The demand for cost-efficient provision of mobile multimedia services is faced with the reality of scarce radio resources. Various digital mobile and broadcast radio technologies have been developed and specifically been optimized. However, existing and emerging multimedia services exhibit challenging requirements in terms of asymmetry, interactivity, real time, and multicast communication. This article describes an evolution of an IP-based infrastructure from today’s networks toward a future multi-radio infrastructure, taking into account the implications on the end-user terminal. This multi-radio infrastructure enables the cooperation of existing radio networks to combine their spectrum-efficient capabilities, whereby high-quality mobile multimedia services shall be provided. Furthermore, the need for dynamic allocation of spectrum to radio services is motivated. The basic functionality and architecture of a multi-radio system are outlined, with a special emphasis on cooperation between different radio systems. Also, an evolution path for the convergence of broadcast and new telecom is described, starting from today’s systems and leading to a fully coordinated system.

Abstract
The demand of both the new telecom industry and digital broadcasters for cost-efficient provisioning of mobile multimedia services faces the reality of scarce radio resources. Various digital mobile and broadcast radio technologies have been developed and specifically been optimized. However, existing and emerging multimedia services exhibit challenging requirements in terms of asymmetry, interactivity, real time, and multicast communication. This article describes an evolution of an IP-based infrastructure from today’s networks toward a future multi-radio infrastructure, taking into account the implications on the end-user terminal. This multi-radio infrastructure enables the cooperation of existing radio networks to combine their spectrum-efficient capabilities, whereby high-quality mobile multimedia services shall be provided. Furthermore, the need for dynamic allocation of spectrum to radio services is motivated. The basic functionality and architecture of a multi-radio system are outlined, with a special emphasis on cooperation between different radio systems. Also, an evolution path for the convergence of broadcast and new telecom is described, starting from today’s systems and leading to a fully coordinated system.

Convergence of Cellular and Broadcast Networks from a Multi-Radio Perspective

Ralf Keller, Thorsten Lohmar, Ralf Tönjes, Jörn Thielecke
Ericsson Research, Ericsson Eurolab Deutschland GmbH

The demand for cost-efficient provision of mobile multimedia services is faced with the reality of scarce radio resources. The requirement of spectrum efficiency has driven the development of various digital radio technologies — digital audio broadcasting (DAB), digital video broadcasting (DVB), Global System for Mobile Communications (GSM), General Packet Radio System (GPRS), Universal Mobile Telecommunications Systems (UMTS), and so on — optimized for specific services, namely broadcast or mobile communication. However, existing and emerging multimedia services exhibit challenging requirements in terms of asymmetry, interactivity, real time, and multicast communication. This article describes an IP-based multi-radio infrastructure that enables the cooperation of existing radio networks to combine their capabilities to ensure spectrum-efficient provision of high-quality mobile multimedia services.

We define multi-radio as the capability of a system to select and combine radio services out of a set of available services to fulfill user service requirements. The selected set might consist in the simplest case of one radio service, offering as closely as possible the required capabilities. In more advanced configurations, a combination of two or even more radio services is required at the same time to do the job. The decision criteria in the selection process are first of all the service requirements of a user, in terms of, say, throughput, delay and cost. However, also network load or other system parameters might be included. But for all these radio service combinations, spectrum is required to enable them.

Today, radio networks operate with fixed long-term spectrum allocations. Systems like GSM [1] are available all over the world in exclusively allocated spectrum. The same will hold true for UMTS [2] when it is introduced. However, the required spectrum varies over both time and location. For example, in many regions there is more demand for mobile voice and data communication during business hours than during leisure time. The same relation is often seen between crowded business centers and sparsely populated areas. The actual required spectrum for a radio service changes with time and location. Therefore, we are investigating dynamic allocation of spectrum to radio services instead of the fixed allocation of today [3]. Note that we refer to aggregated user requests when we talk about more demand for a service; individual requests can be demanding, of course, irrespective or time and location.

Overall, the multi-radio approach to use spectrum resources more efficiently addresses the cooperation of different radio systems, preferably in a common frequency range combined with dynamic spectrum allocation and deallocation. We see a need to address all these issues within one approach because it is already clear that the existing spectrum allocation for mobile communication services is not sufficient in face of the tremendous growth rates for this type of communication. Hence, for all additional services we have to open new spectrum. A fixed worldwide allocation is difficult if not impossible to achieve, but dynamic alloca-

1 Even if we concentrate on DVB-T in our projects, the outlined convergence can be applied to other digital broadcasting and especially digital TV standards as well (e.g., to ATSC DTV and to ISDB-T).
tion could possibly open a lot of regional spectrum capacity. In addition, from a system and especially from a terminal design perspective, the closer two services are allocated in a common frequency range, the easier close cooperation is to achieve. This holds especially true for UMTS and broadcast services supporting mobile users like DVB — Terrestrial (DVB-T) [4], which are of main interest in our investigation.1

In the following section, we outline the basic functionality and the architecture of a multi-radio system, where we put a special emphasis on the cooperation between different radio systems. After that, we describe an evolution path starting from today’s systems and leading to a fully coordinated system, followed by an overview where we tackle the various needs investigations by different projects. Finally, we give an outlook on future work.

**Functionality and Architecture of a Multi-Radio System**

Multi-radio requires a system architecture that enables the selection and combination of radio services out of a set of available services to fulfill the requested service requirements of a user. Especially, the multi-radio architecture must provide a means for simultaneous access via different radio systems. However, global and continuous coverage is not guaranteed: In contrast to today’s cellular networks, the spectrum of some RANs is not allocated nationwide or continent-wide. Moreover, availability and used spectrum are changeable.

The general multi-radio architecture is depicted in Fig. 1. Each RAN covers one region with a unique radio service. Location dependency could imply that RAN2-1, say, a UMTS Terrestrial RAN (UTRAN), operates in continent-wide allocated spectrum, whereas RAN1-1 and RAN2-2 cover only limited regions with a specific radio service. In one specific region, more than one radio service might be available; hence the coverage area of different RANs might overlap. Temporal dependency could imply that the radio service offered by RAN2-2 is not accessible at all times.

The dynamic multi-radio environment requires that the system announces which radio services are available and which spectrum they use. Because of the dynamic nature of this environment, the information content may change over the time and may vary in different regions; hence, the system announcements must be regularly repeated. One useful generic means to provide this information is a common coordination channel (CCC) [3]. The CCC is a logical channel. At least one system in each participating area must transmit the CCC. Preferably the system that is available in most regions should provide the CCC. It can provide information on available services, service capabilities, used spectrum, and traffic characteristics. However, the contents can depend on the involved systems, the actual location, and the time of day.

The region-dependent availability of radio services imposes high constraints on mobility. The availability of regional radio services must be announced to the mobile users entering the coverage area. In addition, the sessions of individual users may not be interrupt-ed or stopped while leaving the coverage area of such a RAN. This means that the architecture shall support some kind of continuity of service. For example, the traffic flows of leaving users can be redirected via other, still available RANs before the radio service becomes too bad for transmissions.

Efficient traffic control2 is needed to support simultaneous transmission via several RANs and to provide a certain QoS. Traffic control is the entity that is responsible for directing the user’s traffic via different RANs. Traffic control might exploit different control parameters, such as user preferences (e.g., minimal costs), terminal capabilities (e.g., display resolution), system capabilities (e.g., bandwidth, delay), traffic and link status (e.g., network load), application preferences and capabilities (e.g., min/max/preferred bandwidth), and operator preferences (e.g., network utilization). The components of the traffic control are distributed over the entire system. The position of each traffic control component depends on the evaluated control parameter.

Additionally, the architecture must contain an entity that controls the DSA for the radio systems.3 The DSA entity can be centralized, or multiple cooperating entities can be distributed over the system.

**Evolution from Today’s Systems Toward a Fully Coordinated System**

Ideally, we could design an optimal multi-radio system which fulfills all requirements on coordination, mobility, transmission capacity, availability and so on from scratch, taking into account the lessons we have learned from previous work. But one of these lessons is that such an approach is extremely time- and resource-consuming. At the same time, this ignores the fact that there are very well designed systems for mobile

---

1 Today’s Systems Toward a Fully Coordinated System

2 Traffic Control (TC) is responsible for the distribution of mobile node traffic connections on the RANs. If this function is performed on the user service level, we call it user-level TC (UL-TC). If it is performed on the transport service level, we call it transport-level TC (TL-TC). Note that in mobile networks usually two levels can be distinguished, which are named differently in existing architectures, but basically always fulfill the same tasks. One level provides transport service, including mobility; the other level provides “end-to-end” user service. Also similar in many architectures is that IP is used on both levels. Examples for those architectures are UMTS as currently specified within ETSI and 3GPP, and Mobile IP, as developed within the IETF.

3 Dynamic spectrum allocation (DSA) is responsible for the distribution of spectrum on the radio access networks (RANs), which might be negotiated beforehand between different spectrum owners (e.g., cellular and broadcast operators). The DSA functionality can be centralized in one entity, or multiple cooperating entities can be distributed over the system. The final DSA output should be a carrier frequency for each transceiver; both new assignment of a new carrier frequency and activation/deactivation of a fixed assigned carrier frequency are possible.
multimedia communication in operation or production; the same holds true for broadcast systems. Hence, we already have, and will even more in the future, multiple radio services available, each optimized for a specific purpose. Therefore, we have chosen to first investigate the capabilities of the different systems. Based on this analysis, we will design a cooperation system, which combines the strength of existing and upcoming systems by selecting the appropriate combination of radio services. Also, we will add capabilities for dynamic spectrum allocation to use the limited spectrum more efficiently.

Pragmatically, we have defined some evolutionary steps, starting from a today’s view on separated systems.

Each step adds more functionality to the previous one, and we highlight especially the functionality and interaction between different system components which need to be in place to realize the respective level of cooperation. Note that this is only one way to provide an evolution path. We have defined the following steps in the evolution path:

4 Other evolution paths are possible as well.

• No coordination — separated systems
• Integrated terminals
• Static system coordination
• Flexible system coordination
• Dynamic system coordination

The systems can be distinguished according to their grade of integration and dynamic capabilities, as described in the following sections. Note that we concentrate in our work on terrestrial wireless systems, and exclude fixed and satellite systems from the discussion.

No Coordination — Separated Systems

To develop an evolution path for multi-radio systems, we start with two digital radio system families available today: cellular mobile systems and digital broadcast systems. Cellular systems like Global System for Mobile Communications (GSM) allow mobile voice and data communication and the upcoming third-generation system UMTS will support mobile multimedia communication. Digital broadcast systems like DAB and DVB-T are optimized for audio or video broadcast services, respectively. In addition to that, they are offering data broadcasting capabilities.

Integrated Terminals

Integrated terminals are already in the market place or at least available as prototypes. Examples are mobile phones with integrated FM radio or TV, such as the Ericsson FM radio solution, television sets with integrated phones, such as the Nokia MediaScreen. More advanced prototypes integrate digital broadcasting technology and mobile phones closely with a laptop, like the Memo terminal [5].

With such terminals, services from both the broadcasting and telecommunication worlds can be used. See Fig. 2 for examples.

Static System Coordination

Today’s reality of separate systems and integrated terminals has several drawbacks. Interactive services are limited to cellular systems, but DVB-T provides a downlink with higher peak data rates than UMTS (DAB corresponds in the same
A multi-radio service provider controls mobility and it directs the traffic. It can also offer value-added services. All control interactions go directly between the terminal and the multi-radio service provider.

In Fig. 4 an interaction diagram between the different entities — terminal, RAN, operator, and multi-radio service provider — is depicted. In this and the following figures, we assume that operator 1 is a broadcast operator and operator 2 is a cellular operator. The resulting hybrid system offers an asymmetric high-bandwidth downlink and interactive communication channels. Examples are the MEMO [5] system that combines DAB and GSM, and the SABINA [6] system that combines DVB-T and GSM. This kind of combination is ideal for many services where the user wants to receive a high quantity of data but sends only brief messages, as in Internet browsing and MP3 or video clip downloading.

**Level 2: Flexible System Coordination**

Static system coordination has several disadvantages. The hybrid system combines static cellular and broadcast systems, which operate in separate frequency bands with long-term spectrum allocation. However, almost all radio systems face a time- and regional-dependent load characteristic due to varying usage patterns. The efficient use of spectrum requires selection of the optimal transmission technology for a given load scenario. The selection and combination of different existing radio technologies will depend on factors such as the number of users, the required bandwidth for up- and downlink, and type of applications. Moreover, the fixed combination of uplink (GSM) and downlink (DVB or DVB-T, respectively) in systems like MEMO and SABINA neglects the possibility of using the capacity available on the GSM downlink. Whereas this might be acceptable for GSM, systems like UMTS will offer higher throughput and more capacity; hence, the downlink of these systems should be used as well.

In a scenario of time- and regional-dependent requirements on spectrum availability, spectral efficiency demands flexible spectrum allocation and deallocation. One useful generic means to organize and thus ease flexible spectrum allocation to different systems is the CCC. An example scenario is to use the same spectrum for DVB-T in one region and for UMTS in another region. It can also be of interest to have a fixed schedule in which the spectrum usage switches between mobile multimedia communication during the day and broadcast push services to download applications or update news on PDAs at night.

The terminal selects the appropriate set of radio services among the available ones. It also performs traffic control on the user service level to pilot the traffic flows via the best-suited combination of radio accesses. Proxies in the network might support this (Fig. 5). For example, in a multimedia application, the different media types are mapped to the most appropriate radio access. In a finer-grained example, the base and enhancement layers of a scalable video stream are directed to different RANs.

Flexible coordination is characterized by a fixed temporal/regional spectrum allocation schedule. It exploits only a priori knowledge about the requirements and does not involve measurements such as carrier-to-interference ratio (C/I) estimates or RAN conditions such as traffic and link status. Consequently, the spectrum allocation rules (e.g., stored in allocation tables) are simple. In this case the CCC is a broadcast channel that announces spectrum-related information (Fig. 6).
Level 3: Dynamic System Coordination

The disadvantage of flexible system coordination is that neither the regional nor the fixed schedule allocation of spectrum takes the dynamically varying service demands into account. But the optimal use of spectrum requires a complex negotiation process between the different entities of a multi-radio system to adapt dynamically to changing requirements. Different radio bearers will dynamically share a common spectrum, allowing for reallocation of bandwidth according to a strategy based on factors such as load characteristics, interference condition, or provider policy decisions (Fig. 7). The main difference between the architectures depicted in Fig. 5 and Fig. 7 is that the relation between operators in the dynamic case can change over time (e.g., different operators cooperate at different times). This implies that standardized interfaces are required. A standardized interface between the two operators is not mandatory in the flexible architecture. Each pair of operators can agree on the necessary protocols and functions.

An introduction scenario for dynamic system coordination has to identify a range of spectrum as DSA spectrum that is allocated explicitly for dynamic spectrum sharing. Different radio systems can, in such DSA spectrum, allocate and free spectrum on demand. Dynamic coordination will enable the time-dependent use of spectrum, without the fixed schedules necessary in a flexible coordinated system. Hence, varying user demands on specific services can be taken into account.

Dynamic coordination is characterized by an automatic spectrum allocation and deallocation process, which allows for systems that “breathe” with respect to requested spectrum. The optimization algorithms might exploit measurements in the radio access network and at the terminal site and might even learn. In this case the CCC is a communication channel used for negotiation of spectrum requests (Fig. 8).

Full exploitation of the capabilities of a multi-radio system requires that the network be able to redirect on its own traffic between RANs to optimize load distribution and overall system performance. Centralized or decentralized control entities pilot the multimedia services to the appropriate radio systems. This transport-level traffic control has to cooperate with the above-described user-level traffic control.

Terminals and Mobility in a Multi-Radio System

Besides the capabilities of the terminals, the grade of mobility support also varies between the different levels of multi-radio systems. In general, a hierarchy of mobility levels can be distinguished. Starting from mobility within one RAN (intra-RAN-mobility), through mobility between RANs of two systems (inter-RAN mobility or intrasystem mobility, respectively), up to mobility between different systems (intersystem mobility). Cellular systems usually offer intrasystem and intra-RAN mobility, that is, handling the mobility of terminals and users entering or leaving the coverage of the specific system and handover between radio access nodes. For example, inter-system mobility between cellular systems can be implemented with Mobile IP [7]. In contrast, broadcast systems offer today no intrasystem mobility support, because by definition all users receive the same content and must select required content from that which is offered.

In statically coordinated systems, multi-radio mobility is implemented in an external node. This multi-radio service provider has to control the mobility functions on multi-radio level (i.e., all movement of terminals entering or leaving the coverage of one of the supported radio system). The intrasystem mobility of the connected systems is unaffected.

From flexible coordinated systems on, all RANs should implement their own mobility management, preferably self-contained, with no direct support from an interconnection or core network. By this the coordinated system has to care only about mobility between RANs. If the RAN has no self-contained mobility management, the core network has to implement the needed mobility functions. Already in flexible but most lately in fully coordinated systems, we see that mobility support is seamlessly provided within a multi-radio system; movements of terminals and changes in spectrum allocation require only adaptations to varying QoS, but do not lead to disruption of service provisioning.

Conclusions and Outlook

Cellular operators and especially UMTS operators will gain if regionally or temporally available spectrum can be used for mobile multimedia communication services. It can thereby be ensured that the mobile communications success story will not be hampered by a lack of suitable harmonized spectrum. In addition, cooperation with broadcast systems can put additional load on the uplink of cellular networks, without limiting normal mobile services; hence, revenues for cellular operators are increased.

Broadcast operators, in particular, are urgently seeking an answer to the question of how interactive services can be enabled. These interactive services are recognized as the value-added service for broadcast networks that will ensure profitability in the long run. The combination of broadcast systems with a mobile return channel could enable new service models, especially if mobility is also taken into account in the broadcast system.

This cooperation could enable new business models combining broadcast and mobile communication services for companies with both UMTS licenses and access to broadcast spectrum. Examples are Deutsche Telekom AG and France Telecom. Also, agreements between friendly operators would support these new business models.

We are participating in two research projects, which both address the convergence of cellular and broadcast networks. The COMCAR project has put its main focus now on the evolution of the UMTS system, the fair coexistence of radio systems in a common frequency range, and regional spectrum flexibility [8]. System enhancements for higher downlink capacity are currently under investigation. In the DRIVE project, specification of a multi-access service provider is under
development, which combines multiple radio access systems in a flexible manner [9]. Also, a proposal on the relation of traffic control and DSA to other system functions is under development. However, besides technical studies, both COMCAR and DRIVE support the discussion of business scenarios.

References
[6] SABINA (System for Asymmetric Broadband Internet Access) project page: http://www.teracom.se/
[8] COMCAR project page: http://www.comcar.de

Biographies
Ralf Keller (Ralf.Keller@ericsson.com) received his doctoral degree in computer science in 1996 from the University of Mannheim. During his studies he concentrated on application protocols for distributed multimedia system. In 1996 he joined Ericsson Eurolab, where he worked in the beginning on wireless ATM systems and mobile electronic commerce. He is currently a senior specialist and project manager, and his work covers multi-access system integration from service, network, and strategic points of view. The main focus is on the evolution of 3G and future generation systems. The area of multi-access system integration in 3G includes topics like the integration of WLANs and broadcasting support into UMTS. He is a member of the IEEE Computer Society.

Ralf Tönjes studied communication engineering at the University of Hannover and biomedical engineering at the University of Strathclyde in Glasgow, Scotland. In 1998 he received his Dr.-Ing. degree in electrical engineering from the University of Hannover. Since 1998 he has with the Mobile Multimedia Networks Research Group at the Ericsson Eurolab Aachen. He has been the responsible project manager for several national and European research projects. His current research interests include wireless communication networks, multi-radio systems, and mobile multimedia services.

Thorsten Lohmar finished his study of electrical engineering at the University of Technology, Aachen in November 1997. After that he started to work in the Research Department of Ericsson Eurolab Deutschland GmbH. There he focused in various projects on DiffServ in mobile networks and interworking between different radio access technologies like GPRS, UMTS, and Wireless LANs.

Jörn Thielecke received the Dipl.-Ing. and Dr.-Ing. degrees in electrical engineering from the University of Erlangen-Nürnberg, Germany, in 1985 and 1991, respectively. In 1982 he was awarded a one-year Fulbright scholarship to attend Georgia Institute of Technology, Atlanta. From 1985 to 1991, he was a research and teaching assistant at the University of Erlangen-Nürnberg. Later he joined Philips Kommunikations Industrie AG, where he worked on CDMA (CoDiT) and GSM projects. In 1996 he taught communications at the Fachhochschule Würzburg-Schweinfurt-Aschaffenburg. Since 1997 he has been responsible for the Radio Access Group of Ericsson Eurolab Deutschland GmbH, Nürnberg, Germany. His research interests include mobile communications systems and their performance, WCDMA, wireless LANs, and currently signal processing for multiple-input multiple-output communications.