with a relative low number of transmitters. They are well suited for fixed and nomadic receivers, and can also support mobile users due to the robustness of COFDM modulation scheme. A generic block diagram of the digital video broadcasting system, DVB-T, is presented in the Figure A.3.

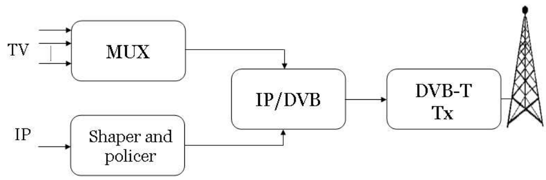

Figure A.3: Digital Video Broadcasting Block Diagram

In general, the dominant part of the transmitted signal is represented by TV and audio programs. They are multiplexed in the MUX and then encapsulated in the DVB stream together with shaped IP traffic. The Shaper/Policer is considered to be a simplified QoS capable three-class IP router. Parameters that describe a DVB-T transmitter are: transmitted power, service area radius, center frequency, FFT size, modulation, convolutional code rate, and guard interval.

The broadcasting business is in general built around a value chain described in Figure A.4.

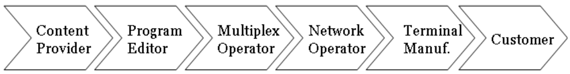

Figure A.4: Digital Broadcasting Value Chain

We should note the clear difference between the following three entities:

- *Program Editor* - builds the service and associated signaling. It is allowed to use a certain capacity in the multiplexer (MUX) and we can see it as a content aggregator.

- *Multiplexer Operator* - has the license for the frequency and owns the the MPEG2 multiplexer, Shaper and Policer, and IP/DVB-T combining block. It creates the MPEG2 transport stream that will be delivered to the end users. It also perform the fixed and statistical multiplexing of the programs supplied by the content providers. In the case of IP traffic, this has to be shaped and perhaps prioritized prior its insertion in the transport stream.

- *Network Operator* - provides the broadcasting infrastructure (DVB-Tx) which covers a certain region. This operator has to guarantee the coverage to the Multiplexer Operator and it is responsible for distribution of the transport streams to the broadcasting transmitters.

The broadcast operator collect revenues from end users in the form of a subscription (flat fee) for a certain period of time and package of programs. If an interaction channel exists, then a revenue model based on pay-per-view may also be possible.

Appendix B

Wireless Foresight

The Wireless Foresight project has been carried out at Wireless@KTH, a center for research and education on wireless systems created by the Royal Institute of Technology (KTH) in Stockholm in cooperation with industry. The objectives of the project, as seen from the perspective of the Center, were to: (1)Initiate and drive a strategic discussion on what research and other activities to perform within the Center, (2) Create and maintain a shared vision about its goals, and (3) Provide visibility.

Wireless Foresight was carried out between September 2001 and May 2002, in a time of quite some turmoil in the wireless industry. After the decade when the Internet and the cell-phone changed our lives and working habits, these two technologies are about to merge. At the same time, the industry was going through one of its worst crises ever. At this crossroads, the future can take any direction. Up or down. Success or failure. In the Wireless Foresight project, we look further ahead, into the wireless world beyond 3G. Which are the most important trends in the wireless industry and what are the long-term fundamental drivers of development? What services will be used in 2015? What technological problems have to be addressed in order to realize a positive wireless future? Which are the most important areas of research?

B.1 Scenarios

The report deals with the state of the wireless industry in 2015 and presents four scenarios of the future: *Wireless Explosion - Creative Destruction*, *Slow Motion*, *Rediscovering Harmony*, and *Big Moguls and Snoopy Governments*. The scenarios are concrete images, including descriptions of the wireless systems of 2015, how these systems are used, and who the most important actors and users are. The main focus of the scenarios is the challenges and development of the wireless industry, i.e. operators, infrastructure vendors, terminal vendors, and service providers/developers. The scenarios are not intended as predictions, but as possible and plausible descriptions of the future. They should be seen as a source of inspiration when thinking about the future of wireless technology and industry.

From the scenarios, important assumptions about the future are identified and several areas for technological research are outlined. A number of critical challenges facing industry are formulated: the high cost for the wireless infrastructure, the slow spectrum release, the stampeding system complexity, impact on health and environment, battery capacity, and the threat of a disruptive market change facing the telco industry. [1].

B.1.1 Scenario 1: Wireless Explosion, Creative Destruction

Keywords: Rapid growth, Datacom winning over telecom, Open IP architectures, Active users, Anarchistic underground culture, User deployed networks, Ad-hoc, Creative destruction, Unlicensed spectrum.

Wireless applications and services are a huge success in 2015, and in a rapidly transforming industry the old market leaders lost their dominant positions. The old telco world with closed, vertically integrated solutions gave way to layered, open architectures based on IP (Internet Protocol). The datacom industry won the market battle. The dominant market leaders did not vanish but the rapid technological development was as ruthless in turning profitable products into low-margin commodities as it earlier had been in creating these markets. In a large but maturing industry, profit margins were therefore squeezed. Industry fragmentation and vertical disintegration accelerated when companies became more and more specialized. When performance of any given technological function was good enough, design and manufacturing knowledge was no longer a critical asset and modularization set in. As a consequence, this part of the market split into several new markets.

During 2005-2010, governments released significant chunks of new spectrum. With much more available spectrum, traffic prices fell rapidly and the dominance of the incumbent operators were reduced. Unlicensed spectrum usage was a huge success. The unlicensed bands drove rapid innovation of cheap install-it-yourself black-box access points, triggering mass user deployed networks. In the industrial countries as well as in the most successful NICs, cellular systems are complemented with a large number of other systems (e.g. ad hoc networks, WLAN access, satellites, high altitude platforms). Most problems concerning seamless roaming, system integration etc. have gradually been solved. Appetite for wireless applications and services is very high and once the new geographical positioning infra-structure was in place, the number of location aware applica-

[1] More information about Wireless@KTH and the project can be found at: *www.wireless.kth.se/foresight*

tions and services grew rapidly. Wireless services are used by everyone and in all segments.

Users were very active and drove this development towards an open IP world with skyrocketing traffic and an abundance of applications. They preferred choice over convenience and did not accept being locked-in to corporate bundles. The Open Source movement, down-loading of music and other copyrighted material, enforced these changes in consumer attitudes and the values of the underground culture gradually became mainstream. Feeling this value shift, governments were more and more reluctant to enforce restrictive IPR (Intellectual Property Rights), further undermining profit margins.

The wireless success changed peoples way of work and lifestyle. Being always connected with context sensitive information, a growing part of the knowledge work force could spend most of their time on the move, in meetings or travelling between meetings. Globalization continued and with it the growing trends of travelling and commuting. The rapid technological development within the communication and information technology industries continued and essentially all markets and industry segments experienced a more or less continuous growth.

B.1.2 Scenario 2: Slow Motion

Keywords: Slow technological and industrial development, Global recession, Radiation a health problem, Environmental awareness, Hacking and security still a problem, Industry consolidation, No service explosion, Big NICs catching up.

The wireless world has developed slowly since the turn of the century. The global economic recession during the first decade in combination with real and perceived health problems due to radiation from wireless devices deeply affected the wireless industry. The telecom, computer, and media industries were severely affected. It became really bad when a large European operator went bankrupt. Many 3G commitments were re-negotiated. Some networks were cancelled and many were merged, resulting in only one or two net-works per country. In many rural areas there is still no 3G coverage.

Even though the demand for mobile services has increased, the service explosion that many people envisaged never materialized. Most services used by consumers are still quite simple, focusing on satisfying basic communication and information needs. Many consumers are simply not prepared to pay for advanced services at the price they are offered. In the Western world and in Japan the mobile lifestyle came to a halt during the first decade of the century. Many people, especially young families, moved from the cities to smaller communities. Telecommuting, working from home or in local offices became increasingly popular. The result is that fewer people travel long distances to work. One important driver behind this shift is the increasing environmental awareness. Environmental groups also started to campaign for decreased usage of communication devices. For some time, usage was negatively affected but eventually industry was able to handle this issue by significantly reducing the power consumption in equipment and devices. Security a problem still waiting to be solved. The problem of hacking and virus creation is still significant. Most security codes are quite easily broken and viruses are easily spread in the wireless networks. Many people feel that they cannot trust electronic transactions and are seldom willing to e-shop.

The wireless industry has gone through substantial change. Consolidation has increased and the number of companies in each market has been reduced. Technological development has slowed down and profit margins have decreased substantially. The industry has matured through consolidation and restructuring. The technological development has slowed down considerably and profit margins in all sectors have decreased substantially.

The big NICs, for example China, India, and Russia, are catching up faster than expected. The big NICs are now by far the most important markets for systems and terminal vendors. Moreover, there are now important global players such as operators, vendors, and service providers based in these countries.

Despite large research efforts on new battery technology, no significant progress has been made. Many wireless applications are almost impossible to run when the terminal is on battery power and even the simple 2.5G handsets have to be recharged after downloading a new song, video-clip, or after a teleconference session.

B.1.3 Scenario 3: Rediscovering Harmony

Keywords: Post-materialistic value shift, Balance in life, Ad-hoc networks, Media saturation, Environmentalism, Fear of radiation, Emotional communication, Area owners, Market refocus.

Balance in life became the dominating value in most industrialized nations where material abundance (and security) could be taken for granted. These are post materialistic times where human and environmental needs are in focus. The wireless industry is experiencing a difficult dilemma: refocus or die! There are fewer service and application providers than predicted around 2000, but the market is not completely dry. The big hurdle is to refocus and rethink business models, offerings, and brand on a market with active and demanding consumers categorized by numerous sub-cultures with individual needs. We see many local operators and service providers that have emerged as a result of the trend to move out of the crammed cities and forming smaller, local communities where people live and work. At the same time there are a few global operators providing global communication for the increasing number of people travelling longer and more often for pleasure, and for smaller but more price insensitive segments.

The high-paced lifestyle that dominated the western world in the closing decades of the last century finally went out of control. The consumers became more and more indifferent to brands and commercial messages and no longer accepted companies ignoring ethics, environment, human needs, and product quality. As a result, the environment and human needs had become valuable in the marketplace. The industrialized world is now based on the idea of a sustainable lifestyle where friends, family, and the environment are key elements.

The move towards the new lifestyle started in two segments: ***Moklofs*** (Mobile Kids with Lots of Friends) and ***Elders***. The Moklofs are strongly focused on entertainment and messaging services. They participate in communities and are very global in their ways of thinking. This segment is open-minded towards new technologies but they do not believe smart marketers trying to sell the latest gizmo. Living in a world of tribes with many lifestyles, they express their affiliation with clothes, looks, and stuff they use. The Elders place high demands on usability and quality of service and they are not afraid of letting their voice be heard. Communicating with the family while on the move or when living apart has turned out to be essential. Healthcare is another important segment, allowing people to check up on their health wherever they are.

Health risks and integrity problems are widely debated, but it is the telco industry's impact on the environment that people are most concerned with. Lower power consumption for terminals and infrastructure is an issue that consumers want to see improved. The perceived health threats (real or not) are hard to battle, forcing the telco industry and governments to find new ways of restoring public trust in wireless technology.

After the initial wave of excitement over the new communication possibilities with 3G, the pace of development slowed down. This left the telco industry confused. The main reason was the industry's inability to adjust to the mass market's new attitudes and values. Some players realize this and are adjusting their business models and offerings to the new fragmented marketplace and are as a result highly successful. The big hurdle is to manage to refocus and rethink business models, offerings, and brand.

Despite the new market focus, there is still a demand for wireless services but the mass market is selective in terms of what kind of information is being received, and when it is delivered. A new market has gradually emerged where personalized and very specific types of services are successful. Examples are: personal (peer-to-peer) communication services, multi-media messaging, personal location based services supporting social interaction, and devices and services forming family intra-nets. The demand for peer-to-peer technology has lead to a fierce debate on how to solve the problems with IPRs.

B.1.4 Scenario 4: Big Moguls and Snoopy Governments

Keywords: Market consolidation, Few big players, Integration, Centralized information control, Secure services, Privacy, Priority, Reduced competition, Winner-take-all, Complexity management.

Through consolidation and mergers, large companies, known as moguls, have come to dominate the market. A mogul is a descendant of the early, big information technology or media companies that managed to survive the crises of the first decade of the 2000s. These (few) grew and expanded outside their original business segments, for instance from being only a systems software manufacturer a company became a big content provider and also started manufacturing devices aimed specifically at using their services. Users like these big companies because they feel they can trust them and their products fulfill their needs. There are also no longer any problems with compatibility of software and hardware as there is basically only one choice. Governments like the big companies since they think they can control them. Smaller players were often bought or put out of business due to the dominant position of the big companies. The moguls, together with the world's governments exert substantial and active control over the information flow and the communication industries.

The companies and government are working against the chaotic freedom that used to characterize the early Internet, and the purpose is to protect society and individuals from various unwanted actors and behavior. Examples are: cybercrime, international terrorism, protecting content owners and others from illegal copying of software, music, movies etc. and battling other forms of information use and abuse. The moguls are supported by government since they are seen as more easily monitored. Anonymity on the Net is no longer possible. All users are automatically identified and registered when acting on the Net. The new devices relied on new, unbreakable encryption technologies, and required a personal certificate, together with user biometrics, for use. At the same time it contained circuitry for monitoring the traffic and sending information on possibly unapproved traffic directly to the applicable government agencies. The world is however not an anti-democratic society where the moguls and governments use the Net and the information to gain power and ultimately dictatorship, even though many people fear that this might be the case. Counter- and freedom movements do exist despite heavy measures against them by governments and large corporations alike.

Network effects, economics of scale, and successful enforcing of Intellectual Property Rights created a new global economy with large players becoming even larger, resulting in a winner-take-all society. With traditional mobile operators dominating over new actors, the strategic success factor proved to be brand and customer ownership. Relieved of heavy debts and government demands for rapid 3G investments in rural areas, the operators could generate just enough cash-flow to continue their 3G investments but at a slower speed. Unlicensed spectrum use is heavily limited by extremely low upper limits of emitted power.

There are numerous wireless applications and services available, but most users prefer the comfortable convenience of one-stop-solutions. Users keep all their information stored at their favorite big company portal, easily accessible from anywhere, at any time. Wireless devices are used for payments, to get profiled advertisements based on geographical location, secure transactions of money between peers and so on.

B.2 Trends and fundamental drivers

The four scenarios are based on a set of fundamental drivers, shaping the development of the wireless world. From the fundamental drivers 14 trends of particular importance have been identified. These are trends whose direction and rate of change are uncertain. They are used as defining dimensions of the scenarios.

- Trend 1. *Development will be more user driven.*

  Up until today it can be argued that vendors and technology have driven the wireless development. This will probably change. The scenarios differ according to the extent the development is user driven and to what segments that are most important drivers.

- *Trend 2. User mobility will increase.*

  In the future we will probably travel more and longer and we will spend more time commuting. The scenarios vary according to how fast traveling will increase and by means of transportation.

- *Trend 3. The service and application market will grow.*

  The future market for wireless services will probably be much larger than today, consisting of both complex and basic services. The scenarios differ along a dimension ranging from an abundance of different services and service types to rather few.

- *Trend 4. User security, integrity, and privacy will become more important.*

  Guaranteeing security, integrity, and privacy is an important problem facing industry. The difficulty and complexity of this issue suggests that it might not be solved by 2015. The scenarios differ according to whether these issues are solved or not.

- *Trend 5. Real or perceived health problems due to radiation will become more important.*

  A big threat to the industry is health problems, real or perceived, due to radiation from devices etc. Research might indicate that the radiation in fact is dangerous. The scenarios are differentiated according to how big a problem these health issues are.

- *Trend 6. Environmental issues will become more important.*

  The trend towards increasing environmental awareness will continue. Two areas of special importance are: energy consumption and potentially detrimental substances used in e.g. terminal cases. The scenarios vary in terms of how big these problems are.

- *Trend 7. Spectrum will become an increasingly scarce resource.*

  Today, most of the spectrum is locked-in by legacy users, e.g. operators, the military and television broadcasters. The shortage is forcing operators to build unnecessary expensive infrastructure. Growing usage will aggravate this problem. The scenarios vary according to how much spectrum that is released and whether for licensed use.

- *Trend 8. The wireless industry will grow.*

  All scenarios are based on the assumption that the wireless communications industry will grow during the coming decade, both in size and scope. The question is how fast.

- *Trend 9. The big NICs will continue their positive development.*

  There are many signs of positive developments in the most important NICs, e.g. China, India, and Russia. These telecom markets are very large, they grow rapidly and new companies are established with an ambition of becoming global players. The scenarios vary according to how important the big NICs become on the wireless scene.

- *Trend 10. Market concentration in the wireless industry will change.*

  The future structure of the wireless industry is an open issue. We might see an increased concentration with a few market leaders wielding great market power or a fragmented marketplace where the market leaders have little power. The scenarios differ according to how the industry structure will develop.

- *Trend 11. The fight for market dominance in the wireless industry will intensify.*

  The merging of telecom, datacom, and media into a single industry will have an important impact on the existing telcos. It is not clear which industry will emerge as the winner. The scenarios differ on whether the traditional telcos sustain their industry dominance or not.

- *Trend 12. Short terminal usage time and complexity management will become increasingly important problems.*

  Power consumption in the mobile devices and how to simultaneously manage many complex and heterogeneous wireless systems are two crucial technical problems. The scenarios vary according to if these problems are solved or not.

- *Trend 13. 3G will be implemented.*

  Currently one of the most important issues for the wireless industry is the deployment of 3G. It seems clear that 3G will be implemented, but the question is at what speed and to what extent. The scenarios differ as to the success of implementing 3G.

- *Trend 14. Protecting IPR on content will become increasingly difficult.*

  The problem of protecting IPR (intellectual property rights), especially on content, is very important for the industry. The scenarios are differentiated according to if these problems are solved or not.

B.3 Fundamental Drivers

Underlying the trends used to define the scenarios is a set of fundamental drivers, valid in all scenarios. We believe they will be valid in the next decade. The drivers are a compilation of common wisdom from a number of areas: technology, socio-economics, politics, business, the telecom industry, and user values. They are detailed in the Wireless Foresight report [27] and book [1].

B.4 Technological Implications and Research Issues

Creating the scenarios gave us the opportunity to place ourselves in the middle of four different future worlds. Here we will introduce a set of statements, technical implications, derived from the scenarios. Assuming they are true in 2015 means that the underlying problems and bottlenecks we face today have been solved. These technical implications can be summarized as follows:

- The wireless infrastructure will be heterogeneous
- Very high-rate and efficient air-interfaces will exist
- Much of the access infrastructure will be ad-hoc deployed
- Traffic will be IP based
- Cost per transmitted bit will be very small
- No harmful radiation from base stations
- Decreased power consumption of the wireless systems
- Terminals will have a wide range of shapes and capabilities
- Wireless terminals will be cheap, very small, and modularized
- Usage time without charging the battery will be very long
- User interfaces will be highly developed and advanced
- M2M will be everywhere
- Wireless devices will be harmless to people and environment

- Wireless services will become a commodity
- Services will be independent of infrastructure and terminals
- Tele-presence and emotional communication will be drivers
- Global roaming and seamless service will be possible
- Broadband services will be available for all transportation systems
- The end-user will be always best-connected
- Ubiquitous computing will be everywhere
- Very high level of security can be provided

B.4.1 Seven key research areas

Seven research areas were formulated based on the technical implications:

1. Air-Interfaces and protocols

   With the increasing use e.g. multimedia services, there will be a need for very high rate and efficient air-interfaces. Air interfaces of at least 100 Mb/s for wide area coverage and up to 1 Gb/s for very short-range personal communication seems to be needed. OFDM (Orthogonal Frequency Division Multiplexing) and UWB (Ultra Wide-Band) are interesting technologies. Other interesting areas are smart antennas (for terminals and base stations) and MIMO channels (Multiple Input Multiple Output).

2. Resource management

   Due to the high cost of developing, building, maintaining, and operating wireless infrastructures in general and cellular infrastructure in particular, efficient resource management will become increasingly important. With resources we mean spectrum, power, and available infrastructures. The large amount and multitude of services in the future will challenge the resource management policies much more than in today's networks. The necessary data rates may vary substantially, from perhaps 10 Kbps for a voice call to 100 Mbps for a data back-up session. Examples of important areas are:

   - Sharing of infrastructure and/or spectrum by many operators
   - Dynamic spectrum allocation between different services and systems according to the demand at certain times during the day
   - Flexible allocation of network capacity in time and space
   - Taking advantage of the commonly asymmetric traffic patterns
   - Decentralized resource management for large and complex networks

3. System integration

   Providing seamless services and global roaming in a very complex world with a multitude of air-interfaces and system architectures will be difficult. Infrastructures and terminals have to be adaptive, e.g. by employing flexible software radios and modular system design. The key issues are complexity management, decentralized system control, multi-mode and adaptive radios, and standardization of interfaces.

4. New and advanced services

   In the future a multitude of new services will be introduced. Of special interest are location aware services and smart spaces and media. Moving the computers into the network and making them invisible to the end user are important features of the future wireless world. Being always connected and having access to computational resources will lead to ubiquitous and seamless services enhanced by smart spaces with a multitude of displays and sensors surrounding the user. However, these services need to be provided in a scalable manner. The same application has to be adapted for low or high data rates, for small or large screens, for low or high price etc.

5. Usability

   At present, the user interfaces of wireless terminals is based mainly on either physical or virtual buttons (existing on a small touch sensitive screen) or input devices like joy-sticks or roller wheels. Most user interfaces are based on proprietary models and are neither standardized, nor intuitive for the user. Research should be focused on developing more user and human centered systems where the technology disappears behind the scenes into task-specific devices, integrated in everyday things.

6. Low cost infrastructure and business models

   A problem with conventional cellular systems (2G, 3G etc.) is that they do not scale in bandwidth in the economical sense. A large part of the infrastructure cost is related to e.g. network planning and site work. Economies of scale, and certainly Moore's Law, are not applicable on site acquisition, road works, erecting towers etc. Also, the cost depends rather weakly on the basic radio technology (e.g. the air interface) since current modulation and signal processing technologies are quite advanced and so close to the theoretical limits (Shannon's Law) that not even a radical improvement in processing capabilities will significantly improve performance. Users are accustomed to be connected anytime and anywhere (i.e. large coverage areas and high availability), meaning that these parameters hardly can be compromised. If affordable multimedia services are to be possible, i.e. higher data rates at constant or lower cost, either some of the other Quality of Service parameters have to be sacrificed or architectures with radically lower cost factors have to be developed. Another important issue is to develop business models where all important actors on the market can make money. Agreements on revenue sharing between e.g. service providers, content owners, and operators have to be developed as well as roaming agreements between actors operating different networks.

7. Health and environmental issues

   The effect of electromagnetic radiation on the human body is an area of crucial importance for the wireless community. As of yet, no generally accepted scientific research has proved that usage of wireless terminals is dangerous, at least not with the radiation levels allowed today. However, there is a need for more research in this area, especially studies of the long-term effects of radiation on the human body. The impact of the communication infrastructure on the environment is another important issue. One important area is the power consumption in the systems to drive computers, servers, base stations etc. Towers, underground cables, high power transmitters, and access roads to base station sites can also have a negative impact on the environment and on aesthetical values.

B.5 Challenges for Industry

There are several important challenges facing the wireless industry in the next ten to fifteen years. Here we highlight a few topics we consider especially important. As opposed to the rest of the report, we are directly expressing our own views here. The discussion is based on topics we believe are critical for a positive development and where industry can stumble if things go wrong or are left unresolved.

Threat from disruptive market change. At first sight, the traditional mobile industry looks very impressive with advanced research and development, high revenues, and billions of users. Products from equipment vendors have a reliability, complexity, and sophistication unheard of anywhere else. But the weaknesses are there, just below the surface. Equipment and systems are complex and hard to control centrally. Complexity and small production volumes make the products very expensive and product development rather slow. This is less of a problem when the only customers are large operators. But the telco vendors and operators, living in a world of long planning cycles and billion dollar orders, are seriously threatened by attackers with a completely different business model - the datacom industry. What the telco industry might overlook are new technologies that can be used as entry points to attack this status quo: IP, unlicensed spectrum, self-deployed networks, ad-hoc and peer-to-peer networks, self-configurable network elements, and open APIs. The players in the fast moving datacom industry are masters at exploiting weaknesses and finding soft points for attack. They understand that users prefer cheap products here and now - if these products can meet their immediate needs for an acceptable service quality. The market accepts unreliable and simple products if the price is low enough. This is a classical setting for a so-called disruptive market change.

Speed up the process of spectrum release. Radio spectrum shortage is one of the most important inhibitors for further industrial development. If governments allocate more spectrum to the wireless industry, growth will be much faster and prices for the consumer will be lower. For historical reasons, most spectrum is locked-in by legacy users, the military, and television broadcasters. Wireless consumer communication has been given less than a tenth of all usable spectrum between 0.5 GHz and 5 GHz, causing a shortage in urban areas and forcing operators to build unnecessarily expensive infrastructure.

3G and the telco debt threat. An obvious threat for the wireless industry is the enormous debts left from the financial hype a few years back, in particular from the 3G auctions. In addition, European operators are now facing future investments of the same magnitude for building the 3G networks. The business case for 3G would be more reasonable if it was allowed to grow organically with usage and if the large costs for erecting mast towers all over Europe when building new networks could be lowered.

Complexity management. In a future world with billions of users seamlessly connected over a number of heterogeneous networks, complexity will be much higher than today. Hand-over, roaming, personal context sensitive user profiles, billing, and uninterrupted sessions will be unmanageably complex to control centrally.

Radiation a problem, real or perceived. The complicated problem of electromagnetic radiation from wireless terminals and base stations has to be taken very seriously by industry. Even if, as many experts argue, the radiation levels permitted today are in fact harmless, it is a threat to industry that needs to be dealt with. The problem is that no proof of danger is not the same thing as proof of harmlessness. If users are afraid, it is a problem, justified or not.

Better batteries in wireless devices. With the very rapid development of processor power and memory capacity, the power consumption of wireless terminals will increase dramatically. At the same time, battery capacity develops much slower. It will be very hard to convince the mass market of using power hungry services if battery time drops too much.

Usability and the user in focus. In contrast to the technology driven development in the past, the wireless future will become much more user driven. Usability and intuitive user interfaces will be very important when service access is achieved through a tiny display.

Cheaper infrastructure and viable business models. The current mobile cellular infrastructures have been deployed under a high-cost business model, which has been possible to maintain by high revenues from the users. This is not a viable way forward. Users will not be prepared to see their average wireless bills increase several hundred percent, which is necessary if future wireless multimedia would be carried over traditional networks. Therefore, innovative new ways of providing wireless bandwidth at affordable costs in a world of many heterogeneous networks have to be developed. An example of an important cost driver to avoid in the future is the traditional macro-cell infrastructure with tower masts.

All industries mature. Looking back into history, it seems evident that all industries, even though considered hi-tech in the early days, eventually matured and entered a phase with slower technological development. A phase with profitability being driven by efficiency in manufacturing and large volumes, leading to low production and distribution costs. The question is not if, but when telecom and wireless will mature.