Edge—Enhanced data rates for GSM and TDMA/136 evolution

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The use of high-level modulation to provide enhanced data rates for GSM evolution is currently being standardized for GSM by the European Telecommunications Standards Institute. Likewise, Edge is being adopted for TDMA/136 evolution by the Universal Wireless Communications Consortium.

The authors describe the architecture and equipment-related modifications that are needed for introducing Edge into a GSM or TDMA system, and explain how the Edge concept affects radio-network planning. They also describe an evaluation of system performance.

Background

GSM and TDMA/136 are second-generation cellular standards with worldwide success. GSM is currently used by more than 135 million subscribers in over 100 countries. The TDMA/136 system family (which includes EIA-553 and IS-54) serves approximately 95 million subscribers in over 95 countries.

While speech is still the main service of these mobile systems, support for data communications over the air interface is rapidly improving. Standard products currently provide data services with bit rates up to 9.6 kbit/s, but forthcoming steps in the evolution of GSM, known as Phases 2 and 2+, are already in the final stages of standardization, which among other things, defines

- high bit-rate, circuit-switched modes (high-speed circuit-switched data, HSCSD[1]);
- packet services (general packet radio service, GPRS[2]).

Each of these functions addresses the need for increased data capabilities. HSCSD introduces multislot operation, and the combination of HSCSD and GPRS adds a new mechanism through the air interface, whereby users can remain connected to the network but only use radio capacity when actually transmitting or receiving data. In addition to these functions, new core network parts—which will be positioned in parallel to the mobile switching center (MSC)—will provide direct access to the Internet/intranet.

HSCSD and GPRS achieve high bit rates through multislot operation. But because these techniques are based on original Gaussian minimum-shift keying (GMSK) modulation, they yield only a moderate increase in bit rates per time slot.

For TDMA/136 evolution, similar standardization activities have been started. In 136+, for example, the combination of multislot operation and the new modulation scheme, 8-PSK (based on the 30 kHz carrier bandwidth), will increase data rates by approximately four times.[3]

The main driver for third-generation wireless communication and IMT-2000 is the ability to supplement standardized services currently available in GSM and TDMA/136 with wideband services. In brief, third-generation systems will provide wide-area coverage at 384 kbit/s and local-area coverage at approximately 2 Mbit/s.[4, 5]

The new 2 GHz frequency band for wideband code-division multiple access (WCDMA) is being supported and standardized by both the European Telecom-

BOX A, ABBREVIATIONS

136+	TDMA/136 8-PSK 30 kHz carrier
136HS	High-speed TDMA/136
8-PSK	Eight-phase-shift keying
APD	Average power decrease
ARIB	Association of Radio Industries and Broadcasting
ARQ	Automatic repeat request
BER	Bit error ratio
BS	Base station
BSC	Base station controller
BTS	Base transceiver station
C/I	Carrier-to-interference ratio
CSD	Circuit-switched data
DCCH	Digital control channel
DTX	Discontinuous transmission
ECSD	Enhanced circuit-switched data
Edge	Enhanced data rates for GSM and TDMA/136 evolution
EGPRS	Enhanced GPRS
ETSI	European Telecommunications Standards Institute
FIFO	First-in, first-out
GGSN	Gateway GPRS support node
GMSK	Gaussian minimum-shift keying
GPRS	General packet radio service
GSM	Global system for mobile communication
HSCSD	High-speed circuit-switched data
IMT-2000	International mobile telecommunication
IP	Internet protocol
MRP	Multiple reuse pattern
MSC	Mobile switching center
RLC	Radio link control
SGSN	Service GPRS support node
TCP	Transmission control protocol
TDMA	Time-division multiple access
UMTS	Universal mobile telecommunications system
UWCC	Universal Wireless Communications Consortium
WCDMA	Wideband code-division multiple access

munications Standards Institute (ETSI) and the Association of Radio Industries and Broadcasting (ARIB). WCDMA will include all the capability required for IMT-2000 compliance. However, evolution toward higher data rates is not limited exclusively to the new 2 GHz frequency band. The Edge air interface (enhanced data rates for GSM and TDMA/136 evolution) also enables networks operating in the 800, 900, 1800 and 1900 MHz frequency bands to provide third-generation capabilities.

Ericsson proposed Edge to ETSI in 1997. That same year, ETSI approved a feasibility study that paved the way for current standardization.[6] Although Edge reuses the GSM carrier bandwidth and time-slot structure, it can also be used with other cellular systems. It can be regarded as a generic air interface for efficiently providing high bit rates and thereby facilitating the evolution of cellular systems toward third-generation capabilities. On these grounds, the Universal Wireless Communications Consortium (UWCC) evaluated the Edge concept for TDMA/136, approving it in January 1998.

Extensive technical presentations of the Edge concept were given at VTC '98, MDMC '98 and NRS '98.[7-10] The presentations included thorough performance evaluations of the Edge concept at link and system levels. In addition, the aspects of introducing Edge into existing GSM systems was addressed at ICUPC.[11] This article summarizes some of the most interesting parts of those presentations.

Network operators who elect to introduce Edge would do so at minimal effort and cost. In other words, to be accepted by operators, the impact of the Edge system on the network architecture must be small, and the system should permit operators to reuse existing base station equipment. What is more, operators should not be required to alter their radio network plans, nor should the introduction of Edge affect the quality of communication.

Edge mainly affects the radio-access part of the network—the base transceiver station (BTS) and base station controller (BSC) in GSM, and the base station (BS) in TDMA—but does not have a negative effect on applications and interfaces based on circuit-switched and packet-switched access. Existing network interfaces are retained through the mobile switching center (MSC) and the serving GPRS support nodes (SGSN). In fact, Edge improves the performance and effectiveness of these applications and serves as an enabler of forthcoming wideband services.

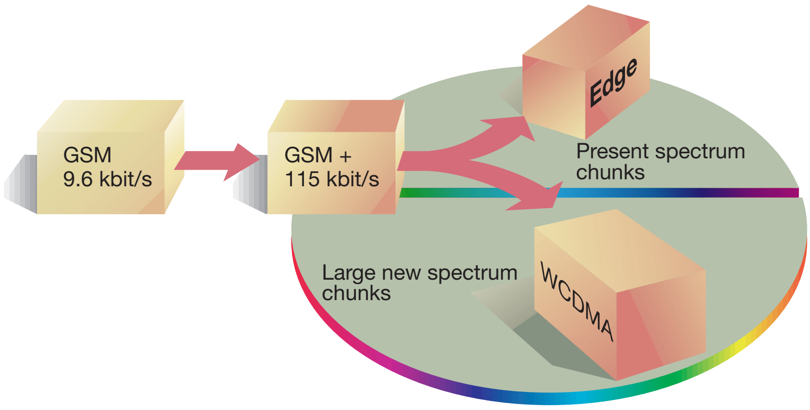


Figure 1
Evolution toward mulitmedia-capable systems.

Overview of the Edge air interface

The Edge air interface is meant to facilitate higher bit rates than can be obtained from current cellular systems. To increase the gross bit rate on the air interface, a new modulation scheme is introduced which provides high data rates, high spectral efficiency, and which is only moderately difficult to implement: eight-phase-shift keying (8-PSK) modulation[12]. The symbol rate of 8-PSK remains at 271 kbit/s, yielding a gross bit rate of 69.2 kbit/s per time slot (compared with the current 22.8 kbit/s), while still fulfilling the GSM spectrum mask and leaving the burst duration unchanged (Figure 2).

Several channel-coding schemes have been defined to ensure robustness in a variety of channel conditions. A technique known as *link adaptation* provides dynamic switching between coding and modulation schemes.[13] The basic idea involves reusing regular GSM data service types, but with increased bit rates. By reusing the GPRS

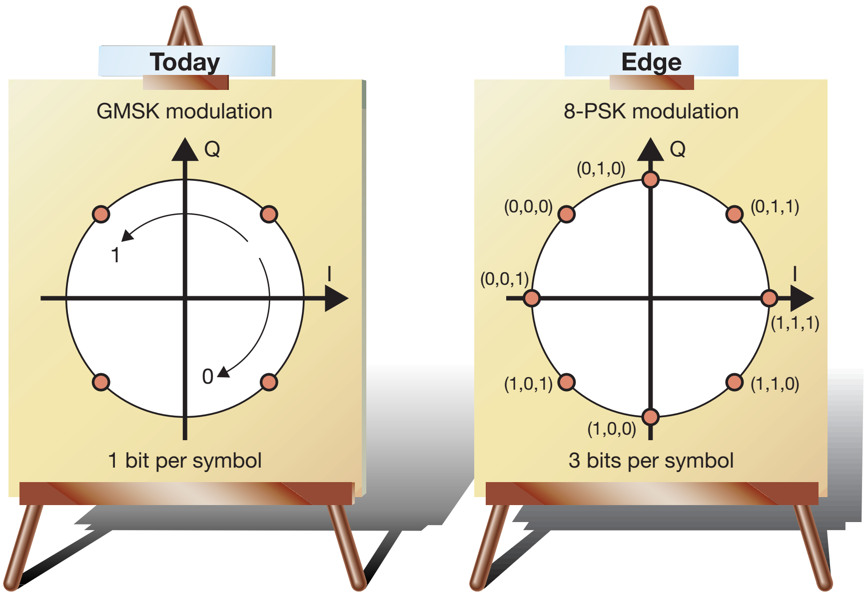


Figure 2
Signal constellations for 8-PSK and GMSK. By extending the signal space from 2 to 8, each symbol contains three times more information.

structure, packet-data services can be provided with an air-interface bit rate that ranges from 11.2 to 69.2 kbit/s per time slot. Circuit-switched services are supported with an air-interface bit rate up to 28.8 kbit/s per time slot.

Multislot operation, which is supported for all services, yields eight times the bit rate provided by a single time slot, and a peak air-interface bit rate of 554 kbit/s for packet data.

Impact on air-interface equipment

Edge-induced modifications to the air interface directly influence the design of base stations and mobile terminals. New terminals and base station transceivers must be developed that can transmit and receive Edge-modulated information.

Effects of linear modulation

The new modulation scheme puts new requirements on the linearity of the power amplifier: as opposed to GMSK, 8-PSK does not have a constant envelope. This is especially true for high-output power equipment. Indeed, the designers' challenge is to build a cost-effective transmitter while fulfilling the GSM spectrum mask.

An unyielding requirement from network operators stipulates that Edge-capable transceivers must fit in a base station cabinet designed for standard transceivers. Accordingly, Edge transceiver performance must be acceptable in terms of both transmit spectrum and heat dissipation. A typical high-power Edge transceiver might need to reduce its average transmit power when transmitting 8-PSK. Compared to GMSK, the average power decrease (APD) could be between 2 and 5 dB.

The design issue for low-power transceivers—that is, microbase, indoor or picobase stations and mobile terminals—poses still further challenges. For instance, transmitter architectures optimized for nonlinear modulation may no longer be used.

Where mobile terminals are concerned, it might be possible to standardize two classes:

- one that requires GMSK transmission in the uplink and 8-PSK in the downlink. The uplink bit rate would be limited to GPRS, whereas Edge bit rates will be provided in the downlink. Since most services are expected to require higher bit rates in the downlink than in the uplink, this solution represents the least complex way of providing attractive services to terminals;
- one that requires 8-PSK transmission in both the uplink and the downlink.

The introduction of different classes of terminals is not a new evolution path for GSM. Today, the GSM standard includes several classes of mobile terminals, ranging from single-slot devices with low complexity to eight-slot devices with high bit rates.[14] Edge technology will introduce several new classes, with different combinations of modulation and multislot capabilities.

Effects of a high gross bit rate

High gross bit rates are too complex to be handled by an optimum equalizer structure. Instead, sub-optimum equalizer designs need to be considered. According to simulations, the design of a good sub-optimum equalizer for 8-PSK will be slightly more complex than that of a standard GSM equalizer.[12]

The increased bit rate (compared to standard GPRS) also reduces robustness in terms of time dispersion and mobile-terminal velocity. For the most part, however, Edge services are expected to be used by quasi-stationary users, the implication being that high mobile-terminal velocity and excessive time dispersion are unlikely. Nevertheless, in cases where mobile velocity and time dispersion exceed Edge capabilities, GMSK modulation can be used instead.

Edge in GSM systems

Impact on GSM network architecture

An increase in bit rates puts new requirements on GSM network architecture. Nonetheless, the introduction of Edge has very limited impact on the core network, and because the GPRS nodes, SGSNs, and gateway GPRS support nodes (GGSN) are more or less independent of user data rates, no new hardware is required.

An apparent bottleneck is the A-bis interface (Figure 3), which currently supports up to 16 kbit/s per traffic channel and time slot. With Edge, the bit rate per traffic channel will approach or exceed 64 kbit/s, which makes it necessary to allocate multiple A-bis slots to each traffic channel. Alternative packet-based solutions can also be discussed.[15] However, the 16 kbit/s limit will be exceeded by the introduction of the two GPRS coding schemes (CS3 and CS4), which have a maximum bit rate of 22.8 kbit/s per traffic channel. This problem is being resolved outside the realm of Edge standardization.

For GPRS-based packet-data services, other nodes and interfaces are already capable of handling higher bit rates per time slot. For circuit-switched services, the A-interface can handle 64 kbit/s per user. Therefore, modifications in the MSC will only affect software.

Radio-network planning

An important prerequisite (and to a large extent, one that will determine the success of Edge) is that network operators should be able to introduce Edge gradually. The initial deployment of Edge-capable transceivers will supplement standard GSM transceivers in a subset of cells where Edge coverage is desired. An integrated mixture of circuit-switched, GPRS and Edge users will thus coexist in the same frequency band. To minimize operator efforts and costs, Edge-related implementation must not require extensive modification of the radio-network plan (including cell planning, frequency planning, the setting of power levels and other cell parameters).

Coverage planning

One characteristic of non-transparent radio-link protocols (for example, protocols that include *automatic repeat request*, ARQ) is that poor radio-link quality only results in a lower bit rate. Unlike speech traffic, a low carrier-to-noise ratio does not cause data sessions to be dropped, but only temporarily reduces user bit rates. Since there is an inherent distribution of carrier interference among users in a GSM cell, an Edge cell simultaneously includes users with different bit rates. Bit rates are higher near the center of the cell, whereas near the cell border, bit rates are limited to that of standard GPRS.

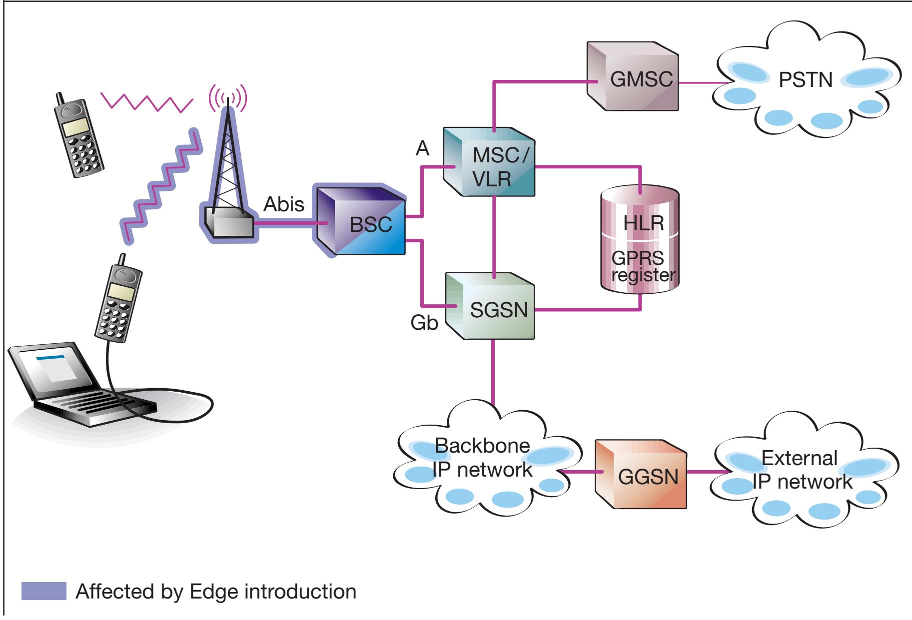
According to test results submitted to standardization bodies, the bit rate per time slot in a system with 95% speech coverage exceeds 45 kbit/s for 30% of the users, and the mean bit rate is 34 kbit/s.[16] Given an APD of 2 dB, the mean bit rate is reduced to 30 kbit/s.

In summary as regards coverage, existing GSM sites provide sufficient coverage for Edge, given that the network operator accepts standard GPRS bit rates at cell borders. For transparent data services, which typically require a constant bit rate, link adaptation must be used to allocate the number of time slots that fulfills requirements for bit rates and bit error ratio (BER).

Frequency planning

Today, the average frequency reuse factor of most mature GSM networks is between 9 and 12. However, we are seeing a trend toward tighter reuse. Indeed, with the introduction of frequency hopping, multiple-reuse patterns (MRP) and discontinuous

Figure 3
GSM network architecture.



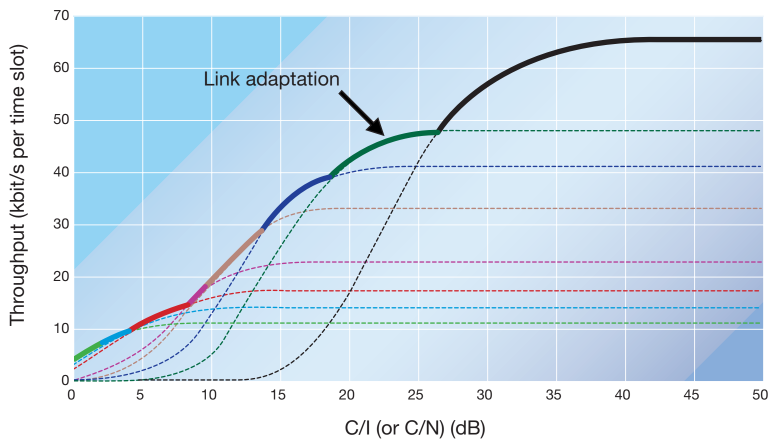


Figure 4
Principle of link adaptation: based on measurements of link quality, it is possible to select the modulation and coding scheme that yield the highest data rate.

transmission (DTX), a reuse factor as low as three becomes feasible.[17] A frequency reuse factor of three implies that each frequency is reused every third base station.

Edge supports this trend. In fact, thanks to link-adaptation techniques, Edge can be introduced into an arbitrary frequency plan, thereby benefiting from a high carrier-to-interference ratio (C/I) near base stations. In summary, we see that Edge can be introduced into an existing GSM frequency plan, and that doing so provides support for future, high-capacity solutions.

Channel management

After Edge has been introduced, a cell will typically include two types of transceiver: standard GSM transceivers and Edge transceivers. Each physical channel (time slot) 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. GPRS packet data;
3. circuit-switched data, enhanced circuit-switched data (ECSD), and GSM speech;
4. Edge packet data (EGPRS), which allows a mix of GPRS and EGPRS users simultaneously.

While standard GSM transceivers only support channel types 1 and 2, Edge transceivers support all four channel types. Physical channels are dynamically defined according to terminal capabilities and needs in the cell. For example, if several speech users are active, the number of type-1 channels is increased, at the expense of GPRS and Edge channels. Obviously, channel management must be automated, to avoid the splitting of channels into static groups. Otherwise, trunking efficiency would diminish.

Link adaptation

The dynamic selection of modulation and coding scheme to suit radio link quality is referred to as *link adaptation*. The Edge standard supports a dynamic-selection algorithm that includes

- the measurement of, and reports on, downlink quality;
- a means of ordering new modulation and coding for the uplink.

Link adaptation is meant to be fully automated; that is, it will not require the network operator to do any addition planning (Figure 4). Possibilities of enhancing ARQ performance through incremental redundancy (Hybrid II/III ARQ[18]) are also under investigation; for example, as proposed for TDMA/136. A scheme of this kind could reduce the need to use link adaptation when selecting modulation. Similarly, the ARQ scheme might be enhanced to handle the "selection" of channel coding. Link adaptation, incremental redundancy and combinations of the two are commonly referred to as *link quality control*.

Power control

Current GSM systems use dynamic power control to increase equity in the system and to extend the life of batteries in mobile terminals. Similar strategies will be employed for GPRS, although the actual signaling procedure will be different.[2] Edge support for power control is anticipated to be more or less identical to that of GSM/GPRS. Thus, network operators will still only be able to affect parameter settings. But because Edge users can benefit from a much higher carrier-to-interference ratio than standard GSM users, Edge power-control parameters will be different.

Edge in TDMA/136 systems

136HS requirements

Some of the requirements imposed on 136HS include considerations that exceed 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 macrocellular performance at high mobile-terminal velocity. In particular, initial macrocellular 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. The spectral efficiency of 136HS should be at least 0.45 bit/s/Hz/site. 136HS should also be able to coexist with second-generation systems in the same spectrum but without degrading their performance.

System architecture

The very introduction of packet-switched GPRS services over the 136+ air interface puts new requirements on the network architecture of TDMA/136 systems. The introduction of Edge in 136HS, however, requires only minor additional changes. Figure 5 shows a schematic drawing of a TDMA/136 system in which GPRS has been introduced to support packet-switched services. TDMA/136 circuit-switched services and GPRS packet-switched services over 136+ or 136HS air interfaces are supported from the same base station. This means that operators can efficiently reuse existing infrastructure.

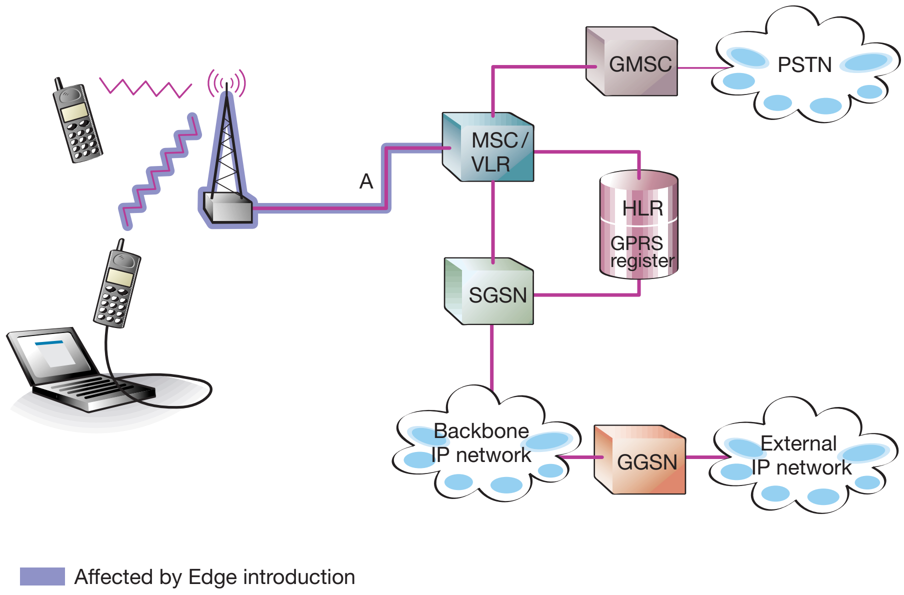


Figure 5
TDMA/136 network architecture.

Coverage planning

To be introduced into current cell plans and use existing base stations, 136HS must provide the same or better coverage as TDMA/136 and 136+. EGPRS with link quality control satisfies this requirement, providing coverage that is at least as good as TDMA/136. Thanks to link quality control, poor radio-link quality does not cause cells to be dropped, but only reduces the user bit rate.

Frequency planning

To meet the requirements for deploying 136HS within 1 MHz of spectrum (initial deployment), it has been proposed that EGPRS be deployed using a 1/3 frequency reuse pattern. Thanks to link quality control, EGPRS can be introduced in a tight frequency plan and still provide high data rates for packet data services.

For example, by means of fractional loading, a 1/3 frequency reuse pattern can offer a C/I that is sufficient for an average system data rate of 384 kbit/s. Based on studies of EGPRS performance from a 1/3 frequency reuse pattern[8, 9] and on simulation results, we conclude that EGPRS and 136HS provide good packet-data performance, thereby allowing for an initial deployment in less than 1 MHz of spectrum.

Control channel aspects

Given a 1/3 frequency reuse pattern and fractional loading in 136HS, Edge carriers cannot transmit continuously at constant power. Therefore, the cell that is most suitable for service cannot be determined using the standard GSM/GPRS procedure of measuring signal strength on the GSM carrier that transmits the broadcast control channel. Instead, to select and reselect cells, 136HS will measure signal strength on the TDMA/136 digital control channel (DCCH). However, all packet channels—that is, traffic and control channels—can be transmitted on the Edge carrier. This arrangement permits tight frequency reuse planning and facilitates a natural integration into existing TDMA/136 systems.

Edge/EGPRS radio-network performance

Simulation models

To analyze the system performance of the EGPRS concept, designers simulate system-level cases. In particular, they study interference-limited and coverage-limited systems. By interference-limited we mean that co-channel interference completely dominates over thermal noise; by coverage-limited we mean non-co-channel interference. Different models are used for simulating and studying each case. Designers also study different scenarios for introducing Edge into GSM and TDMA/136 systems.

General cellular network modeling

The simulation environment includes a regular cellular layout that consists of several equally sized, three-sector macrocells. Standard nine- and three-sector frequency reuse patterns are used for the GSM and TDMA/136 scenarios, respectively. In each case, one carrier, comprising eight time slots, is available in each sector. In the GSM scenario, this corresponds to a total of nine carriers; for TDMA/136, three carriers. Distance attenuation is calculated as follows:

$$L = C + 35 \cdot log(d),$$

where L is loss in dB, C is a constant, and d is distance.

We assume log-normal fading (shadow fading) with a standard deviation of 6 dB. Apart from 3 dB uncertainty, due to the handover margin, cell selection is based on least-path loss. Antenna diversity is not considered. Since Internet traffic is believed to be highly asymmetrical, only the downlink is studied. Link-level results from a previous study are used.[9] In the TDMA/136 scenario, the link-level results do not include frequency hopping, whereas in the case of GSM, ideal frequency hopping has been assumed. Frequency hopping is not explicitly modeled at the system level. The combination of link-level results and frequency hopping corresponds to a form of cyclic frequency hopping, which does not yield interference diversity.

Capacity simulations in interference-limited systems

The capacity simulations are dynamic and several mobile terminals are studied over time. During the simulation, they enter and exit the system. Similarly, in each phase or time-step of the simulation, various terminals are likely to become active and begin transmitting a packet of random size. The position or location of the terminals remains fixed throughout the simulation; that is, mobility is not modeled.

The carrier-to-interference ratio is calculated for each active link in each time-step (20 ms), which corresponds to the duration of a radio link control (RLC) block. In order to determine whether or not RLC blocks are transmitted successfully, block errors—based on C/I, modulation and the coding scheme—are generated for each block and user. Erroneous RLC blocks are retransmitted. This procedure, together with basing a traffic model on measured data, results in very accurate modeling of bursty interference in packet-data systems.

Modeling Internet traffic

The simulated traffic model was derived from a measurement-based model of WWW-traffic model that has been slightly modified to generate shorter packets—in order to produce bursty interference.[19]

Users enter the system according to a Poisson process, in which the arrival rate is a parameter for varying load. Users in the system transmit a geometrically distributed number of packets, of which the mean is 10 packets. The lapse of time between the generation of packets by different users is Pareto-distributed with a mean of 10 s (the Pareto-shape parameter is 1.4). Packet sizes are generated from a log-normal distribution with a mean of 4.1 kbytes, and a standard deviation of 30 kbytes. An extra 50 bytes are added to the generated packet sizes in order to model a minimum packet size that corresponds to Internet protocol (IP) and transmission control protocol (TCP) headers. Furthermore, the distribution is truncated at 100 kbytes, to limit simulation times, but also because mobile users are not likely to request very large files.

Modeling link adaptation

Users in the system regularly select the modulation and coding scheme to ensure the maximum packet bit rate. The time interval between selections is referred to as an *update interval*. In simulations, the update interval is set at 10 RLC blocks, or 200 ms. The C/I used for the selection is the value calculated for the last RLC block sent in the most recent update interval. In combination with link adaptation, EGPRS will also sup-

BOX B, EQUATIONS

Equation 1

$$\Delta E_b = \frac{R_{GSM}}{R_{Edge}} = \frac{271}{3 \cdot 271} = -4.8 dB\ GSM$$

Equation 2

$$\Delta E_b = \frac{R_{TDMA/136}}{R_{Edge}} = \frac{48.6}{3 \cdot 271} = -12 dB\ TDMA/136$$

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

Equation 3

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

port the use of incremental redundancy, although this feature is not included in simulations. Incremental redundancy is expected to improve system-level results by 20 to 30%.

Admission control, scheduling and dropping user sessions

No admission control algorithm is used in the simulations. Instead, every user that generates packets is allocated resources or queued. Scheduling is managed in a packet-based, first-in, first-out (FIFO) fashion. User sessions with poor link quality are dropped according to a leaky-bucket algorithm: each user's counter is initially set at its maximum value of 32. A negatively acknowledged block (NACK) decreases the counter by one, whereas each acknowledged block (ACK) increases it by two. If the counter reaches zero, the session is dropped. The drop rate is less than 1%, even at maximum load. More sophisticated algorithms are expected to improve system performance.

Coverage simulations in noise-limited systems

Where coverage is limited, performance is independent of interference or traffic dynamics. Therefore a static simulation technique can be used. Snapshots are taken of the system, in which stationary mobile terminals are placed randomly according to a uniform distribution. GSM and TDMA/136 systems with 95% speech coverage are used as a reference, to determine what coverage can be achieved from Edge in existing cell plans. Edge performance is then analyzed assuming the same carrier output power as was recorded in these reference systems. For GSM, assuming a full-rate speech coder, speech coverage requires a signal-to-noise ratio (E_b/N_0) of 6 dB; for TDMA/136, the requirement is 15.7 dB. These are the values found at the 5th percentile of the E_b/N_0 distributions in the cell. When 8-PSK is introduced (the Edge modulation scheme), the E_b/N_0 distributions are lower, due to the higher gross bit rate. Therefore, assuming the same carrier output power, we can calculate the difference in E_b/N_0 for Edge, compared to standard GSM and TDMA/136 modulations (Box B, Equations 1 and 2).

Measuring performance

Unlike circuit-switched systems, packet-data systems have no fixed capacity limitations; that is, packets that cannot be transmitted immediately are queued until resources become available. When the load exceeds acceptable limits, more and more packets are queued, until system delay becomes intolerable.

Thus, to correctly measure the performance of cellular packet-data systems, we must study not only spectral efficiency *per se* but also the spectral efficiency that can be achieved for maximum levels of delay. Nonetheless, the absolute maximum delay that can be accepted by a user is difficult to define. For example, because they take longer to transmit, long packets are more likely to exceed an absolute limit than short packets—even without queuing and retransmission. Even so, some recipients are certain to be satisfied at having received large amounts of data, despite higher absolute delays. This line of reasoning leads to the introduction of a measure of *normalized delay*. Further, assuming that the acceptable delay can be doubled for packets that are twice the size of ordinary packets, tripled for packets thrice the size, and so on, then we can project the normalization in a linear fashion by dividing absolute delay by the size of the packet. We thus define the measurement of normalized delay as being the *total absolute delay (queuing time plus transmission time) divided by packet size in kbits.* Note: The normalized packet delay is the inverse of the bit rate measured per packet. Accordingly, the maximum acceptable normalized delay for a packet corresponds to the minimum acceptable bit rate for that packet. In summary, this line of reasoning leads to a performance measure that shows the *spectral efficiency that can be achieved for a given maximum normalized delay requirement*.

This measurement, however, does not indicate how fair the system is to its users. To determine fairness, we measure the average packet bit rate per user 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*.

Simulation results

Capacity, GSM scenario

Beginning with GSM, Figure 6 shows the distribution of normalized delay among transmitted packets at different loads. Load is measured in terms of average number of users per sector. As expected, delay increases as load increases. Different loads also result in different levels of spectral efficiency.

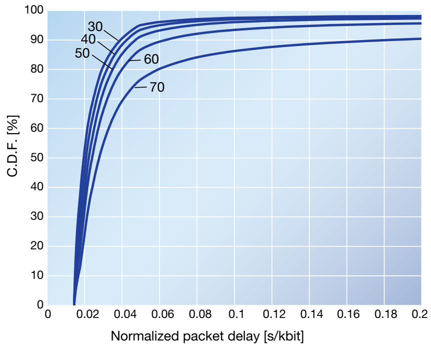
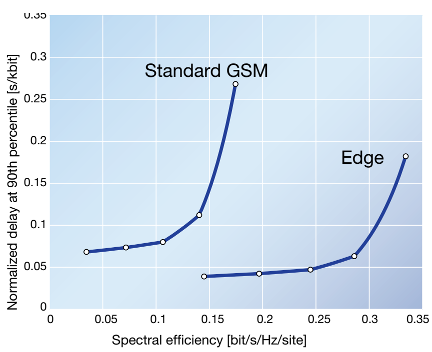


Figure 6
Distribution of normalized delay for different numbers of users per sector, Edge/GSM case.

Figure 7
Spectral efficiency versus normalized delay, Edge/GSM and standard GSM. The average number of users per sector is given for each simulated value.



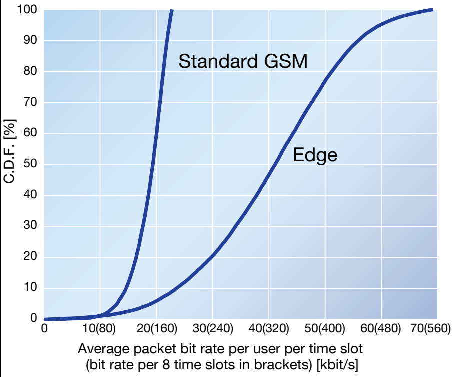


Figure 8
Distributed average packet bit rate per user for Edge: 60 users per sector (0.28 bits/Hz/site), compared to standard GSM with 27 users per sector (0.11 bits/Hz/site).

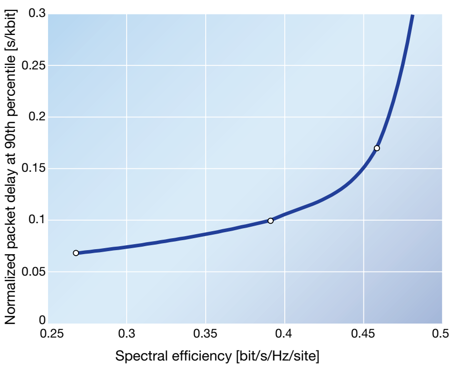


Figure 9
Spectral efficiency versus normalized delay, Edge/TDMA/136. The average number of users per sector is given for each simulated value.

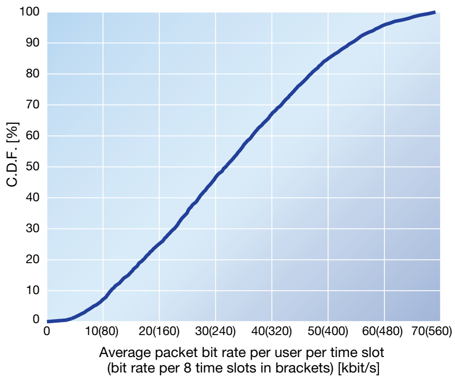


Figure 10
Distributed average packet bit rate per user: 32 users per sector (0.46 bits/Hz/site), Edge/TDMA/136.

Figure 7 shows the spectral efficiencies achieved for the same loads (as in Figure 6) when plotted against the 90th percentile of normalized delay (90% of the packets having a total delay of less than 0.15 s per kbit). Standard GSM is also compared. Note: The spectral efficiency for the same maximum delay is more than doubled. Assuming maximum delay of 0.15 s per kbit at the 90th percentile, Edge offers a spectral efficiency of 0.33 bit/s/Hz/site.

As mentioned previously, the measure of spectral efficiency says nothing about how fairly data rates are distributed among users in the system. To investigate system fairness, we measure the distribution of average packet bit rate. Figure 8 shows the distribution of average packet bit rate per user (one or eight time slots). The loads resulted in normalized delays just under 0.15 s per kbit. Note also the significant increase in the packet bit rate when Edge was introduced. At the studied load level, when eight time slots were used, we see that approximately 30% of the users obtained a packet bit rate exceeding 384 kbit/s, and that 97% of the users obtained a packet bit rate exceeding 144 kbit/s.

Capacity, TDMA scenario

The same analysis is repeated for TDMA/136. From Figure 9 we see that normalized delay at the 90th percentile is a function of the spectral efficiencies reached for different loads. We see further that very high spectral efficiency can be achieved. The forward error correction and ARQ schemes efficiently handle the high interference levels caused by a tight 1/3 frequency reuse pattern. In fact, spectral efficiencies achieved from the 1/3 reuse pattern are higher than those from the 3/9 reuse pattern.

Assuming a maximum delay requirement of 0.15 s per kbit at the 90th percentile, we can obtain a spectral efficiency of 0.46 bits/Hz/site. Fairness among users is shown in Figure 10. When eight time slots are used, approximately 20% of the users obtain a packet bit rate that exceeds 384 kbit/s, and 80% obtain a packet bit rate exceeding 144 kbit/s. The offered load corresponds to a normalized delay just under 0.15 s/kbit.

Coverage simulations

The coverage simulations gave E_b/N_0 distributions for both GSM and TDMA/136 scenarios. From the original E_b/N_0 distributions we can calculate the 8-PSK distributions (Box B, Equations 1 and 2). From link-level simulations, we know the block error-rate performance of different modulation and coding schemes. With this information, we can transform the E_b/N_0 distribution into packet bit rate distribution (Box B, Equation 3) and—assuming ideal link adaptation—map the E_b/N_0 values to the highest achievable packet bit rate.

Figure 11 shows the distribution of packet bit rate coverage for GSM. It also compares standard GPRS. As can be seen, all users obtain higher packet bit rates from Edge. Thus, existing cell plans can be reused when Edge is introduced. When eight time slots are used, approximately 75% of the users obtain a packet bit rate that exceeds 144 kbit/s, whereas for 22% of the users the packet bit rate exceeds 384 kbit/s. Even better coverage is achieved from TDMA/136 (not shown). This is due to the signal-to-noise requirement for speech coverage. When eight time slots are used, approximately 78% of the users obtain a packet bit rate exceeding 144 kbit/s, whereas for 25% of the users the data bit rate exceeds 384 kbit/s. Here too, existing sites can be reused. Still better coverage can be achieved from smart antennas or by applying simple antenna-diversity techniques.

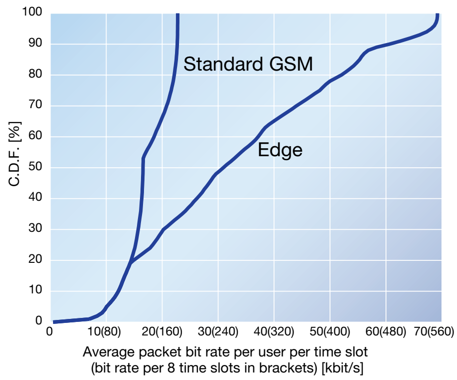


Figure 11
Distributed average packet bit rate per user: coverage-limited Edge-GSM and standard GSM.

Conclusion

Operators who introduce Edge into GSM and TDMA/136 systems can efficiently reuse existing infrastructure:

- Edge increases GSM data rates to 384 kbits/s.
- The introduction need not affect operator coverage and frequency plans.
- Because Edge-capable physical channels may be used for standard GSM services, fixed channel allocation between services is not needed. Thus, from an operator's point of view, Edge services may be introduced in a smooth fashion.
- The results of simulated packet-data performance indicate that Edge enables significantly higher peak rates and approximately triples the spectral efficiency associated with standard GSM and TDMA/136.
- Edge increases packet bit-rate coverage, which means that operators of GSM or TDMA/136 systems can reuse existing sites. Edge achieves good spectral efficiency using only a limited amount of spectrum.

Edge serves as an enabler of forthcoming wideband services in GSM and TDMA/136.

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