EDGE, Enhanced Data Rates for GSM and TDMA/136 Evolution

Anders Furuskär, Sara Mazur, Frank Müller and Håkan Olofsson
Ericsson Radio Systems
S-164 80 Stockholm, Sweden

ABSTRACT

Two of the major second generation standards, GSM and TDMA/136[1], have built the foundation to offer a common global radio access for data services. Through use of a common physical layer, EDGE (Enhanced Data rates for GSM and TDMA/136 Evolution), both standards will have the same evolutionary path towards providing third-generation services.

EDGE is currently subject to standardization in TIA TR45.3 and ETSI SMG, a process which will be finalized in the end of 1999. Compared to the existing data services in GSM and TDMA/136, EDGE will provide significantly higher user bit rates and spectral efficiency. EDGE can be introduced in these systems in a smooth way, using existing frequency plans of already deployed networks.

This paper gives the rationale behind the development of the EDGE concept, presents the EDGE technology and addresses performance by means of system simulations.

1   INTRODUCTION

Standardization of third-generation mobile communication systems is now rapidly progressing in all regions of the world. Bodies involved in the standardization work include ETSI in Europe, ARIB in Japan, TIA and T1P1 in the United States and TTA in South Korea [1]. The work is based on recommendations for International Mobile Telecommunications-2000 (IMT-2000), which have been developed by the International Telecommunication Union (ITU) since the late 1980s.

IMT-2000 systems will enhance the services provided by second generation systems with high data rates and multimedia capabilities. With the rapid emergence of Internet-based techniques to provide multimedia to the mass market, providing multimedia capabilities to mobile communications is equivalent to providing good Internet access to mobile users. To support the need for different services, the IMT-2000 bit rate requirements set by ITU can be summarized as 384 kbps with full area coverage, and 2 Mbps for local area coverage [2].

In line with the efforts of ITU to provide global recommendations for IMT-2000, a spectrum identification has been made, identifying parts of the 2 GHz band for IMT-2000 usage. Deploying IMT-2000 capable systems is however not limited to this spectrum band. The EDGE concept, a new TDMA-based radio access technology for both TDMA/136 and GSM systems, provides third-generation capabilities in the existing (800, 900, 1800 and 1900 MHz) frequency bands.

This paper describes the EDGE concept, including the rationale behind the development, as well as the used technology and its simulated performance. Section 2 of the paper gives a global overview of second generation systems migration to IMT-2000. The rest of the paper is focused on EDGE, including standardization background and efforts in Section 3, the EDGE technology in Section 4, aspects of introducing EDGE in GSM and TDMA/136 systems in Sections 5-6, and capacity and coverage performance in Section 7.

---

1. TDMA/136 is also known as D-AMPS and IS-136.

2 SECOND GENERATION EVOLUTION TO UMTS/IMT-2000

GSM and TDMA/136 are two second generation cellular standards with world-wide success. Today GSM is used by more than 67 million subscribers in 100 countries, and the TDMA/136 system family (incl. EIA-553 and IS-54) serves over 90 million subscribers in over 100 countries worldwide.

Although speech is still the main service in these systems, support for data communication over the radio interface is being rapidly improved. The current GSM standard provides data services with user bit rates up to 14.4 kbps for circuit switched data and up to 22.8 kbps for packet data. Higher bit rates can be achieved with multi-slot operation, but since both HSCSD and GPRS are based on the original GMSK modulation, the increase of bit rates is slight [3] [4].

For TDMA/136 evolution, similar standardization activities are on-going. In 136+ the combination of multi-slot operation and the new modulation scheme 8PSK based on the 30 kHz carrier bandwidth enables data rates approximately four times higher than today [5].

2.1 THE RADIO PERSPECTIVE

From a radio access perspective, adding third-generation capabilities to these systems mainly means supporting even higher bit rates. Possible scenarios depend on spectrum availability for the network operator. Depending on the spectrum situation, two different migration scenarios must be supported, namely

- Refarming of existing spectrum bands; and
- New or modified spectrum bands.

To support the different spectrum scenarios, two third-generation radio access building blocks have been identified:

- EDGE uses high-level modulation in 200 kHz TDMA and is based on plug-in transceiver equipment thereby enabling the migration of existing bands in small spectrum chunks.
- UMTS is a new radio access network based on 5 MHz WCDMA and optimized for efficient support of third-generation services. UMTS can be used in both new and existing spectra.

2.2 THE NETWORK PERSPECTIVE

Adding third-generation capabilities from a network perspective implies the addition of packet switching, Internet access, and IP connectivity capabilities.

With this approach, the existing mobile networks will reuse the elements of mobility support, user authentication/service handling, and circuit-switching. Packet switching/IP capabilities will then be added to provide a mobile multimedia core network by evolving existing mobile telephony networks.

2.3 THE GLOBAL APPROACH

The building blocks EDGE/WCDMA for radio access and packet switching/IP capabilities have been accepted in the standards selection process as the main technology elements to evolve mobile communications into multimedia/third-generation. The standardization bodies representing the GSM, TDMA/136, and PDC user communities have all made these selections. The standards selections are as follows:

ETSI/T1P1 (GSM):

- EDGE and WCDMA radio access
- Evolved GSM core network, including packet/IP capabilities

ARIB/TTC:

- WCDMA radio access
- Evolved GSM core network, including packet/IP capabilities

TR45.3 (TDMA/136):

- EDGE radio access
- Evolved IS-41 network, with introduction of packet/IP evolution

With these selections, Japan will join the global GSM community in the IMT-2000 perspective with WCDMA and evolved GSM core networks. The TDMA/136 community will, with the EDGE selection, obtain great synergies with the GSM community for IP-based services. Thus, the goal of a global standard has success-fully been reached.

From now on, the paper will focus on the EDGE concept and standard.

3 DEVELOPMENT OF THE EDGE CONCEPT

EDGE provides an evolutionary path from existing standards for delivering third-generation services in existing spectrum bands. The advantages of EDGE include fast availability, reuse of existing GSM and TDMA/136 infrastructure, as well as support for gradual introduction. For example, as a 1/3 frequency reuse overlay to TDMA/136, EDGE can be deployed using as little as 600 kHz of total bandwidth. In GSM, EDGE can be introduced using a minimum of only one time slot per base station.

EDGE was first proposed to ETSI as an evolution of GSM in the beginning of 1997. During 1997, a feasibility study was completed and approved by ETSI, making way for the currently on-going standardization [6]. Although EDGE reuses the GSM carrier bandwidth and time slot structure, it is by no means restricted to use within GSM cellular systems. Instead it can be seen as a generic air interface for efficiently providing high bit rates, facilitating an evolution of existing cellular systems towards third-generation capabilities.

In the development of its third-generation wireless technology, the TDMA/136 community decided to take on an evolutionary approach and base its third-generation proposal on evolution of existing second generation systems. In the Universal Wireless Consortium (UWCC) the 136 High Speed (136HS) radio interface was proposed as a means to satisfy the requirements for an IMT2000 Radio Transmission Technology, with additional requirements for the consideration of commercially effective evolution and deployment in current TDMA/136 networks. After evaluating a number of different proposals, EDGE was adopted by UWCC in January 1998 as the outdoor component of 136HS to provide 384 kbps data services. One of the arguments in favor of this approach was leveraging the technology evolution for both GSM and TDMA/136 systems, also leading to opportunities for global roaming. Consequently, EDGE was included in the UWC-136 IMT-2000 proposal. UWC-136 was adopted by TR-45 in February 1998 and submitted by the US delegation to ITU as a Radio Transmission Technology candidate for IMT-2000 [7].

Since then, EDGE development has been concurrently carried out in ETSI and UWCC to guarantee a high degree of synergy with both GSM and TDMA/136. The standardization roadmap for EDGE foresees two phases. In the first phase the emphasis has been placed on EGPRS (Enhanced GPRS) and ECSD (Enhanced Circuit Switched Data). Both are targeted in ETSI for standards release 1999 with products to follow shortly afterwards. The second phase of EDGE targeted for release 2000 is currently being defined with improvements for multimedia and real-time services as possible work items.

4 EDGE: THE TECHNOLOGY

Technically, EDGE is primarily a radio interface improvement, but in a more general context it can also be viewed as a system concept that allows the GSM and TDMA/136 radio access networks to offer a set of new radio access bearers to their core networks. This EDGE concept description starts with a technical motivation, and continues with a presentation of radio interface characteristics and radio protocols. Finally, the resulting bearers are presented and discussed.

4.1 TECHNICAL ROOM FOR IMPROVEMENT OF EXISTING RADIO INTERFACES

One fundamental characteristic of a cellular system is that different users tend to have different channel qualities in terms of signal-to-interference ratio (SIR), due to differences in distance to the base station, fading and interference. Despite attempts to affect channel quality through power control, there will typically be a distribution of channel quality in a system, for example according to Figure 1 (left). A traditional service such as speech requires a certain target SIR to give good quality: below the target, quality is unacceptable, while above the target the quality is good and practically independent of channel quality. Thus, the radio network planning must make sure that only a small fraction of users are below the SIR target. Unfortunately, a large part of the user population will then experience an excessive SIR, i.e. an excellent channel quality from which they cannot benefit. This is the case for today's GSM and TDMA/136 systems, both for speech and data services, thereby giving room for enhancements in spectral efficiency.

EDGE is designed to improve the situation by employing what is referred to here as *link quality control*. Link quality control adapts the protection of the data to the channel quality, so that for all channel qualities, an optimal bit rate is obtained (further elaboration in Section 4.3.1). The principle is illustrated in Figure 1 (right), showing user quality in terms of information bit rate with EDGE (EGPRS) and standard GPRS as a function of channel quality. Standard GPRS saturates at rather low SIR, whereas EDGE user quality increases with increased channel quality.

Naturally, to obtain the characteristics in Figure 1, EDGE must include transmission modes with significantly higher

information bit rates than those of standard GSM and TDMA/136. This is the reason for the introduction of the new modulation, 8PSK, which is the core of the EDGE concept. This is further described in the next section.
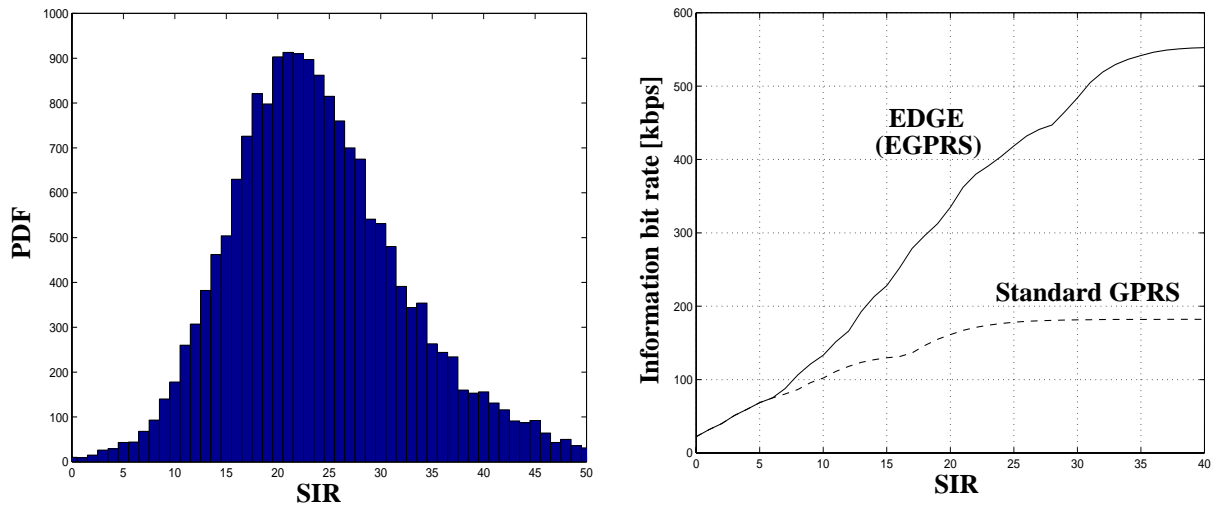

Figure 1.   A typical channel quality distribution (left), and the perceived user quality in terms of bit rate for EDGE and standard GPRS assuming an 8-slot terminal (right).

4.2   RADIO INTERFACE BASIC PARAMETERS

The EDGE air interface is intended to facilitate higher bit rates than those currently achievable in existing cellular systems. In order to increase the gross bit rate, 8PSK, a linear high-level modulation is introduced. 8PSK, depicted in Figure 2, is selected since it provides high data rates, high spectral efficiency and moderate implementation complexity. GMSK modulation as defined in GSM is also part of the EDGE system concept. The symbol rate is 271 ksps for both modulations, leading to gross bit rates per time slot of 22.8 kbps and 69.2 kbps for GMSK and 8PSK respectively (including two stealing bits per burst). The 8PSK pulse shape is linearized GMSK [8], allowing 8PSK to fit into the GSM spectrum mask.

Many EDGE physical layer parameters are identical to those of GSM. The carrier spacing is 200 kHz, and GSM's TDMA frame structure is unchanged. Also the 8PSK burst format is similar: a burst includes a training sequence of 26 symbols in the middle, 3 tail symbols at either end and 8.25 guard symbols at one end. Each burst carries 2x58 data symbols, each comprising 3 bits (Figure 3).

Channel coding and interleaving are intimately related to the layer 2 protocols. Hence, we have chosen to describe those schemes in Sections 4.3.1 and 4.3.2, although in principle they belong to the physical layer.
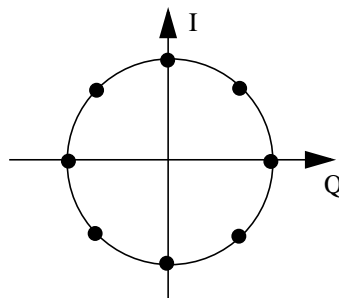

Figure 2.   8PSK modulation: signal constellation in the phase plane.

4.3   RADIO PROTOCOL DESIGN

The radio protocol strategy for EDGE is to reuse the protocols of GSM/GPRS whenever possible, thus minimizing the need for new protocol implementation. However, due to the higher bit rates and to new insights obtained in the radio protocol field, some protocols are changed to optimize performance. The EDGE concept includes one packet-

| 3 | 58 | 26 | 58 | 3 | 8.25 |

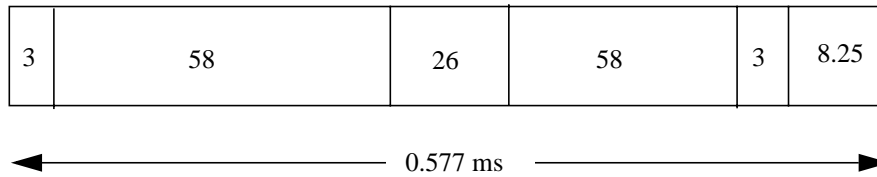$\longleftarrow$ 0.577 ms $\longrightarrow$

Figure 3.   The burst format for EDGE is very similar to that of GSM, including a training sequence of 26 symbols in the middle, 3 tail symbols at either end and 8.25 guard symbols at one end. Each burst carries 2x58 data symbols.

switched mode and one circuit-switched mode, denoted Enhanced General Packet Radio Service (EGPRS) and Enhanced Circuit Switched Data (ECSD) respectively. At the time of writing, both modes are still subject to standardization, and details described below may therefore change in the final standard.

4.3.1 PACKET-SWITCHED TRANSMISSION: ENHANCED GPRS

Due to the higher bit rate and the need for adapting the data protection to the channel quality, the EDGE RLC protocol is somewhat different from the corresponding GPRS protocol. The main changes are related to the improvements in the link quality control scheme. As already mentioned in Section 4.1, link quality control is a common term for techniques to adapt the robustness of the radio link to the varying channel quality. Examples of link quality control techniques are *link adaptation* and *incremental redundancy.*

A link adaptation scheme regularly estimates the link quality and subsequently selects the most appropriate modulation and coding scheme for coming transmissions in order to maximize the user bit rate [9] [10]. Another way to cope with the link quality variations is incremental redundancy [11]. In an incremental redundancy scheme, information is first sent with very little coding, yielding a high bit rate if decoding is immediately successful. If decoding fails, additional coded bits (redundancy) are sent, until decoding succeeds. The more coding that has to be sent, the less the resulting bit rate and the higher the delay.

EGPRS will support a combined link adaptation and incremental redundancy scheme. In this scheme, the initial code rate for the incremental redundancy scheme is based on measurements of the link quality. Benefits of this approach are the robustness and high throughput of the incremental redundancy operation in combination with the lower delays and lower memory requirements enabled by adaptive initial code rate.

As in GPRS, the different initial code rates are obtained by puncturing a different number of bits from a common convolutional code (rate 1/3 for 8PSK). The resulting coding schemes are listed in Table 1. Incremental redundancy operation is enabled by puncturing a different set of bits each time a block is re-transmitted. Hereby the code rate is gradually decreased towards 1/3 for every new transmission of the block. The selection of the initial modulation and code rate to use is based on regular measurements of the link quality.

Channel name	Code Rate	Modulation	Radio Interface rate per time slot
CS-1	0.49	GMSK	11.2 kbps
CS-2	0.64	GMSK	14.5 kbps
CS-3	0.73	GMSK	16.7 kbps
CS-4	1	GMSK	22.8 kbps
PCS-1	0.33	8PSK	22.8 kbps
PCS-2	0.50	8PSK	34.3 kbps
PCS-3	0.6	8PSK	41.25 kbps
PCS-4	0.75	8PSK	51.6 kbps
PCS-5	0.83	8PSK	57.35 kbps
PCS-6	1	8PSK	69.2 kbps

Table 1 **Channel coding schemes for EDGE packet switched transmission (EGPRS). The first four are those of standard GPRS, while the last six use 8PSK modulation.**

4.3.2 CIRCUIT-SWITCHED TRANSMISSION: ENHANCED CSD

For the ECSD mode of EDGE, the aim is to keep the existing GSM circuit-switched data protocols as intact as possible. A data frame is interleaved over 22 TDMA frames as in GSM, and three new 8PSK channel coding schemes are defined along with the four already existing for GSM. As shown in Table 2, the radio interface rate varies between 3.6 and 38.8 kbps per time slot.

For non-transparent transmission, the current assumption is that the radio link protocol of GSM is to be used.

Channel name	Code Rate	Modulation	Radio Interface rate per time slot
TCH/F2.4	0.16	GMSK	3.6 kbps
TCH/F4.8	0.26	GMSK	6 kbps
TCH/F9.6	0.53	GMSK	12 kbps
TCH/F14.4	0.64	GMSK	14.5 kbps
ECSD TCS-1 (NT+T)	0.42	8PSK	29 kbps
ECSD TCS-2 (T)	0.46	8PSK	32 kbps
ECSD TCS-3 (NT)	0.56	8PSK	38.8 kbps

Table 2 **Channel coding schemes for EDGE circuit switched transmission (ECSD). The first four are those of standard GSM, while the last three use 8PSK modulation.**

4.4 OFFERED EDGE RADIO ACCESS BEARERS

The result of the EDGE radio interface and protocol enhancements is a set of radio access bearers that are offered from the radio access network to carry data over the wireless link. The definition of these bearers specifies what the user can expect from EDGE.

4.4.1 PACKET-SWITCHED BEARERS

The GPRS architecture provides IP connectivity from the mobile station to an external fixed IP network. For each radio access bearer that serves a connection, a quality of service (QoS) profile is defined. The parameters included are priority, reliability, delay, and maximum and mean bit rate [12]. A specified combination of these parameters defines a bearer, and different such bearers can be selected to suit the needs of different applications.

The EDGE introduction calls for an updated parameter space for the QoS parameters. For example, the maximum bit rate possible for an EGPRS bearer will be at least 384 kbps for terminal speeds up to 100 km/h and 144 kbps for terminal speeds up to 250 km/h [13]. Also mean bit rate and delay classes may be affected by the introduction of EDGE.

Due to varying characteristics of different future applications, and also due to potentially different subscriptions, there is a need for even more advanced support of differentiated QoS to different users. Improvements in the GPRS standard are ongoing within the framework of GPRS phase II within ETSI SMG.

4.4.2 CIRCUIT-SWITCHED BEARERS

The current GSM standard supports both transparent and non-transparent radio access bearers. 8 transparent bearers are defined, offering constant bit rates in the range of 9.6-64 kbps [14].

A non-transparent bearer employs a radio link protocol (RLP) to ensure virtually error free data delivery. For this case, there are 8 bearers offering maximum user bit rates ranging from 4.8 to 57.6 kbps [14]. The actual user bit rate may vary according to the channel quality and the resulting rate of re-transmission.

The introduction of EDGE implies no change of the bearer definitions. The bit rates are the same, but what is new is the way the bearers are realized in terms of channel coding schemes defined in Table 2. For example, a 57.6 kbps non-transparent bearer can be realized with coding scheme ECSD TCS-1 and two time slots, while the same bearer requires four time slots with standard GSM (using coding scheme TCH/F14.4).

Thus, EDGE circuit-switched transmission makes the high bit rate bearers available with fewer time slots, which is advantageous from a terminal implementation perspective. Additionally, since each user needs fewer time slots, more users can be accepted, which increases the capacity of the system.

4.4.3 ASYMMETRIC SERVICES DUE TO TERMINAL IMPLEMENTATION

For mobile stations, there is a trade-off between the new possibilities of EDGE and the requirements for low cost, small size and long battery life. The 8PSK transmitter is more of a challenge to incorporate into a low complexity mobile station with today's commercial technology than the receiver is.

The approach taken by ETSI is to standardize two mobile classes, one that requires only GMSK transmission in the uplink and 8PSK in the downlink, and one that requires 8PSK in both links. For the former class, the uplink bit rate will be limited to that of GSM/GPRS, while the EDGE bit rate is still provided in the downlink. Since most services are expected to require higher bit rates in the downlink than in the uplink, this is a way of providing attractive services with a low complexity mobile station. Similarly, the number of time slots available in up- and downlinks do not need to be the same. Transparent services will, however, be symmetrical.

This is not a new evolution path for GSM mobiles: already today, the GSM standard includes a large number of mobile station classes, ranging from single-slot mobile stations with low complexity to 8-slot mobiles providing high bit rates [15]. EDGE will introduce a number of new classes, with different combinations of modulation and multi-slot capabilities.

5   EDGE IN GSM SYSTEMS

5.1   EFFECTS ON THE GSM SYSTEM ARCHITECTURE

The increased bit rates of EDGE put requirements on the GSM/GPRS network architecture. Figure 4 illustrates the GSM/GPRS architecture, where shaded parts are discussed in this section. Other nodes and interfaces are not affected at all by the EDGE introduction.

An apparent bottle-neck is the A-bis interface, which today supports up to 16 kbps per traffic channel. With EDGE, the bit rate per traffic channel will approach 64 kbps, which makes allocation of multiple A-bis slots to one traffic channel necessary. Alternative ATM or IP based solutions to this problem can also be discussed, see e.g. [16]. One important fact is, however, that the 16 kbps limit will be exceeded already by the introduction of two coding schemes (CS3 and CS4) in GPRS, which have a maximal bit rate per traffic channel of 22.8 kbps. Consequently, the Abis limitation problem is being solved outside the EDGE standardization, and it is therefore a GPRS-related, not an EDGE-related modification.

For the GPRS-based packet data services, other nodes and interfaces are already capable of handling higher bit rates, and are thus not affected. For circuit-switched services, the A interface can handle 64 kbps per user, which is not exceeded by EDGE circuit-switched bearers.
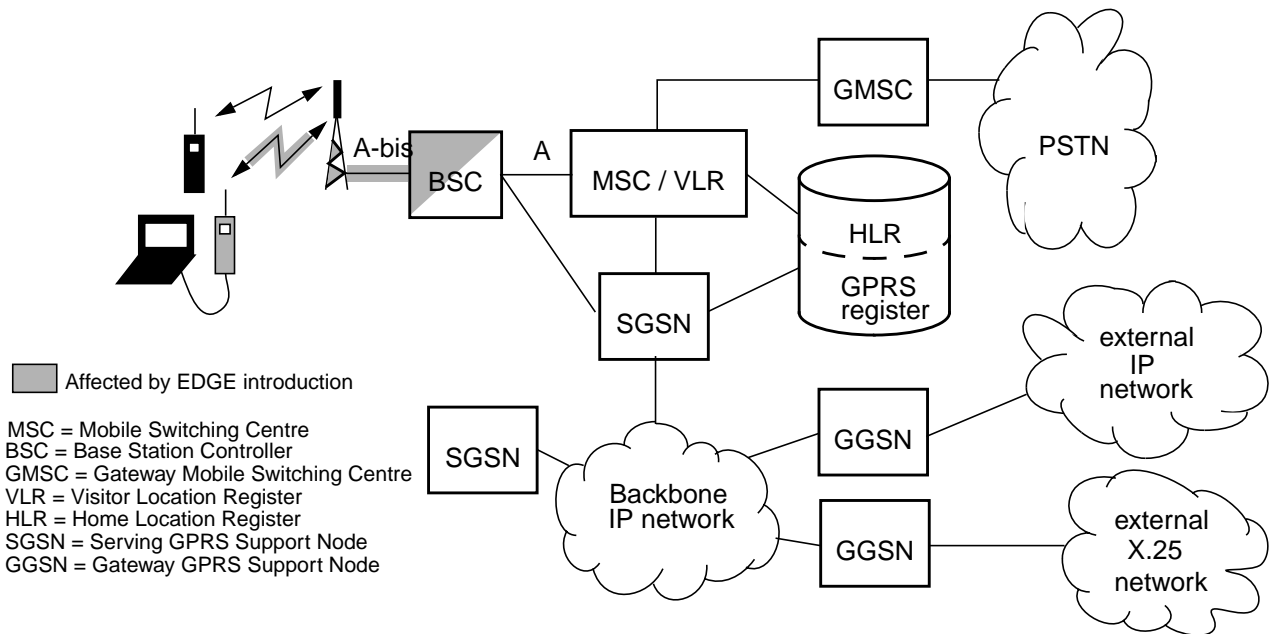
Figure 4. GSM/GPRS network architecture. Only the shaded nodes and interfaces are affected by the introduction of EDGE.

5.2 IMPACT ON GSM RADIO NETWORK PLANNING

An important prerequisite, which to a large extent will determine the success of EDGE in GSM, is that a network operator is able to introduce EDGE gradually. For initial deployment, EDGE-capable transceivers will supplement standard GSM/GPRS transceivers in a subset of the existing cells where EDGE coverage is desired. Hence, an integrated mix of GSM, GPRS and EDGE users will co-exist in the same frequency band.

To minimize effort and cost for the network operator, radio network planning (including cell planning, frequency planning, setting of power and other cell parameters) must not require extensive modification. This section discusses the influence of EDGE on radio network planning, primarily for non-transparent services. Some of these aspects are further discussed in relation to simulations (Section 7).

5.2.1 COVERAGE PLANNING

One characteristic of non-transparent radio link protocols (i.e., protocols including ARQ) is that a low radio link quality only results in lower bit rate for the user. Hence, low SIR for a user does not result in a dropped call, as for speech, but in a temporary decrease of user bit rate. Coverage performance of EGPRS is provided in Section 7.2.2.

For transparent bearers, which typically offer a constant bit rate, link quality control must be extended to incorporate resource allocation, in the sense that the number of dynamically allocated time slots fits the bit rate and BER requirement. Transparent bearers, as defined in Section 4.4.2, will thus be available in the entire GSM cell, but require fewer time slots in the center of the cell (where 8PSK coding schemes can be used).

5.2.2 FREQUENCY PLANNING

Most mature GSM networks of today have an average frequency reuse factor of around 9 (meaning that available frequencies are divided into 9 frequency groups). However, there is also a trend towards tighter reuse factors. With the use of frequency hopping, Multiple Reuse Patterns (MRP) and discontinuous transmission (DTX), reuse factors as low as 3 become feasible, see e.g. [17] [18]. EDGE supports a variety of reuse patterns, as shown in [19] and [20] where the performance in 1/3 and 3/9 reuse systems is studied (see also Section 7.2). In fact, by its use of link quality control, EDGE can be introduced in an arbitrary frequency plan, and benefit from high SIR closer to the base stations.

Thus, the conclusion is that EDGE can be introduced in an existing GSM frequency plan, and that it also supports future high capacity solutions based on tighter frequency reuse.

5.2.3 CHANNEL MANAGEMENT

After EDGE introduction, a cell will typically include two types of transceivers: standard GSM transceivers and EDGE transceivers (Figure 5). Each physical channel (time slot) used for traffic in the cell can be viewed as being one of at least four channel types:

1) GSM speech and GSM circuit-switched data (CSD);

2) GSM packet data (GPRS);

3) GSM speech and circuit-switched data (CSD and ECSD); and

4) packet data (GPRS and EGPRS).

While standard GSM transceivers support only channel types 1-2, EDGE transceivers support all four channel types. Physical channels are dynamically defined according to the need in the cell. For example, if a large number of speech users are currently active, the number of channels of type 1 and 3 is increased, at the expense of less GPRS and EGPRS channels.

It is of paramount importance that this channel management procedure is automated, to avoid splitting the channels into static groups. Such groups would reduce trunking efficiency, and the network operator would be faced with a difficult and time consuming dimensioning problem.

1 ▨ GSM/CSD physical channel
2 ▨ GPRS physical channel
3 ☐ GSM/CSD/ECSD physical channel
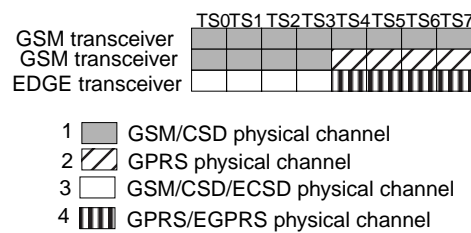4 ▥ GPRS/EGPRS physical channel

Figure 5. Example of transceiver and channel plan in one cell. Both standard GSM and EDGE transceivers exist, and the physical channels (time slots) are dynamically defined according to the current capacity need in the cell. Time slots used for control signaling are not included in the example

6   EDGE IN TDMA/136 SYSTEMS

6.1   136HS REQUIREMENTS

Some of the requirements posed on 136HS include considerations which are beyond the ITU requirements for IMT-2000 but are crucial to TDMA/136 operators. Such considerations include flexible spectrum allocation, high spectral efficiency, compatibility with TDMA/136 and 136+ and support for macro cellular performance at higher mobile speeds. In particular, initial macro cellular deployment should not require clearance of more than 1 MHz of spectrum, and support for hierarchical cell structures should be maintained from TDMA/136 to enhance spectrum management flexibility. The spectral efficiency of 136HS should be at least 0.45 bps/Hz/site. 136HS should also be able to coexist in the same spectrum as existing second generation systems without degrading the performance of the existing systems.

6.2   SYSTEM ARCHITECTURE

Already the introduction of packet switched GPRS services over the 136+ radio interface will place requirements on the network architecture in TDMA/136 systems. The introduction of EDGE in 136HS will only require minor additional changes. Figure 6 shows a schematic drawing of a TDMA/136 system where GPRS has been introduced for support of packet switched services. Both TDMA/136 circuit switched services and GPRS packet switched services over the 136+ or 136HS radio interfaces are supported from the same base station, which allows an efficient reuse of existing infrastructure.

6.3   COVERAGE PLANNING

One requirement on 136HS is to provide coverage equal to that of TDMA/136 and 136+, to enable an introduction in the present cell planning using existing base stations. EGPRS with link quality control satisfies this requirement and provides coverage at least as good as TDMA/136. As a result of the link quality control, a low radio link quality will not cause a dropped call, but only give a reduced bit rate for the user. Coverage performance of EGPRS in a TDMA/136 system is provided in Section 7.2.2.

6.4   FREQUENCY PLANNING

To meet the requirements of initial deployment within 1 MHz of spectrum, EGPRS deployment in a 1/3 frequency reuse is proposed for 136HS. As explained in Section 5.2.2, EGPRS can, thanks to its use of link quality control, be
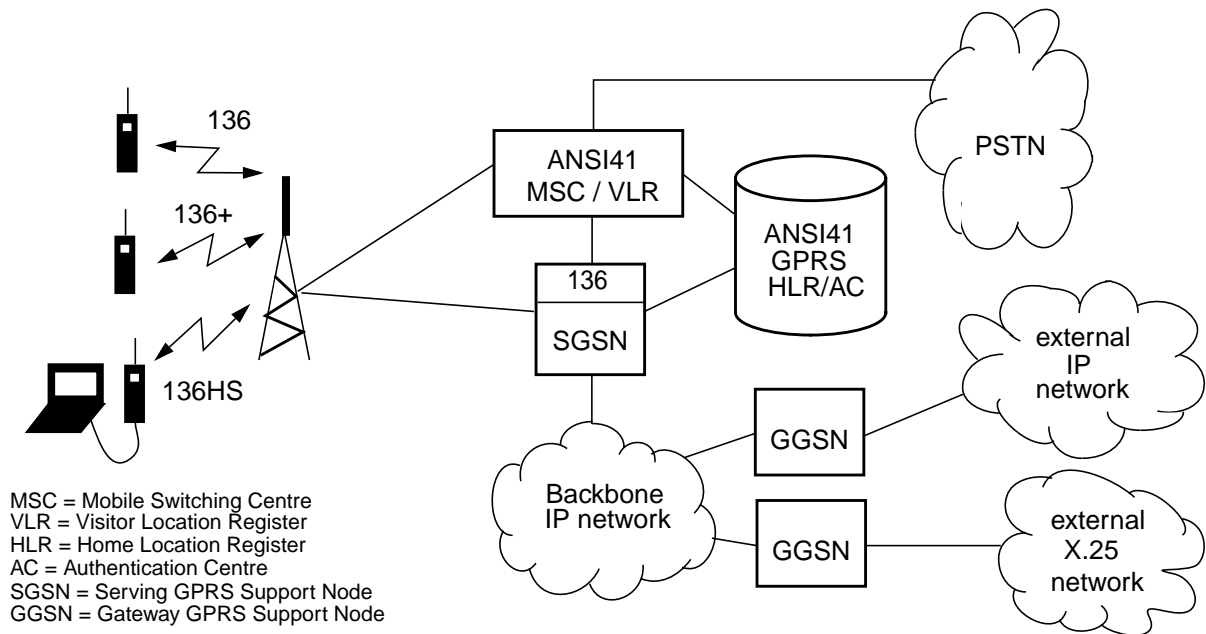
Figure 6. Network architecture of a TDMA/136 system equipped with GPRS over both the 136+ and 136HS radio interfaces.

introduced in a tight frequency plan and still provide high data rates for packet data services. For example, a SIR sufficient for a system average data rate of 384 kbps can be achieved in a 1/3 reuse by means of fractional loading. The good performance of EGPRS in a 1/3 reuse has earlier been shown in [19] and [20] and is further studied in Section 7.2.1. Thus, the conclusion is that EGPRS as 136HS can provide good packet data performance in a 1/3 frequency reuse, hence allowing for initial deployment in less than 1 MHz of spectrum.

6.5 CONTROL CHANNEL ASPECTS

In 136HS, using a 1/3 reuse with fractional loading, no EDGE carrier will be transmitted at constant power continuously. Hence, the cell most suitable for service can not be determined using the standard GSM/GPRS procedure of measuring the signal strength on the GSM carrier transmitting the broadcast control channel. Instead, 136HS can utilize signal strength measurements on the discontinuously transmitted 200 kHz EDGE carrier, or measure on the TDMA/136 Digital Control Channel (DCCH) for cell selection and reselection. All packet channels, both traffic and control, can however be transmitted on the EDGE carrier. This control channel arrangement will allow for the tight frequency reuse planning of 136HS and at the same time provide a natural integration with the existing TDMA/136 system.

7   EGPRS PERFORMANCE

This section investigates the system performance of the EGPRS concept. The simulation models are first described followed by extensive evaluations of capacity and coverage. The evaluation approach used is the same as in [19], [20] and [21]. Simulations focussed on power control aspects have been reported in [22].

7.1   SIMULATION MODELS

In order to analyze the system performance of the EGPRS concept, system level simulations are performed. Both interference limited systems, where co-channel interference totally dominates over thermal noise, and coverage limited systems (without co-channel interference) are studied. Different models are used for the two cases. Further, two scenarios where EDGE is introduced in a GSM system and in a TDMA/136 system are addressed.

7.1.1   GENERAL CELLULAR NETWORK MODELING

The simulation environment includes a regular cellular layout consisting of a large number of equally sized 3-sector macro cells. Standard 9 sector and 3 sector frequency reuse patterns are used for the GSM and TDMA/136 scenarios respectively. In both cases, one carrier comprising 8 time slots is available in each sector. This corresponds to a total usage of 9 carriers in the GSM scenario, and 3 carriers in the TDMA/136 scenario. The distance attenuation is calculated according to the formula L = C + 35 * log(d). Log-normal fading with 6 dB standard deviation is assumed. Cell selection is performed based on least path loss, apart from an uncertainty of 3 dB due to the handover margin. No antenna diversity is used. Since the studied WWW traffic is believed to be highly asymmetrical, only the downlink of

the system is studied. The performance of the less crucial uplink can be expected to be similar.

Link level results from [20] are used. In the TDMA/136 scenario, link level results without frequency hopping are used, reflecting the limited possibilities for frequency hopping within the narrow band used for initial deployment. In the GSM scenario, however, ideal frequency hopping is assumed. Frequency hopping is not explicitly modeled on the system level in either case. Note that the combination with link level results that include frequency hopping corresponds to a form of cyclic frequency hopping, which gives no interference diversity.

7.1.2 CAPACITY SIMULATIONS IN INTERFERENCE LIMITED SYSTEM

The capacity simulations are dynamic. A large number of mobile stations are studied over a period of time. Mobile stations enter and leave the system during the simulation. In each time step of the simulation, a mobile station in the system becomes active with a certain probability, and then starts transmitting a packet of random size. The mobile stations remain stationary throughout the simulation, i.e. mobility is not modeled. The time step of the simulator is 20 ms, which corresponds to the duration of an RLC block.

In each time step, carrier to interference ratios (C/I) for all active links are calculated. Based on the C/I and the modulation and coding scheme used for each user, block errors are generated to decide whether the transmission of the RLC block was successful or not. Erroneous RLC blocks are retransmitted.

WWW Traffic Modeling

The basis for the traffic model used in the simulator is a measurement based WWW traffic model [23]. The model is slightly modified to generate shorter packets in order to get a bursty interference behavior.

Users enter the system according to a Poisson process. The arrival rate of this process is a parameter used to vary the offered load. A user in the system transmits a geometrically distributed number of packets with a mean of 10 packets. The time between a packet is generated for each user using a Pareto distribution with a mean of 10 seconds (Pareto shape parameter = 1.4). The sizes of the packets are generated from a Log-normal distribution with a mean of 4.1 kbyte (8.1 kbyte in [23]), and a standard deviation of 30 kbyte. In order to model a minimum packet size corresponding to an IP and TCP header, an extra 50 bytes is added to the generated packet sizes. Further, the distribution is truncated at 100 kbyte, in order to limit simulation times, but also to take into account that very large file sizes are unlikely to be requested by mobile users.

Link Adaptation Modeling

Users in the system regularly get to select what modulation and coding scheme to use. The time between the selections is referred to as the *update interval*. After each update interval, the modulation and coding scheme maximizing the throughput is selected. In the simulations the update interval is set to 10 RLC blocks, corresponding to 200 ms. The C/I used for the selection is the value calculated for the last RLC block sent in the previous update interval.

EGPRS will also support the use of incremental redundancy in combination with link adaptation, see Section 4. This is not included in the simulations. The use of incremental redundancy can be expected to improve the system level results by some 20 -30%.

Admission Control, Scheduling and Dropping

No admission control algorithm is used in the simulations. All users that generate packets are allocated resources or put in the queues. Scheduling is done in a packet based FIFO fashion. Users with poor link quality are dropped according to a leaky bucket algorithm. The counter for each user is initially set at its maximum value of 32, each NACK decreases this counter by 1, and each ACK increases it by 2. When the counter reaches zero, the user is dropped. This results in a user dropping rate of less than 1% even at the highest load.

More sophisticated algorithms than the above are expected to improve the system performance.

7.1.3 COVERAGE SIMULATIONS IN NOISE LIMITED SYSTEMS

Since in the coverage limited case, the performance does not depend on the interference or traffic dynamics, a static simulation technique can be used. Snapshots of the system are taken, in which stationary mobiles are placed randomly according to a uniform distribution. In order to investigate the coverage achievable for EDGE with existing cell plans, GSM and TDMA/136 systems with 95% speech coverage are used as a reference. With this reference the results are valid for both up- and downlink. The EDGE performance is then analyzed assuming the same carrier output power as in these reference systems. Additionally, within EGPRS the same average power is assumed for GMSK and 8PSK. In the GSM case, assuming a full rate speech coder, speech coverage requires an E_b/N_0 of 6 dB. For TDMA/136, the requirement is 15.7 dB. Thus, these are the values found at the 5th percentile of the E_b/N_0 distribu-

tions in the cell. When introducing the EDGE modulation scheme 8PSK, the E_b/N_0 distributions will be lowered, due to the higher gross bit rate. Assuming the same carrier output power, the difference in E_b/N_0 for EDGE compared to the standard GSM and TDMA/136 modulations is simply calculated as:

$$\Delta E_b = \frac{R_{GSM}}{R_{EDGE}} = \frac{271}{3 \cdot 271} = -4.8 \ dB \quad GSM \tag{7.1}$$

$$\Delta E_b = \frac{R_{TDMA}}{R_{EDGE}} = \frac{48.6}{3 \cdot 271} = -12.2 \ dB \quad TDMA \tag{7.2}$$

where R_{GSM} and $R_{TDMA/136}$ are the gross rates of standard GSM and standard TDMA/136 respectively, and R_{EDGE} is the gross rate of the EDGE carrier.

7.1.4 PERFORMANCE MEASURES

Unlike circuit switched systems, packet data systems have no hard capacity limit. Packets that cannot be immediately transmitted are queued, and sent as soon as resources become available. When the offered load is increased beyond that acceptable for the system, more and more packets will be queued, and the system delay will eventually become intolerable. A correct performance measure for a cellular packet data system is thus the spectral efficiency achievable for a certain delay requirement. However, an absolute maximum delay accepted by a user is hard to define. Longer packets will more likely than short exceed such an absolute limit - even without queuing and retransmissions - since they take longer time to transmit. Still, the receiving users might be satisfied with these packets despite the higher absolute delays, because of the large amount of data they have received.

This leads to the introduction of a normalized delay measure. Further, assuming that twice as long a delay is acceptable for twice as large a packet etc., the normalization can be done linearly, see Figure 7. A simple way of doing this is to divide the absolute delay by the size of the packet. Hence, we define the normalized delay measure as total delay (queuing time plus transmission time) in seconds divided by packet size in kbit. It can be noted that the normalized packet delay defined above is the inverse of the bit rate measured per packet. Thus, requiring a certain maximum normalized delay for a packet corresponds to requiring a minimum bit rate for that packet.

Altogether, the above reasoning results in a performance measure in the form of 'spectral efficiency achievable for a certain normalized delay requirement'. This measure however says nothing about the fairness of the system among users. To investigate fairness, the average packet bit rate per user is measured by averaging the bit rate of each of its packets, where packet bit rate is defined as packet size divided by time for queuing and transmission.

7.2 SIMULATION RESULTS

The results of the capacity and coverage simulations are analyzed below. In each section, both a GSM scenario and a TDMA/136 scenario is studied.

7.2.1 CAPACITY RESULTS

In this section, for both scenarios, the normalized delay and spectral efficiency of the systems are first studied at different loads. The fairness among the users in the system is then analyzed at a load resulting in an acceptable normalized delay.

Beginning with the GSM scenario, Figure 8 shows normalized delay distributions among the transmitted packets for some different offered loads. The offered load is measured in average number of users per sector. As expected, the delay increases with offered load. The different offered loads also result in different spectral efficiencies. Figure 9 shows the spectral efficiencies achieved for the same offered loads as in Figure 8, plotted against the 90th percentile of the normalized delay. A comparison to standard GSM is also made. Notice that the spectral efficiency for the same delay requirement is more than doubled. Assuming a delay requirement of 0.15 s per kbit at the 90th percentile (90% of the packets having a total delay of less than 0.15s per kbit), a spectral efficiency of 0.33 bps/Hz/site is obtained in the EDGE case. Notice that one site comprises 3 sectors.

As mentioned in the performance measure section, the spectral efficiency measure says nothing about the fairness of the system among users. To investigate system fairness, the distribution of the average packet bit rate per user is measured. The distribution of average packet bit rate per user per 1 (8) time slots is plotted in Figure 10. Offered loads that result in normalized delays just below 0.15 s per kbit are used. Notice the significant increase in packet bit rate when EDGE is introduced. At the studied offered load, it is seen that approximately 30% of the users achieve a packet bit rate exceeding 384 kbps, and that 97% of the users achieve a packet bit rate exceeding 144 kbps, assuming use of 8 time slots.

Figures 11 - 13 show the normalized delay distribution, spectral efficiency versus normalized delay, and average user

packet bit rate for the TDMA/136 scenario. Figure 11 shows how normalized delays in the system increase as the offered load is increased. In Figure 12, spectral efficiencies reached for the different offered loads as a function of the normalized delay at the 90th percentile are shown. It is seen that very high spectral efficiencies are achievable also in this case. The forward error correction and ARQ schemes efficiently handle the high interference levels caused by the tight 1/3 reuse. Actually, higher spectral efficiencies are achieved in the 1/3 reuse than in the 3/9 reuse, indicating that EGPRS is highly robust to tight reuse patterns.

Assuming a delay requirement of 0.15s per kbit at the 90th percentile, a spectral efficiency of 0.46 bps/Hz/site is obtained with the WWW traffic model. Again notice that one site comprises 3 sectors. The fairness among users is shown in Figure 13. It is seen that approximately 20% of the users achieve a packet bit rate exceeding 384 kbps, and that 80% achieve a packet bit rate exceeding 144 kbps, assuming the use of 8 time slots. The offered load used corresponds to a normalized delay just below 0.15 s/kbit.

7.2.2 COVERAGE SIMULATIONS

The coverage simulations result in E_b/N_0 distributions for both the GSM and TDMA/136 scenarios. From these original E_b/N_0 distributions, the distributions for 8PSK are calculated using (7.1) and (7.2). Additionally, from link level simulations, the block error rate performance for the different modulation and coding schemes is also known. With use of the block error rate performance results, the E_b/N_0 distribution is transformed to a packet bit rate distribution using the formula:

$$S_{max} = max_n \left\{ R_n \cdot \left(1 - BLER_n \left(\frac{E_b}{N_0} \right) \right) \right\}$$ (7.3)

which simply maps the E_b/N_0 values on the highest achievable packet bit rate, assuming ideal link adaptation.

Packet bit rate coverage distributions for the GSM scenario are given in Figure 14. A comparison is also made to standard GPRS. It is seen that a majority of the users achieve a higher packet bit rate when EDGE is introduced. Thus existing cell plans can be reused when EDGE is introduced. Approximately 75% of the users achieve a packet bit rate exceeding 144 kbps using 8 time slots, while approximately 26% exceed 384 kbps.

For the TDMA/136 case, it is seen in Figure 15 that even better coverage is achieved due to the higher E_b/N_0 requirement for speech coverage. Approximately 78% of the users achieve a packet bit rate exceeding 144 kbps using 8 time slots, while approximately 32% exceed 384 kbps. Existing sites can thus be reused also in this case.

Even better coverage can be achieved by using smart antennas or simple antenna diversity techniques.
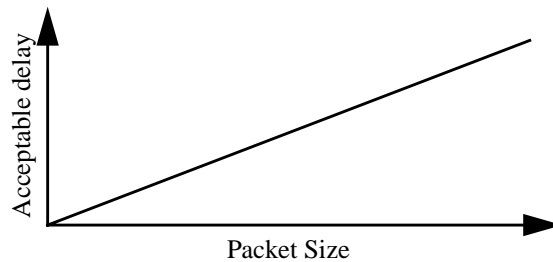

Figure 7.   The acceptable delay is assumed to depend linearly on the packet size.
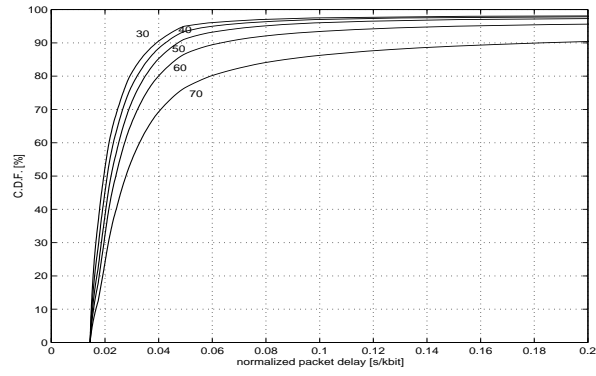
Figure 8.   Normalized delay distribution for some different numbers of users per sector, EDGE/GSM case.
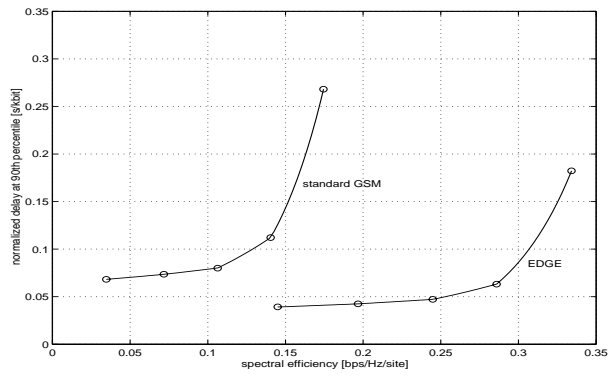

Figure 9.   Spectral efficiency versus normalized delay, EDGE/GSM and standard GSM case.
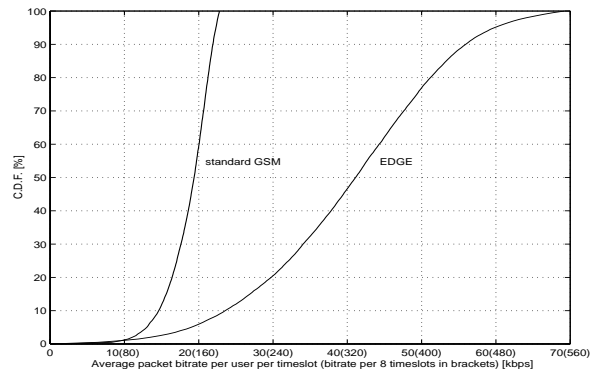

Figure 10.   Average packet bit rate per user distribution for EDGE in the case of 60 users per sector (0.28 bps/Hz/site), compared to standard GSM with 27 users per sector (0.11 bps/Hz/site).
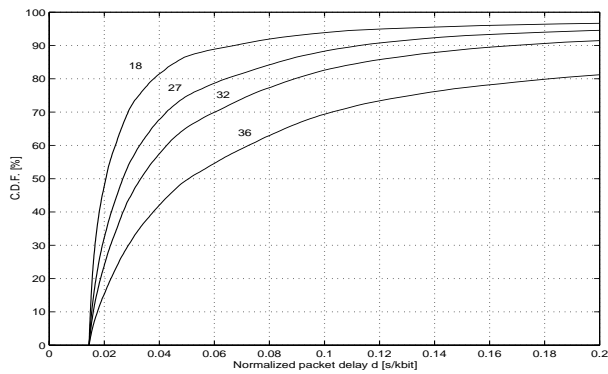

Figure 11.   Normalized delay distribution for some different numbers of users per sector, EDGE/TDMA/136 case.
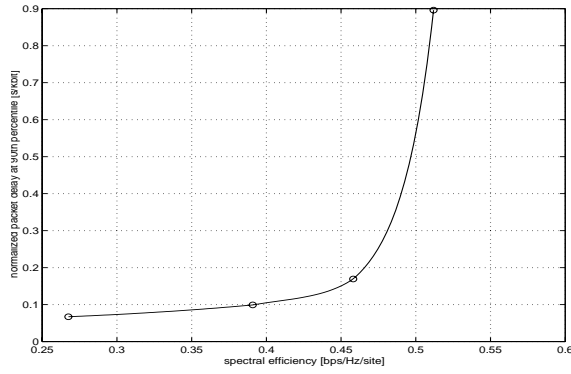
14

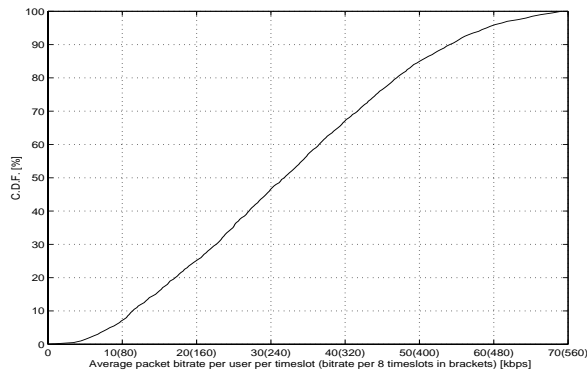**Figure 12. Spectral efficiency versus normalized delay, EDGE/TDMA/136 case.**

Figure 13. Average packet bit rate per user distribution in the case of 32 users per sector (0.46 bps/Hz/site), EDGE/TDMA/136 case.
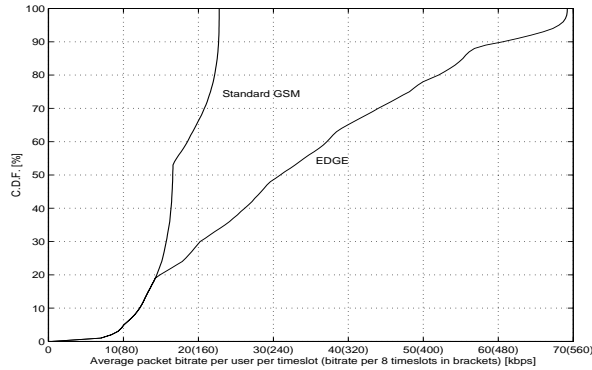

Figure 14. Average packet bit rate per user distribution, coverage limited EDGE-GSM and standard GSM case.
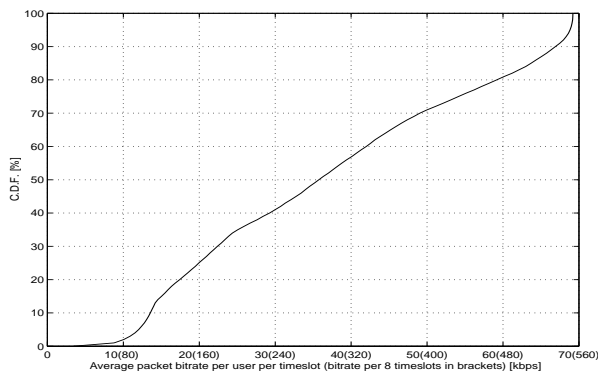

Figure 15. Average packet bit rate per user distribution, coverage limited EDGE/TDMA/136 case.

8 CONCLUSIONS

With the continuous globalization of telecommunication standards, the convergence of TDMA/136 and GSM is a logical next step. The common access of data services for TDMA/136 and GSM can be offered to over 160 Million subscribers of both standards and will thereby create a huge market potential. Due to the convergence of the systems, roaming between both communities will be possible. Furthermore, the smooth introduction of EDGE in TDMA/136 and GSM will allow operators to improve services and capacity on demand.

Regarding performance, the presented packet data simulation results show that compared to standard GSM, EDGE enables significantly higher peak rates, and approximately triples the spectral efficiency. Also the packet bit rate coverage of the EDGE concept is improved compared to standard GSM, enabling existing sites to be reused. It is also shown that EDGE supports the UWCC requirement of spectral efficiencies exceeding 0.45 bps/Hz/site in a 1/3 frequency reuse with fractional loading. This scenario is primarily intended for TDMA/136 evolution using only a very limited amount of spectrum. Packet bit rate coverage simulations of the EDGE concept in the TDMA/136 scenario show that existing sites can be reused also in this case.

REFERENCES

[1] E. Dahlman et al, "UMTS/IMT-2000 based on Wideband CDMA", *IEEE Communications Magazine, September 1998.*

[2] Recommendation ITU-R M.1225, "Guidelines for Evaluation of Radio Transmission Technologies for IMT-2000".

[3] ETSI. TS 101 038 V5.0.1 (1997-04), "Digital Cellular Telecommunications system (Phase 2+); High Speed Circuit Switched Data (HSCSD) - Stage 2 (GSM 03.34)".

[4] ETSI. TS 03 64 V5.1.0 (1997-11), "Digital Cellular Telecommunications system (Phase 2+); General Packet Radio Service (GPRS); Overall Description of the GPRS Radio Interface; Stage 2 (GSM 03.64 version 5.1.0)".

[5] S. Labonte, "A Proposal for the Evolution of IS-136", in *Proc. IEEE VTC'98.*

[6] ETSI. Tdoc SMG2 95/97. "EDGE Feasibility Study, Work Item 184; Improved Data Rates through Optimised Modulation", version 0.3, December 1997.

[7] The UWC-136 RTT Candidate Submission.

[8] P. Jung, "Laurent's Representation of Binary Digital Continuous Phase Modulated Signals with Modulation Index 1/2 Revisited", IEEE Trans. Comm., vol. COM-42, pp. 221-224, February/March/April, 1994.

[9] J. Dunlop et al, "Estimation of the Performance of Link Adaptation in Mobile Radio", in *Proc. IEEE VTC'95*, Chicago 1994.

[10] A. Goldsmith and S. G. Chua, "Adaptive Coded Modulation for Fading Channels", in IEEE Transactions on Communications, vol. 46, no. 5, May 1998, pp 595-602.

[11] S. Kallel, "Analysis of a Type II Hybrid ARQ Scheme with Code Combining", IEEE Transactions on Communications, vol 38 no 8, August 1990.

[12] ETSI. GSM 02.60, "General Packet Radio Service (GPRS); Service description; stage 1", v. 7.0.0, April 1998.

[13] ETSI. GSM 10.59, "Project scheduling and open issues for EDGE", v. 1.1.0, July 1998.

[14] ETSI. GSM 02.34, "High Speed Circuit Switched Data (HSCSD) - Stage 1", v. 5.2.0, July 1997.

[15] ETSI. GSM 05.02, "Multiplexing and multiple access on the radio path", v. 6.2.0., July 1997.

[16] H. Nakamura, H. Tsuboya, M. Nakano and A. Nakajima, "Applying ATM to Mobile Infrastructure Networks", in IEEE Communications Magazine, Vol. 36, No. 1, Jan 1998.

[17] H. Olofsson, J. Näslund and J. Sköld, "Interference Diversity Gain in Frequency Hopping GSM", *in Proceedings of the IEEE VTC'95.*

[18] S. Engström et al, "Multiple Reuse Patterns for Frequency Planning in GSM Networks", *in Proceedings of IEEE VTC'98.*

[19] A. Furuskär, M. Frodigh, H. Olofsson, J. Sköld, "System Performance of EDGE, a Proposal for Enhanced Data Rates in Existing Digital Cellular Systems", in *proceedings of IEEE VTC'98*

[20] K. Zangi, A. Furuskär and M. Höök, "EDGE: Enhanced Data Rates for Global Evolution of GSM and IS-136", in *proceedings of Multi Dimensional Mobile Communications 1998 (MDMC'98)*

[21] A. Furuskär, M. Höök, C. Johansson, S. Jäverbring and K. Zangi, "EDGE-Enhanced Data Rates for Global Evolution", in *proceedings of Nordic Radio Symposium 1998 (NRS'98)*

[22] H. Olofsson and A. Furuskär, "Aspects of Introducing EDGE in Existing GSM Networks", in *proceedings of IEEE ICUPC'98*

[23] K. Blomquist, J.-Å. Kjellberg, "A Study of Self-Similar Data Traffic and Development of a WWW Traffic Model", MSc Thesis, Linköping University, Sweden, June 1997

BIOGRAPHY

Anders Furuskär received his M.Sc. degree in electrical engineering from the Royal Institute of Technology, Stockholm, Sweden in 1996, appointed graduate of the year. Since 1990 he has been with Ericsson. During 1990-1996 he worked mainly with development of Radio in the Local Loop systems. 1997 he joined the Access Networks Research department at Ericsson Research. His current research includes different aspects of radio resource management. He is actively participating in the standardization of EDGE in ETSI.

Sara Mazur received her Ph.D and M.Sc. degrees in electrical engineering from the Royal Institute of Technology, Stockholm, Sweden in 1994 and 1989. She joined the department for Radio Access and Antenna Systems Research at Ericsson Radio Systems in 1995, where she worked with research on adaptive antennas in cellular systems. Since 1998 she has been with the business unit for TDMA systems and she is currently manager for the Technology Evolution Radio Access Network unit within the Systems and Technology department. Her research areas include radio access technologies and radio resource management for cellular systems.

Frank Müller holds an M.Sc. degree in electrical engineering from the Ruhr-Universität, Bochum, Germany. He has been with the Access Technologies and Signal Processing Research department at Ericsson Research since 1995 and is currently Ericsson responsible for the EDGE standardization in ETSI. Frank Müller acts as work item rapportour for the ETSI EDGE BSS work item.

Håkan Olofsson received his M.Sc. in engineering physics from the university of Uppsala in Sweden in 1994. He joined Ericsson Radio Systems the same year, where he conducted studies of frequency hopping in cellular systems. Since 1995 he has participated in various internal and external research activities, including the international European research program ACTS. He is a Senior Specialist at Ericsson Research in the fields of user quality and system capacity for wireless systems. His research interests include radio resource management for circuit- and packet-switched communications, with reference to both current and future mobile radio systems.