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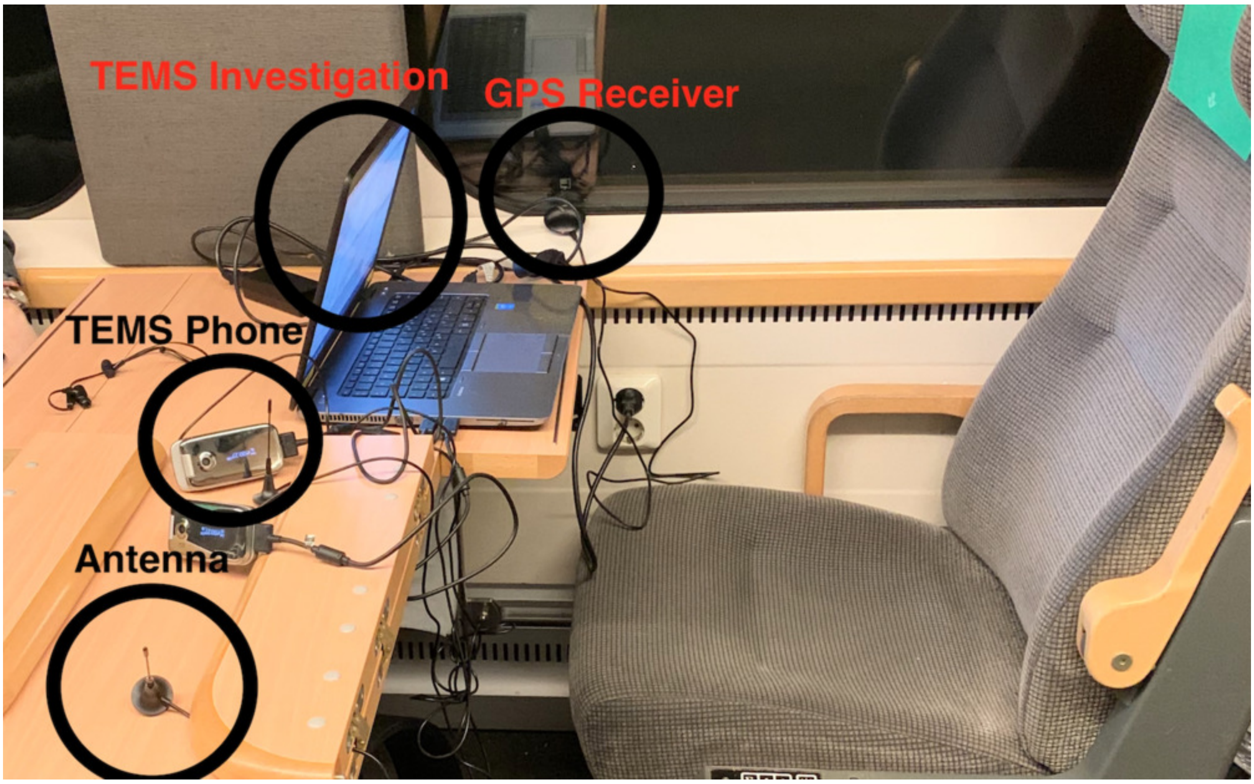

Alternative Technologies for providing Voice Services on-board Trains

A benchmarking study

Master's thesis in Communication Engineering

Herman Mikkelsen Ylander

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Alternative Technologies for providing Voice Services onboard Trains

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Cover: Measurement setup onboard X2000 from Gothenburg to Stockholm.

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Abstract

Providing cellular voice onboard trains has proven to be a challenging task. The metallic chassis and the coating on the windows acts as a radio shields. In combination with sparsely spaced cellular base stations on rural routes, the coverage onboard inter-city trains is often poor. Hence, onboard systems for providing cellular coverage of voice services are most often required.

Since the late 90-ties, analog "amplify and forward" radio repeaters have been used extensively to provide coverage of cellular voice onboard trains. However, repeater systems have proven to be both expensive and technically problematic for both train- as well as mobile network operators. New modern IP based systems for providing voice services (VoIP) have during the last 15 years been developed and it is the goal of this thesis to investigate the possibility of replacing the repeaters with such a system.

In this thesis, three alternative technologies for providing cellular voice onboard trains are therefore investigate and benchmarked. The technologies under investigation are:

- circuit-switched voice on GSM and 3G (CS), provided with and without repeaters
- Voice over IP on LTE (4G) also known as VoLTE, provided with and without repeaters
- Voice over IP over the onboard Wi-Fi network (VoWiFi).

To benchmark these system against each other, we choose to measure the following "key performance indicators" (KPIs):

- Availability: the ability to establish a call
- Retainability: the ability to retain a call
- Geographical Coverage in terms of signal strength onboard the train along the route.
- Voice quality [relative unit]

The measurements were conducted onboard Swedish X2000 trains, en-route between Stockholm and Gothenburg. For measurements of the performance of circuit switched voice, the network analyzing tool "TEMS Investigation" was used. Continuous two minute calls were performed and Availability, Retainability and Coverage were measured simultaneously over each of the Swedish mobile networks.

In order to determine the voice quality, a simplified set up for measuring PESQ (Perceptual Evaluation of Speech Quality) was developed. In the study we compared the voice quality of VoLTE and VoWiFi.

Our results show that VoWiFi over the onboard Wi-Fi network is clearly the best performing technology with nearly 100 % availability and nearly 100 % retainability. Circuit-switched voice on GSM and 3G (UMTS), provided with repeaters, resulted in 96% availability and 95% retainability for GSM and 94% availability and 97% retainability for UMTS.

In terms of coverage VoWiFi is significantly better than VoLTE. Being able to utilize the antennas located on the roof of the train bypasses the shielding RF shielding effects of the train chassis and the windows. The worst LTE network operator had bad coverage 75 % of the time, while the worst VoWiFi coverage was bad only 10 % of the time.

VoLTE was in our study the worst performing technology with 90% availability and 84% retainability. However, the voice quality measurements resulted in the highest score for VoLTE, slightly better performing VoWiFi.

In conclusion the study shows that there are alternative VoIP technologies for providing onboard cellular voice services. In particular the study shows that VoWiFi is the superior voice communications technology when it comes to availability, retainablility and geographical coverage.

Keywords: train, communication, voice, VoWiFi, GSM, UMTS, LTE, availability, retainability, voice quality.

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Herman Mikkelsen Ylander, Gothenburg, June 2019

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1
Introduction

Ubiquitous mobile connectivity is something that, ever since the release of GSM, is taken for granted. This is the case everywhere in society, in particular, onboard trains. Just like at home or in the office, Passengers expect cellular voice services to be available at all times, in order to, e.g., conduct business while travelling. According to the Swedish Post and Telecom Authority (Post- och Telestyrelsen PTS) the amount of outgoing mobile voice minutes has increased dramatically since the year 2000, as illustrated in figure 1.1 [1].

From the train operators point of view, being able to provide constant cellular voice services, is an important service when competing against alternative transportation methods, such as aviation.

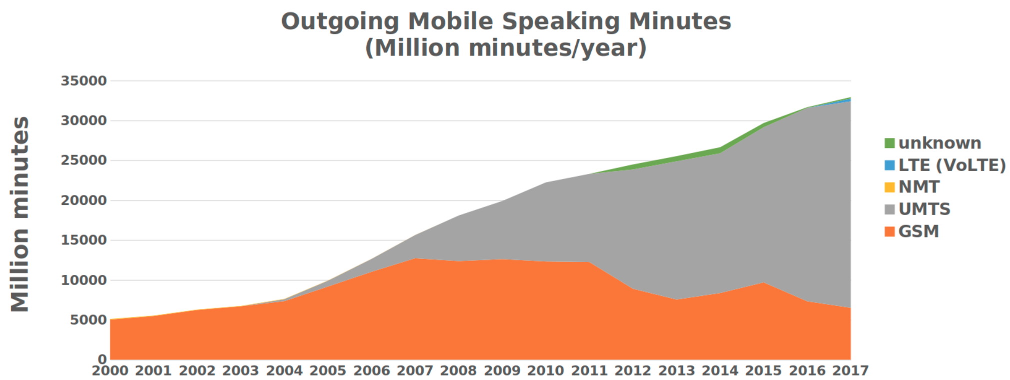


Figure 1.1: Outgoing mobile voice minutes in Sweden, data is taken from PTS[1]

For multiple reasons, the task of providing cellular coverage onboard trains has proven to be difficult for the network operators. The main reasons being the vast rural distances the inter-city trains travel, the structure of the train and the high load on the radio network serving the area in which the train travels through [2]. The design of the train carriages causes severe problems with radio signal attenuation, due to the metallic body and the metal film often being used in windows for onboard climate reason [3].

To improve the cellular reception onboard, mobile network providers and train operators install repeaters in the train carriages connected to antennas on the roof [4]. These repeaters are usually so called Amplify-and-forward, which amplify the signal within a specific frequency band, in order to match the signal strength levels outside the train. However, not only are these repeaters expensive, but they also cause undesired effects such as interference with mobile users surrounding the train, self oscillating effects and high load on the cellular network due to the high amounts of simultaneous handovers [3][5].

Over the past 30 years the mobile networks have gradually evolved from circuit-switched systems toward packet-switched (IP) for both data and voice services. Already in the early 2000's voice over IP network technologies (VoIP) were developed e.g. Skype. With the introduction of 3G, IP was introduced in the mobile networks. Hence making it possible to use VoIP as a cheap alternative to the traditional circuit-switched voice services provided by the mobile operators. In order to compete with cheap Over-The-Top (OTT) services, such as Skype, Whatsapp, Viber etc, that provide voice over IP (VoIP) services, mobile manufacturers and mobile network providers have introduced Voice over WiFi (VoWiFi). VoWiFi is an IP based voice service, that allows real-time IP packets carrying voice over the WiFi network. For VoWiFi to be an alternative to regular voice services on trains, a stable, onboard WiFi network is required.

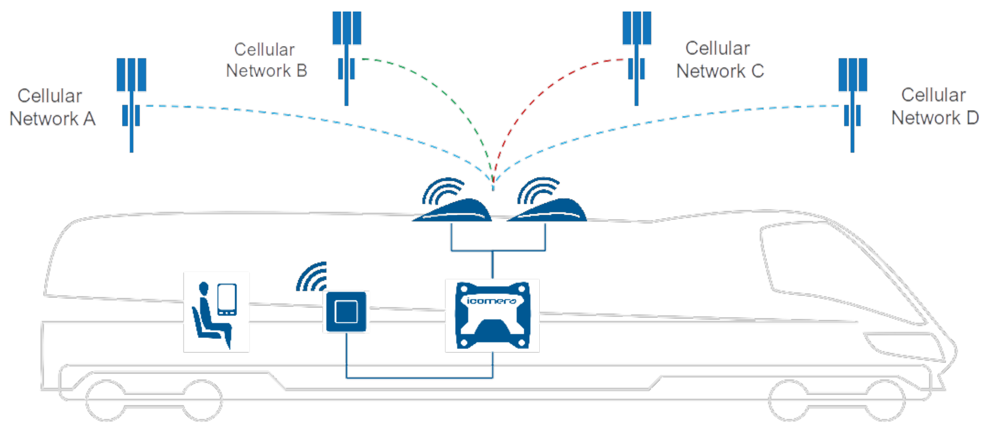


Figure 1.2: Icomeras onboard Wi-Fi solution [courtesy of Icomera AB]

There are several ways of providing WiFi to train passengers today. Typically the onboard WiFi network is provided by a router directly, or via access points located in the carriage, as illustrated in figure 1.2. The router is usually connected to one or several antennas located outside the train carriage, and connected to the internet through a communication link. This communication link can be provided through, a satellite over the LTE network, using a specific mobile carrier or over several network providers' LTE networks using link aggregation. Since real-time voice communication is sensitive to latency, satellite communication is not the best option due to the vast communication distances.

Icomera's WiFi solution is a technology that uses link aggregation to provide WiFi on trains and is illustrated in figure 1.2. This solution makes it possible to do load balancing of the data traffic over the different links to optimize performance. By using this WiFi solution, redundancy to onboard communication is added, since in the case of failure in one link, there are several other link that can be used [6]. Figure 1.2 also shows that multiple cellular networks outside the train can be used, resulting in improved coverage, and figure 1.3 illustrates the strength on link aggregation when it comes to capacity.

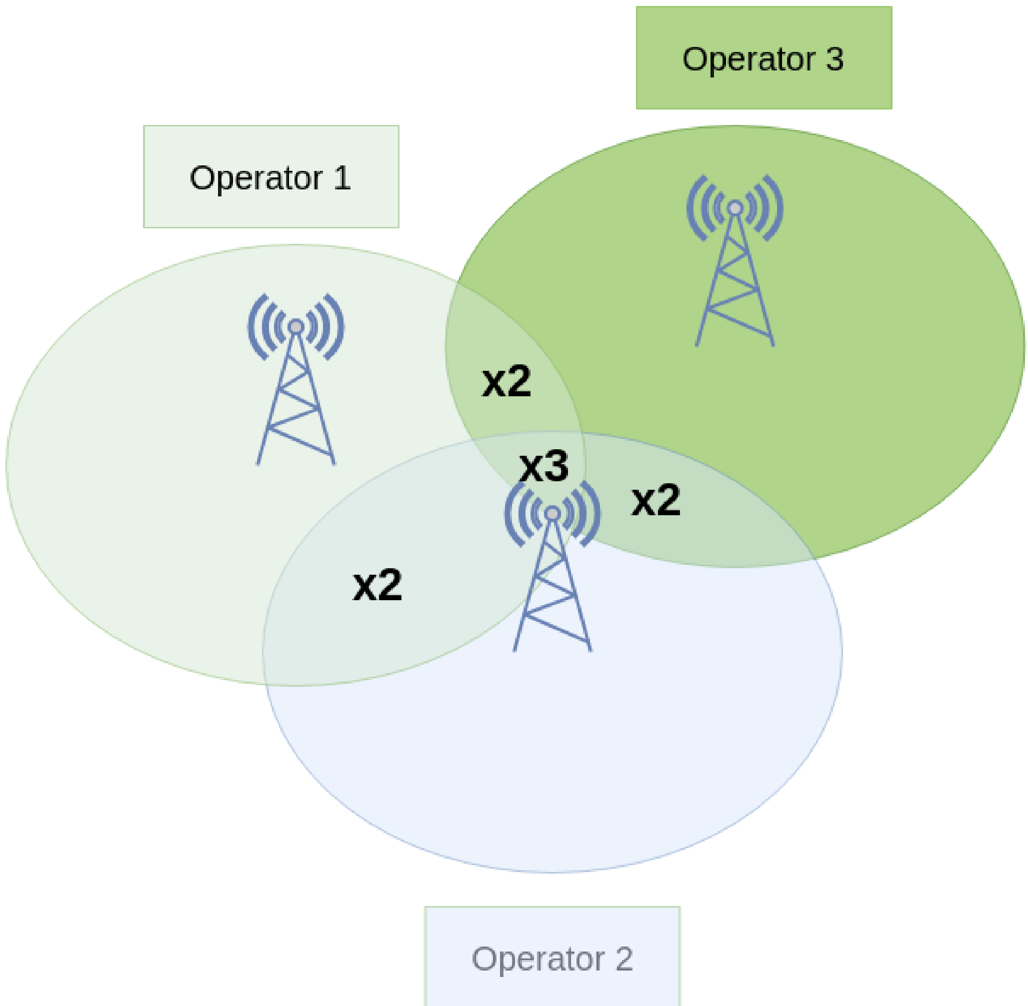


Figure 1.3: The effects on network capacity due to link aggregation [courtesy of Icomera AB]

1.1 Voice in cellular networks

There are predominantly two types of network topologies used to transport voice over the cellular networks. The traditional Circuit-Switched network topology (CS) and the Packet-Switched topology (PS). In circuit switched networks a dedicated bandwidth is assigned to each voice call. This allows the user(s) to utilize the full bandwidth, and a certain Quality of service (QoS) is guaranteed. For packet switched networks however, the user(s) do not occupy the entire bandwidth when performing voice calls, instead the sampled voice IP packets are routed independently over the internet [7][8]. Figure 1.4 illustrates the an example of each network topology. The older generations, i.e. 2G and 3G carries cellular voice over the CS network and the Public Switched Telephone Network (PSTN). The newer LTE network uses the PS network for both voice communication as well as data traffic.

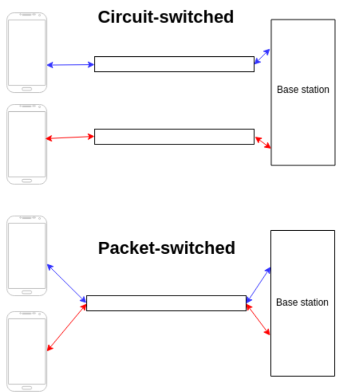


Figure 1.4: Illustration of the use of channel resources in circuit-switched and packet-switched radio networks

1.2 Scope

The objective of this master's thesis is to assess different technologies for providing voice services onboard the government owned Swedish train operator SJ's X2000 trains operating on the route Gothenburg-Stockholm. SJ's X2000 trains operating on the route Gothenburg-Stockholm, Sweden. The thesis will be limited to cellular voice services, and the ability to make calls onboard. OTT VoIP services (e.g. Skype) will not be assessed.

The onboard cellular repeater provides coverage inside the train, and enables the use of 2G, 3G and LTE (VoLTE) voice services, while the onboard Wi-Fi network enables the use of VoWiFi.

The ability to establish a call (Availability), to maintain a call (Retainability) and the voice quality will be evaluated separately for each generation cellular network and for VoWiFi. Finally, a comparison of the previously stated key performance indicators (KPI) will be made in order to determine the optimal solution for providing the passengers the best quality of experience service (QoS) possible.

The measurements will be conducted through a, so called, “Drive test”, meaning that they will take place on board the train, and not in simulations or in ideal laboratory environments.

1.3 Aim and contribution

The aim of this master’s thesis is to compare different technologies for providing voice services onboard trains. The goal with the outcome of the thesis is to provide alternative methods for offering train passengers reliable and stable voice services, and improve the Quality of Experience (QOE) when traveling by train. The goal with the results is not only for the train operators to get better knowledge of the onboard speech service quality, but also for the network providers when planning the network. The thesis will be divided into the following substudies:

- Evaluate the GSM and UMTS network, and measure the relevant voice KPIs.
- Evaluate the VoLTE and VoWiFI network, and measure the relevant voice KPIs.
- Evaluate and compare the voice quality of the network generations of interest.

1.4 Previous work

There are several previous studies and investigations done, in order to improve cellular connectivity on board trains. Many are strictly theoretical, but some are also based on field measurements. Papers such as [6] and [9] focus on providing high throughput on board trains, using carrier aggregation with multiple MIMO antennas mounted on the roof. In [2] the authors evaluate the performance of using onboard amplify-and-forward repeaters compared with using direct transmission from macro sites. In [10], the authors analyse different repeater deployments based on field tests from dense urban city centers and sparsely populated rural areas, in contrast to a static repeater configuration. In [3] the authors conduct measurements in order to identify and optimize No Service areas, on board a test train in Austria. In [11] the author evaluates the use of RF repeaters in buildings in order to improve speech coverage and capacity inside buildings. Here the author also clearly describes the importance of good network planning when installing repeaters, so that it does not degrade the performance of the up/downlink. However, to the best knowledge of the author of this thesis, there has been no previous study of cellular voice and the performance of calling over Wi-Fi on board trains before. The aim of this thesis is to fill that void.

2
Voice over wireless systems

There are several factors that have a direct impact on the quality of the voice call in a mobile wireless systems. One factor is the characteristic of the RF signal itself, and the effects caused when propagating through different environments. If the signal is too weak, or the quality of the signal is too poor, in terms of Signal-to-noise ratio (SNR), the user will experience disturbances in keeping or establishing a voice call. Another factor, that may degrade the QoS is the capacity of, or load on, the wireless radio network. These factors have proved to cause severe complications in communication on board trains. If a train travels through a sparsely populated area where the mobile network is optimized accordingly, there might be disturbances if, for example, hundreds of passengers are trying to establish or retain a voice call simultaneously.

This chapter describes the theory behind providing capacity for voice services in a wireless network. for circuit-switched networks queuing theory, in terms of Erlang Bs blocking probability, will be described while resource blocks for VoLTE is explained. Finally cellular repeaters are described, which are used onboard the SJ X2000 trains. The network architectures for GSM, UMTS and LTE are presented in appendix A.

2.1 Voice dimensioning in circuit switched mobile networks

In a cellular radio network, each base station's (BS) coverage area is called a cell, and is often illustrated with a hexagonal area, as shown in figure 2.1. When a mobile phone (UE) is turned on, or enters a cell, the UE will automatically attempt to establish a connection to the BS.

As can be seen from figure 2.1, every neighboring cell uses different radio resources , in order to avoid interference, and the cells have a size R and a reuse distance D [12]. These radio resources can be frequency, time or codes depending on the generation of the wireless network.

When designing and optimizing a network for voice traffic it is important to assume a certain traffic pattern, in particular the traffic volume in peak hour which is used for dimensioning. In cases when several UEs in a coverage cell initiate a call simultaneously, there is always a chance that the serving base station is congested, i.e. there are no available radio resources, and some UEs will be denied service in the form of a dropped or blocked call.

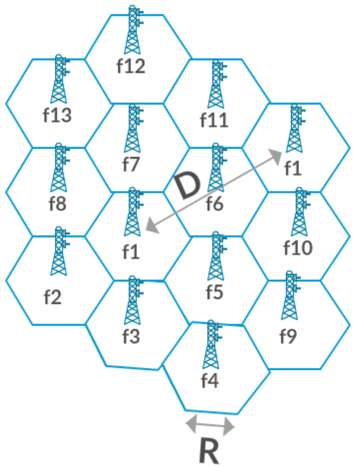


Figure 2.1: Cellular system layout, and frequency planning.

The probability of calls being blocked, in circuit-switched systems, is estimated using traditional teletraffic models which are based on queueing theory [12]. An Erlang is a unit of telecommunications traffic measurement and describes the continuous use of a voice path, through the wireless radio network, and is used to describe the total traffic volume of one hour.

There are several traffic models that use the Erlang unit, and are used to statistically estimate the required amount of lines (channels) in a network, the most common one being Erlang B. In telecommunication, the Erlang B formula is used to determine the amount of lines required, given a known busy hour traffic figure, and the number of blocked calls[13]. An example of a 24 hour voice traffic pattern is illustrated in figure 2.2, where the network providers optimize their network for busy hour traffic.

The Erlang B formula is defined as

$$E_\eta(\rho_c) = \frac{\frac{\rho_c^\eta}{\eta!}}{\sum_{k=0}^{\eta}(\frac{\rho_c^k}{k!})} \tag{2.1}$$

where η is the number of available serving channels, ρ_c is the total offered traffic, given in Erlangs, and $E_\eta(\rho_c)$ is the probability of blocking [13].

Traditionally the mobile network operators are required to optimize their networks such that the blocking probability is less than than 2 %. In Sweden this threshold was set by PTS in the spectrum licence agreement. The Erlang B formula can be used in order to calculate the amount of lines needed in each cell in order to fulfill PTS requirements, and at the same time minimize the economic cost of the network.

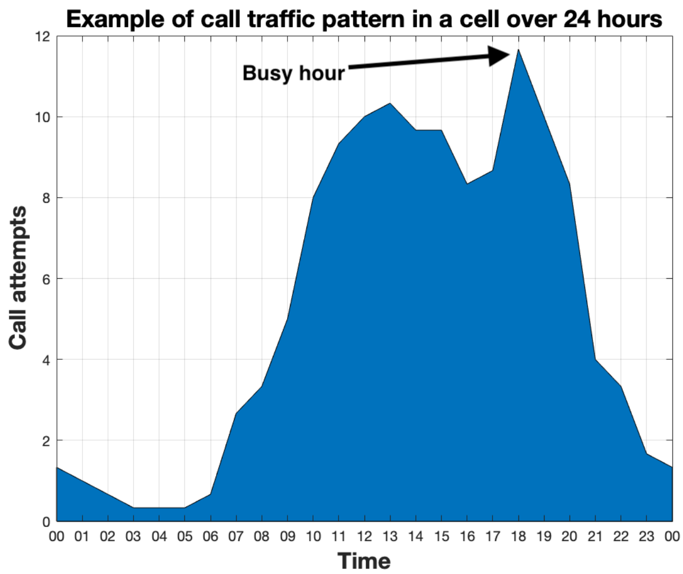


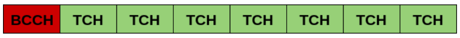
Figure 2.2: Traffic patter over 24 hours. Mobile network providers optimize for peak hours burst in call attempts.

2.2 GSM Voice Capacity

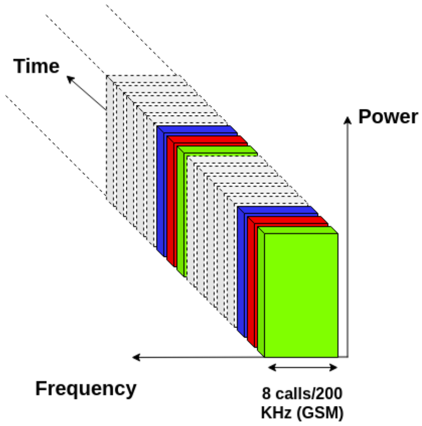
With the growing demand for cellular connectivity in the late 80s', it became clear that the existing first generation analog mobile network would not meet the demands for the coming centuries [14]. Therefore, in the early 1990s, the second generation (2G) network emerged, and unlike its analog predecessor, it was a fully digital network. The GSM network was originally designed for the 900 MHz band, however today it also operates over the 800, 1800 and 1900 MHz bands[14].

GSM uses a time division multiple access (TDMA) scheme. In TDMA each UE is assigned a specific time slot where it is allowed to transmit and receive over the entire bandwidth as illustrated in figure 2.3b. In GSM there are 8 time slots per frame. However, one slot is used by the Broadcast control channel (BCCH) as a signaling channel, resulting in only seven available traffic channels (TCH)[14]. Each GSM channel has a bandwidth of 200 kHz, where each user is assigned a 577 μs time slot every 5.615 ms. An illustration of the GSM downlink frame structure is presented in figure 2.3a[14].

Considering a simple example where there are 1000 users located in a specific cell, and that 10 % of these users make calls during busy hour each voice call lasting for 12 minutes. This results in; 100*12 = 1200min $\rightarrow$1200/60 = 20 Erlangs. In order to dimension a GSM cell for 20 Erlangs, formula 2.1 is used together with the 2 % blocking threshold and the frame structure illustrated in 2.3a, and gives the values;



(a) Downlink frame structure for GSM



(b) The TDMA channel access

Figure 2.3: GSM radio specifications

- One channel ⇒ 7 TCH, with 2 % blocking results in 3 Erlangs.
- 2 channels ⇒ 15 TCH, with 2 % blocking results in 11 Erlangs.
- 3 channels ⇒ 23 TCH, with 2% blocking results in 16 Erlangs
- 4 channels ⇒ 31 TCH, with 2 % blocking results in 23 Erlangs,

therefore 4 GSM radio channels in this specific cell are required to handle busy hour voice traffic.

2.3 UMTS Voice Capacity

The Universal Mobile Telecommunication system (UMTS), also known as the third generation (3G) network was standardized and released in year 2000. UMTS uses Wideband Code Division Multiple Access (WCDMA) as its multiple access technology. Similar to GSM, UMTS uses the circuit switched network technology for voice services, and packed switched network for data services.

There are several advantages of using CDMA, as opposed to TDMA and FDMA, in cellular voice services. One advantage is that it allows several users to simultaneously access the time and frequency resources, as illustrated in figure 2.5b. This turns out to be more efficient in cases of long periods of silence in voice calls [15]. Another advantage is that the entire frequency band can be used in each cell, i.e the reuse factor D from figure 2.1, is set to one. This is due to the fact that frequency is not the shared channel resource, and interference from neighboring cells will not effect the capacity.

There are predominantly two codes that are used when modulating a WCDMA information sequence; the Channelisation code and the Scrambling code. Figure 2.4 illustrates the binary modulation of a voice data sequence in WCDMA.

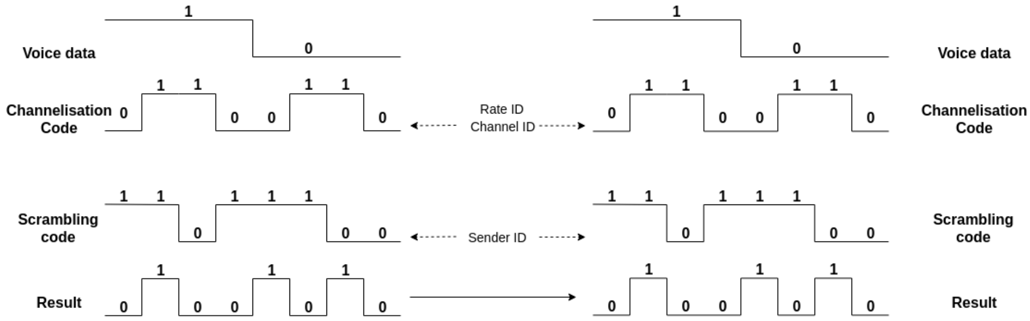
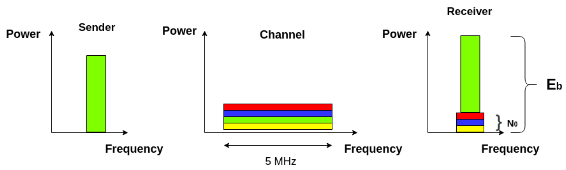
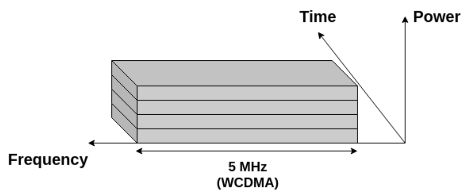


Figure 2.4: An illustration of the codes used in WCDMA, in order to spread the narrowband voice data to a wideband code

The channelisation code is used in both the uplink (UL) and downlink (DL). In the DL it is used to separate the connection between the UEs hence, each UE has its unique channelisation code. In the UL it is implemented in order to separate the various control channels from the actual data channels [16]. The channelisation code spreads the voice data over the entire bandwidth of 5 MHz, and each code is orthogonal with respect to each other. Figure 2.5a shows the transmission of WCDMA data in the frequency domain. It illustrates that the narrowband voice data is modulated over a wideband (5 MHz) spectrum [17].



(a) The narrowband voice data is spread over a 5 MHz bandwidth. The received signal power includes a noise N0



(b) Multiple users share frequency and time resources in CDMA. WCDMA channels have a bandwidth of 5 MHz

Figure 2.5: The CDMA channel access. Power is the common shared resource in CDMA. The more UEs that transmit the higher received power at the receiver (a). CDMA users share time and frequency (b)

The scrambling code is also used in both the UL and DL. In the DL it is used by the UE to determine what base station to receive information from, i.e. determining the correct serving base station. In the UL the scrambling code is used by the BS to differentiate the signals received from multiple UEs simultaneously. The scrambling code is used in WCDMA to separate the base stations, in a similar way as frequency is used in GSM. The scrambling code does not change the signal bandwidth, and is usually a pseudo-random code [16].

In WCDMA, power control is used in both the UL and DL to minimize the interference by ensuring that sufficient transmission power to each UE is used[16][18]. The common pilot channel (CPICH) is used as reference, in order to determine a rough estimate of the path loss and to adjust the transmit power accordingly. In UMTS, the common shared resource between all users is power. Since multiple users share the same channel, the network planning procedure cannot separate the capacity and coverage planning due to the amount of users that simultaneously transmit (capacity). This will affect the receivers noise power levels (coverage) [15]. This implies that as the amount of users increase in a cell, the UEs at the edge of the cell will experience a degraded signal, resulting in a smaller coverage area[18].
[17] shows that the amount of simultaneous users in a call M is calculated using

$$M = 1 + \frac{\frac{G}{\rho} - \frac{P_N}{P_s}}{\nu(1 + f_{UL})} \tag{2.2}$$

where G is the gain, ρ is the required SNR at the receiver, P_N is the noise power, ν is the activity ratio and f_{UL} is the ratio between the neighboring cells frequency and the active cells frequency. The load factor is calculated using

$$\eta = \frac{(1 + f_{UL})(M - 1)\nu P_s}{(1 + f_{UL})(M - 1)\nu P_s + P_N} \tag{2.3}$$

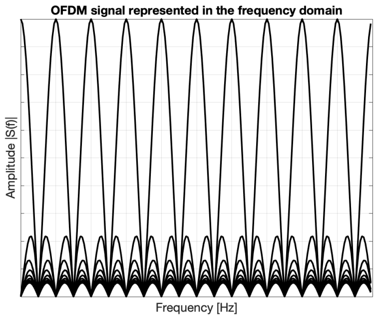
where one can see that both the amount of simultaneous users (M) and the load factor (η) directly proportional to the received power levels (P_s) at the base station. One can see that once the received power is set to a maximum ($P_s = \infty$), $\eta \rightarrow 100\%$ and the maximum amount of simultaneous users will be saturated and any further increase of transmit power will not help increase capacity[17], thus resulting in the UEs furthest away from the base station (cell edge) experiencing degraded coverage.

It is slightly more complicated to calculate the cell capacity in a UMTS mobile network. This is due to the fact that other parameters such as the distance from the mobile to the base station and the interference level affect the Erlang capacity [19]. In [19] Holma et al calculates the amount of traffic channels by using an assumed link-budget. The link-budget assumes realistic parameters such as: a bit rate of 12.2 kbps (Speech) a $Eb/N0$ of 4 dB (speech), blocking probability of 2 % as well as a noise rise of 50 %. With this assumed link-budget [19] calculates 61 channels per cell, resulting in $\sim$ 51 Erlangs per cell.

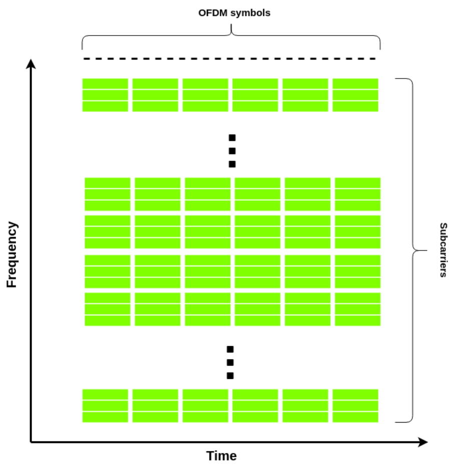
2.4 LTE and VoLTE capacity

The 4th generation wireless mobile network, Long Term Evolution (LTE) was introduced in 2010[20]. Unlike the earlier mobile network generations, LTE is strictly an IP based network[20]. LTE uses a multiple access technique known as Orthogonal frequency-division multiple access (OFDMA), where data is encoded over several narrow band sub-carrier frequencies and time slots.

VoLTE is the service used to perform calls over the LTE network. Traditionally the LTE network was designed for data traffic, and would fallback to the circuit-switched networks (UMTS or GSM) when voice calls are performed. However this turned out to introduce problems for the mobile network providers, as well as for the users, and therefore VoLTE was introduced. Since VoLTE operates strictly over the packet switched network, the traditional Erlang capacity models have to be substituted with IP-based models.



(a) OFDM signal represented in the frequency domain with 10 subcarriers.



(b) Representation of OFDM (and LTE) channel resources. Both over frequency and time.

Figure 2.6: The representation of the OFDM the channel access used in LTE, with an illustration of the signal in frequency domain(a) and an illustration of the channel resources (b)

In LTE, the radio resources are defined in resource blocks (RB) and are determined by the amount of OFDM sub carriers in the allocated bandwidth. Figure 2.6b illustrates a RB, that is divided into resource elements (RE) over both frequency and time. A RB is the smallest unit a user can be assigned by the schedulers in the LTE BS (E-NodeB), and consists of 12 adjacent OFDM subcarriers and one 0.5 ms time slot with a sub carrier spacing of 15 kHz[21][22]. Each RB usually consists of 84 resource elements. However, this depends on the length of the cyclic prefix [22].

In order to determine the capacity of an LTE cell, where VoLTE calls are made, knowledge of the IP packet size of each VoLTE call is required. The packet size depends on multiple parameters, such as; the radio conditions, the codec used for the call and the E-NodeBs compression capabilities [8]. The radio channel quality unit in LTE is known as channel quality index (CQI), and determines the modulation, coding scheme and the amount of RBs the E-NodeB scheduler should assign each user. CQI is an integer from 1-15, and the corresponding characteristics are presented in table 2.1. Users with high CQI will be assigned more RBs than users with low values, such as users close to the cell edge [23].

Table 2.1: Channel quality indicator for LTE with corresponding modulation, code rate and spectral efficiency

CQI	Modulation type	Code rate x 1024	Efficiency
0		To poor signal. No reception	
1	QPSK	78	0.1523
2	QPSK	193	0.2344
3	QPSK	449	0.3770
4	QPSK	378	0.6017
5	QPSK	490	0.8771
6	QPSK	616	1.1758
7	16-QAM	466	1.4766
8	16-QAM	567	1.9142
9	16-QAM	666	2.4063
10	64-QAM	772	2.7304
11	64-QAM	873	3.3223
12	64-QAM	711	3.9024
13	64-QAM	797	4.5234
14	64-QAM	885	5.1161
15	64-QAM	948	5.5547

Table 2.1 illustrates the different CQI levels from 1 (being the worst) to 15 (being the best), with their corresponding modulation type, code rate and efficiency.

Assuming the 3GPP AMR-WB codec with 12.65kbps is used, and perfect radio conditions, i.e. a CQI of 15 one can calculate the capacity of VoLTE cells[24]. VoLTE packets are transmitted every 20 ms[25], resulting in a data size of $12.65 \cdot 20 = 253$ bits every 20 ms. Including the IP header, RTP header and the payload results in a frame size in the order of 320 bits [26]. With a CQI of 15, $\log_2(64) \cdot \frac{948}{1024} = 5.553$ bits are carried per symbol, a single RB can then carry $5.553 \cdot 14 \cdot 12 = 932$ bits, which is almost 3 VoLTE calls. However, the smallest amount of RBs that the BS can schedule a user is one, therefore with a CQI of 15 each user requires one RB for a VoLTE call. Hence, with a bandwidth of 5 MHz, 25 RBs are generated every 1 ms. During 20 ms, $15 \cdot 20 = 500$ RBs are therefore available.

2.5 Cellular radio repeaters

Radio repeaters are used to increase the coverage area in environments where building new base stations are not a feasible option [27]. Cellular repeaters are usually deployed in environments where, for some reason, the RF signal is severely attenuated, or to provide coverage to environments located beyond the coverage area of certain cells. These scenarios can be in cities, where buildings are blocking the signal path, in rural scarcely populated areas where obsticles like mountains attenuates the signal, on board public transportation where the metallic construction of a train causes significant attenuation of signals or in tunnels.

On board the X2000, radio repeaters are installed to overcome the shielding effects of the walls and windows of the train carriages. The repeaters are analog, band-selective, bi-directional amplifiers, which means that they will amplify both undesired noise as well as the actual desired signal within the supported frequency band[28]. The repeater amplifies the signal in two directions, from the UE on board the train(uplink) and from the base station to the UE(downlink). The repeater will therefore increase, not only the signal power, but also the noise power. The noise power of the output of the repeater is calculated using

$$N = 10\log_{10}(N_0 B) + G + NF \tag{2.4}$$

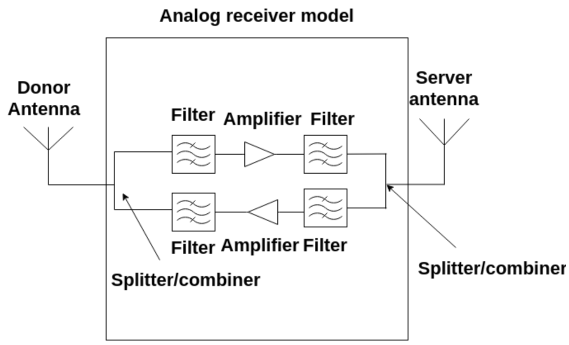
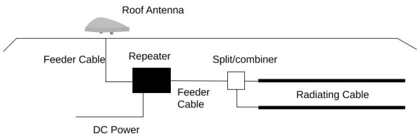


Figure 2.7: Basic model of a amplify-and-forward cellular analog repeater

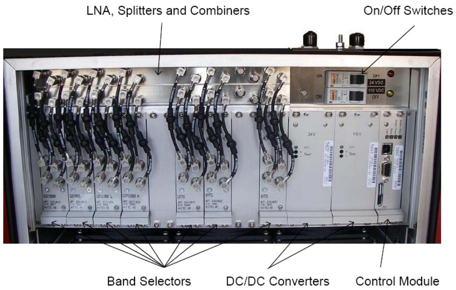
where G is the gain, N_0 is the thermal noise spectral density, B is the bandwidth and NF is the noise figure [10]. The noise figure, NF, depends on the performance of the repeaters. For the installed repeaters on X2000 the NF is $\sim$ 4.5 dB for the DL and $\sim$ 7.5 dB for the UL, over all supported frequencies.

Figure 2.8a illustrates a block diagram of the repeater installation for SJ X2000. One can see that there is only a single antenna mounted on the roof, for each repeater, which means they do not support Multiple Input Multiple Output (MIMO) communication.

The gain G is not static, and depends on the outside signal strength, as well as the isolation between the donor antenna and the server antenna. According to [10], the gain should be at least 15 dB lower than the isolation between the two antennas, in order to avoid feedback loops and the cause of oscillations. In order to avoid these self oscillations repeaters regulate their gain using automatic gain control (AGC) that regulate the gain to the server antenna.



(a) Block diagram of the repeater installation for SJ's X2000



(b) Inside the repeater onboard SJ's X2000

Figure 2.8: Illustrations of SJ's X2000 configuration

A block diagram of the configuration onboard the X2000 train is illustrated in figure 2.8a. Figure 2.8b shows what the repeaters looks like underneath the protective box and the main components are marked.

2.6 VoWiFi

When an UE performs a VoLTE call, it communicates over the Evolved Packet Core (EPC) through the LTE base station. The LTE radio network (E-UTRAN) is however not the only access technique available, in order to communicate with the EPC[29]. Figure 2.9 illustrates the different radio access technologies. The Non-3GPP radio access methods are divided into two categories, the trusted and the non-trusted technologies. The network provider, operating the core network, decides if a network is trusted or not.
The fact that a non-3GPP network is trusted or not determines the path through which the IP traffic is routed to reach the packet gateway (P-GW) in the core network. Trusted network are usually operated by the network providers them selves and the security precautions required are controlled. In non-trusted networks, however, the IP-traffic is routed, using an IPSec tunnel to an additional gateway, before reaching the P-GW. This gateway is called the Evolved Packet Data Gateway(ePDG), and is used for security reasons, since the network provider does not trust the access network [29][30]. The voice packets are then routed to either the internet or PSTN, depending on the recipients voice service capabilities, e.g. a call from VoIP to GSM. The architecture is presented in figure 2.10.

VoWiFi is a packet-switched voice service that enables cellular voice over the WiFi network. The ability of calling over the WiFi network, in terms of VoIP, has been around for a long time, however these services require Over-The-Top (OTT) applications such as Skype. In order for the network providers to take back revenue from the OTT companies, VoWiFi has been integrated in modern smartphones working without any need for OTT applications. This gives the user a global ID in the form of a telephone number, also when connected to the WiFi networks, and does not require accounts on VoIP services. Introducing VoWiFi is also a cheap alternative

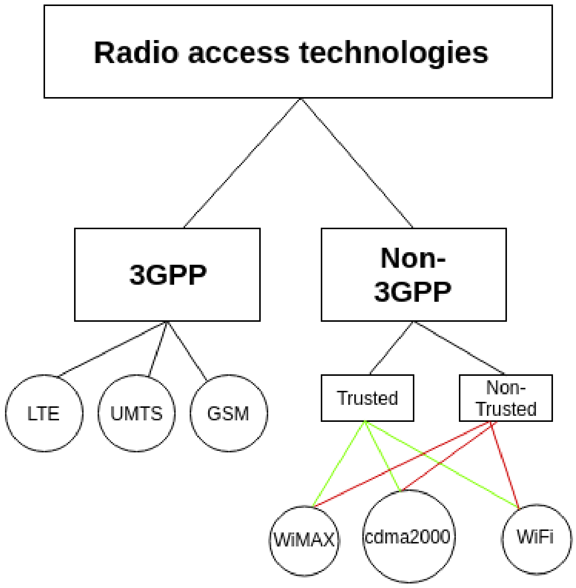


Figure 2.9: The different radio access technologies divided under their respective category.

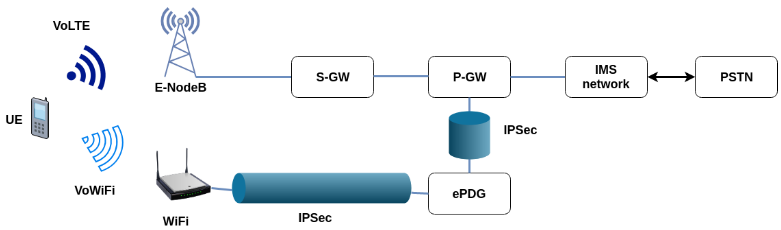


Figure 2.10: The architecture of a VoWiFi network. The WLAN is routed to the ePDG, and into the P-GW

to deploying additional infrastructure in , for example, indoor environments where coverage is poor[31].
On board SJ's X2000, the WiFi configuration is illustrated in figure 1.2, where the UEs, located throughout the carriages of the train, are connected with an access point over the IEEE 802.11 standard WiFi network supporting both the 2.4 or 5 GHz spectrum. Each access point is then connected to a modem, located in the central parts of the train, through a backend network either through Ethernet or wireless links. The data is transported from the modem via one or more antennas, located on the roof, over the LTE network to the carriers radio network through the EPC and to the Internet. The antenna array on the roof is illustrated in figure 2.11, and includes 8 antennas. When performing a voice call over VoWiFI, from on board the train, the voice data packets will be routed through the WiFi network, which will route the data over the radio network with the highest performance, and availability and to the Internet. This makes it possible to perform a voice call, even

Figure 2.11: The antenna array located on the roof of the bistro carriage on X2000. These antennas provide connectivity to Icomeras onboard WiFi network.

through there is no cellular coverage from the subscribed network provider.

3

Measurement Methods

In order to determine the availability, retainability and speech quality for the different technologies used for providing voice services, on board the SJ X2000 train fleet, multiple so called "Drive-tests" were performed. A drive-test is a method used, often by network providers, to measure the quality of their networks in specific geographical areas. A drive test provides better knowledge of the actual user experience, as opposed to software simulations of the network, where more general signal propagation models of stochastic channels are used.

This chapter describes the methods used to collect data used for the benchmarking of voice service technologies. The chapter also describes the design of the train carriages, the route of the drive test, the software used to gathers data, as well as the equipment used. An illustration of the X2000, which is the train model where the measurements were conducted, is presented in figure 3.1.

Figure 3.1: The train model X2000 where the measurements were conducted

3.1 The measurement setup

The drive-tests were performed on the busy route between Gothenburg and Stockholm, Sweden. The route is approximately 500 km with a traveling duration of roughly 3 hours. A map of the entire route is presented in figure 3.2. The route runs mostly through sparsely populated areas on the country side, with the exception of some small cities along the way.

The onboard repeaters are located in the overhead compartment in each carriage of the train, as illustrated in figure 3.3. Each repeater is connected to an antenna located on the roof outside the carriage.

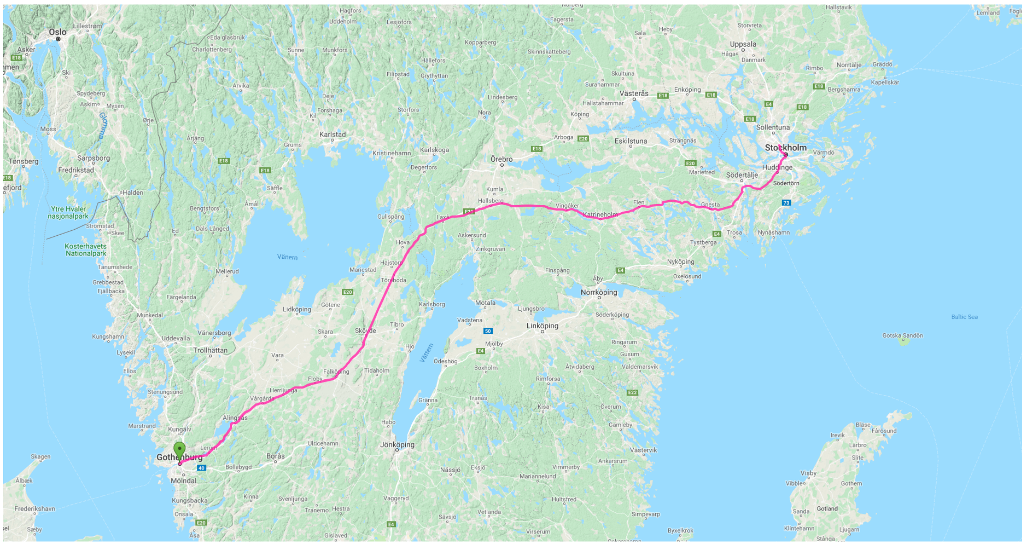


Figure 3.2: The X2000 route between the Swedish majors cities of Stockholm and Gothenburg

Figure 3.3: The onboard repeater, located on the overhead compartment in each carriage

Figure 3.7 shows the entire design of the train carriage, with a leaky coaxial cable in the ceiling, connected to the repeater at the rear end. This radiating cable distributes the radio signals from the repeater inside the carriages. The measurement equipment used for the test was placed on the table in front of the seat about 50 cm meters from the ground, and with a distance of approximately 2.5-3 m to the radiating cable above.

Figure 3.4: Overview of the train carriage from the back. The repeaters is located on the overhead department in the front, and the leaky cable is located in the ceiling

All measurements were conducted onboard SJs X2000 trains. However the specific train was not kept constant and could vary from the entire X2000 fleet. The position onboard the train was not kept constant, since this proved to be hard to accomplish in practice, due to the binding seat number of the train ticket. However, every drive test was conducted from a window seat, since the GPS required direct contact, in order to receive a signal. All tests were conducted from 2nd class carriages, i.e. carriage number 3-7.

The voice services for each generation of cellular network were tested in separate drive tests. However, the phone was not locked onto any specific frequency band within the network generation. For example GSM could be utilizing either the 900 MHz or the 1800 MHz frequency bands. The Swedish frequency bands and their corresponding network standards are presented in table 3.1.

During drive-tests voice calls were made, and the availability and retainability were calculated using (3.1) and (3.2) respectively.

$$\text{Retainability} = 100 - (100(\frac{\sum \text{dropped calls}}{\sum \text{call attempts}})) \tag{3.1}$$

$$\text{Availability} = 100 - (100(\frac{\sum \text{blocked calls}}{\sum \text{call attempts}})) \tag{3.2}$$

Table 3.1: The various network generations with their corresponding frequency bands in Sweden

Network generation	Frequency band [MHz]
GSM	900
	1800
UMTS	900
	2100
LTE	800
	900
	1800
	2600

3.2 Network quality parameters

Depending on the generation of the mobile network, there are different parameters used to determine the network quality. The quality of the network is determined by both the signal strength at the receiver (in order to achieve sufficient coverage) and the quality of the signal in order to be able to provide high quality services.

The quality of a RF signal is often measured as the received SNR. The network performance parameters for the different generations of mobile networks are presented in table 3.2.

Table 3.2: Network performance parameters for GSM, UMTS and LTE

Mobile network generation	Signal quality	Signal strength
GSM	RxQual[0-7]	RxLev[dBm]
UMTS	CPICH Ec/N0[dB]	CPICH RSCP[dBm]
LTE	RSRQ[dB]	RSRP[dBm]

In GSM the quality of the signal is determined by the RxQual, and is a measure of the Bit-error rate (BER) after demodulation. RxQual is an integer from 0 (being the best) to 7 (being the worst). Table 3.3 illustrates what RxQual values corresponds to what BER. To describe signal strength, a unit called RxLev is used which scales from 0-63 from the received signal strength indicator (RSSI)[14].

Table 3.3: RxQual values and corresponding BER

RxQual	**BER**
0	BER $\leq$ 0.2%
1	0.2%<BER$\leq$ 0.4%
2	0.4%<BER$\leq$ 0.8%
3	0.8%<BER$\leq$ 1.6%
4	1.6%<BER$\leq$ 3.2%
5	3.2%<BER$\leq$ 6.4%
6	6.4%<BER$\leq$ 12.8%
7	12.8%<BER

In order to determine the network quality of UMTS, the Common Pilot Channel (CPICH) is used [32]. The data carried in the CPICH is known by all UEs located in the same serving cell. The signal quality in UMTS is determined by the pilot channel quality per chip (code) divided by the received spectral density i.e. CPICH $\frac{E_c}{N0}$ dB. The signal strength is measured in the received signal strength of the CPICH, or the CPICH Received signal code power (RSCP). The transmitted signals strength from the BTS may vary from different network operators, but usually it is transmitted with 10 % of the total transmit power of the base station.

In LTE the radio parameters Reference Signal Received Power(RSRP) and Reference Signal Received Quality(RSRQ) are used to determine the signal strength and signal quality respectively. RSRP is determined by calculating the linear average over several resource elements that carry cell-specific reference signals [33]. The RSRQ is calculated using

$$RSRQ = N\left(\frac{RSRP}{RSSI}\right) \tag{3.3}$$

where, N is the number of resource blocks, and RSSI is the total received power including interfering channels, thermal noise, etc [33].

Table 3.4: Values of signal strength according to the network analyzing software

	GSM RxLev[dBm]	**UMTS CPICH RSCP[dBm]**	**LTE RSRP[dBm]**
Excellent	> -80	> -60	> -80
Good	-80 to -90	-60 to -85	-80 to -90
Fair to poor	-90 to -100	-85 to -95	-90 to -100
Bad	< -100	< -95	< -100

3.3 TEMS Investigation

The software used to evaluate the radio parameters, as well as to keep track of blocked and dropped calls, was the mobile network analysing tool TEMS Investigation. The test mobile phones had the TEMS software pre-installed making it possible to perform voice call scripts from the pc running TEMS Investigation. The test script built in TEMS dials a fixed number, and once the call is answered, it keeps the call for two minutes and finally hangs up. The calls were made to the Swedish speaking clock service "Fröken Ur". Fröken Ur will answer the incoming calls, and repeatedly say the current time and date. TEMS was also used to lock the test phones on the specific cellular network generation.

Figure 3.5 illustrates the script used in TEMS to perform the continuous 2 minute, calls, and figure 3.6 shows the TEMS interface, and the various parameters it collects during tests. TEMS collects network parameters, both from the serving cell, as well as neighboring cells. The log files, containing parameters such as, signal strength, signal quality, dropped calls and blocked calls, were then post processed and analyzed using Python scripts.

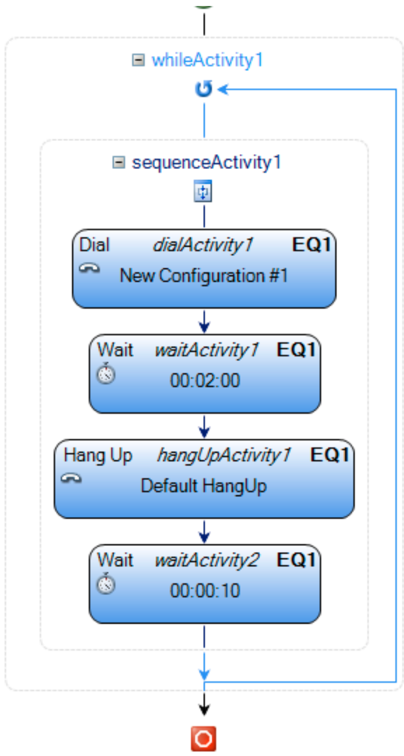


Figure 3.5: The TEMS script used to generate the continuous two minute calls

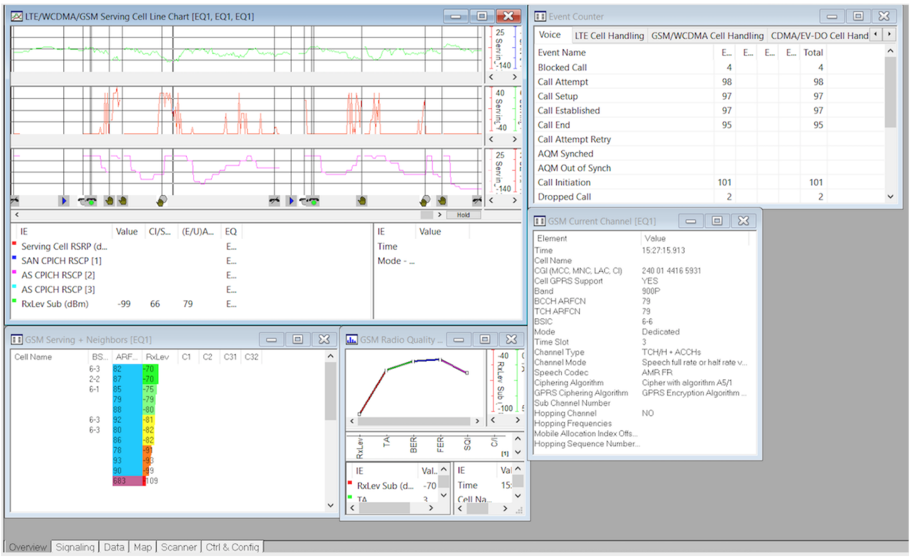


Figure 3.6: The TEMS Investigation interface with the various real-time data points. TEMS was used to gather data such as dropped calls, blocked calls and signal strength parameters.

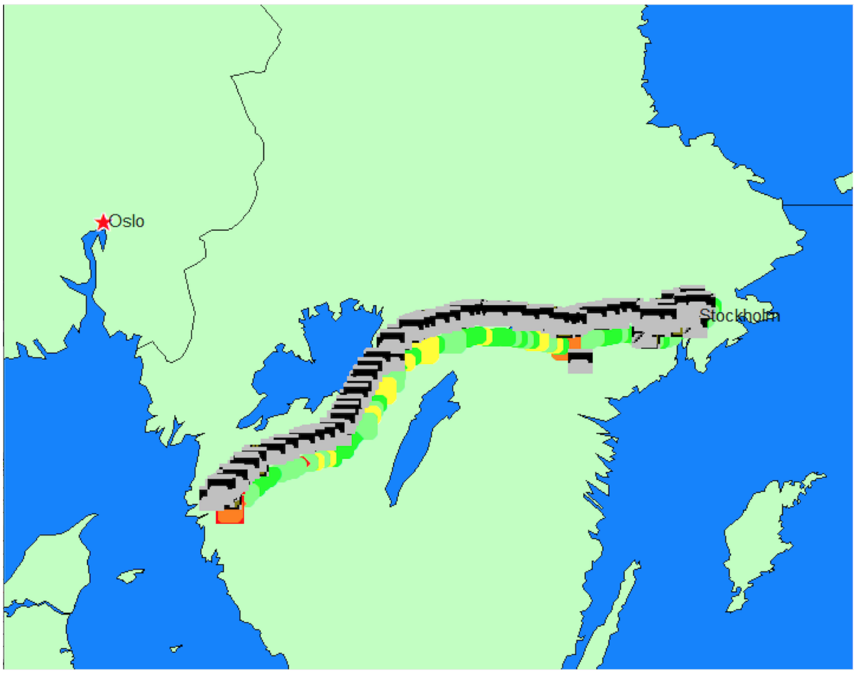


Figure 3.7: The GPS receiver provides the geographical coordinates for each TEMS Investigation sample point

3.4 Measurement campaign

This section describes the test methodology used, to gather the KPIs of interest for the different mobile network standards. When testing the older, circuit-switched networks, i.e. GSM and UMTS the same test phones were used. When conducting drive tests on the packet-switched networks the test phone had to be upgraded. Drive tests over all Swedish network providers were conducted, however, they will not be referred to by name in this report.

3.4.1 GSM and UMTS Meassurement Campaign

To evaluate the onboard speech Quality of Experience (QoE) for the GSM and UMTS network, three Sony Ericsson Z750i mobile phones were used. Each phone was connected to a different network operator making it possible to measure several networks for each drive test. Figure 3.8a shows the equipment used. It consists of one antenna, with gain $G \sim 3$ dBi connected to each test phone, a drive test suitcase including power supply to each phone, as well as a USB switch connecting each phone to the test PC with a USB cable. Figure 3.8b illustrates the setup of the test equipment on board the train. A GPS receiver was used to get the positioning coordinates for each data sample. Due to the shielding effects of the train carriages the GPS had to be stuck to the window to establish reception. Whenever a call is either dropped or blocked, it is reported as an event in TEMS Investigation. The GSM and UMTS coverage radio parameters were also logged and processed. The parameters are presented in table 3.2.

(a) GSM and UMTS measurement equipment

(b) The onboard setup

Figure 3.8: Measurement equipment and on board setup for GSM and UMTS

3.4.2 VoLTE and VoWIFI measurement campaign

In order to evaluate the performance of VoLTE and VoWiFI, the test phone was shifted to a Samsung Galaxy S9. Figure 3.9 illustrates the equipment used to analyze the packet based voice services. The test phone is connected to the PC running

TEMS Investigation through a USB type C cable. A GPS receiver is connected through a separate USB cable in order to get positioning data.

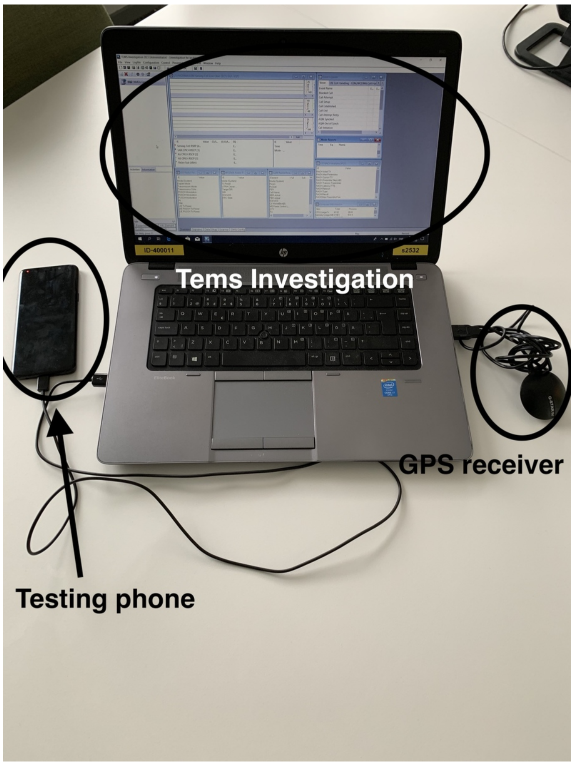


Figure 3.9: The equipment used to analyse the voice services VoLTE and VoWiFi

In order to determine a definite percentage of availability and retainability, many drive-tests had to be performed. However, due to the time limitation of this thesis only two drive-test for VoLTE and two drive-test for VoWiFi were conducted for each network provider. When testing VoLTE the test phone was locked onto the LTE network, and the same script as for GSM and UMTS was used.

However, for TEMS Investigation to be compatible with VoWiFI a custom phone has to be used. Such a phone was not possible to acquire in the time span of this thesis, and therefore the application "G-NetTrack pro" was used [34]. This application was installed on the Samsung Galaxy S9, and made it possible to perform continuous two minute calls. When testing the VoWiFi, the test phone was connected to the onboard WiFi, and flight mode was activated to ensure that the phone would not fall back to VoLTE.

3.5 Voice quality measurement campaign

The voice quality onboard was evaluated using the "Perceptual Evaluation of Speech Quality" (PESQ) algorithm. The algorithm compares the degraded voice sequence with a reference voice sequence. PESQ provides a subjective score of the voice sequence and was standardized in ITU-T recommendation p.862 in 2001 [35].

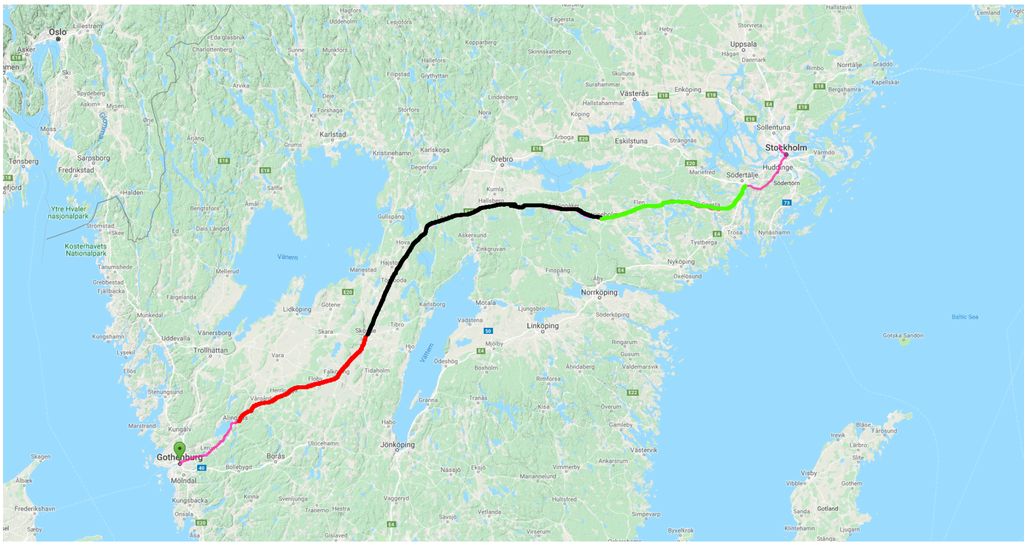


Figure 3.10: The segments along the route of which the voice quality was measured. The first segment is Allingsås-Skövde (Red), the second segment is Skövde-Katrineholm (Black) and the final segment is Katrineholm-Södertälje (Green).

An overview of the voice quality measurement configuration is illustrated in figure 3.11. Since PESQ requires a known voice sequence to be transmitted over the the voice call, an automatic answer client was programmed in Python, that answers every incoming call, and plays a known voice sequence. The voice sequence includes one male and one female voice, spoken in American English for a total duration of ≈ 120 s. The voice calls were recorded on 3 segments of the route between Stockholm and Gothenburg. The first one being from Alingsås to Skövde, the second one from Skövde to Katrineholm and the final one from Katrineholm to Södertälje. The segments are illustrated in figure 3.10. The total number of recorded voice calls were ~ 60. The voice quality was only evaluated for packet-switched voice, i.e. VoLTE and VoWiFi.
The Python answering client is tunneled to the internet through an IPSec tunnel to a cloud communication server where a phone number is assigned to the Python client. The cloud server is then connected to the mobile network through a gateway, and transmitted over the wireless channel. On the receiving side, onboard the train, is a cell phone connected with an 3.5 mm audio cable to a laptop. The laptop is running the recording software, "Audacity", making it possible to record every incoming voice sequence and save them as WAV files.

The PESQ score was then evaluated in the post processing procedure, using a python wrapper to compile the source code downloaded as a C file from ITU-T. The recorded calls were split into shorter voice segments, of approximately 10 s and compared with the reference tone. The PESQ algorithm returns a score ranging from 0.5 (being the worst) to 4.5 (being the best). This score is, however only used to compare the voice quality using this specific test method, and not to be used as a general Mean Opinion Score (MOS) and compared with other measurement methods. This is due

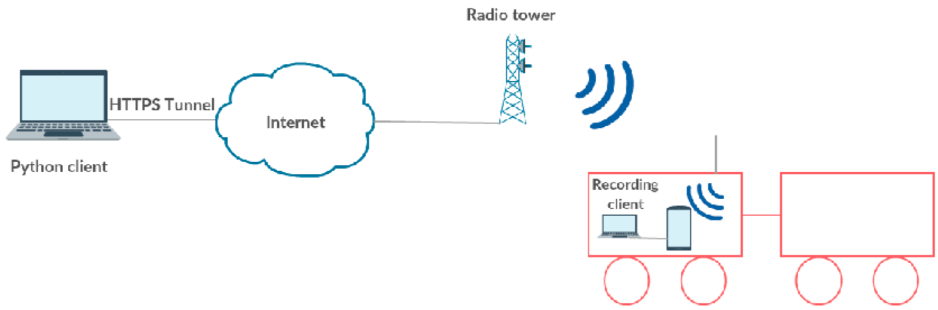
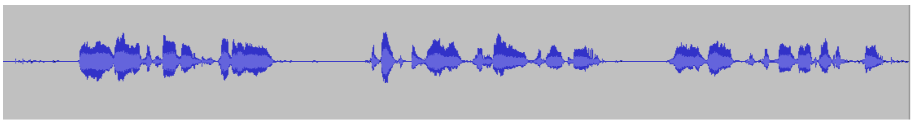


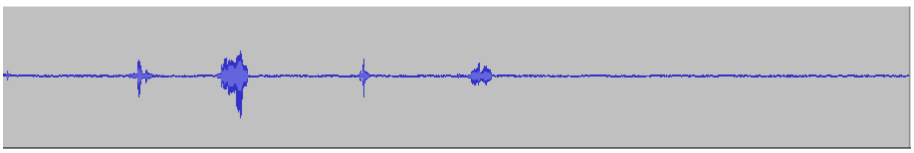
Figure 3.11: Overview of voice quality measurements

to the fact that the 3.5 mm audio cable will add some noise to the recorded voice tone, and this would not be the case if commercial testing phones would be used instead.

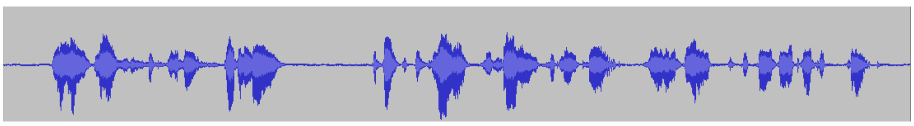
Figure 3.12 illustrates two voice sequence compared with the reference sequence in PESQ. Figure 3.12a is the first reference sequence used to compare the degraded signals. Figure 3.12b illustrates a VoLTE recording with a low voice score. One can see from this figure that the call is suffering from packet loss. Figure 3.12c illustrates a VoWiFi recording with a low score. This call is suffering from delays, and jitter. These recording have a duration of 8 seconds.



(a) One reference sequence



(b) Degraded VoLTE call, suffering from packet loss



(c) Degraded VoWiFi call, suffering from high latency

Figure 3.12: Illustration of the reference voice sequence, and two degraded recorded sequences, from Audacity.

4 Results

In Sweden there are four Mobile network operators. However, different mobile network operators might share radio network depending on the cellular network standard. In GSM one network operator has its own radio network, and two operators share the radio network. In UMTS two network operators share one radio network and two other operators share the second radio network. In LTE two Mobile network operators share one radio network and the other Mobile network operators have their own radio networks. In this thesis, the Network Operators are kept anonymous and referred to as MNOs.

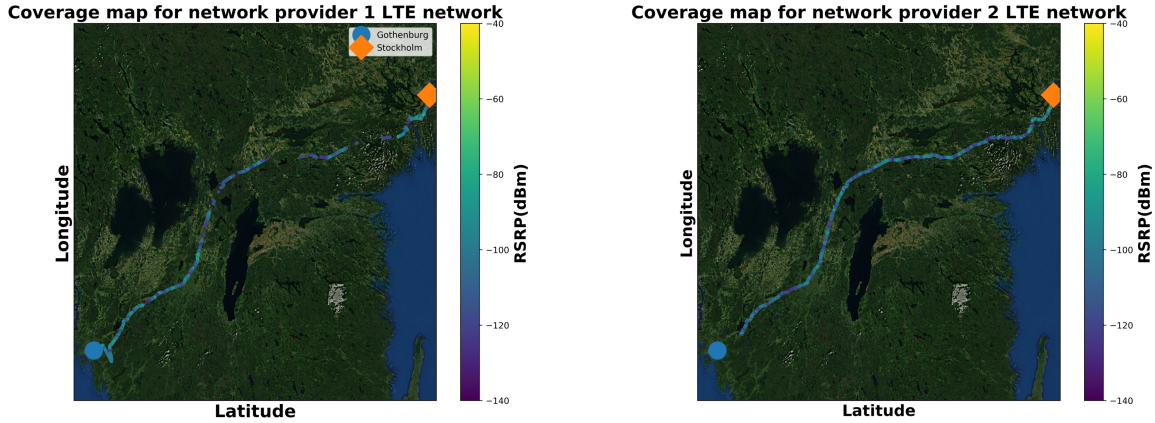
This chapter presents the results obtained from the measurement campaigns. The results include converage, availability and retainablity for the GSM, UMTS, LTE and WiFi networks on board X2000 trains on the route between Gothenburg and Stockholm. The cellular measurements are conducted both with and without the support of the onboard repeaters. In particular we present results from circuit-switched voice over GSM and UMTS, VoIP over LTE (VoLTE) and Wi-FI calling (VoWiFi). In addition the voice quality is evaluated for the packet switched services (VoLTE and VoWiFi).

4.1 Onboard coverage

The coverage onboard the X2000 train along the route is presented in this subsection. The signal strength parameters are presented separately for each voice technology and network operator. Figures 4.1 and 4.2 present the coverage along the entire test route. The data is illustrated with a heat map, where the darker color denotes worse the coverage.

The coverage parameters for GSM, UMTS and LTE are presented as cumulative distribution functions (CDF) and presented in in figures 4.3, 4.4 and 4.5. The log files containing, the signal strength parameters (RxLev for GSM, CPICH RSCP for UMTS and RSRP for LTE), were exported using CSV files from TEMS Investigation. These CSV files are then post-processed in Python. The CSV files from each measurement contains roughly 40,000 samples, together with the corresponding longitude and latitude coordinates.

Figure 4.3 presents the RxLev values for the two GSM network providers (MNO1 and MNO2) as measured through the onboard repeater. The figure also shows that the Network provider with the lowest RxLev is MNO2. The figure also shows that



(a) Coverage map of MNO1

(b) Coverage map of MNO2

Figure 4.1: The coverage map of two LTE networks operating on a frequency band not supported by the onboard repeaters

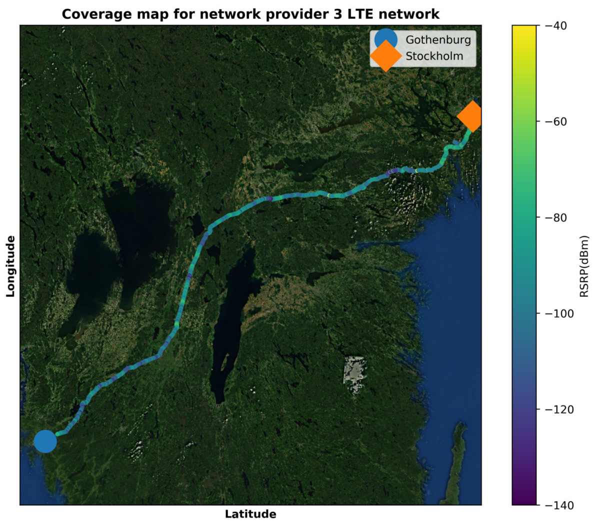


Figure 4.2: LTE coverage map for MNO3 measured onboard X2000. This network provider has a LTE band in the frequency band supported by the onboard repeater

MNO2 has poor to fair RxLev $\sim$ 10 % of the time, good RxLev $\sim$ 20 % of the time and excellent RxLev $\sim$ 70 % of the time. The gradings are presented in table 3.4.

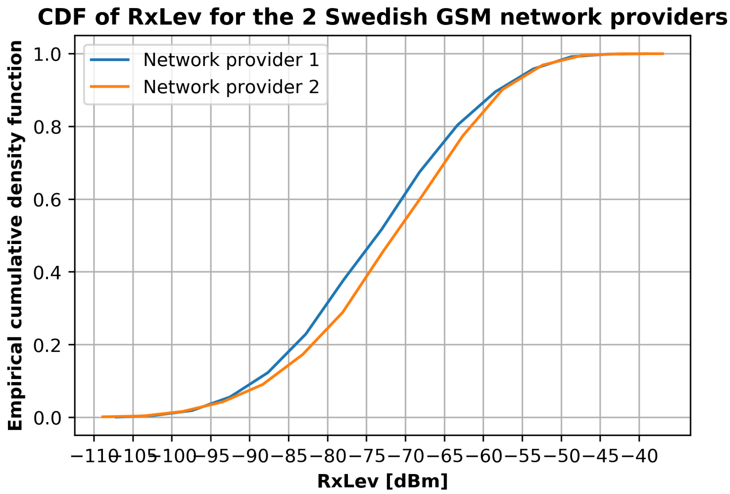


Figure 4.3: The RxLev onboard X2000 for the two GSM network providers in Sweden

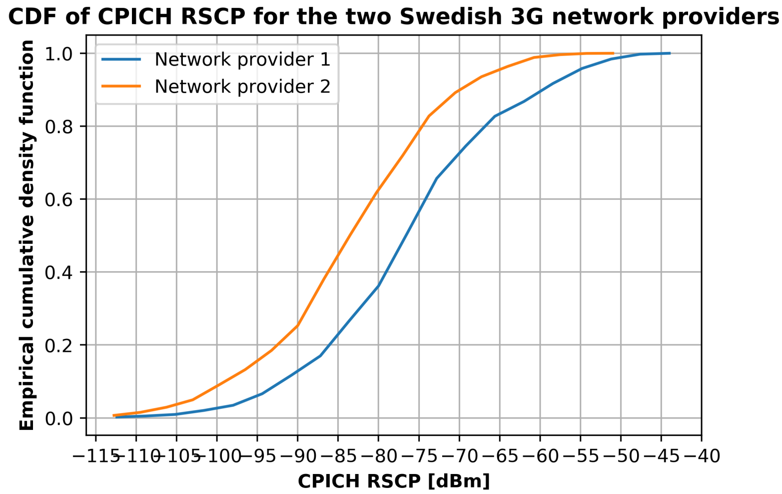


Figure 4.4: The CPICH RSCP onboard X2000 for the two 3G network providers in Sweden

Figure 4.4 presents the CPICH RSCP values for the two UMTS network providers (MNO1 and MNO2) also as measured through the onboard repeater. The network provider with the worst CHPICH RSCP network operator 2. One can see that network operator 2 has poor to fair RSCP values $\sim$ 5 % of the time, good $\sim$ 70 % of the time and excellent $\sim$ 10 % of the time.

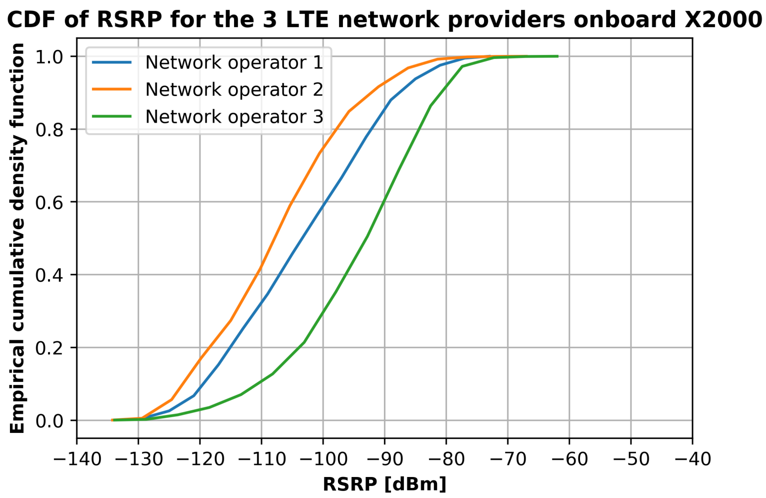


Figure 4.5: The RSRP onboard X2000 for the 3 LTE network providers in Sweden. The signal strength parameters are measured from onboard the train.

Figure 4.5 shows that the LTE coverage parameter RSRP for the three networks onboard the train. The network with the lowest RSRP values, i.e. network 2, performs bad $\sim$ 75 % of the time and good only $\sim$ 10 % of the time.

However, Network operator 3 which has a LTE band supported by the onboard repeater, performed significantly better than the other two. This is illustrated in figure 4.5. However, the network provider performed good only $\sim$ 40 % of the time.

For comparison figure 4.6 illustrates the RSRP values received by the onboard router from the antennas located on the train roof. One can see from the figure that the coverage is significantly better than the onboard LTE network. Figure 4.7 illustrates the coverage map when aggregating over all the links, and for each coordinate selecting the link with the highest RSRP. Aggregating the links based on the KPI RSRP does not have to be the way the links are aggregated onboard SJs X2000, however, the figure shows the potential link aggregation has to increase the coverage. This RSRP data is taken from the same X2000 trains the VoLTE measurements were conducted, in order to get a fair comparison of coverage.

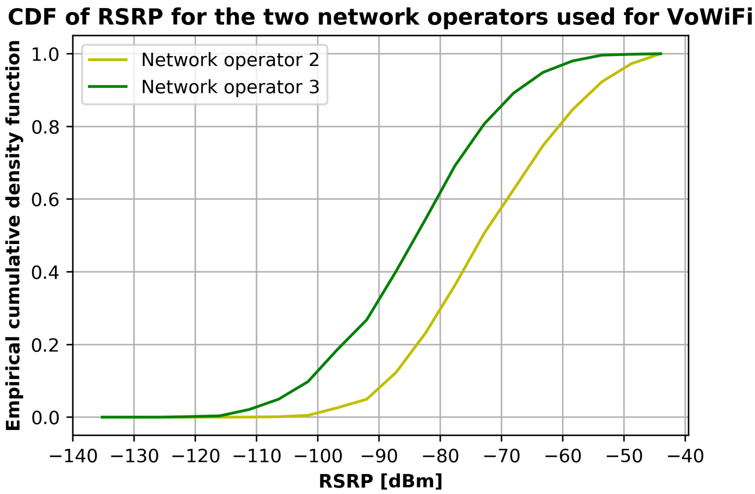


Figure 4.6: The measured RSRP from the LTE antennas used by the onboard WiFi router. The signal strength is collected from the antennas located on the roof of the X2000 train.

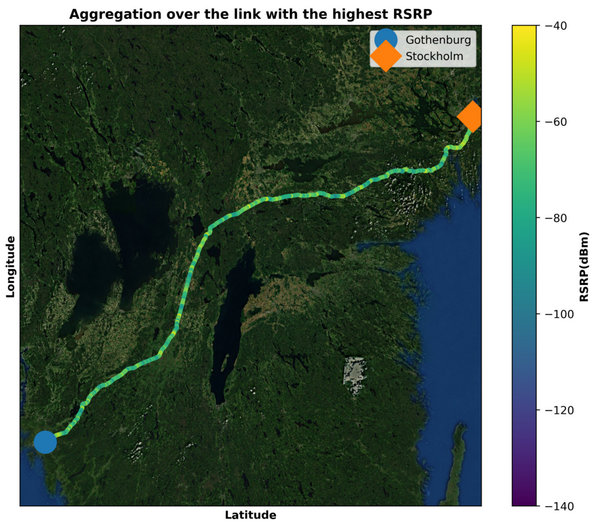
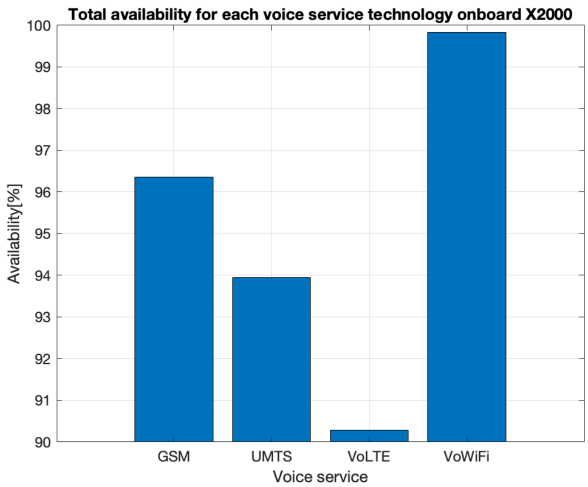


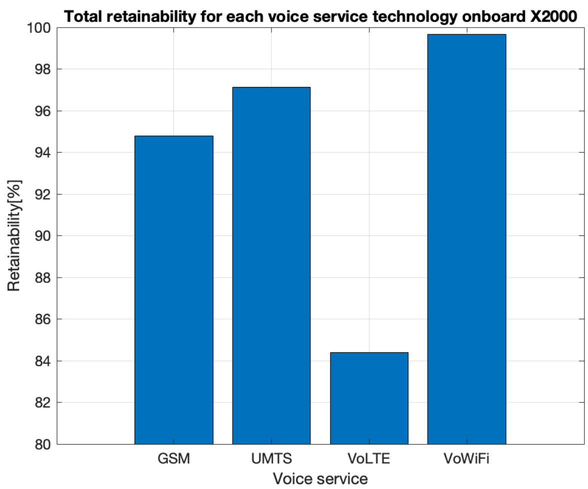
Figure 4.7: The coverage map showing the RSRP used by the onboard WiFi network. The map aggregates the the network with the strongest RSRP value.

4.2 Availability and retainability

This section presents the results from the measurement campaign where availability and retainability for each generation mobile network are the main KPIs. Figure 4.8 presents the total retainability and availability from all measurement campaigns. The availability and retainability is calculated using (3.2) and (3.1) respectively. As stated in the previous chapter, the data was post processed using Python scripts. It was noted that the dropped and blocked calls from GSM and UMTS did not occur in the same geographical area for each measurement. For VoLTE, however, the dropped and blocked calls occurred in the same geographical area. This was especially the case in the tunnels between Södertälje and Stockholm.



(a) Availability for each voice service



(b) Retainability for each voice service

Figure 4.8: The total availability and retainability for each voice service measured from onboard X2000

When analysing figure 4.8a one can see that GSM has an availability of $\sim$ 96%. UMTS has a slightly lower availablility of $\sim$ 94%. The cellular voice standard with the lowest availability is VoLTE with just 90%. VoWiFi has the highest availability with nearly 100 %.

From figure 4.8b one can see that GSM has a retainability of $\sim$ 95%. Voice over UMTS achieved a measured retainability of $\sim$ 97%. The voice technology with the lowest retainability is VoLTE with $\sim$ 84%. The highest performing voice technology when it comes to availability is VoWiFi with nearly 100 %.

The number of measurements performed varied for the different network standards. For GSM and UMTS four measurement campaigns were conducted for each network provider. Due to time limitations and the fact that only one network providers network could be measured per trip, only two measurement campaigns were conducted for VoLTE and VoWiFi each.

Tables 4.1 - 4.4 presents the data gathered when testing the GSM, UMTS, VoLTE and VoWiFi networks respectively. The tables show the total call, successful calls, dropped calls, blocked calls, availability and retainability, for each network provider. Note that network provider 2 in figure 4.1 has about 100 calls more than network provider 1. The reason LTE network operator 1 is empty in figure 4.3 is since the VoLTE service for this specific provider was not able to be activated on the test phone.

Table 4.1: The GSM results from the measurement campaign

Operator	**Call Attempts**	**Successful calls**	**Dropped calls**	**Blocked calls**	**Availability[%]**	**Retainability[%]**
Network provider 1	288	271	6	11	96.18	97.92
Network provider 2	389	355	15	19	95.12	95.14

Table 4.2: The UMTS results from the measurement campaign

Operator	**Call Attempts**	**Successful calls**	**Dropped calls**	**Blocked calls**	**Availability[%]**	**Retainability[%]**
Network provider 1	358	326	4	28	92.18	98.88
Network provider 2	358	333	17	8	97.77	95.25
Network provider 3	358	319	10	29	91.90	97.12

Table 4.3: The VoLTE results from the measurement campaign

Operator	**Call Attempts**	**Successful calls**	**Dropped calls**	**Blocked calls**	**Availability[%]**	**Retainability[%]**
Network provider 1	-	-	-	-	-	-
Network provider 2	178	119	37	22	87.64	79.21
Network provider 3	213	173	24	16	92.49	88.73

Table 4.4: The VoWiFi results from the measurement campaign

Operator	**Call Attempts**	**Successfull calls**	**Dopped calls**	**Blocked calls**	**Availability[%]**	**Retainability[%]**
Network operator 1	196	195	1	1	99.49	99.49
Network operator 2	200	199	1	0	100	99.5
Network operator 3	185	185	0	0	100	100

4.3 Voice quality test

The averaged voice quality scores for each measurement route is presented in figure 4.9. Note that there are fewer samples for VoLTE than for VoWiFi, due to the high amount of blocked and dropped calls that occured when calling over VoLTE.

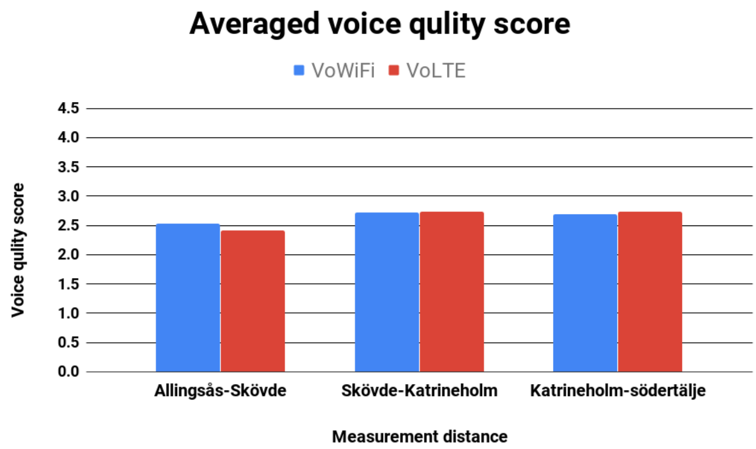


Figure 4.9: The averaged voice quality scores from the different measuring distances. The voice quality was measured on the rout between Allingsås-Skövde, Skövde-Katrineholm and Katrineholm - Södertälje

5
Discussion

This chapter discusses the results presented in the previous chapter. The validity of the results as well as the method used to achieve them will be discussed here. Future implementations of VoWiFi will also be discussed, as well as how this voice technology can be used by mobile operators to offload their LTE, and in the future 5G networks

5.1 The measurement significance

The results from the drive tests show that the voice technology with both the highest availability and retainability onboard SJ's X2000 is VoWiFi. There are, however parameters that the results do not fully reflect. The results do not take into account for the amount of passengers onboard the train at the particular time of the tests. With a higher number of passengers onboard the train the load on the cellular repeaters or the onboard WiFi will increase, and therefore degrade the QoS. The results also assume that the cellular repeaters onboard SJs X2000 fleet are similar and fully operational. If the repeater in the carriage where the test is conducted malfunctions the amount of blocked and dropped calls will statistically increase. The results do not either take into consideration faults that may occur in the mobile network providers core network.

To be able to determine a more significant result of the availability and retainability along the route more measurement samples would be required. From the limited number of meassurements it is not possible to conclude any performance differences between GSM and UMTS. However, the results from VoLTE is statistically worse than GSM/UMTS and VoWiFi is significantly better. With more measurements, factors such as a malfunctioning repeater, malfunctioning onboard WiFi network or malfunctioning test equipment during one of drive-tests will not have such a huge impact on the overall data.

5.1.1 Coverage

When studying the coverage results for GSM one can draw the conclusion that the RxLev is good or excellent along the route. This proves that the GSM coverage is good enough to perform voice calls for the entire duration of the route, thanks to the onboard repeater.

Much thanks to the onboard repeaters, one can also see that the network operators UMTS coverage is also sufficient onboard X2000. Just like in the case for GSM, this proves that the coverage is good enough to perform voice calls over UMTS for the entire duration of the route. However, one should keep in mind that different network providers may have different transmit powers on their CPICH. They may result in some of the coverage values indicated in figure 4.4 may in fact be worse than the boundary values presented in table 3.4.

The poor LTE coverage from networks 1 and 2 presented in figure 4.5 is due to the lack of support by the onboard repeater. Network 3 performs significantly better than the two other networks due to the repeater support in the 900 MHz frequency band. Even though this is a stronger performance than the two other LTE network operators, it is a very poor performance compared to the measured LTE coverage on the roof of the train as can be seen in figure 4.6.

When comparing the coverage maps presented in figures 4.1a, 4.1b and 4.2 with the aggregated coverage map presented in figure 4.7, one can see that the RSRP values for the aggregated LTE networks are higher throughout the testing route. One can also see that the coverage is more constant, meaning there are no, so called "white spots" when aggregating over the operators. The RSRP values illustrated in figure 4.6 are the values taken from the antennas located on the roof of the train connected to the onboard Wi-Fi system. Therefore one can conclude that the coverage when performing VoWiFi calls is excellent throughout the entire test route, with no "white spots".

5.1.2 Availability and retainability

The availability for the different cellular voice technologies is illustrated in figure 4.8. The figure makes it clear that the voice technology with the highest availability and retainability is VoWiFi. VoWiFi has almost 100 % availability and retainability. The voice technology with the worst performance, in terms of availability and retainability, is VoLTE. One reason for this is the fact that network provider 1 and 2 do not have any LTE frequency bands supported by the onboard repeater.

Unfortunately the VoLTE service for network provider 1 was not supported on the subscription used when testing the network, resulting in no data for the VoLTE service is included in the results. However, when analyzing the coverage map in figure 4.1a one can make the assumption that the availability and retainability would be similar to, or even worse than network provider 2.

Regarding the circuit-switched networks, i.e. GSM and UMTS, one can see from the previous section that the coverage is more than adequate for the duration of the route. However, the results in figure 4.8 show that the availability and retainability is not perfect, in fact the availability for UMTS is rather low compared to VoWiFi. Therefore a reasonable explanation for the dropped and blocked calls can may be the capacity limitations in the cellular network, and the cellular network are poorly optimized. This refers back to the theory section, local dimensioning of the network.

5.2 Voice quality

Figure 4.9 shows that the averaged voice quality score for VoWiFi is similar to VoLTE. Due to the high amounts of dropped and blocked calls when calling over VoLTE, the voice samples turned out to be significantly fewer than those recorded when calling over VoWiFi.

As mentioned in chapter 3 the method for measuring voice quality is not optimal and should not be compared to the more general MOS score measured with the POLQA algorithm. The 3.5 mm audio cable used adds a noise to the input of the recording software. The amplification of the sound on the mobile is also a tradeoff. If the output volume from the test mobile is too high the sound will experience distortion. However if the output volume is to low, the noise will dominate the recorded sound and PESQ will return a score lower than the actual sound quality. For the purpose of this thesis, the author experimented with different volume levels, and found a level where the recordings sounded adequate.

The PESQ algorithm is not the optimal way for determining the voice quality of packet-switched voice services. It was introduced in 2001, to determine the voice quality of the cellular voice services at the time, before the existence of VoLTE and VoWiFi. The more modern Perceptual Objective Listening Quality Analysis (POLQA), or models based on IP parameters such as latency, packet loss and jitter would be a more optimal way to determine the onboard voice quality.

5.3 Future implementations of VoWiFi

The Swedish licences for spectrum on the 900 MHz and 1800 MHz will expire in 2025. On these frequency bands many mobile operators have circuit-switched voice, i.e GSM and UMTS, and the expiring licenses will most likely be the end of circuit-switched voice. Moving all customers from the circuit-switched network to the packet-switched network will result in a increased load on the LTE, or by 2025 the 5G network, and alternative voice services, such as VoWiFi, will be a method for offloading the mobile networks. In [36] Cisco predicts that 48 % of the data in the 5G networks will be offloaded by WiFi networks by 2021. With the support for VoWiFi in modern smart phones this prediction will also be the case for voice services.

When it comes to VoWiFi on board public transportation, such as trains, VoWiFi is a technically feasible alternative to onboard repeaters. With the expiring circuit-switched voice services, and the new frequency bands introduced to 5G, the analog repeaters will require an update, which will result in an economically expensive procedure. Instead the onboard WiFi network can be utilized, not only for data, but also for voice services.

5.4 Future work

There several other measurements that can be performed in the future. One measurement would be using the state-of-the-art algorithm, POLQA, that returns a more general MOS score. Another measurement would be to test different routs, and different train models. Testing the handover between VoLTe and VoWiFi is of great importance in order to improve the QOS. This could be an interesting case study, in order make the handover seamless in cases where a call is conducted when the caller moves from the train onto the platform.

6
Conclusion

The traditional circuit-switched voice networks are slowly moving towards packet-switched, giving way for alternative IP-based wireless voice services. Not only do the packed-switched voice services increase the capacity for each cell, but it also provides an opportunity for other enterprises, beside the network operators themselves, to provide coverage for their customers. This is the case onboard public transportation, specifically onboard trains.

Providing coverage onboard trains has proved to be difficult due to the shielding effects of the train chassis, as well as due to the poor coverage in the vast rural locations along the train tracks. Onboard WiFi solution often bypasses the shielding effect of the train chassis by using cellular antennas on the train roof connected to an onboard routers and access points throughout the train distributing passenger WiFi. The system uses link aggregation to maximize the capacity as well as increases the coverage.

This report shows that the occurrence of dropped and blocked calls is a problem with circuit-switched and packed-switched voice over LTE. Based on the measurements performed in this report, VoWiFi using a WiFI solution is a feasible alternative to providing voice services onboard trains. This report shows that calling over VoWiFi, onboard SJ's X2000, outperforms GSM, UMTS and VoLTE when it comes to availability and retainability, on the route Gothenburg to Stockholm. Cellular repeaters onboard trains are not only expensive to install, but they may also cause undesired effects to the RF signals onboard, and next to the train tracks.

Degraded voice quality is a direct consequence of poor coverage and poor channel conditions. This has also proved to be the case onboard the X2000 trains. When it comes to voice quality onboard VoLTE and VoWiFi have similar quality according to the PESQ algorithm. It is important to recognize the fact that these results are specific to the method, testing route, train carriage configuration, repeater models and onboard WiFi system.

In conclusion we find that VoWiFi is a voice technology superior to cellular voice technologies provided by repeaters onboard trains both from a technical and, probably, also from an economical point of view.

Bibliography

[1] PTS, "*Mobile voice and data - number of outgoing calls (millions) from end-user.*" [Online]. Available: https://statistik.pts.se/variablevalue/VariableValuesResult/2132/?tableName=Tabell%2014%20Samtal%20-%20antal&&subheader=Mobile%20voice%20and%20data%20-%20number%20of%20outgoing%20calls%20(millions)%20from%20end-user%20[6]*

[2] T. Berisha, P. Svoboda, S. Ojak, and C. F. Mecklenbrauker, "Cellular network quality improvements for high speed train passengers by on-board amplify-and-forward relays," in *2016 International Symposium on Wireless Communication Systems (ISWCS)*. IEEE, 2016, pp. 325–329.

[3] T. Berisha, P. Svoboda, S. Ojak, and C. F. C.F.Mecklenbrauker, "Benchmarking in-train coverage measurements of mobile cellular users," in *Vehicular Technology Conference (VTC-Fall), 2017 IEEE 86th*. IEEE, 2017, pp. 1–5.

[4] OFCOM. An assessment of the effects of repeaters on mobile networks. [Online]. Available: https://www.ofcom.org.uk/__data/assets/pdf_file/0017/85004/eeffects_of_repeaters_on_mobile_networks.pdf

[5] Y. Zhou and B. Ai, "Evaluation of high-speed train communication handover models based on DEA," in *2014 IEEE 79th Vehicular Technology Conference (VTC Spring)*. IEEE, 2014, pp. 1–5.

[6] M. Alasali, C. Beckman, and M. Karlsson, "Providing internet to trains using MIMO in LTE networks," in *Connected Vehicles and Expo (ICCVE), 2014 International Conference on*. IEEE, 2014, pp. 810–814.

[7] A. Valdar, *Understanding telecommunications networks*. IET, 2006, vol. 52.

[8] M. Poikselkä, H. Holma, J. Hongisto, J. Kallio, and A. Toskala, *Voice over LTE: VoLTE*. John Wiley & Sons, 2012.

[9] J. Garcia, S. Alfredsson, A. Brunstrom, and C. Beckman, "Train velocity and data throughput-a large scale LTE cellular measurements study," in *2017 IEEE 86th Vehicular Technology Conference (VTC-Fall)*. IEEE, 2017, pp. 1–6.

[10] M. Lerch, P. Svoboda, D. Maierhofer, J. Resch, A. Brantner, V. Raida, and M. Rupp, "Measurement based modelling of in-train repeater deployments," in *IEEE 89th Vehicular Technology Conference (VTC2019-Spring), Kuala Lumpur, Malaysia*, 2019.

[11] K. Hiltunen, "Using RF repeaters to improve WCDMA HSDPA coverage and capacity inside buildings," in *2006 IEEE 17th International Symposium on Personal, Indoor and Mobile Radio Communications*. IEEE, 2006, pp. 1–5.

[12] L. Ahlin, J. Zander, and S. Ben Slimane, *Principles of wireless communications*. Studentlitteratur, 2006.

[13] V. Garg, *Wireless communications & networking*. Elsevier, 2010.

[14] S. M. Redl, M. K. Weber, and M. W. Oliphant, *An introduction to GSM.* Artech house, 1995.

[15] J. Laiho, A. Wacker, and T. Novosad, *Radio network planning and optimisation for UMTS.* John Wiley & Sons, 2006.

[16] H. Holma and A. Toskala, *WCDMA for UMTS: Radio access for third generation mobile communications.* john wiley & sons, 2005.

[17] M. Rahnema, “UMTS network planning, optimization, and inter-operation with gsm,” 2008.

[18] J. P. Castro, *The UMTS network and radio access technology.* Wiley Online Library, 2001.

[19] H. Holma and A. Toskala, *WCDMA for UMTS.: Radio Access for Third Generation Mobile Communications.* John Wiley & Sons, 2005.

[20] M. Nohrborg, “LTE overview,” 3rd Generation Partnership Project (3GPP), Tech. Rep., 2008. [Online]. Available: https://www.3gpp.org/technologies/keywords-acronyms/98-lte

[21] D. López-Pérez, A. Ladányi, A. Jüttner, H. Rivano, and J. Zhang, “Optimization method for the joint allocation of modulation schemes, coding rates, resource blocks and power in self-organizing LTE networks,” in *2011 Proceedings IEEE INFOCOM.* IEEE, 2011, pp. 111–115.

[22] E. Dahlman, S. Parkvall, and J. Skold, *4G: LTE/LTE-advanced for mobile broadband.* Academic press, 2013.

[23] M. R. Tabany, C. G. Guy, and R. S. Sherratt, “A novel downlink semi-persistent packet scheduling scheme for VoLTE traffic over heterogeneous wireless networks,” *EURASIP Journal on Wireless Communications and Networking*, vol. 2017, no. 1, p. 62, 2017.

[24] 3GPP, *“AMR wideband speech codec; transcoding functions,”*. [Online]. Available: https://www.3gpp.org/ftp/Specs/archive/26_series/26.190/

[25] A. Elnashar, M. A. El-Saidny, and M. Yehia, “Performance evaluation of VoLTE based on field measurement data,” *arXiv preprint arXiv:1810.02968*, 2018.

[26] D.-H. Nguyen, H. Nguyen, and E. Renault, “A new non-intrusive model for measuring VoLTE quality based on wideband e-model,” *Communications on Applied Electronics*, vol. 5, no. 8, p. 8, 2016.

[27] J. Shapira and S. Miller, *CDMA radio with repeaters.* Springer Science & Business Media, 2007.

[28] P. Lähdekorpi, T. Isotalo, S. U. Khan, and J. Lempiäinen, “Implementation aspects of RF-repeaters in cellular networks,” in *21st Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications.* IEEE, 2010, pp. 2511–2516.

[29] F. Firmin. The evolved packet core. [Online]. Available: https://www.3gpp.org/technologies/keywords-acronyms/100-the-evolved-packet-core

[30] Cisco. Wi-Fi calling white paper. [Online]. Available: https://www.cisco.com/c/en/us/solutions/collateral/enterprise-networks/802-11ac-solution/white-paper-c11-735826.html

[31] S. F. M. Ngongang, N. Tadayon, and G. Kaddoum, “Voice over Wi-Fi: feasibility analysis,” in *2016 Advances in Wireless and Optical Communications (RTUWO).* IEEE, 2016, pp. 133–138.

[32] E. Dahlman, S. Parkvall, J. Sköld, and P. Beming, *3G evolution: HSPA and LTE for mobile broadband*. Academic press, 2010.

[33] 3GPP, "Evolved universal terrestrial radio access (E-UTRA)," vol. 9. [Online]. Available: https://www.etsi.org/deliver/etsi_ts/136200_136299/136214/09.02.00_60/ts_136214v090200p.pdf

[34] Gyokovsolutions. G-nettrack pro manuals. [Online]. Available: https://www.gyokovsolutions.com/manuals/gnettrackpro_manual.php

[35] A. W. Rix, J. G. Beerends, M. P. Hollier, and A. P. Hekstra, "Perceptual evaluation of speech quality (PESQ) a new method for speech quality assessment of telephone networks and codecs," in *2001 IEEE International Conference on Acoustics, Speech, and Signal Processing. Proceedings (Cat. No. 01CH37221)*, vol. 2. IEEE, 2001, pp. 749–752.

[36] "*Cisco visual networking index: Global mobile data traffic forecast update, 2017–2022 white paper*." [Online]. Available: https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white-paper-c11-738429.html

[37] J. Eberspächer, H.-J. Vögel, C. Bettstetter, and C. Hartmann, *GSM-architecture, protocols and services*. John Wiley & Sons, 2008.

[38] GSM the base station subsystem (BSS). [Online]. Available: https://www.tutorialspoint.com/gsm/gsm_base_station_subsystem.htm

[39] GSM the operation support subsystem (OSS). [Online]. Available: https://www.tutorialspoint.com/gsm/gsm_operation_support_subsystem.htm

[40] C. Cox, *An introduction to LTE: LTE, LTE-advanced, SAE and 4G mobile communications*. John Wiley & Sons, 2012.

A

Appendix 1

A.1 GSM network architecture

An illustration of the GSM network architecture is presented in figure A.1 and is divided into three subsystems; the Base Station Subsystem (BSS), the Network Switching Subsystem (NSS) and the Operation Support Subsystem (OSS).

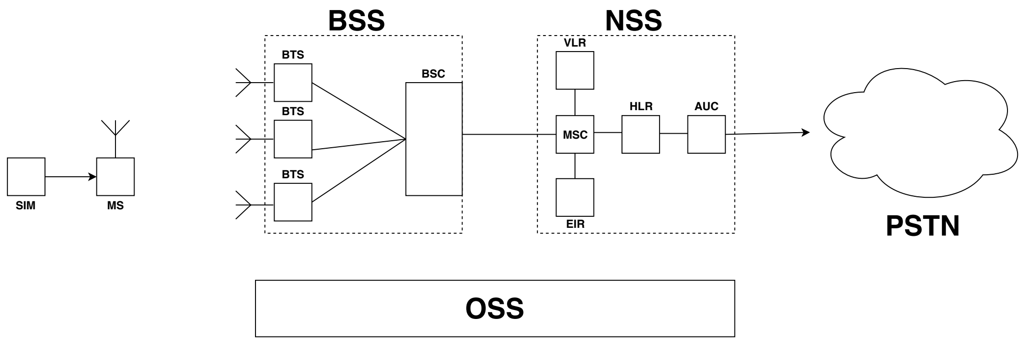


Figure A.1: The GSM network architecture, simplified to three main blocks.

The BSS is the radio network interface of the GSM network and is composed of two components, the Base Transceiver Stations (BTS) and the Base station Controller (BSC). The BTS is the networks counterpart of the Mobile Station (MS). A BTS consists of both transmitters and receivers, and are usually located on an elevated position in order to provide a large coverage area, i.e. a large cell size [37]. A single base station mast can consist of several transceivers, each of which determines a separate channel [14]. The BTS is the unit in that handles radio parameters such as time and frequency synchronization as well as uplink channel measurements [38]. The BSC is the part if the BSS that controls the handovers of the MS to different BTS, as well as manages the radio resources. A single BSC can manage multiple BTS, depending on the mobile network operator or the equipment manufacturer.

The NSS, or also called the Core Network handles services such as roaming and authentication validation. The NSS consists of the following blocks:

- The *gateway mobile services switching center* (GMSC) which is the interface of the cellular network to the PSTN [14].

- The *visitor location register* (VLR), which contains temporary information of the MSs currently located in a MSC.

- The *home location register* (HLR), which contains information about the MSs registered on the specific MSC.

- The *equipment identity register* (EIR), which stores information about the serial numbers of each specific MS. This register is optional for each network provider, and is used to blacklist phones that have been stolen or, for some other reason, aren't allowed to operate on the network [14].

- The *authentication center* (AUC) that provides the HLR with the parameters needed to authenticate a MS.

The final block in the simplified GSM model is the operation support subsystem (OSS). This is the GSM subsystem the network providers use to monitor their core network, as well as the BSS. The OSS is of great importance for the network providers in order to be able to offer the subscribers the desired QOS. The OSS gives the *network operation center* (NOC) the ability to, in real time, monitor ongoing network maintenance or capacity simulations on their network [39].

A.1.1 UMTS network architecture

The UMTS network is divided into two main network subsystems, the radio network and the core network, and is illustrated in figure A.2. As part of the radio network block are the base stations, or Node B as they are called in 3G, and the Radio Network Controller (RNC). The Node B is the counterpart of the MS in the UMTS mobile network, and corresponds the the BTS in the previous generation GSM. The Node B is in charge for the wireless interface in UMTS, which involves channel coding, interleaving, rate adaptation, modulation and demodulation of the radio signals [19]. The Node Bs are controlled by the RNC. One RNC can control either one, or several Node Bs. The RNC allocates the radio resources for the wireless interface of the Node Bs and is the logical gateway between the packet switched and the circuit switched packed core network [19].

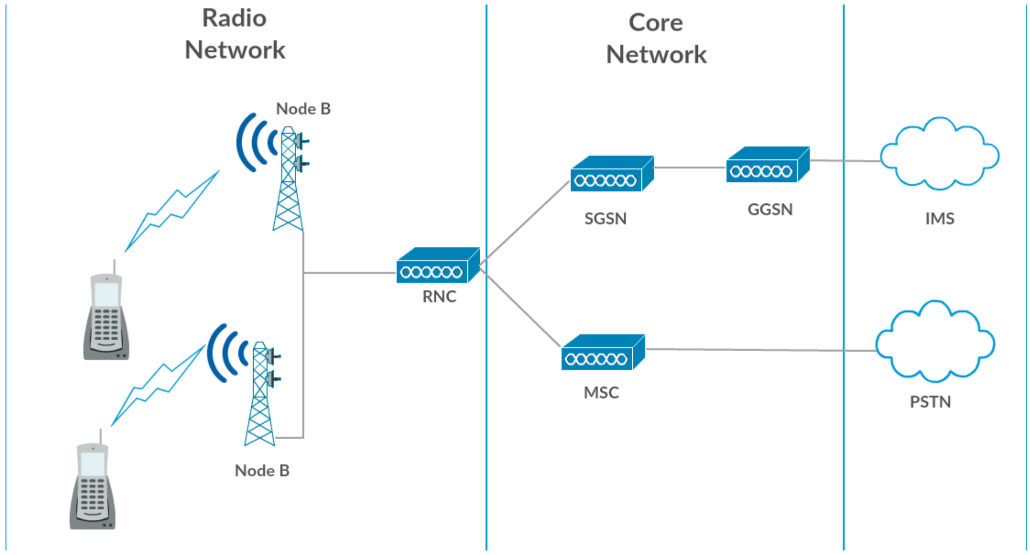


Figure A.2: System architecture of the UMTS mobile network.

The UMTS core network is divided in a circuit switched part, and a circuit-switched part. The packet switched side (lower block in the Core Network subsystem in figure A.2) is the Mobile switching center (MSC). The circuit-switched part of the UMTS Core Network is similar to the one in GSM, and will therefore not be described again. The packet switched part, also known as general packet radio service (GPRS) consists of a Serving GPRS support node (SGSN), and Gateway GPRS support node (GGSN).

A.1.2 LTE architecture

A simplified model of the LTE network architecture is illustrated in figure A.3, where the LTE networks is divided into two subsystems the Evolved Universal Terrestrial Radio Access Network (E-UTRAN) and the Enhanced packet core (EPC).

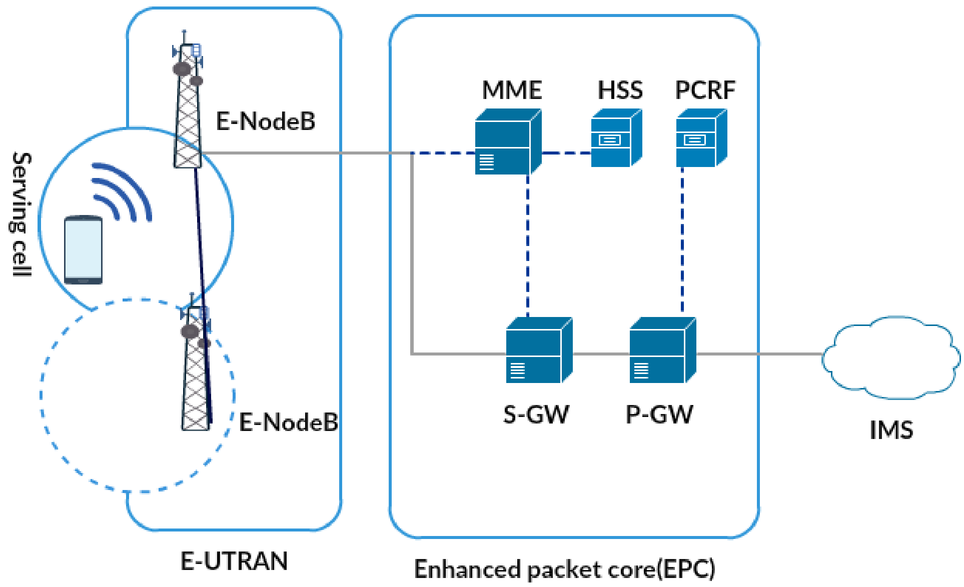


Figure A.3: The LTE network architecture.

The E-UTRAN, or the LTE radio access network, handles the wireless interface between the MS and the EPC, and consists of the Evolved NodeB (E-nodeB), the base stations in LTE. The main functionalities of the E-NodeB is to handle the radio transmissions to the UEs, both the uplink and downlink, as well as managing the signaling channels used for services such as handovers [40]. In the LTE E-UTRAN the functionality of the RNC has been merged into the E-NodeB, in order to reduce the latency and provide better QOS for data traffic such as video streaming and live VoIP calls [40].

The second sub system of the LTE network is the core network, or the Enhanced packet core. The EPC consists of the following directories and gateways [40];

- The Mobility management entity (MME), that stores information about it.
- The Home subscriber server, that stores information about the subscribers of the network operator.
- The Serving gateway, a router that directs packets between the P-GW and the radio network.
- The Packet data network gateway, is the gateway between LTE network and the different networks such as the PSTN, Internet and IMS.

In figure A.3 the dotted lines represent the signaling paths, and the whole lines represent the IP-packet paths.