Is GSM-R the limiting factor for the ERTMS system capacity?

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Abstract
The European Rail Traffic Management System, ERTMS, is introduced as a common signalling system for the European railway network. ERTMS consist of two main parts, the signalling part ETCS and the radio transmission system GSM-R, based on the well-established GSM standard.

The question to be answered in this thesis is if the capacity of GSM-R is limiting the ETCS part in any way. If that is the fact, how can the limitations be overcome?

Looking forward, will public mobile system with high transmission capacity like GPRS, LTE etc influence GSM-R? GSM-R year 2020: how will it look?

The thesis describes the basic functions of ETCS and GSM-R, and the way they are interconnected.

The study shows that the capacity of GSM-R is sufficient for signalling on the line, even for high speed traffic. Problems occur with a high density of GSM-R users in a limited area, for example at large stations and marshalling yards. Also the combination of a station, with many but slowly moving units, and a main line, with few but fast moving units, passing through the same area can cause problems. The thesis describes various ways to solve this issue. Right now these problems are solved with advanced cell-planning and the use of lower level implementation of ERTMS, not depend on GSM-R. In the longer run the main solution is to introduce higher capacity packet-switched solutions like GPRS.

An even greater problem at the moment is that public mobile operators providing high-speed data services in the near-by frequency bands interfere with GSM-R. The solution to this problem is presented as well as the problems the solution itself is causing.

In the long term perspective ERTMS will depend more and more on reliable data communication by radio and packet-switched high speed radio solutions, which will definitely be a part of ERTMS.

To address the question raised in the thesis title: is GSM-R the limiting factor for the ERTMS system capacity?

NO, considering the actions taken and the sometimes unconventional solutions used based on engineering expertise and creativity, GSM-R is not the limiting factor in ERTMS right now.

YES, in the long run and with broader usage of ERTMS, GSM-R has to have a higher capacity, more functionality and be a more standardized system: more “plug&play” than “plug&pray”.

Front page picture by Per Olofsson.
Sammanfattning


Frågan som skall besvaras i denna uppsats är om GSM-R:s kapacitet begränsar ETCS-delen i något avseende. Om detta är fallet, hur kan man i så fall hantera dessa begränsningar.

I framtiden, hur kommer mobilsystem med hög transmissionskapacitet som GPRS, LTE etc påverka GSM-R? GSM-R år 2020, hur kommer det utformas?

Basfunktionerna hos ETCS och GSM-R, samt hur dessa samverkar beskrivs i uppsatsen.


På längre sikt så kommer ERTMS vara mer och mer beroende av tillförlitlig datakommunikation och paketkopplade radiolösningar är då en del av ERTMS.

Svaret på frågan som ställs i uppsatsens titel, om GSM-R:s kapacitet begränsar ETCS-delen är:

NEJ, tack vare de åtgärder som vidtagits och de i vissa avseende okonventionella lösningar som baseras på ingenjörsämässig expertis och kreativitet används är inte GSM-R någon begränsning.

JA, på längre sikt och med en utvecklad användning av ERTMS så behöver GSM-R ha högre kapacitet, mer funktionalitet och vara ett mer standardiserat system.
1. Objective for the master thesis

This thesis is performed as a part of a master degree at the School of Architecture and the Built Environment at the Royal Institute of Technology (KTH) in Stockholm. The thesis gives 30 academic credits of the 120 in a Master exam.

The thesis shall seek answers to the following questions:

- Is the present version of GSM-R limiting the capacity of the ERTMS system?
- If that is the case, how to improve GSM-R so it is not the limiting factor?
- Will new generations of mobile telecom systems, like GPRS, LTE etc, influence GSM-R in the future?
- GSM-R year 2020: what will be the requirements and functionality?

2. Background

The European Rail Traffic Management System, ERTMS, is introduced as a common signalling system for the European railway network.

ERTMS consist of two main parts: the signalling part ETCS and the radio transmission system GSM-R, based on the well-established GSM standard. The railway signalling industry has focused on the development of ETCS, and seems to consider the GSM-R part as a de facto standard, not possible or needed to develop further.

Parallel to that, there is an active, not to say intense, development on-going in the telecommunication industry. New network systems and standards are introduced for more advanced voice and data services. Especially for data services 3G-systems and descendants systems like LTE have the potential for very advanced ITC solutions.

The intention with this master thesis is to examine the capacity limits of the present GSM-R standard and when there is a need for a replacement. Also to draw a picture in what way new capacity can improve the ERTMS system and the railway system in general.

3. Work-plan and methodology

3.1 Outline of project and thesis

The main structure of the work and the resulting thesis is described below.

The Pre-study contained general set-up of the thesis work, collection and reading of basic material and reviewing of objectives. The result is to be found in chapters 1 to 4.

Systems overview is general description of ETCS and GSM-R, with a focus on the two sub-systems interconnection. The descriptions are in chapter 5.

Capacity is studied and various aspects of it. Train traffic capacity of the combined system as well as limiting factors of GSM-R. Chapter 6 and 7.
The handling of capacity limiting factors of the GSM-R system today and how they are handled in the sort and medium term perspective. Chapter 8.

Future improvements of ERTMS. Planned and discussed improvements of ERTMS as well as of the two subsystem, and the influence of these on GSM-R. Chapter 9.

Conclusions. Analysis and conclusions of findings. As a summary, the questions set in Chapter 1 Objective will be answered. Chapter 10 and 11.

3.2 Used methodology
The idea for this thesis has been developed in close cooperation with the Radio department of Trafikverket, the Swedish Transport Administration. The main sponsor for the thesis at Trafikverket has been Jonas Lindh; without his support and knowledge this thesis would have been impossible to fulfil. Supervisor at KTH has been Anders Lindahl, also a valuable support and tutor for this assignment.

Literature will be the main source of information. As the intention is that ERTMS shall be a highly standardised system for common and to a large extent mandatory use within Europe, a standard and recommendation document is available, as well as documents describing the implementation of the system. Papers and presentation slides from conferences and meetings are also a source to be used for describing the present status and problems occurring.

To clarify issues not or only vaguely covered in the literature, discussions with experts in the matter, mostly from Trafikverket, have been an important source of information.

The information collected will be analysed regarding limiting factors, how they are mitigated today and in the longer term.

Conclusions will be drawn if the GSM-R system is the limiting factor today and in the longer terms. Also a suggestion for a future (year 2020) GSM-R or its successors system will be made.

The study will focus on the GSM-R part of the ERTMS system and its interworking with ETCS. Only when needed for the understanding of GSM-R the ETCS system will be discussed. The usage of GSM-R as an information carrier for purposes other than ETCS will only be dealt with regarding the year 2020 GSM-R.
4. History of ERTMS

Already back in 1957 the first European transport policy was rather vague aiming at a non-discriminatory access for operators to infrastructure. Not very much happened until the 91/440 Directive which included the requirement for separation of the infrastructure and the operations of the rail traffic. In 1993 the European Commission started to give high priority to the Trans-European transport network with important priority to rail projects. Considering the present situation at that time with a variety of signalling systems, power systems, loading profiles etc, there was a strong need for among other things a common signalling system. The initial studies for a common signalling system began 1989 and in April 2000 the ERTMS mandatory specification was handed over to the European commission.

![Functional structure of ERTMS and associated European activities](http://www.uic.org/IMG/pdf/session-b.pdf)

In figure 1 the structure of the European Railway Traffic Management System, ERTMS, is shown. A definition of what ERTMS is to be found in the UIC Compendium on ETCS [A]. ERTMS “is made up of all the train-borne, trackside and lineside equipment that is necessary for supervising and controlling, in real-time, the train operation according to the traffic conditions based on the appropriate Level of Application.” This document will focus on the ETCS and the GSM-R part and their interworking. Even if not covered in this document, both ETCS and GSM-R can be used to utilise the other parts (Europtirails and INESS) of the ERTMS concept.

ETCS, European Train Control System is a subset of ERTMS and shall provide a level of protection against overspeed and overrun depending upon capability of the lineside infrastructure. The development started as mentioned before 1989 and in November 2003 the commercial application of ETCS level\(^1\) in Switzerland ended its tests and was open for normal operation. Before that, pilot applications were done on various test sites, for example:

- Germany, Berlin – Halle – Leipzig 154 km, level 1 and 2
- Italy, Firenze – Arezzo 70 km, level 2
- Spain, Albacete – Villar de Chinchilla, 38 km, level 1 and 2
- The Netherlands, Maastricht – Heerlen and Leewarden – Meppel, level 1 and 2

\(^1\) The concept of levels in ETCS is described in chapter 5.
Europtirails objective is to deliver real-time information about cross border trains running in international traffic. The system provides information about train location, timetable, delays, reason for delays and estimated time of arrival. The system is implemented on the European continent but not yet in Scandinavia.

Integrated European Signalling System, INESS, aims at defining and develops specifications and hardware for a new generation of interlocking systems that shall work together with ETCS and GSM-R. The project will build on harmonized national operational requirements already existing, and has presented its results in February 2012. The project has so far resulted in many important reports, among them INESS specifications that shall be enforced as a norm and later as a TSI, Technical Specification for Interoperability. UIC will also use the specifications as an input in a follow-up project to build an INESS interlocking functional prototype.

GSM-R is based on the GSM standard for mobile telecommunication with added railway specific functionality. It is operating on designated frequencies in the 900 MHz band. It acts as a general railway radio system as well as transmission media for ETCS signal information.

In the years 1985 to 1989 the UIC radio frequency group acted to reserve specific spectrum for railway use. It was also discussed which of the (at that time) available radio systems, GSM or TETRA, that should be most suitable. TETRA is designed for closed user groups and designed to be suitable for “blue-light organisations”, like police, military, fire-brigade and other types of rescue and supervising authorities. GSM was chosen as the basis for GSM-R as it was at the time the only commercially available system, already proven, intended for public use and with products that could be used with a minimum of modifications.

GSM-R was first introduced as a replacement of older, mainly analogue, mobile voice communication systems, with not only the features of the standard GSM system but also with railway specific features. It was intended for communication between the staff on the train, with traffic management and operational centres, with staff dealing with shunting, maintenance, repair etc, and as a services telephone for staff and passengers on stations or on the line. The specific voice features are:

- Functional addressing – get in contact with the staff on a specific train only by dialling the train number
- Local dependant addressing – the train driver gets direct contact with the train controller responsible for the area the train is passing through
- Voice group call service – the train controller can reach all trains in the area he is responsible for
- Railway emergency call, REC – makes the train driver able to warn the train controller as well as all other trains at close range for an upcoming hazard as the radios automatically take the call
- Priority of calls - When an emergency or voice group call is established, they have priority over other calls with lower priority. The call set up time for a call with priority is < 2 seconds.

For non-voice services the main data application is the data transmission of ETCS signalling messages, the focus of this thesis. But also other data formats like SMS and GPRS are used for the support of various processes. Examples are:
• Activation and control of objects like switch-points and level crossings
• Control of passenger information devices in stations and on trains

As an example the Swedish GSM-R system “MobiSIR” run by Trafikverket started operation of the system in June 2000. As of spring 2011 [1] the number of users is 7,000 that exchange 400,000 voice calls per month, whereof 40,000 are to trains and 90,000 are to the train operation centre. The number of ETCS data calls is still very limited, only 1,500 per month, due to the still limited use of higher level ETCS systems.
5. System overview

5.1 ETCS levels

The ETCS system is defined in different levels. Each level has as specified functionality and requirements that must be met to offer the defined safety associated with that level.

**Level 0**

![Figure 2. ETCS level 0](image)

- Non-ETCS equipped lines
- No ETCS wayside equipment
- Movement Authority\(^2\), MA, from optical signals

This covers ETCS equipped trains running on unequipped lines. Full ETCS train data has to be entered for two reasons: to support the few ETCS functionalities that run on level 0 (train speed, supervision of maximum speed) and not having to stop when entering higher level areas.

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\(^2\) Movement Authority = Permission for a train to run to a specific location within the constraints of the infrastructure, i.e. to pass a signal.
**Level STM**

![Diagram of ETCS level STM](image)

**Figure 3. ETCS level STM**

- ETCS equipment onboard
- No ETCS wayside equipment
- STM reads information from existing wayside equipment
- Nationally equipped train with no ETSC onboard may also operate the line
- Simplifies migration to full ETCS

This level is used for ETCS equipped trains that with a STM, Specific Transmission Module, can convert the signals from the national transmission system. A separate STM has to be designed for each national legacy system, and the level of supervision is dependent on the underlying national system. As for level 0 full ETCS train data has to be entered and Eurobalises must be read to enter higher level areas without having to stop.
• Movement Authority and speed profile from controlled Eurobalises
• Full ATP supervision
• Train detection by track circuits or axle counters
• Fixed block signalling
• Enhancement of existing signalling system

In Level 1 the track-side occupancy detection equipment as well as the line-side signalling is kept. The signalling to the ETCS equipment on-board the train is done with Eurobalises. Level 1 can to a large extent be compared with existing systems like the Swedish ATC 2, but using the ETCS concept and equipment instead.
Infill functionality added
Realised by Euroloops, radio or balises

The infill functionality improves the line capacity by providing the on-board ETCS equipment with “infill”, that is updated information about the status of the signal ahead. A distant signal is set to “stop”, and the train has started reducing speed so as not to pass it. If the distant signal turns to “go” before the train has reached it, the infill functionality updates the on-board ETCS equipment with that information, and the train retains its normal speed. This functionality can be implemented in different ways, and using GSM-R is one option. By 2009 the GSM-R solutions was still at prototype level.
In level 2 the dynamic signalling information towards the train is done via GSM-R. Static signalling is done by fixed Eurobalises, mainly reference information for distance calculations, odometry, and some static infrastructure information. The train detection system like track circuits are kept for train integrity reasons among others.
Level 3

As level 2, except

- Train integrity by on-board equipment
- Train detection by reports from on-board ATP
- Track circuits or axle counters not required
- Moving block signalling is possible

Level 3 reduces the line-side equipment to Eurobalises, mainly used for updating the odometry. As train integrity is no longer possible to check by track circuits or axle counters, the train must have on-board equipment to ensure that. As moving block signalling is introduced, level 3 can increase the capacity of the line.

ERTMS Regional

As level 3, except

- No dynamic coded balises
- No automatic train integrity check
- Fixed block
- Reduced speed

The regional version of level 3 is intended for low traffic lines. The intention was to have a system at 50% of the cost of a conventional CTC system, an objective that also was reached. The cost for introducing and maintaining this level is low as a minimum of line-side equipment is used, and transmission is done by GSM-R and GPRS for the line-side. The main difference towards level 3 is that fixed block is used and there is no requirement on automatic integrity check. Instead, this is the
responsibility of the driver, and it also introduces restrictions in the way the running train is allowed to proceed. The maximum speed is a trade-off between capacity and security, but is normally limited to 120 – 140 km/h.

**Level compatibility**

The levels are downwards compatible; a level 3 equipped train can run on level 2 and 1 equipped infrastructure, and a level 2 train on a level 1 infrastructure.

**GSM-R usage**

For the ETCS functionality GSM-R is used for levels higher than level 1, starting with level 1 with infill option based on GSM-R. The lower levels can of course use GSM-R as a mobile radio system with railway specific functionality without the connection to ETCS.
5.2 ERTMS System overview

The function of the three parts of the ERTMS system that is in the focus of this thesis is as follos:

- **ETCS wayside (track side)** – Functionality to provide a safe path for a specific train. The static parts of ETCS, control of signals and other wayside equipment like balises, track circuits, axel-counters, euroloops etc. Interface towards interlocking and control centres as well as GSM-R via the RBC.

- **GSM-R** – The voice and data communication functions for driver calls, operation and data communication. Interfaces the RBC in ETCS wayside, controls the mobile radio traffic, distributes it to the out-placed radio transmission equipment and via the air-gap and the receiving antenna interfaces the ETCS on-board system. Acts as the train radio with the same services as a public GSM. GSM-R is also used for the communication of non-ETCS information, and is therefore connected to other systems than ETCS.

- **ETCS on-board** – Functionality for running a train in a safe way. Controls the movement of the train, displays information to the driver, collects information from balises, euroloops, odometers, and communicates via GSM-R.

The functionality of the different parts is described in more details in the “Functionality Requirements Specification”, FRS [3], as well as in the “Technical Specification for Interoperability” TSI. These are the formal documents and are continuously supervised and updated. They are to be found at the UIC website. A good description of the system is also to be found in the “Compendium on ERTMS” [A ].
5.3 The interconnection between ETCS and GSM-R

5.3.1 Used transmission media

The connection chain from the fixed part of ETCS to the on board system of ETCS is shown in figure 9. Please note that we are focusing on the connection via GSM-R, and not considering the balise or Euroloops link!

![Figure 9 ERTMS transmission from fixed ETCS part to the on board system.](image)

The interface between the fixed part of ETCS is the RBC (Radio Block Centre) and for GSM-R the MSC (Mobile Switching Centre) [4]. This interface is using the protocol ISDN 30B+D that consists of 30 64kb/s B-connections plus a 16kb/s D-channel for signalling purposes. Together this makes up a 2 Mb/s connection. Between the MSC and the more outspread part of the GSM-R system, the BSC (Base Station Controller), two 2Mb/s systems is used for redundancy sake. The same apply for the connection between the BSC and the BTS (Base Transceiver System), but for security reasons the BTS is connected in a loop, always having two possible connections. The transmission media can be opto-fibre cable, coaxial cables or radio links, the latter often used in rural conditions.

To the MSC a second BSC system is connected in figure 9 shown with a dashed line. The BTS of this second BSC is nested with the one of the first BTS. In this way it is possible for the BTS and the connected TRX (Transceiver³) to cover up for a failing BTS and TRX.

The BTS is normally placed close to the TRX in the mast or tower and the internal connection between them is done with suitable media.

³ Transceiver = A transmitter and receiver in the same unit.
In the air-gap 7 channels with 9.6 kb/s bitrate per TRX is used for both ETCS data and speech using a protocol named $U_m$. The antenna connected to the EDOR (EIRENE Data Only Radio) receives the signal then fed into the EVC (European Vital Computer). Both the EDOR and the EVC is part of the on-board ETCS system.

What is characteristic for this system of connections is that the bit-rate capacity is low, because of the low data traffic level that ETCS generates, but the demand on redundancy and reliability is high, higher than for a public GSM system. For more about the Quality of Service requirements see chapter 5.4.

5.3.2 Available frequencies and radio channels

Dedicated frequencies are reserved by CEPT, European Conference of Postal and Telecommunications Administrations, for the use of GSM-R for operational communications by railway companies. For uplink communication 4 MHz is reserved in the 876 – 880 MHz band, and for downlink 4 MHz in the 921 – 925 MHz band. As these frequencies are agreed on a European basis, they allow border crossing and international traffic. The 4 MHz for GSM-R makes 19 frequency channels of 200 kHz each available. One of the frequency channels, $F^{20}$ in the picture, is used as guard band.

![Figure 10. The 19 + 1 200kHz frequency channels in the GSM-R frequency spectrum](image)

On a national basis the frequencies in the extended, E-GSM-R, band can be used. The E-GSM-R band is a 3 MHz slot in uplink 873 – 876 MHz and 918 – 921 MHz downlink. This makes another 15 frequency channels available. This band is not yet used.

Each 200 kHz frequency channel has 8 timeslots available to be used as data or voice channels, whereof one is used as the common control channel for the radio system (this concept is called Common Channel Signalling and is used for the internal control of the radio transmission system), and the remaining 7 are used for voice or data communication. One control channel can be used for two frequency channels, making $7 + 8 = 15$ timeslots/channels available for communication.

To ensure the high levels of Quality of Services (QoS) it is stated that circuit switched connection shall be used for ETCS messages. This means that there is a continuous connection set between the base station and the moving unit, ensuring a high QoS, but it is not a very efficient usage of the connection, as the amount of data exchanged is rather low. It could be described as the radio beam is working as a fictional “cable”!
Instead of circuit switching, packet switching can be used. In this case more than one user shares the same connection and the information transmitted is split up in packages sent each one after another, and only when there is a need for it. This is a more efficient way to use the available media, up to 7 times more efficient than a circuit switched connection. The concept is used in GSM-R for non ETCS data applications with GPRS technology.

Using circuit switching, there is 19 frequencies available. Each frequency contains 7 timeslots for communication, making a total 19 x 7 = 133 channels for communication. If using the concept of one control channel for two frequencies, this makes a total of 142 available. These channels shall be used for both voice and ETCS data communication.

5.3.3 The cellular concept
Mobile cellular networks are built on the concept that the same frequencies are reused again and again on certain geographical distances, this way making the best use of a limited number of frequencies. The area covered is divided into cells, thereof the term cellular network. Each cell is assigned one or more frequencies, and neighbouring cells are assigned different frequencies. In this way it is possible to keep track of in which cell a cellular mobile is situated. As stated before, each frequency can serve 7 mobiles at the same time. In figure 12 a railway line is covered by four cells, here described as rectangles.

All frequencies Fn could be different, but if just the distance is long enough between them, F1 could be equal to F3 and F2 equal to F4. But F1 might not be equal to F2! Theoretically 2 frequencies could cover a line where 7 mobile units each one equipped with a radio could be in a cell at the same time. A typical length of a cell is 5 kilometres, but presently Trafikverket uses up to 8 kilometres.
Larger areas are covered with a pattern of cells forming a cluster. A classic configuration in the mobile business is the hexagon cluster consisting of 7 cells, each cell with a different frequency. In figure 13 each frequency, or set of frequencies, is represented by an individual colour.

![Hexagon Cluster](image)

**Figure 13. The classic hexagon cluster. More clusters, using the same set of frequencies, can be added to cover a large area.**

By using different sorts of sector-antennas, the experienced cell-planner can cover areas very efficiently using the relatively few available frequencies. An extreme variant is the so called “Stockholm model”, first introduced by the Swedish PTT “Televerket” for the use of NMT900 in the city centre of Stockholm with a huge density of mobile phone users.

![Sector Antenna](image)

**Figure 14. Examples of the use of sectored cell cluster. The “Stockholm model” to the right.**

Please notice that these coverage models are just theoretical. Radio waves are not easy to train to stay in hexagons; the success of the cell planning is heavily depending on the skills of very experienced engineers.

### 5.3.4 Moving to another cell

The GSM-R system keeps track of in which cell the individual mobile radio is positioned. The position is stored in the Home Location Register, HLR, a part of the GSM-R system. When a mobile radio is moving from one cell to another, the system performs a hand-over and the HLR is automatically updated. To ensure a continuous and uninterrupted connection, this is done in a hand-over zone where the two cells cover each other. The length of the handover zone is dependent on the time to do a proper handover and the speed of the moving unit. Trafikverket calculates with a maximum time of 9 seconds and 200 km/h which makes a 500 meters zone necessary.

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4 According to a very informal and anonymous source at the headquarters of one of the leading operators in Sweden, this was the reason why this operator did not received a 3G license. “The others pulled in as many base-stations they never could afford just to show that they have enough coverage. Our guys should show that they were the real experts that did know the coverage behind every single blue-berry plant in the whole country. It is a beauty contest, better to be beautiful than smart!”
When the mobile radio enters a cell that belongs to another GSM-R operator, a roaming process takes place. A requirement is that the two different operators, for example Trafikverkets GSM-R and Tele2 public mobile GSM network, have a roaming agreement. When the mobile radio leaves the cell that belongs to Trafikverket’s network, and enter the cell that belongs to the Tele 2 network, the following happens: The HLR of Trafikverket is updated that the mobile radio has left the network, and the Visitor Location Register, VLR, of Tele2 is updated with information about the visiting radio as well as its position. In this way the mobile radio can be used as normal (but the call charge might be different, normally higher!) when not being in its “home” network.

5.4 Quality of Service (QoS) requirements on the GSM-R connection

For acceptable operation on Level 1 infill and higher, the following QoS requirements on the established connection have to be met:

- Transmission interface rate
- Connection establishment failure probability
- Connection loss rate

The QoS requirements are stated in the document GSM-R Interfaces Class 1 Requirements, Subset-093 [4]. A summary of the requirements is shown in the table below.
The requirements shall be meet in speeds up to 500 km/h on straight lines as well as in tunnels, cuttings, on elevated structures, at gradients and on bridges and stations. The parameters are valid for an end-to-end for one train, and shall not be depending on network load.

Connection establishment delay of mobile originated calls is defined as the maximum elapsed time between the connection establishment request and the indication of successful connection establishment. The delay shall not be depending on the user data rate. Delays more than 10 seconds shall be considered as connection established errors.

Connection establishment error ratio is the ratio of unsuccessful connection establishment attempts to the total number of connection establishment attempts. This applies for the end-to-end bearer service. As above, connection establishments delays > 10 seconds shall be considered as connection establishment errors. The GSM-R network should be designed in such a way that at least two consecutive connection establishment attempts will be possible.

The end-to-end transfer delay is the elapsed time between the request for transfer of a user data block and the indication of a successfully transferred end-to-end user data block. The delay is defined as the time elapsed between the delivery of the first bit in the data block to the transmitting service access point, and the receiving of the last bit on the receiving access point.

Connection loss rate is the number of connections unintentionally released per accumulated connection time. The stated ratio < 0.01/h is valid if the connection establishment error ratio is < 0.01.

A transmission interference period is the period during the data transmission phase of an existing connection in which, caused by the bearer service, no error-free transmission of user data units of 30 bytes is possible. To be considered as error-free, none of the 30 bytes of data shall derivate from the ones transmitted.

An error-free period shall follow every transmission interference period to retransmit user data units in error (wrong or lost) and user data units waiting to be served.

<table>
<thead>
<tr>
<th>QoS Parameter</th>
<th>Value (see 6.3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connection establishment delay of mobile originated calls</td>
<td>&lt; 8.5 s (95%), ≤ 10 s (100%)</td>
</tr>
<tr>
<td>Connection establishment error ratio</td>
<td>&lt; 10⁻²</td>
</tr>
<tr>
<td>Maximum end-to-end transfer delay (of 30 byte data block)</td>
<td>≤ 0.5 s (99%)</td>
</tr>
<tr>
<td>Connection loss rate</td>
<td>≤ 10⁻²/h</td>
</tr>
<tr>
<td>Transmission interference period</td>
<td>&lt; 0.8 s (95%), &lt; 1 s (99%)</td>
</tr>
<tr>
<td>Error-free period</td>
<td>&gt; 20 s (95%), &gt; 7 s (99%)</td>
</tr>
<tr>
<td>Network registration delay</td>
<td>≤ 30 s (95%), ≤ 35 s (99%), ≤ 40 s (100%)</td>
</tr>
</tbody>
</table>

Table 1 GSM-R QoS parameter overview
The network registration delay is the elapsed time from the request for registration to indication of successful registration by +CREG response. Network registration delays > 40 seconds are considered as registration errors.

According to an expert at Trafikverket, the requirements for GSM-R are much higher, as an indication 10 times higher compared to the standards for GSM used for public mobile service. The same source states that the “Connection loss rate” requirement has demanded themost focus so far.

5.5 Quote on interfacing
It is appropriate at this stage of the thesis to quote Sabine Reppert from Siemens Transportation System statement from the UIC ERTMS conference in December 2003 [5]:

“Even though there are standards defined, interfacing ETCS with GSM-R is a complex task. Do not expect it to be “plug&play”. If you do not have the necessary experience, it is like “plug&pray”.

---

5 +CREG, a command that is send back as an answer to a successful request for registration.
6. Defining capacity in the ETCS/GSM-R system context

6.1 Capacity related to the number of trains
The capacity of this system can be defined as how many moving units in a specified area the system can control at the same time. The area can be a fixed block or any other type of limited geographical area.

Other definitions of “capacity” in a railway system are used, for example passenger kilometres per time unit, tonnes per time unit, weight or volume per meter track. These definitions are depending on other factors than the signalling system, even if the number of trains handled can be an important part of it.

In this document, four cases for considering the signal capacity can be identified:

- Single track line
- Double or multiple track line
- Small yard, i.e. main track and one or two sidings
- Large yard, marshalling yard, large passenger terminal

6.2 Capacity related to data messages
Due to the fact that the radio connection for data transmission shall be based on the circuit switched principle, a moving train is continuously connected via GSM-R on the whole journey from A to B, not only when messages are sent.

The amount of data sent on this continuous connection is very low. A position update message consists of 14 bytes and a movement authority message to the train is between 40 to 500 bytes, average 250 bytes.

As an example, if one position update message and one movement authority message is sent every single minute, 14x8 + 250x8=2.112 bits are sent during this minute. The transmission speed is 9.600 bits per second, which equals to 576.000 bits that is possible to send during this minute. The usage is then 0,4 % of the available capacity.

6.3 Capacity related to available data and voice channels
The available 7 timeslots for one GSM-R frequency is the minimum for a cell. They can be used for both voice and data; in that way the capacity is shared between data and voice calls. If needed, more frequencies and thereby timeslots can be allocated to one cell.

The telecom traffic is studied in the science of traffic theory, and a short summary of it shall be made here. Telecom traffic is measured in Erlang and the definition is that a call lasting 1 hour is equal to 1 Erlang. 30 calls lasting 2 minutes each is also equal to 1 Erlang.

The traffic is described in traffic models that can be used to calculate the need of telecom lines or in this case radio channels during the busiest hour, accepting a decided level of congestion or rejected calls. There are different formulas for the calculations; one of the most common is the Erlang

\[ E = \frac{m \times t}{E} \]

\[ m \times t \leq E \]

\[ E = \frac{m \times t}{E} \]

\[ m \times t \leq E \]

6. 1 byte = 8 bits. Just for confusion, data speed is measured in bits per seconds, length of messages in bytes.
formula, which appear in three different varieties depending on how rejected calls are handled. The Erlang B formula implies that a rejected call is lost, in Extended Erlang B formula a given percentage of calls immediately make a new attempt and in the Erlang C formula a rejected call queues up until it can be handled.

The amount of voice traffic varies; in the case of disturbance and in shunting yards, the volume can be rather high, occupying 3 to 4 channels for that use. On the other hand, the calls are of this nature short and used to exchange more or less formal orders and information.

An example: Banedanmark\(^7\) has estimated the voice traffic to be 3 calls lasting 30 seconds each per hour for one user for such situations[6]. This equals to 0.025 Erlang and the estimated number of users is 50, making the total traffic 1.25 Erlang. Banedanmark consider 4 channels to be needed. According to Erlang B this equals to the probability of blocking of 0.097 if 3 channels is used, 0.029 if 4 are used and 0.007 if 5 channels are used. Compare this what is stated for QoS requirements for a data call in chapter 5.4: Connection establishment error ratio shall be less than 0.01. Only when using 5 channels this requirement is met. On the other hand, there are stronger requirements on data calls than on voice calls.

6.4 Priority of different types of calls
A data call has priority over a voice call, except for railway emergency calls, REC, that have priority over all other calls. In the case a train enters a cell or starts up in a cell where all timeslots are occupied, the following cases occur:

- If there are voice calls ongoing, one of them will be pre-empted, as the ETCS data call has higher priority.
- If all time-slots are engaged in ETCS data calls, the entering/start up train will not have any connection, and is therefore brought to a stop.
- If an emergency call REC is set up, it will have priority of all other calls and all ongoing voice calls are pre-empted and all units in the affected area are connected to the emergency call. If all timeslots are engaged in ETCS data calls, one of them will be pre-empted and the emergency call will use that timeslot.

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\(^7\) Banedanmark operates the Danish railway infrastructure owned by the government
7. Factors limiting the signalling system capacity
In this chapter limiting factors are listed and their effect on the system is described.

7.1 Limited availability of speech/data channels in a cell.
As mentioned before, in the air-gap a circuit switched connection is used. This means from the start until it reaches its destination a train continuously occupies a data channel.

The limited number of available frequencies, 19, and as a consequence of that, limited number of available speech and data channels, 7 per frequency, is a limitation of the system when the requirement is that there always one channel available for each moving train.

The GSM-R system is using a cell concept for coverage and best usage of the limited number of frequencies.

As described in 5.3.3 it is possible to cover a line with just two frequencies, see below.

![Figure 16. Covering a track line with two different frequencies.](image)

This will provide 7 speech/data channels and can be considered as a minimum configuration. The configuration is unreliable, should one cell not be properly working the train will be forced to stop.

![Figure 17. Covering a track line with two different clusters (top). If one cell stop working, the coverage is still obtained. (bottom)](image)

To increase the reliability, you can let 4 cells cover the same area as in figure 16. The blue/red cluster is here overlapped with the green/brown cluster. If one of the cells fails, as in the lower figure, there is still coverage of the line. To provide redundancy each cluster is connected to its own BSC, so even if the BSC or the connection to that BSC is faulty, full coverage is still obtained.
By using 4 cells instead of two to cover the same area, the focus is to increase reliability more than the capacity, even if that will increase as well.

For the usage between stations, “out on the line”, the capacity of GSM-R was considered sufficient even for high-speed lines when the GSM-R system was established. This is still true, but some other factors not foreseen have occurred. Some examples are discussed below.

The problem of interference has come into existence because of the introduction of high-capacity public mobile services, see chapter 7.2.

![Figure N. The Öresund area. Map from Google.com](image)

In the area of Öresund, the geographical distance between Denmark and Sweden is quiet short; the two countries are separated by water which has little attenuation on radio waves. On both sides railways runs close to the shore, from Helsingborg to Malmö in Sweden and from Helsingør to København in Denmark. Therefore, only 9 of the available 19 frequencies are allowed to be used on the Swedish side of this area. [7]

When going from one level 2 to another level 2 area, each one of them is belonging to a separate RBC. During the transition between the two areas there is a need to communicate with both areas. This creates a need for two EDOR receivers in the moving unit, and therefore also enough channels available. It is preferred to have this overlapping area on the line and not on stations and other areas with high concentrations of trains.
7.2 Cell planning on areas with high density of trains

Cell planning on a high speed line means large cells covering long stretches of the line, as there are few trains moving in the cells at the same time and the cell hand-over to the next cell takes it up to 10 seconds, and a train moving in 350 km/h runs close to a kilometre in that time. There can be a need for more channels when double or quadruple track is used. Still, when using Level 2 with fixed blocks with one train per block on the same time, there should not be more need of available channels than can be covered by one or two TRX, i.e. 7 or 14 channels.

On a station or a railway yard there are often more than one train or moving units in a dense area standing still or moving slowly. There might be railway staff dealing with switching that requires more speech traffic than out on the line. On a small station with one or two main tracks and a few side tracks for marshalling, this is not a problem. One factor to consider though is that if trains are passing the station in high speed the cell size must consider the hand-over area as mentioned in chapter 5.3.4.

On a large station or large marshalling yard, there are many movements on a rather dense area, but in low speed. In Sweden this applies to the central station in Stockholm, Malmö and Gothenburg. It is therefore a need to have many small cells that can handle many calls in a limited area.

In Hallsberg there is a very large marshalling yard with many locomotives involved in the switching work, and in the vicinity there is a high speed line passing by. This means that there is both a high density of trains requiring many channels on a small area, and fast moving trains that require as little hand over as possible.

Finally, when congested situations or other abnormal situations like severe weather conditions or accidents occur, the normal line for high speed conditions might turn into a “parking place for trains”. Where there is normally one or two trains in the same cell, there might be an increased number of trains, which also has an increased usage of speech channels.

7.3 Interference with other mobile systems

Figure 18. GSM-R frequency overview. Picture from [8]
GSM-R is working in a reserved spectrum in the 900 Mhz band. Close to that, other public mobile service providers operate GSM systems as well as the subsequent third and fourth generation mobile systems like UMTS, WiMax and LTE.

As the public mobile operators sometimes have cell coverage close to or overlapping the GSM-R cell and also with a higher field-strength, there is a risk of interference and severe disturbance of the GSM-R traffic. At the ERA GSM-R Conference in October 2011 [9] it was reported that this problem is identified at over 400 locations in Europe, and that the size of such locations could be from a few meters up to a few hundred meters.

The disturbance decreases or makes it impossible to use the GSM-R connection in the disturbed location. This results in failed transmission of MA, which causes the train to stop, jammed traffic, delays and bad performance of the network. Railway emergency calls can be affected, an even higher risk for casualties.

The problem has resulted in a report ECC 162 from May 2011 [8] from CEPT, European Conference of Postal and Telecommunications Administrations and has also been investigated in a report by Trafikverket [10] from November 2011. The CEPT report focuses on how to handle the problem (see chapter 8.2), the one from Trafikverket focuses on the reasons for the disturbance.

It is also to be noticed that even if the ERTMS system level 2 and above for its safety is depending on more or less uninterrupted radio-link connection, GSM-R has the same legal status regarding disturbance as any other common mobile telecom service. Compare this to the extended, legal protection that security radio communication has for civil aviation or marine traffic.

The reason why the problem occurs is according to Trafikverket:

- The suggested allowed signal levels for UMTS/LTE in the vicinity of railway track are 500 to 1000 times higher than the one that GSM-R equipment is designed for.
- The influence of disturbance is often equipment dependent. Even if the units are fulfilling the requirements, there are considerable variations between different models and suppliers.
- The performance of GSM-R equipment when exposed to high levels from a neighbouring frequency channel has a strong non-linear pattern and distinct threshold phenomena can be observed. This means that there is influence of multi-level effects.
- The main influence seems to be intermodulation effects of uneven levels that is formed in the GSM-R receivers signal route.
- To avoid the problem, the signal level planning has to be done considering space, frequency and amplitude.

7.4 Internal transmission systems limitations

In the transmission chain between the RBC and the EVC in the moving unit there are many different protocols and interfaces to pass. If any conversion is made, it has to be ensured that the correctness of the data is guaranteed, as well as the capacity. As stated in chapter 6.2 the needed capacity is not very high, but the requirement on reliability are very high.

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8 In the Trafikverket report different source of information has been used. The author therefore considers it to be a good compilation of the matter.
The bottleneck in the system is the air-gap. The bitrate of 9.6 kb/s is enough, but the number of channels is limited. A limiting factor is that the wireless transmission system, as all such systems, has a need for internal signalling according to the common channel signalling principle. Of the 8 available speech/data channels per TRX, one is used for this purpose. One signalling channel can be used for two TRX making 15 channels available, but for security reasons two signalling channels can be used for one TRX as well, making only 6 channels usable. A useful compromise between reliability and capacity is 2 signalling channels for three TRX, making a total of 22 channels for data/voice traffic. As a comparison, Trafikverket is running 11 BSC that feeds 1200 BTS [1]!

7.5 Summary of limiting factors

- ERTMS was originally designed for high speed lines, where relatively few trains appear in the same area at the same time. For that purpose GSM-R has satisfactory capacity.
- Interference from other public mobile services with high data capacity is presently a problem more in focus than lack of capacity. The interferences decrease the capacity of or makes it impossible to use available radio frequency channels.
- Local conditions, like the available 19 frequencies that have to be shared with an GSM-R operator in a neighbouring country, might reduce the capacity.
- Cell-planning can solve the problem with many trains in a limited yard area, as well as providing enough capacity on the line. Problems occur when the two are mixed, such as a high speed line passing close to a large marshalling yard.
- Even though the air-gap is the bottleneck of the system, the track from the fixed ETCS part to the on board ETCS system contains many interfaces and protocol conversions. If not considered, this can limit the capacity.
8. How to mitigate the limitations and increase the capacity - discussion
In this chapter the action taken now is described, as well as what can be done in the near future to solve the problem.

8.1 Increase wireless transmission capacity
Now or in the near future, 1 to 3 years, there is mainly the following ways to increase the capacity of GSM-R:

- More frequencies
- Packet switched transmission
- Half-rate 4,8
- Cell structures
- Level 2/Level 1 combination
- Restriction of usage

The pros and cons of the options are discussed in this chapter.

8.1.1 More frequencies
Radio spectrum is a limited resource, and it is therefore not very possible that there will be more frequencies than the present GSM-R and E-GSM-R band reserved for railway use.

The E-GSM-R band is an extension to be used based on national regulation. This restriction is made because in some countries this band is still used for other purposes. It is therefore possible for countries where the band is unused to use it, but not for moving units operating in more than one country.

If it can be decided that the E-GSM-R shall be reserved for only railway use and available for international use, 15 more frequency channels are made available.

8.1.2 Packet switched transmission
Going from circuit switched to packet switched connections increases the capacity with a factor 8. Considering the very low usage of the data channels, this is a very easy way to increase the capacity. GPRS, the standard for packet switched data on GSM-R is already in use for non-ETCS services.

Factors limiting the usage of GPRS, are that it is not considered to fulfil the QoS requirements, it is not possible to use for speech and the present EDORs must be replaced or updated to handle GPRS.

8.1.3 Half rate 4,8 kb/s
For voice, using half the rate of a speech channel is available as a way to mitigate congestion. During normal conditions full rate 9,6 kb/s is used, providing good speech quality, but when congestion appears the rate could be reduced to 4,8 kb/s which is giving an acceptable speech quality but doubling the capacity of each speech channels. As this is part of the standard available cab radios should be able to handle it.

For data, the half rate solution was rejected some years ago, giving preference to the GPRS solution which improves the capacity even more.
8.1.4 Cell structures

Already with the predecessors to GSM the planning engineers did deal with the problem of lack of frequencies and an unexpected rise of the numbers of subscribers. The usage of sectors and antennas with a narrow antenna lobe was a tool for the planners, and cell-clusters like the Stockholm model (see 5.3.3) were developed during that time.

To cover a main line, high-speed or not, is not a problem, and covering a yard with many slow moving units can also be planned for by using small cell clusters.

The problematic combination of a yard and a main line at the same place can be solved by adding an “umbrella cell”, a cell covering a large area but with relatively few frequencies for the fast moving trains, and a small cell cluster for the slow moving trains.

In places where queues or congestion can be expected, the number of frequency channels must be increased, compared with the usual one or two frequencies allotted.

8.1.5 Level 2/Level 1 combinations

A solution for very large stations, in Sweden this is discussed for the central station in Stockholm, Gothenburg and Malmö, and large marshalling yards like Hallsberg. This is a fully implementable solution not using GSM-R, but has the drawback that it is a costly solution with active balises and lineside signalling, equipment that is not needed at higher levels. Besides, even if the signalling information is shown to the driver on a standardized ETCS display, the line signalling is not the same in all of Europe, which can cause confusion and is therefore a safety hazard.

8.1.6 Restriction of usage

The limited capacity problem can be solved not only by technical solution, but also by formal regulation. Examples from Banedanmark [6] are that trains are not allowed to enter cell areas that have no channels free. Trains standing longer than a stated time shall disconnect from the ETCS system.

Restrictions like this can solve the problems in case of congestion and other abnormal situations, but there is a risk that a dispatcher or operation manager will have to intervene, using the voice part of GSM-R but then all channels are blocked by data calls.

8.2 Limiting interference with other mobile systems

In the CEPT report [8] different ways to solve or mitigate the interference problem is discussed. If the problem is limited to only a few cases, the recommended way to solve it is to set up a work-group with the involved operators and solve the problem in cooperation.

To take preventive action, the following is recommended:

- Definition of a minimum isolation corridor to railway tracks - reduced public GSM/UMTS coverage along railway tracks. Counteract the concept that GSM-R train radios should be able to roam on the public GSM network if the GSM-R network is unavailable.
- Setting a coordination distance between the base stations of public mobile networks and the railway. Both parties would coordinate any base stations planned within a certain coordination area. - This creates a significant coordination effort to both public and GSM-R operators, given the high number of the stations to be coordinated. Therefore, it is
recognized that the relevance/efficiency of such a procedure strongly depends on the cases of interferences that occur.

Both this way to plan ahead is dependent on the willingness of the involved parties to cooperate. The position of the GSM-R operator could be strengthened if the security aspect was considered more in the legal system, as discussed above.

The CEPT report also mentions various technical solutions:

- Increased GSM-R field strength – A stronger carrier signal increases the immunity of the terminal towards disturbing frequency.
- Adding GSM-R base station – Improve coverage, but add extra hands-over. In dense urban areas frequency resources may be limited.
- Adding of fixed GSM-R repeaters – Improves signal levels. Can cause problems in hand-over zones.
- Co-location of public mobile network and GSM-R base stations – Reduces interference problems, in particular when the same technology and the same level of power are used.
- Output power reduction from public mobile network base stations – Impact on coverage, capacity and service availability of the public network. Limits the possibility for GSM-R train radio to roam to the public network in case of problems.
- Adjusting the public network base station and/or the GSM-R base station antenna characteristic – Base station antennas will be directed in a way that the antenna beam does not hit the other base station antennas. May lead to a power reduction towards railway track. Directing the antenna of the public service away from the railway track leads to reduced public GSM coverage, and reduces the possibility for train radio to roam to the public service if the GSM-R network is not available.
- Redundancy on the GSM-R signalling messages – redundancy is already included in the GSM-R signalling messages. Adding further redundancy might prevent the real time operation of the GSM-R network.
- GSM-R cab radio improvements
  - Filtering – By using RF filtering of the GSM-R downlink band, the blocking problems can be reduced to non-critical levels. Could be introduced as additional filters for all new cab radio installations.
  - Receiver diversity – Space diversity would allow the GSM-R base station to decrease power. Diversity antennas are difficult to implement on the engines roof.
  - Enhanced receiver performance – more advanced mobiles can significantly improve the robustness of the GSM-R downlink operation.
  - New generation of receivers – Designed with a higher overloading threshold. Compliance with the ETSI specifications shall be sufficient, but receiver parameters are for some cases at the limit.
- Slow frequency hopping – Works well in medium and slow speed areas. Only applicable if enough GSM-R frequency channels are available.
- Improved filters in public mobile network base stations – Reduces unwanted emissions. Public mobile network coverage area is reduced due to loss in the filter.
As an example, in Sweden Trafikverket and the public mobile operators together with the Swedish regulatory body for telecommunication, PTS\(^9\), has agreed on a temporary protection of GSM-R until end June 2015.

The agreement states that:

- The public operators will install unwanted emission limiting filters in their base stations close to GSM-R areas
- Trafikverket has to increase the signal level in the GSM-R system with at least 12dB
- External GSM-R terminal protective filters have to be implemented in the CAB radio and EDOR

This means that the on-board equipment no longer conforms to the ETCS standard; it can be considered as a local solution not according to the EIRENE FRS and SRS. This limits the international usage of the equipped vehicles.

Trafikverket has made an extensive investigation of available filters, and have found out that the performance is rather heterogeneous, with mixed performance between different models and suppliers. If filtering shall be a common solution for the co-existence of GSM-R and high capacity systems like UMTS and LTE, some extensive work has to be done here.

### 8.3 Summary – suggested actions to take

The focus right now from the GSM-R operators is on the interference from 3 and 4 generation public mobile services for high speed data connection. The problem can be solved by using filters, mutual agreements on cell planning and limitations on field strength. Filters are not yet, as of spring 2012, a part of the ERTMS standards, which is an issue in the longer terms.

More frequencies than those now decided in the GSM-R and E-GSM-R band are unlikely to be dedicated to the ERTMS system.

Packet switched transmission, GPRS, and half rate 4,8 kb/s are both giving a substantial increase in capacity; half rate with a factor 2 for voice only, and GPRS with a factor 8 for data. Half rate for voice is already part of the standard. The GPRS data solution is still under evolution, and needs to be standardized and, as well as more frequencies, requires new or updated GSM-R cab radios and EDOR. This means a substantial cost, especially for the radios which compared to standard GSM handhelds are much more expensive. GSM radios are produced in the number of millions with a lifecycle of 18 months providing economy of scale, GSM-R radios are produced in thousands or ten thousands with much longer life length.

Cell structures, level2/level 1 combination and restriction of usage are possible to implement today, but there are limitations on how much more capacity can be improved. The level 1 and 2 combination is most likely to be most common solution for large yards, especially if a level 1-like system already exists, and it can later be converted into a level 2 system when solutions providing the needed capacity are available.

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\(^9\) PTS stands for Post och Telestyrelsen.
9. Who is limiting who?

9.1 The capacity requirements of ETCS vs GSM-R - discussion

It has been hard to find calculations of the maximum numbers of trains that GSM-R can handle at the same time in a defined area. It has been even harder to find the capacity maximum of the ETCS part.

Theoretically, if all 19 frequencies are to be used, 18 of them can be assigned to one cell and just 1 to the neighboring cell. This gives $18 \times 7 = 126$ channels in that cell, and 7 channels in the neighboring one. If not all frequencies have a signaling channel, a few more can be added to the 126. This is considered to be a theoretical maximum, hardly a realistic alternative.

In the literature, the author have found three examples where the limits of the ETCS and GSM-R system are discussed.

In the Malmö area [7] from Hyllie – Malmö central station – Arlöv, a distance approximately 20 kilometer with a passenger station, a large marshaling yard and a container terminal, the need is considered to be 100 data channels and 50 channels for speech and handover. The area is served by 16 cells, the largest with 28 channels, the smallest with 6 channels and most common 14 channels. Total 214 channels are available in the area to cover the expected need.

On Västerdalsbanan, a 134 kilometer long regional line which is Trafikverket’s test site for ERTMS Regional, a level 3 based system specifically made for lines with low traffic. The equipment is from Bombardier, Interflo550, and can handle 30 simultaneous train movements from one RBC [11].

Banedanmark [6] has made a memo about level 2 solutions for large stations and junction areas. They state that the practical limit is approximately 25 trains per square kilometer, which can be raised to 28 when extensive network planning is done, using sectored and umbrella cells.

The conclusion of these three examples is that the ETCS/GSM-R combination has a practical maximum of 25 to 30 trains in a limited area, and Banedanmark states it to be 25 per square kilometer.

The capacity for GSM-R is enough for main lines and high speed lines. During congested or other abnormal situations the capacity of GSM-R can be a limitation.

On large stations and marshaling yards with many moving units in a dense area, combined with high volume of voice traffic from the staff working in the same area, the shortcomings of GSM-R capacity start to show, especially if trains are passing through the area at high speed.

9.2 Suggestion on what to do now

In the short run, the focus is on the interference problem from stronger public mobile services that is limiting the usage of GSM-R at all. This can be solved by filters, but they are not yet a part of the ERTMS standard.

The capacity of the ETCS/GSM-R combination is normally enough for line usage, but can be a problem on areas with high traffic density. Skilled technicians can solve that with advanced cell
planning, but an option is to go for level 1 solution in such areas, that later can be upgraded to level 2 areas when appropriate (=GPRS) technology is available.

Another issue, not dealing with capacity, is to make ERTMS recognized as a more reliable system than it is today. Too much headline space in the press has been dealing with stoppage, canceled trains and wasted money. It is not in the scope of this thesis to sort out what is true, rumors, or just false statements; still it is something to consider when capacity is discussed.

9.3 GSM-R year 2020 – discussion
The future ERTMS has of course been discussed in various groups and gatherings. In a document dated May 1999 Siemens discussed the future of GSM-R [C]. They state that future supplementary services will not be part of the GSM network element, instead on an Intelligent Network platform connected to the GSM-R system. Siemens also discuss the low data rates, and that GPRS shall be introduced as a packet mode transmission technology, directly interworking with IP networks. Not only increasing the data transmission capacity, it also opens for non real-time critical applications like file transfer, email, mobile railway internet etc. Siemens is describing the problems to support the high QoS requirements for ETCS generated data messages with GPRS, but is convinced that GPRS is the way forward. On the other hand, at this time they have foreseen no need for the more advanced UTMS technology.

At the UIC ERTMS World Conference in April 2012 the issue of using GPRS for ETCS was still on the table. The GSM-R Industry Group members have committed themselves to develop an ETCS over GPRS together with UIC, ERTMS user group, UNISIG and railways. At the same conference UIC representatives [12] state that the packet switched technology is essential as it is a solution to the lack of capacity = frequencies and it is also future safe. GPRS is the only available technology today and standard GPRS shall be used, no GPRS-R! A European pilot will start in April 2012, and is scheduled to end in 2014. Previous tests performed 2008 to 2011 have showed that GPRS is feasible for ETCS. The packet switched technology opens the world of IP, and the focus is on applications rather than services.

At the same conference it was discussed if the usage of ERTMS outside Europe where some countries go for ERTMS compliant applications, Mexico, New Zealand and South Korea for example, and others go for an ERTMS-like application, USA, Russia and China, can cause a risk of fragmentation of the standard. In the USA there is a lack of spectrum that makes it impossible to use the GSM-R and E-GSM-R band. Other frequencies or radio bearer has to be considered. This will limit the ERTMS benefits for both suppliers and customers; the economy of scale may be lost. This is so far the input from the conference in April 2012.

Presently, the public mobile industry is moving towards technology that can handle more and more capacity, to be able to use the same sorts of IP-based services as you have at home with your broadband connection. This part of the industry is therefore migrating towards the Long Term Evolution, LTE, 4G technology. The railway industry is on the other hand depending on long term standards like GSM-R, not needing to change the invested equipment. UIC was aware of this potential conflict and took the initiative to a technical study report of the impact of LTE on GSM-R that was published in 2009. The results was presented to ERIG, the UIC ERTMS Platform and at the Infrastructure Forum and a follow up study, “The Future Railways Mobile Telecommunications
Systems Study” [13] was started in 2010 and presented at a meeting November 30 2010. Also, the 9 members of GSM-R industry group committed to support GSM-R until 2025.

With the present EIRENE specification in mind, the railways have to decide the radio mobile needs and be open for new services that could improve railway operations; this done with a technology-free approach. The outcome shall be a document “Railway Mobile Communication System User Requirements Specification”, a base for discussion between the railways and suppliers regarding the successor to GSM-R.

The meeting of November 30 2010 concluded [13]:

“The public market will evolve towards LTE. Sooner or later this will affect GSM, and when GSM reaches the end of its lifecycle, GSM-R survival will be matter of years (depending also on developments within the railways). LTE’s current level of maturity and its use with voice-based applications (which account for most railway-related needs), mean any decisions taken at present would be premature. The deadline for a decision is not today, but it will not be far away, most likely in just a few years’ time.”

To conclude, GPRS for ETCS data is still not a part of the standard but will probably be around 2015. The industry is aware of the development in the public mobile industry, packet switch and IP is not to be neglected. Around 2025 we can see the closure of GSM-R and the result of an evolution towards a LTE based railway implementation.

Remarkably little is said on what applications that are going to be run on this new high capacity network! The telecom operators once had the chance to be the drivers and benefit takers of the 3-party driven development of applications, but lost it around 2008 to Google, Apple and Microsoft to mention the most flagrant examples. To be pessimistic, the infrastructure operators have to invest heavily in a high capacity ERTMS radio network, but it is Google Rail, iTTrain and RailWindows that makes the money!

10. Final conclusions
To summarize the answers to the four questions raised in chapter 1:

• Is the present version of GSM-R limiting the capacity of the ERTMS system? – Only in very high density traffic areas at the moment, spring 2012.

• If that is the case, how to improve GSM-R not to be the limiting factor? – Advanced cell planning and the usage of level 1/level 2 combination.

• Will new generations of mobile telecom systems, like GPRS, LTE etc, influence GSM-R in the future? – Negative as interference problems occur, positive as a way of higher capacity and open GSM-R for more services and functionality.

• GSM-R year 2020 – GPRS for ETCS in place, preparing for closing of GSM-R and beginning of LTE-R. The capacity is there, but where are applications and services that needs the capacity?
11. And the answer is........
To the question in the title, is GSM-R the limiting factor for the ERTMS system capacity?

NO, considering the actions taken and the sometimes unconventional solutions used based on engineering expertise and creativity, GSM-R is not the limiting factor in ERTMS right now.

YES, in the long run and with broader usage of ERTMS, GSM-R has to have a higher capacity, more functionality and be a more standardized system, more “plug&play” than “plug&pray”.
12. Future studies

Telecom traffic theory is a well-established discipline, and there is much effort made regarding research and theory about train traffic and train capacity at KTH. Still, the author got the impression that the number of moving units that is possible to handle at the same time is determined more on practical experience than by theoretical calculations. Even if there is a solid theoretical background to the estimations made by for example Banedanmark, this is an issue for further studies.

With the introduction of GPRS to be used together with GSM-R, more data transmission capacity will be provided. Already today the public mobile services use commercially available systems with capacity far above what GPRS is capable of, and these systems will definitely influence the future of GSM-R and ERTMS. With future increased transmission capacity, what to use the higher capacity for? Will there even be excess capacity?

During the introduction of ERTMS many problems have to be solved, especially when going from a situation with several national signaling systems to a unified European system. Also, countries outside of Europe intend to use this “international” system. Will the different implementations of ERTMS be compatible with each other, is the system converging to a homogenous standard or diverging to national standards bases on a common core?

The requirements on a signaling system are very high regarding quality of service, security, availability and reliability. The downtime shall be if not zero, as close to that as possible, and no train shall be delayed due to a malfunctioning signaling system. In what way can that demanding objective be reached, and in what way can academic research contribute to it?
13. List of acronyms

ATC  Automatic Train Control
ATP  Automatic Train Protection
BSC  Base Station Controller
BTS  Base Transceiver Station
CEPT European Conference of Postal and Telecommunications Administration
CTC  Centralized Traffic Control
EDOR EIRENE Data Only Radio
ECC  Electronic Communications Committee
E-GSM-R Extended (frequency band) GSM-R
ERA  European Railway Agency
ERTMS European Rail Traffic Management System
ETCS European Train Control System
EVC  European Vital Computer
FRS  Functional Requirements Specification
GPRS General Packet Radio Service
GSM  Global System for Mobile communication
GSM-R Global System for Mobile communication - Railways
HLR  Home Location Register
INESS Integrated European Signaling System
IP  Internet Protocol
ISDN Integrated Services Digital Network
ITC  Information and communications technology
LEU  Lineside Electronic Unit
LTE Long-Term Evolution, 4 generation mobile systems
MA  Movement Authority
MSC  Mobile Switching Centre
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>NMT900</td>
<td>Nordic Mobile Telephony, analog system operating in the 900 MHz band.</td>
</tr>
<tr>
<td>PTT</td>
<td>Post, Telegraph and Telephone administration</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of Service</td>
</tr>
<tr>
<td>RBC</td>
<td>Radio Block Centre</td>
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<tr>
<td>REC</td>
<td>Railway Emergency Call</td>
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<tr>
<td>SMS</td>
<td>Short Message Service</td>
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<tr>
<td>STM</td>
<td>Specific Transmission Module</td>
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<tr>
<td>TETRA</td>
<td>Terrestrial Trunked Radio</td>
</tr>
<tr>
<td>TRX</td>
<td>Transceiver</td>
</tr>
<tr>
<td>TSI</td>
<td>Technical Specification for Interoperability</td>
</tr>
<tr>
<td>UIC</td>
<td>Union Internationale des Chemins de fer</td>
</tr>
<tr>
<td>UMTS</td>
<td>Universal Mobile Telecommunications System</td>
</tr>
<tr>
<td>WiMax</td>
<td>Worldwide Interoperability for Microwave Access</td>
</tr>
<tr>
<td>VLR</td>
<td>Visitor Location Register</td>
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</table>
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Post Script

This picture, taken by Robin Simonsson (thanks Robin!) showing the railway ferryboat at Puttgarden, symbolize that there are still areas not covered by GSM-R, yet.

The front page pictures is provided by Per Olofsson, thanks Per!

A great Thank You to Jonas Lind, Trafikverket, who has been the industrial sponsor and a very valuable source of information. Also to my Professor at KTH, Bo-Lennart Nelldal, ensuring the thesis fulfills the academic requirements, as well as a knowledge source of information about the railway system. The day to day work has been supervised and supported by Anders Lindahl, thanks to you as well. Michael Bayley in his role as opponent at the final seminar presentation shall have thanks for valuable input on how to improve the thesis. And, finally, all members of my family who’s truckloads of positive support gave me strength to proceed when times was hard.